Multi-Line Hybrid Flow Shop Scheduling Problem with Energy Considerations

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***Abstract* — This paper deals with the modelling of a new energy efficient scheduling problem. More specifically, it focuses on a multi-line hybrid flow shop. The problem consists of optimizing total energy cost under Time-of-Use pricing with respect to additional constraints: (i) total energy consumption, (ii) peak power limitations and (iii) makespan. An exact solving approach is investigated and results are analysed on a sample of randomly generated instances**.

Keywords—Scheduling, Multi-line Hybrid Flow-shop, Energy efficiency, time of use pricing

I. INTRODUCTION

The industry is one of the largest energy consumers. Industries utilize traditional metrics including cost, time, quality, and flexibility to assess the performance of their operational, tactic and strategic decisions. High-energy prices have driven industrials to consider the improvement of their energy performance for economic prosperity. Improving energy efficiency can be achieved by optimizing three criteria: (i) total energy consumption, (ii) peak power load, (iii) energy cost. Many research works have been done in the area of energy efficient scheduling systems. Moreover, results have shown the relevance of integrating energy efficiency criteria within manufacturing systems. Most papers focus on one or two aspects of energy efficient scheduling with total energy consumption being one of the most common criterion. Furthermore, energy efficiency was introduced in the scientific literature on three different levels. At the machine level, Mori et al. [1] proposed a study with the goal to improve the energy efficiency of machine tools. Considering products, Krishnan et al. [2] suggested methods for sustainable product design considering carbon footprint and energy efficiency. Finally, production systems which are treated in this paper.

In this paper, we investigate a mixed integer linear model for a multi-line hybrid flow shop-scheduling problem. We include all three criteria of energy efficiency while considering known operations power profiles. Several production lines offer path flexibility for the jobs assigned to them, thanks to several available machines at a given stage. The objective function consists of minimizing energy cost subject to total energy consumption and peak power constraints over all the lines. Reducing energy costs can be achieved by on/off strategies, or, by using variable energy prices, which consists of producing more when energy prices are low.

In the problem at hand, a time-of-use pricing model is considered where energy prices are specified for all periods of time ahead of scheduling. The contribution of the paper is summarized as follows:

- To our best knowledge, multi-line hybrid flow shop energy efficient scheduling problem has been treated for the first time in this paper.
- The model relies on the three energy aspects: total energy consumption, peak power consumption, and energy cost under TOU pricing as constraints or objective. The makespan is selected as a constraint.
- Variable power profiles of machining operations are considered.

This paper is structured as follows: Section 2 gives an overview about the literature review related to energy efficient scheduling followed by the definition of the research problem in section 3. A mixed integer linear model is proposed and detailed in section 4. In Section 5, a case study serves as an assessment of the performance, and the results of the mathematical model are discussed in Section 6. Finally, Section 7 concludes this research work and introduces future perspectives.

II. LITTERATURE REVIEW

Hundreds of articles treated energy optimization problems within manufacturing systems. Mouzon et al. [3] developed heuristics and a multi-objective mathematical model to reduce total energy consumption and total completion time on a single machine. Additionally, Mouzon and Yildirim [4] proposed a metaheuristic to reduce total energy consumption and total tardiness on a single machine scheduling problem.

Kemmoé-Tchomté et al. [5] proposed a linear mathematical model and an exact approach using CPLEX solver to reduce the makespan with peak power restrictions. Meng et al. [6] discussed six mixed integer linear models with on/off strategy to reduce the idle time and total energy consumption for a flexible job shop scheduling problem. The author used an exact method to compare the performance of the proposed models based on their size and complexity. Masmoudi et al. [7] proposed a time-indexed, a disjunctive formulation, and a heuristic to reduce the makespan and energy cost for a job shop-scheduling problem. Bruzzone et al. [8] proposed a time-indexed linear model to minimize the makespan subject to power peak restriction for a flexible flow shop scheduling problem. Dai et al. [9] proposed a multi-objective model and a genetic algorithm to optimize total energy consumption and makespan for a flexible flow shop scheduling problem. Fang et al. [10] worked on a disjunctive and a time-indexed mathematical formulation as well as two heuristics to reduce the makespan with an upper bound on the peak consumption for a Permutation flow shop-scheduling problem. Yan et al. [11] proposed a multi-objective model and a meta-heuristic to reduce the makespan and total energy consumption for a flexible flow shop problem.

As stated in Neufeld et al. [12], hybrid and flexible flow shop are common in the industry because they offer flexibility to the industrial system. Ruiz and Vasquez Rodriguez [13] have proposed a detailed classification of hybrid flow shop scheduling problems. Few energy aspects optimization have been considered and integrated in hybrid flow shop scheduling problem. Energy blocks methodology is a common methodology used to accurately model energy consumption of an industrial system, which has been proposed to integrate energy efficiency and effectiveness metrics within operations scheduling and planning Weinert et al. [14]. Schulz et al. [15] discussed a multi-objective model to simultaneously reduce the makespan, peak power consumption and total energy consumption cost using real time energy pricing strategy (RTE) and proposed an iterated local search algorithm (heuristic) for a hybrid flow shop scheduling problem. Wang et al. [16] proposed a mixed integer model and heuristics to minimize total energy consumption and makespan for hybrid flow shop problem. Ding et al. [17] proposed a multi-objective model and meta-heuristic to optimize energy cost under time of use prices and total tardiness for a flexible flow shop scheduling problem. Lu et al. [18] proposed a mixed integer linear model and a meta-heuristic to minimize total energy consumption for a hybrid flow shop scheduling problem with parallel machines and batch production. Chen et al. [19] selected the makespan and total energy consumption under time of use and ladder electricity prices strategies as energy efficiency indicators to achieve carbon neutrality. The indicators were integrated within a multi-objective model and a heuristic was discussed for the resolution.

Multi-line systems have recently been introduced in the scientific literature. To the best of our knowledge, multi-line production systems have not been treated with energy considerations. On the other hand, they are generally found under the terminology of "distributed" shop floors, modelling lines located at different production sites, rather than actual multi-line systems. Ruiz, Pan and Naderi [20] discussed a heuristic to optimize the makespan for a distributed flow shop scheduling problem. Shao et al. [21] performed a meta-heuristic for a distributed hybrid flow shop-scheduling problem with identical factories. According to Brammer et al. [22], multi-line production systems aim at improving the production capacity and synchronization. The authors proposed a mixed integer linear program with the goal to optimize the makespan and a reinforcement learning approach for a multi-line permutation flow shop-scheduling problem.

III. Problem Formulation

In this paper, a multi-line hybrid flow shop problem with time of use (TOU) pricing is considered. A set J of n jobs has to be processed on a set L of different production lines. A job $j \in J$ should be assigned to a line $l \in L_j$, where L_j denotes the subset of available lines for the job j. Each job j is divided into a set of operations O_{jl} which size depends on the number of stages of the line. Once a line is selected for the job j, it is hence processed on $|O_{jl}|$ consecutive stages. A stage is defined by one or more parallel heterogeneous machines $m \in M_{jlo}$, with $o \in \{1,..,|O_{jl}|\}$. Thus, once a job $j \in J$ is assigned to a line $l \in L$, it incorporates the line's path flexibility. Each operation $o \in O_{jl}$ has a processing time P_{jlom}, and a total energy consumption E_{jlom}. Energy blocks methodology is considered to subdivide every operation $o \in O_{jl}$ into P_{jlom} sub-operations. This method allows to consider more accurately the variability of power profiles. Considering an operation $o \in O_{jl}$, and assigned to machine $m \in M_{jlo}$, the power requirement of its i^{th} sub-operation ($i \in [1..P_{jlom}]$) is noted W_{ijlom}. The schedule is subject to a deadline modelled as a predetermined makespan C_{max}, and the time horizon is divided into $t \in [1..C_{max}]$ unitary periods. W_{max} and TEC_{max} are respectively the maximum allowed power usage and total energy consumption during the schedule. Finally, the problem consists in determining the starting time of each operation (s_{jlom}^{t}) in order to minimize the total energy cost C_T considering a price Q_t per period of time t.

The problem is also based on the following assumptions:

- All jobs once assigned to a line must follow the same processing sequence with no pre-emption
- Parallel machines are assumed to be heterogeneous in terms of power requirements and processing times.
- Set up times are included in the processing times
- Infinite storage capacity between stages
- The production lines share one common resource: the power supply.

IV. Mixed Integer linear model

We propose a mixed integer linear model to solve the multi-line hybrid flow shop problem with the goal of optimizing energy cost subject to peak power, total energy consumption and makespan constraints.

The decision variables are defined as follows:

s_{jlom}^{t}: Binary variable indicating if the operation o of job j has started on the machine m of line l at time period t.

The goal is to minimize energy cost with respect to total energy consumption, peak power and makespan constraints considering variable power profiles. The model is formulated as follows:

Objective function:

$$\boldsymbol{Min\ C_T} = \sum_{j\in J}\sum_{l\in L_j}\sum_{o\in O_{jl}}\sum_{m\in M_{ojl}}\sum_{t=0}^{T-P_{jlom}}\sum_{t'=0}^{P_{jlom}} \boldsymbol{W_{t'jlom} . Q_{t+t'} . s_{jlom}^{t}}$$

Subject to:

$$\sum_{l \in L_j} \sum_{m \in M_{jl1}} \sum_{t=0}^{P_{jl1m}} s_{jl1m} = 1,\ \forall j \in J \quad (1)$$

$$s_{jlom}^{t} \leq \sum_{m' \in M_{jl(o+1)}} \sum_{t'=t+P_{jlom}}^{T-P_{jl(o+1)m'}} s_{jl(o+1)m'}^{t'}\ \forall j \in J, \quad (2)$$
$$l \in L_j, \forall o \in [1..|O_{jl}|-1], \forall m \in M_{jlo},\ \forall t \in [0,\ T - P_{jlom}]$$

$$s_{jlom}^{t} + \sum_{t'=t}^{t+P_{jlom}-1} s_{j'lom}^{t'} \leq 1 \quad (3)$$
$$\forall j, j' \in J,\ j \neq j', \forall l \in L_j, \forall o \in O_{jl}, \forall\ m \in M_{jlo},\ \forall t \in [0; T - P_{jlom}]$$

$$\sum_{m \in M_{jlo}} \sum_{t=0}^{T-P_{jlom}} (t + P_{jlom} - 1).s_{jlom}^{t} \leq C_{max} \quad (4)$$
$$\forall j \in J,\ l \in L_j, \forall o \in O_{jl}$$

$$\sum_{j \in J} \sum_{l \in L_j} \sum_{o \in O_{jl}} \sum_{m \in M_{jlo}} \sum_{t=0}^{min(t,P_{jlom}-1)} W_{t'jlom}.s_{jlom}^{t-t'} \quad (5)$$
$$\leq W_{max}^{T}\ , \forall t\ \in [0,\ T[$$

$$\sum_{j \in J} \sum_{l \in L_j} \sum_{o \in O_{jl}} \sum_{m \in M_{jlo}} \sum_{t \in T} E_{jlom}.s_{jlom}^{t} \leq TEC_{max}^{T} \quad (6)$$

$$s_{jlom}^{t} \in \{0; 1\}, \forall\ j \in J, \forall\ \ l \in L_j, \forall\ o \in O_{jl}, \forall m \in M_{jlo}, \forall t \in [0, C_{max} - P_{jlom}]$$

Constraint (1) ensures that for every job $j \in J$, the starting date of its first operation on a line $l \in L_j$ on a machine $m \in M_{jl1}$ at $t \in [0, T - P_{jlom}]$ is unique. Constraint (2) imposes the respect of the processing order of operations of a job j by defining the starting dates accordingly. This constraint also ensures that the job remains on its selected line. Constraint (3) ensures that a machine can process only one job at a time. Constraint (4) assumes that the total completion time for each job cannot exceed the makespan limit. The set of constraints (5) and (6) takes into account an upper bound on both peak power and total energy consumption during the whole planning horizon.

V. NUMERICAL EXAMPLE

We consider a system of three jobs, two lines and five machines (Fig.1). Line number 1 has two stages where there are parallel machines (M2 and M3) on the second stage. On line number 2, there are two stages and each stage is constituted of one machine. We assume that j_0 can be processed both on line 1 and 2, j_1 can only be processed on line 1, j_2 can only be processed on line 2. The processing times and energy consumptions are predefined. (*Table1*) represents energy prices defined per consecutive time slot durations (i.e. the 1st period lasts 2 time-units and the energy price accounts for 5 monetary units).

This pricing scheme of 24 time units would repeat cyclically depending on the considered value of C_{max}.

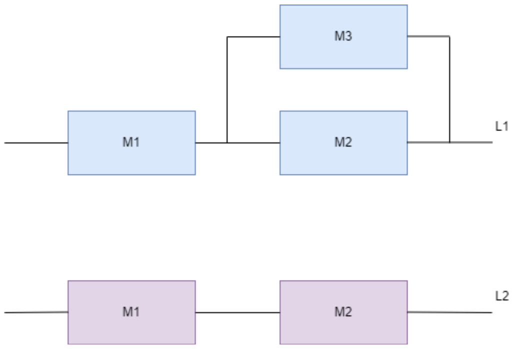

Fig. 1. Example of a production system's architecture.

TABLE I. ENERGY PRICES EVOLUTION PER TIME DURATIONS

Periods	Duration (Time units)	Energy Prices Q_t (Monetary units)
1	2	5
2	3	10
3	5	12
4	6	18
5	4	16
6	4	9

The model is implemented considering the following parameters on this specific problem: Maximum total energy consumption TEC_{max}^{T}= 500; maximum power peak W_{max}^{T}= 30; Maximum makespan C_{max}= 23. The result is displayed as a Gantt chart in Fig.2. As can be viewed in this figure, the returned optimal cost equals 5496. According to these parameters, job j_2 and j_0 are ending their process at 23 which is equal to the maximum makespan. As it is, the schedule does not benefit from favourable pricing time slots, and only the second operation of j_1 is postponed to time 16, avoiding the high energy price of period *P4*. The maximum power peak is attained at times 15 and 20 with three operations processed simultaneously. In this scenario, the observed energy consumption is below the maximum considered threshold (i.e. 500).

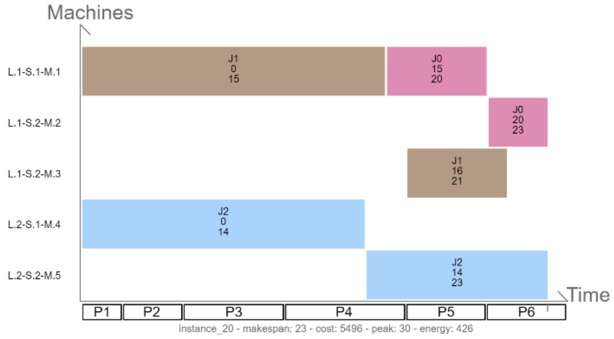

Fig. 2. Optimal schedule minimizing the cost with consideration to a limit on makespan (valued 23), total energy consumption and peak power as constraints (cost: 5496)

When a higher makespan is considered (all other parameters remain equal to their previous assigned values), a decrease in energy cost is observed in Fig. 3. In this scenario, the makespan is set to 30, and the observed optimal cost is equal to 4231, representing a decrease of 23% compared to Fig.2.

As can be observed, nothing is scheduled from time 15 to 19, as it covers the end of period *P4* and period *P5* which are the most expensive ones. Moreover, some operations are scheduled from time 24 to 29, which corresponds to periods of time *P1/P2*. It can be noticed that the schedule do not use all the available time (i.e. makespan limit), as operations are not ending at time 30, since this would intersect with period *P3*, which is more expensive than *P2*. Finally, the peak power consumption decreased, as well as the energy consumption, having second operations of j_1 and j_0 being assigned to different machines.

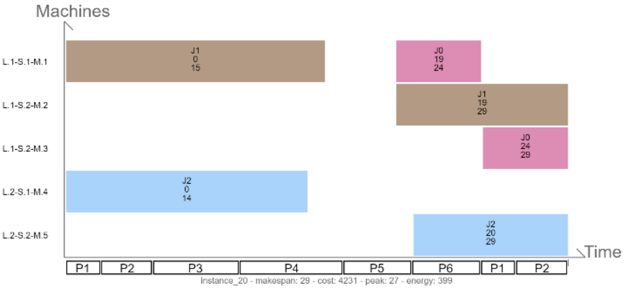

Fig. 3. Optimal schedule minimizing the cost with consideration to a limit on the makespan (valued 30), total energy consumption and energy peak (cost: 4231)

These two figures illustrate the trade-off that could operate due to the different parameters, and especially the impact of the makespan, as a higher one could allow low cost solutions considering the energy pricing. However, the peak power threshold could also imply to postpone some operations, and hence avoid benefiting from favourable pricings while having a large makespan. The constraint on total energy consumption could also have such consequences, as a long operation could have a higher energy consumption (and a lower peak power), and overlap several periods including expensive ones.

VI. COMPUTER EXPERIMENTS

We randomly generated 15 instances in order to analyse the performance and limits of the proposed model. These instances contain up to 10 jobs, 4 lines, 15 stages and 33 machines (distributed among the different available lines). Instances' structure and considered parameters are given in Table 2. In this table, *Ins* refers to instances, *J* to the number of jobs, *l* to number of lines, *m* to the number of machines (distributed over the whole production system), *s* to the maximum number of stages per line, *op* to the maximum number of operations (as the number of scheduled operations can differ depending on the selected line), and *#Periods* to the number of cost periods in the considered instance. C_{max} to the maximum makespan, E_{max} to the total energy consumption, W_{max} to the peak power of the problem. Results are obtained on CPLEX 20.1 and a time limit on computation time is set to 600 seconds to avoid large computation times.

As resulted in Table 2, we consider a limit on C_{max} valued at 40 for instances 0 to 8, and 60 for instance 9 (because of its larger schedule duration). These limits on makespan have been empirically defined based on first experiments on the makespan constraint. Instances 10 to 14 have larger C_{max} values because of their size and difficulties to find solutions considering lower makespan values. W_{max} is set dynamically depending on each instance considering a lower bound on this value to ensure feasibility (given an appropriate C_{max}), while C_{max} and E_{max} are set manually.

TABLE II. PARAMETERS OF THE MODELS IMPLEMENTATION ON DESIGNED INSTANCES

Ins	J	l	m	s	op	#Periods	C_{max}	E_{max}	W_{max}
0	4	3	14	3	12	6	40	1500	65
1	3	3	9	3	9	8	40	1250	66
2	3	2	7	3	9	8	40	750	65
3	5	3	15	3	15	6	40	1500	67
4	5	2	11	3	15	6	40	1250	63
5	7	2	15	3	21	8	40	2000	65
6	10	3	14	3	30	10	40	2250	67
7	5	3	15	4	20	10	40	2000	67
8	5	3	15	4	20	10	40	2500	72
9	5	3	15	5	25	6	60	2500	68
10	7	3	15	4	28	5	300	5000	354
11	9	3	13	4	36	9	300	5000	355
12	6	3	15	4	24	6	300	5000	366
13	10	4	29	5	50	5	300	5000	356
14	6	4	33	5	30	6	300	5000	353

Based on the considered parameters, the solver returns several indicators that are gathered in Table 3. In this table, $Mkpn$ relates to the observed makespan (that could be lower than the value of the parameter C_{max} as mentioned in the explanation of Fig. 3), E and W are the observed values of energy and power supply. This table also presents the energy cost ($e - cost$), the CPU time in seconds spent by the solver to generate a solution, and the gap in percentage between the lower and the upper bound (GAP%).

TABLE III. OBSERVED VALUES ON $Mkpn$ ($makespan$), E AND W, CPU TIME AND GAP OF THE OBTAINED SOLUTIONS ACCORDING TO PARAMETERS GIVEN IN TABLE II

Ins	$Mkpn$	E	W	$e - cost$	CPU (s)	GAP %
0	39	1313	64	37883	600	25
1	33	1029	66	17786	2	0
2	28	626	65	14617	1	0
3	40	1470	67	28517	160	0
4	40	1114	62	17325	71	0
5	40	2016	65	47413	600	49.3
6	40	2245	67	46780	600	13.2
7	40	1862	67	50497	600	34.1
8	40	2266	72	54958	600	36.9
9	60	2264	68	60488	600	35.6
10	-	-	-	-	600	-
11	-	-	-	-	600	-
12	-	-	-	-	600	-
13	-	-	-	-	600	-
14	-	-	-	-	600	-

As mentioned in Table 3, the obtained solutions for instances 1, 2, 3 and 4 are optimal as the gap is 0%, and feasible for the rest of instances including instances 0, 5, 6, 7, 8 and 9 with a gap >0%. Computation time of these instances remain low, however it attained almost 160 seconds for solving instance 3, while it is below 100 seconds for solving instance 4 which is comparable in term of maximum number of operations. The explanation lays in the number of possible lines and machines to process the jobs (3 for instance 3, 2 for instance 4). Furthermore, for instances 10 to 14, we observe difficulties for the model to obtain feasible solutions (denoted by '-' in Table 3). As the value of the makespan increased due to the size of the problems, duration of operations, and considering high number of operations and number of machines (i.e. instance 14 with operations between 18 and 30, and 33 machines), the model do not generate a solution for different CPU time limits (i.e. 600 sec; 1200 sec; 3000sec). In addition, we notice that the number of cost periods is not the primary reason affecting the capability of the solver to find solutions, as instances 10 to 14 and instances 0 to 5 have approximately similar number of cost periods. This can be explained by the complexity of the multi-line hybrid flow shop with conflicting energy and productivity constraints as well as a high number of machines and operations.

VII. Conclusion and Perspectives

In this paper, a multi-line hybrid flow shop with energy considerations is investigated. To the best of our knowledge, it is the first time for a multi-line production system to be tackled considering energy efficiency aspects. A formalization of the problem is given, a MILP approach is developed and first experiments are conducted on a set of instances. The approach allows tackling small size instances; however, problems quickly become intractable, due to their NP-Hardness proven by Johnson [23], and Gupta et al. [24] as a generalization of hybrid flow shop problems.

In order to bridge this gap, a heuristic approach could be investigated. Such an approach could be extended with matheuristics paradigm, by embedding an exact decoding approach to evaluate solutions and to tackle the complexity of allocating starting dates of operations due to Time of Use aspects. Furthermore, as production systems are subject to disturbances, changes in processing times or on starting dates of operations could have huge impact on observed energy costs, and may hinder the schedule to be respected from the perspective of its different constraints (i.e. peak power limitation, total energy consumption, makespan). Hence, stochastic approaches could be investigated to build proactive schedules that may be less sensitive to unexpected events.

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