Energy-efficient flexible flow shop scheduling with renewable energy sources and energy storage systems *

Joyce Mhanna[1,2], Hajar Nouinou[1], Simon Caillard[3], David Baudry[4]

[1] CESI LINEACT, 54000 Nancy, France

[2] Agence de l'environnement et de la Maîtrise de l'Energie, 49004 Angers, France

[3] CESI LINEACT, 67380 Strasbourg, France

[4] CESI LINEACT, 76800 Rouen, France

{jmhanna, hnouinou, scaillard, dbaudry}@cesi.fr

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1 Introduction

In France, the industrial sector is responsible for 18% of the total energy consumption in 2023, nevertheless, only 7% of it comes from renewable energy sources [1]. With the increasing concern over climate change and global warming, industries have started to integrate programs based on demand-side management which includes energy efficiency and demand response to reduce carbon emissions from their manufacturing process.

The energy efficiency objective is to decrease energy consumption without reducing production outputs. There are several methods to achieve energy-efficiency in production scheduling, such as turn on/turn off, reducing machine speeds, and flexible systems [2]. Moreover, demand response leads the industrial customers to reduce or shift their energy consumption in response to the electricity price fluctuation. Price-based programs are part of the demand response strategy where the price of electricity is fixed according to daily periods, such as Time Of Use pricing (TOU), real-time pricing, and critical peak pricing [2]. Due to the intermittency and variability of renewable energy sources, Energy Storage Systems (ESS) are also employed in the manufacturing process to store any excess of energy generation and use it later on.

To the best of our knowledge, very few studies have considered both flexibility and energy efficiency in production scheduling, particularly in a Flexible Flow Shop (FFS) environment. Zhai et al. (2017) [3] develop a Mixed Integer Linear Programming (MILP) model of a flow shop scheduling problem. They considered on-site wind generation, real-time electricity pricing, and turn on/ turn off strategy, with the aim of minimizing the total electricity cost. Zhang et al. (2017) [4] consider the hybrid variant of the previous problem for a grid-connected factory by using TOU electricity cost with an integrated onsite solar power generation and battery storage systems. They developed a MILP model to minimize the total electricity cost. These two articles have proved that while using renewable energy, the manufacturer significantly reduces cost and energy consumption.

2 Problem description and formalization

The present work focuses on the integration of energy efficiency by considering the machine turn on/turn off strategy, and energy flexibility by taking into account the TOU pricing, the onsite solar power, and the ESS, while scheduling production operations in a FFS environment. Our objectives are twofold. On one front, we aim to enhance the energy flexibility of the

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production scheduling process, adopting a strategy that aligns with achieving a low-carbon economy by minimizing total electricity costs. On another front, our focus is on improving production efficiency through the minimization of makespan. The FFS scheduling problem is known to be NP-hard [5] and integrating the minimization of the electricity cost makes the problem even more complex.

This study adresses the problem of scheduling a set of jobs J in a FFS environment, where there is a set of series H of two stages at least, and each stage h has a set of non-related parallel machines M_h. For each machine k at a stage h is associated an idle energy I_{kh}, and a turn on/turn off energy O_{kh}. A set G of TOU pricing is considered for the grid electricity, where the prices variate according to on-peak, mid-peak, and off-peak periods. Moreover, the ESS are charged and discharged during the scheduling process. For this problem, several assumptions are made : (1) the factory has onsite photovoltaic generation, ESS, and grid electricity purchased based on TOU pricing, (2) buffers are considered between the stages, (3) each machine has three states, including off, idle, and working modes, (4) each machine on each stage can process at most one job at a time, (5) all the jobs and machines are available at time zero, (6) job preemption is neglected. A new MILP model is formulated, based on that of Zhang et al. (2017) [4] in which the constraints inherent to our problem have been added. The model uses 11 decision variables and the objective functions optimize the total electricity cost and the makespan. Moreover, since the problem is NP-hard, numerical experiments were conducted on small scale instances involving 10 jobs to be scheduled on 2 stages including 2 parallel machines each. While using the power grid and the generated renewable energy and taking into account the minimization of the makespan, the model decides to charge the ESS during off-peak or mid-peak periods in order to discharge them during on-peak periods. These experiments are promising and validate the proposed model.

3 Conclusion and perspectives

In this study, the manufacturer will be able to obtain the best compromise between the total electricity cost and the production efficiency, as the two objectives are considered in a FFS environment. In future work, sensitivity analysis can be developed by evaluating the impact of several parameters, including electricity prices, and battery sizes. Furthermore, it is important to develop heuristic and metaheuristic methods in order to solve the problem for large instances. Integrating the power consumption reduction where the customers receive rewards after their acceptance of reducing their energy consumption would be insightful. Taking into account the dynamic aspect of the problem will get us closer to the real-world scenarios.

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