The Group Shop Scheduling Problem with power requirements

Damien Lamy, Simon Thevenin

The Group Shop Scheduling Problem with power requirements

Damien Lamy[1] and Simon Thevenin[2]

[1] Mines Saint-Etienne, Institut Henri Fayol, F - 42023 Saint-Etienne, France
Damien.lamy@emse.fr
[2] IMT Atlantique, LS2N - UMR CNRS 6004, F-44307 Nantes, France
simon.thevenin @imt-atlantique.fr

Keywords: Scheduling, Energy-Efficiency, Group-shop, Linear Programming.

1 Introduction

The last few years have seen a growing interest in reducing the energy consumption of production systems since they are responsible for more than 50% of the global delivered energy worldwide (U.S. Energy Information Administration 2016). Besides technological advances, the consideration of energy consumption during operations management is an efficient approach to reduce energy wastes. Three main energy efficiency measures exist in scheduling : (1) total energy consumption; (2) time-of-use pricing; (3) peak power limit. This work focuses on power peak constraint, which prevents to exceed the power threshold contracted between the factory and its energy supplier. In other words, this constraint prevents the simultaneous processing of multiple operations with high energy consumption. Most of the literature on scheduling with energy constraints concerns the total energy consumption and time-of-use pricing, and very few works consider peak power limitations (Giret *et. al.* (2015)). Recently, Kemmoe *et. al.* (2017) proposed a method for the job shop scheduling problem with power thresholds. In the present work, we investigate the extent to which a more flexible shop-floor organization (namely, the group shop) improves the productivity under power limitations.

The Group-Shop Scheduling Problem (GSP) generalises the Job-Shop Scheduling Problem (JSP) and the Open-Shop Scheduling Problem (OSP). On the one hand, in the JSP, jobs are composed of operations to schedule according to pre-given routes. On the other hand, in an OSP the routing is a decision of the scheduling problem. The GSP stands at the frontier of these two problems since it gives the operations' routing partially. As the JSP and the OSP are NP-hard (Garey and Johnson 1979), the GSP is NP-hard too. Therefore, multiple metaheuristics have been proposed to solve the GSP, such as the ant colony optimization (Blum and Sampels 2004), tabu search and simulated annealing (Liu *et. al.* 2005), genetic algorithms (Ahmadizar and Shahmaleki 2014). In addition, some extension of the classical GSP have been considered, such as stochastic processing time and release dates (Ahmadizar*et. al.* 2010), or the GSP with sequence-dependent setup and transportation times (Ahmadizar and Shahmaleki 2014). However, to the best of our knowledge, the present work is the first to consider the GSP with power limitation constraints. The closest work is Liu *et. al.* (2019), where the authors consider an ultra-flexible Job-shop, but the objective is to minimize total energy consumption rather than to schedule operations with a power limitation.

The rest of the paper is organized as follows. Section 2 gives a formal description of the considered problem and a mixed-integer linear programming formulation, and Section 3 reports experimental results that assesses the impact of the flexibility offered by the group-shop to efficiently schedule operations subjected to a power limitation. Finally, a conclusion ends the paper.

2 Problem description

This section formally states the Group-Shop scheduling Problem with Power Requirements (GSPPR), before to give its mathematical formulation.

The GSPPR is to schedule a set of n jobs, where each job j consists of a set $\mathcal{O}_j = \{O_{j1} \dots O_{jm}\}$ of operations to perform on machine $M_1 \dots M_m$, respectively. Each operation k of the entire set of operation $\mathcal{O}$ is associated with a duration P_k and a power requirement W_k. The objective of the considered problem is to minimize the makespan c_{max}, that is, the completion time of the last performed job. However, the schedule must respect some precedence constraints between the operations. More precisely, the set of operations of a job j is partitioned into groups, and G_{jk} denotes the k^{th} group of job j. The precedence constraints require to complete all the operations of the group G_{jk} before the start of any operation of the group G_{jl} if $k \leq l$. However, the operations of a group can be scheduled in any order. In addition, the schedule must respect the energy threshold, that is the total energy consumption of the operations performed simultaneously must be lower than the threshold W_{max}. Finally, the operations are non-preemptive and available at time 0.

In short, the GSPPR requires to schedule all operations efficiently without exceeding the power threshold. Note that the GSP generalizes the JSP and the OSP. Indeed, an instance of the GSP with a single operation per group is an instance of the JSP, and an instance of the GSP with a single group per job is an instance of the OSP.

The disjunctive formulation with the flow representation of energy is classically used for the JSP (Kemmoe *et. al.* 2017), and the model (1) - (8) is the adaptation of this formulation for the GSPPR. Model (1) - (8) is based on the following variables:

- x_{ij} is equal to 1 if operation i is processed before operation j, and 0 otherwise
- ϕ_{ij} represents the flow transferred from operation i to j
- s_i is the starting time of operation i

$$\min c_{max} \tag{1}$$

s.t.

$$c_{max} \geq s_i + P_i \qquad \forall \quad i \in \mathcal{O} \tag{2}$$

$$s_j \geq s_i + P_i - M(1 - x_{ij}) \qquad \forall \quad i, j \in \mathcal{O} \tag{3}$$

$$\sum_{j \in \mathcal{O}} \phi_{0j} \leq W_{max} \tag{4}$$

$$\phi_{ij} \leq x_{ij} W_i \qquad \forall \quad i, j \in \mathcal{O} \tag{5}$$

$$\sum_{j \in \mathcal{O} - \{i\}} \phi_{ij} \leq W_j \qquad \forall \quad i \in \mathcal{O} \tag{6}$$

$$\phi_{0j} + \sum_{i \in \mathcal{O} - \{j\}} \phi_{ij} = W_i \qquad \forall \quad j \in \mathcal{O} \tag{7}$$

$$x_{ij} + x_{ji} = 1 \qquad \forall \quad i, j \in \mathcal{O} \tag{8}$$

To respect the precedence constraint, $x_{oo'}$ is set to 1 if operations o and o' belong to the same job j, $o \in G_{jk}$ and $o' \in G_{jl}$ with $k \leq l$. Equations (3) compute the start time of each operation based on its predecessors, and equations (2) set the makespan to the completion time of the last operation. The energy consumption is modeled with a flow. Constraint (4) ensures that the source transmits at most W_{max} units of energy in total, and Constraints (5) states that each operation can transmit the energy flow to one of its successors only. Equations (6) state that each operation j must receive W_j units of energy, whereas equations (7) forbid an operation to transmit more energy than it received. Finally, the redundant constraints (8) are introduced to strengthen the formulation.

3 Computational experiments

As this paper is the first to consider the GSPPR, no instances exist in the literature. Therefore, we generated the instances randomly, with a number of jobs and machines selected in the interval $[3, 10]$, and operations assigned randomly to groups. The duration of each operation i, P_j, is generated randomly in the interval $[1, 100]$, while its power requirement is generated randomly in the interval $[1, 30]$. Finally, three different values for the power limit W_{max} are considered: MaxThreshold (i.e. enough power to process all operations), MaxThreshold/2 and MaxThreshold/3. For each couple (m, W_{max}), 10 instances are generated.

The integer linear program (1) - (8) is implemented with CPLEX 12.8, and the experiments were run on a Xeon E3-1505M processor with a time limit of 600 seconds.

Table 1. Results on small instances with different power thresholds

m	MaxThreshold			MaxThreshold/2			MaxThreshold/3		
	AVG_CPU(s)	AVG_GAP(%)	NB_OPT	AVG_CPU(s)	AVG_GAP(%)	NB_OPT	AVG_CPU(s)	AVG_GAP(%)	NB_OPT
3	92.75	3.94	7	456.125	27.29	2	526	50.73	1
4	222.75	5.71	6	383	28.81	3	600	66.17	0
5	224.5	6.49	6	450.25	31.05	2	600	68.12	0
6	237.5	6.24	5	388.625	23.46	3	539	53.87	1
7	280.75	10.29	5	450.5	33.41	2	526	57.96	1
8	328.625	12.36	4	455.375	32.47	2	525	55.07	1
9	300.5	11.38	5	402.125	27.00	3	600	45.31	1
10	451.25	23.90	2	457.625	40.36	2	526	50.40	1

Table 1 reports the performance of the CPLEX solver for different power thresholds. Each row of the table corresponds to a set of instances with the same number of machines (m). When the power threshold is high, the optimal solutions (see NB_OPT) is easy to reach. On the contrary, CPLEX has some difficulties to find optimal solutions for low power thresholds (closed to the minimal value under which it is not possible to schedule operations). Actually, CPLEX was not able to find an upper bound for a fifth of the instances in this scenario.

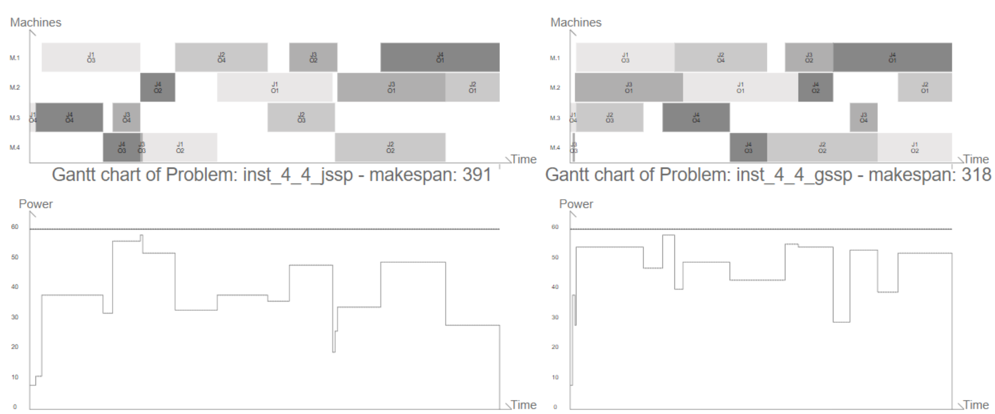

Fig. 1. Gantt chart of the optimal solution of the GSP (on the right), and the solution of the Job-shop instance (on the left) created by adding random precedences between the operations of a group.

Figure 1 compares the makespan in GSP and JSP. The left side gives the Gantt chart of the optimal solution of a GSPPR instance, whereas the left side shows the solution of JSSPR instance obtained by adding random precedences between the operations of each group. The GSPPR instance has a makespan of 318 versus 391 for JSPPR. Moreover, the power thresholds of the GSPPR instance can be reduced up to 30%, and the makespan remains lower than the one of the JSPPR with the initial power limit.

In production management, the process plans (the operation to perform and their order) are classically decided before to schedule the operation. This study shows that integrating these decision yields some flexibility on the shop floor, and this allows better performance, or to operate with lower energy thresholds.

4 Conclusion

This paper investigates the problem of minimizing the makespan in a Group-shop Scheduling Problem with power requirements and a power limitation (GSPPR). As the Group-shop allows some flexibility in the processing order of the operations of a job, preliminary results show that the Group-shop leads to a significant reduction of the makespan in the context of power-constrained schedules when compared to the classical Job-shop. For instance, an operation with a low power requirement can be scheduled at the right moment, when the available power is not used by other operations. As CPLEX solves small size instances only, future works include the development of metaheuristics and constrained programming approaches for the GSPPR. In addition, extensions of the GSPPR are of practical interest. For instance, the present model contains only operations with constant power requirements, which is close to cumulative problems (as stressed in Baptiste *et. al.* (2001)), and it could be extended to more real power profiles. Also, in the presence of human operators, there exist some uncertainties on the processing time of the operation. These random processing times lead to random power limit excesses, and the design of schedule robust to these uncertainties is crucial to avoid exceeding contracts based on power thresholds.

References

Ahmadizar, F., Ghazanfari, M. and Fatemi Ghomi, S.M.T. 2010, "Group shops scheduling with makespan criterion subject to random release dates and processing times", *Computers Operations Research*, Vol. 37 No. 1, pp. 152-162.

Ahmadizar, F. and Shahmaleki, P., 2014, " Group-shop scheduling with sequence-dependent set-up and transportation times", *Applied Mathematical Modelling*, Vol. 38 No. 22, pp. 5080-5091.

Baptiste P., Le Pape C., Nuijten W., 2001, " Cumulative Scheduling Problems", *In: Constraint-Based Scheduling. International Series in Operations Research Management Science*, Vol. 39., pp. 149-158.

Blum, C. and Sampels, M., 2004, "An ant colony optimization algorithm for shop scheduling problems", *Journal of Mathematical Modelling and Algorithms*, Vol. 3 No. 3, pp. 285-308.

Garey, M.R. and Johnson, D.S., 1979. "Computers and intractability", vol. 29, *New York: wh freeman*.

Giret, A., Trentesaux, D. and Prabhu, V., 2015, "Sustainability in manufacturing operations scheduling: A state of the art review", *Journal of Manufacturing Systems*, Vol. 37, pp. 126-140.

Kemmoe, S., Lamy, D. and Tchernev, N., 2017, "Job-shop like manufacturing system with variable power threshold and operations with power requirements", *International Journal of Production Research*, Vol. 55 No. 20, pp. 6011-6032.

Liu, N., Zhang, Y.F. and Lu, W.F., 2019, "Improving Energy Efficiency in Discrete Parts Manufacturing System Using an Ultra-Flexible Job Shop Scheduling Algorithm", *International Journal of Precision Engineering and Manufacturing-Green Technology.*

Liu, S.Q., Ong, H.L. and Ng, K.M., 2005, "A fast tabu search algorithm for the group shop scheduling problem", *Advances in Engineering Software*, Vol. 36 No. 8, pp. 533-539.