Production scheduling considering dynamic electricity price in energy-efficient factories ⋆

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Abstract: Factories account for more than 42% of global energy consumption. In order to contribute to reduce carbon footprint and increase energy efficiency, it is important to optimize the tasks and time of product manufacturing according to the renewable generation and lower prices of the grid but without compromising production quality and output. This paper aims to develop flexible optimization platform for industrial production processes. The proposed production scheduling model is formulated as a 15-minute interval of one week timespan adopting mixed-integer linear optimization model and solved in TOMLAB. The model considers general production constraints for different products and takes into account with the photovoltaic generation of the factory as well as the dynamic price of the grid. The results are compared with a reference case without photovoltaic and where the dynamic price is not considered. The energy cost savings can amount up to 29% or 100 € in the considered example.

Keywords: Energy consumption, energy-efficiency factory, optimization, production scheduling

1. INTRODUCTION

Workshop production scheduling is an important tool to achieve the necessary operational energy efficiency gains within the manufacturing industry as identified in Gahm et al. (2016). The aggressive market competition in the industry leaves little room for inefficiencies in the operational department since costs and performance degradation can quickly escalate. Energy consumption in factories accounts for more than 42% worldwide according to Desta et al. (2018). In fact, energy consumption of factories represents a considerable burden for their operation cost as reported in some works including Gahm et al. (2016); May et al. (2015). A key challenge is to improve the ratio between energy input and the necessary output of a production industry. In other words, this represents the energy efficiency of an industry and is a central aspect of sustainable manufacturing Gahm et al. (2016).

In the production scheduling problems of factories the most common challenges we can identify include to minimize manufacturing makespan, increase energy efficiency and reduce energy consumption. Several optimization approaches have been proposed in the literature to address these issues. Many works adopt heuristic-based algorithms to solve the minimization cost under dynamic electricity prices. Heuristic-based algorithms are powerful tools that can solve complex optimization problems with ease and

have been successfully applied to many fields related with energy cf. Soares et al. (2018). May et al. (2015) adopt a genetic algorithm approach to solve a multi-objective energy scheduling model considering the energy consumption and makespan of the workshop. The proposed algorithm can achieve satisfactory makespan solutions as good as the best available tools but with reduced energy consumption. Jiang et al. (2014) propose a multi-objective flexible job-shop scheduling optimization model, in which the makespan, processing cost, energy consumption and cost-weighted processing quality are considered. The multi-objective model is solved by NSGA-II with a modified genetic component. Nevertheless, deterministic optimization has also been proposed. Fang et al. (2011) present a deterministic mixed-integer linear programming model for the flow shop scheduling problem considering the peak total power consumption, the carbon footprint, and the makespan. Shrouf et al. (2014) propose a model to minimize energy consumption cost by considering the fluctuations in energy prices. The proposed algorithm is highly scalable in real-time. OpenADR protocol for automated demand response (DR) is a promising means to enable energy cost savings and smooth the demand without compromising the factory output. The work of Desta et al. (2018) proposes two approaches for scheduling a production line constrained with maximum available power, i.e. DR requests.

An analysis of the current works reveals that production scheduling is a complex optimization problem that may involve many different constraints for the products and production tasks. The problem has been consistently tackled with heuristic optimization since it is hard to

fulfill solution time requirements. In our opinion demand response consideration in the optimization models is yet not so well explored and further work would benefit this field. This paper is part of the on-going work in SPEAR project. The SPEAR aims to develop a flexible optimization platform that helps to improve a broad spectrum of industrial production processes in terms of energy-related aspects. The focus of the project is the energy optimization of plants' production processes, production lines and (industrial) buildings. In this scope, this paper uses time of use price in the production scheduling optimization model and combines the photovoltaic (PV) generation available in the factory to find the most suitable time to decide the adequate series of products to be manufactured.

This paper is organized in 5 sections: after this introduction and related work, Section 2 presents the methodology of the work, including the mathematical formulation with respective constraints of the problem; Section 3 presents the case study including a reference production plan for comparison purposes; Section 4 presents the results and discussion of the work. Finally, conclusions are fully drawn in Section 5.

2. METHODOLOGY

In this section we present the mathematical formulation of the production scheduling optimization model.

Fig. 1 depicts an example of a production scheduling of a single cell line namely illustrating the start time for each product (in this example each product can have different manufacturing duration). Each product can also have variable power consumption in the production cell. However, in our optimization model each product have the same production task duration for sake of simplification. The production plant also needs to predict the available solar power (this is a necessary input to the optimization model). Aggregating all this it means that there is a variable energy cost depending on the scheduled production and available PV generation.
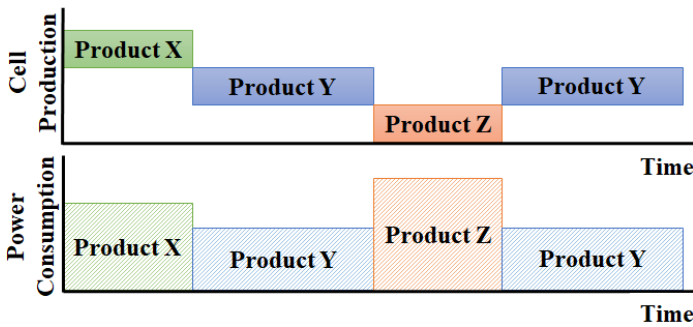

Fig. 1. Production scheduling of a single production cell

The objective function described in (1) aims to minimize the total cost of the electricity. The incentive received of the PV generation is also considered and will reduce the total operation cost related with energy supply.

Objective function

$$OF = \left[\begin{array}{c} \sum_{t=1}^{T} Pcons_{(t)} \cdot EnCost_{(t)} - \\ \sum_{t=1}^{T} PVe_{(t)} \cdot PVinc_{(t)} \end{array} \right] \quad (1)$$

Constraints

The optimization model is constrained by the following conditions, namely the 4 different constraints represented by (2)-(5).

Total power consumption is given by (2) where it corresponds to the sum of each machine energy consumption (that varies with the product being produced) minus the incentive from the PV power excess that is not self consumed in the factory.

$$Pcons_{(t)} = \left(\sum_{p \epsilon \Omega_P} pcons_{(p,t)} \times w_{(p,t)} \right) - \\ PV_{(t)} + PVe_{(t)} \quad \forall t \in T, \forall w \in \{0,1\} \quad (2)$$

The factory can only produce on product in each time period. This is possible using constraint (3) as can be seen below:

$$\sum_{p \epsilon \Omega_P} w_{(p,t)} \leq 1 \quad \forall t \in T, \forall w \in \{0,1\} \quad (3)$$

The PV power excess is a positive continuous variable, which can measure the power that can be sold to the grid, as stated in (4).

$$PVe_{(t)} \geq 0 \ \ \forall t \in T \quad (4)$$

The factory has a given output demand for each product to be fulfilled. This is assured by constraint (5).

$$\sum_{p \epsilon \Omega_P} \sum_{t=1}^{T} w_{(p,t)} = prodDem_{(p)} \\ \forall t \in T, \forall w \in \{0,1\} \quad (5)$$

where:
T is the timespan;

Ω_P is the set of products;

p is the product belonging to the set of products;

$Pcons_{(t)}$ is the total energy consumption in period t;

$EnCost_{(t)}$ is the energy cost in period t;

$PV(t)$ is the self-consumed photovoltaic generation in period t;

$PVe_{(t)}$ is the photovoltaic generation not self-consumed in period t;

$w_{(p,t)}$ is a binary variable which states if product p is produced in period t;

$PVinc_{(t)}$ incoming from energy sold to the network;

$prodDem_{(p)}$ output demand for each product p.

The above optimization model and research work has been developed on a computer with one Intel Xeon E5-2620 v2 processor and 16 GB of RAM running Windows 10 Pro using the MATLAB R2018a and TOMLAB 8.1 64 bits with CPLEX solver.

3. CASE STUDY

In order to test the optimization model we created a case study using a large timespan of one week with timestep of 15 minutes and considering 3 different products, PV electricity production and varying electricity prices. Since each product can have different manufacturing requirements, the power consumption can also change. The power consumption of each product varies according to Table 1. The production duration of each product is 15 minutes in this example. The demand for each product is also given, i.e. number of identical products to be produced. The total amount to produce is 672 products which corresponds to 672 periods of 15-minutes interval in one week. This means the factory/machine will always be occupied to satisfy the given total demand.

Table 1. Energy consumption and production
time for the three considered products

Product	Power consumption (kW)	Production time (min.)	Demand (units)
X	12	15	200
Y	15	15	152
Z	18	15	320

The PV electricity generation profile can be seen in Fig. 2. The peak power generation of the PV units installed in the factory happens around noon with a peak power of 4.25 kW during 21st March 2019. The total energy generated during the week is nearly 130 kWh with an average of 0.77 kW. The lowest PV energy generation occurs during 22nd March 2019 with 14 kWh.

In the future with smart meter technologies it is expected that electricity prices can vary during the day for every consumer while being more aligned with electricity market prices and renewable generation availability. This will favour more demand when renewable generation is available than compared with traditional price schemes. The dynamic electricity price utilized in this case study can be seen in Fig. 2. We chose to depict only for the first day since the prices vary similarly in the other days. Prices have been randomly generated but real prices can be used. The lowest price is 0.12 EUR/kWh while the highest price is 0.22 EUR/kWh while the average is 0.17 EUR/kWh. It is important to note that in this work, stochastic behavior of PV and energy price is not considered and this issue is open for future work.

We establish four different cases as described afterwards. These cases attempt to cover the different possibilities within the factory plant and in order to evaluate our production scheduling model. We simulate the four cases to analyze the energy cost in the different simulation conditions.

- Case A: PV power generation and dynamic price is not considered (reference case);
- Case B: PV power generation is considered whereas the dynamic price is not;
- Case C: PV power generation is not considered whereas the dynamic price is (with optimization);
- Case D: PV power generation and dynamic price are considered (with optimization).

4. RESULTS AND DISCUSSION

In this section we present the main results of the proposed methodology. We compared the results of the optimization presented in Section 2 with the case without PV power generation and dynamic price as can be seen in 2. Case A presents the highest energy cost for the production plant with 445 EUR. Case C presents the second highest energy cost with an amount of 432 EUR. Case B and D present a energy cost of 359 and 345 EUR, respectively. PV power generation helps to reduce the energy cost of the factory by a considerable margin of 85 EUR a week (cf. case A and case B). With dynamic price the factory can reduce the cost a little further with around 15 EUR savings per week, i.e. reducing the total energy cost from 359 to 345 EUR (Case B vs D).

Table 2. Total cost for each case

Case	PV	Dynamic Price	Total Cost(EUR/week)
A			444,83
B	✓		359,01
C		✓	432,43
D	✓	✓	344,58

The production scheduling without optimization considering dynamic price is shown in Fig. 3. It can be seen that without information concerning the dynamic price, the production schedule is more straightforward. The product X is first scheduled until the demand is reached in the second day with 200 units of input demand. The product Y is scheduled between the third day and the fourth with 150 units of demand. The product Z is scheduled on fourth day onward with a demand of 320 units. This scenario is similar to what a production manager would do intuitively without concerning with the energy costs.

Fig. 4a) - g) present the week production scheduling using dynamic price information in the optimization. It can be observed that the products are now being scheduled with a different order than in Fig. 3. The optimization decides to shift products often due to the power consumption rate of each individual product and the dynamic price that varies rapidly (and randomly in this case study). In a more realistic scenario dynamic price may vary less and affect production shifting accordingly. Product Z with the highest production power rate is more scheduled in the days where solar generation is higher (cf. Fig. 2 and Fig. 6, regarding solar power generation and power consumption, respectively). Table 3 depicts the total amount of products manufactured. It confirms that Product Z is more produced in 19th and 21st of March and coinciding with the most sunny days as depicted in Fig. 2. 23nd and 25nd of March.

Table 3. Total production by day and product

Product	Day of March 2019						
	19th	20th	21st	22nd	23nd	24nd	25nd
X	26	27	18	32	31	31	35
Y	18	23	19	20	23	20	29
Z	52	46	59	44	42	45	32

Fig. 5 represents the power consumption for the reference case without optimization over the entire simulated week. The peak power in this case is achieved when product Z starts its cycle of production and it translates into
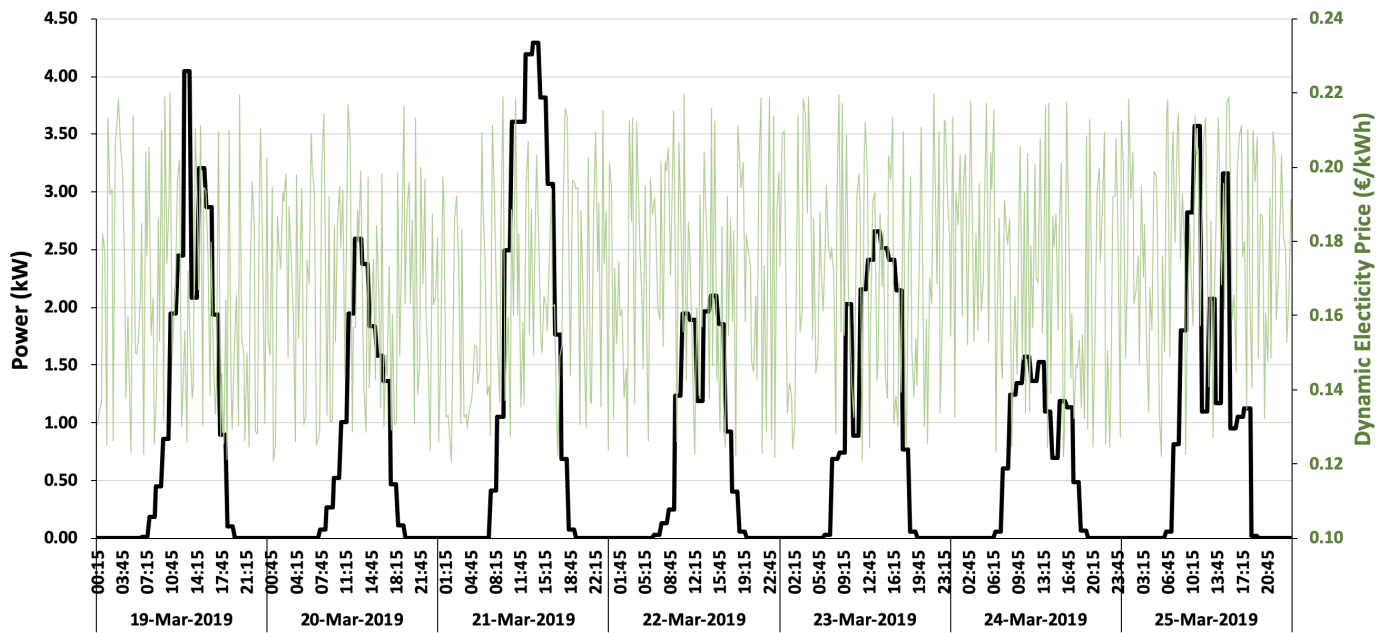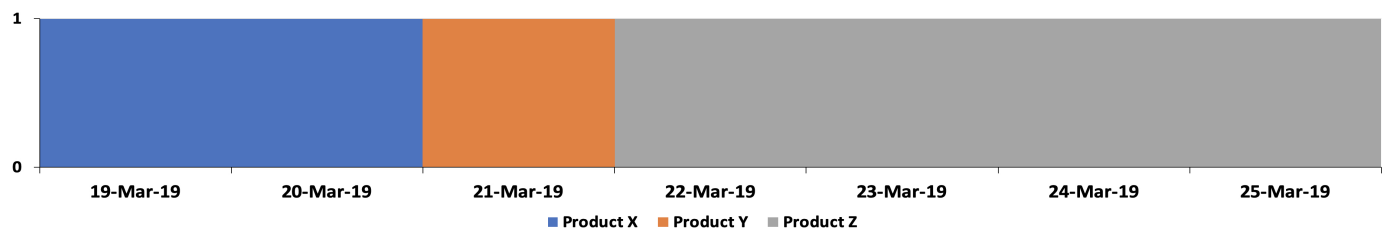
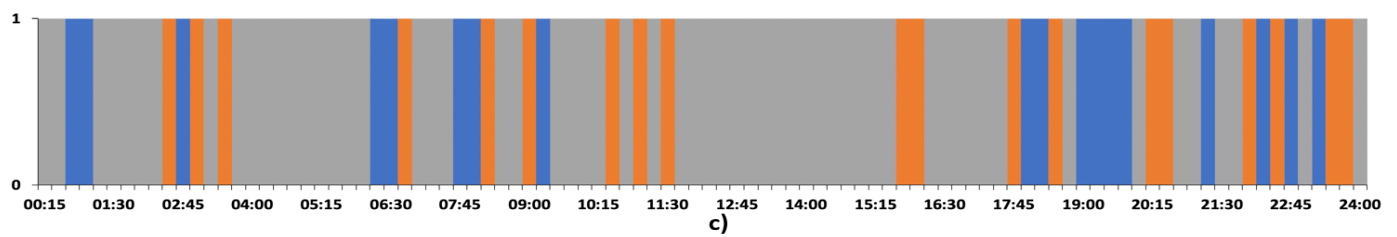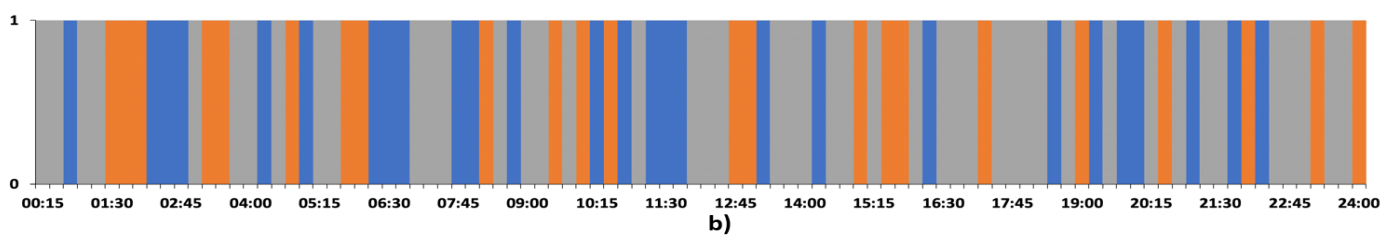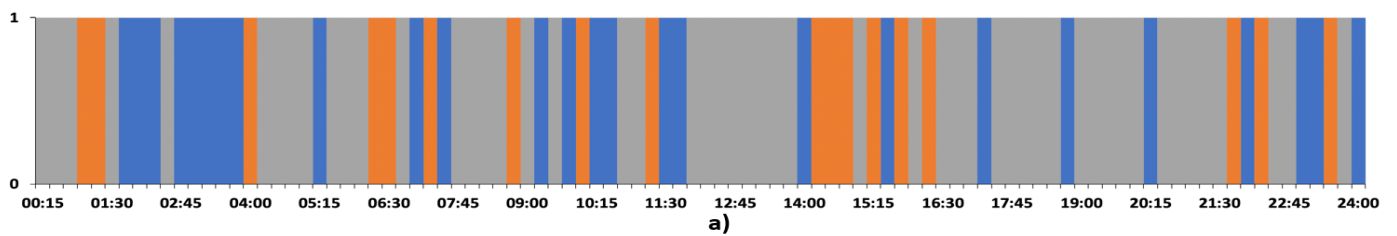Fig. 2. PV solar power generation in the factory

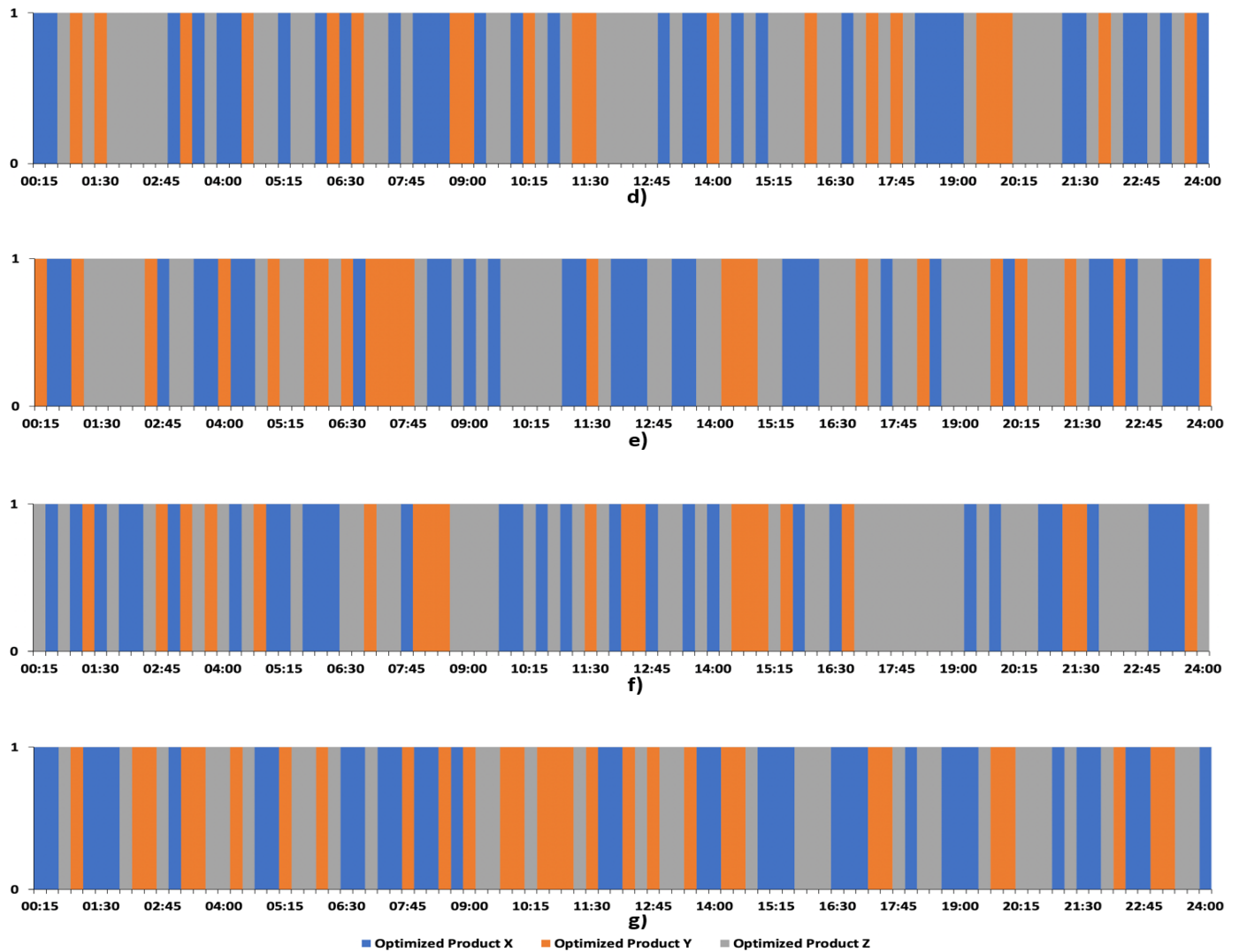Fig. 3. Production scheduling over the week for the reference case without optimization (Case A and Case B)

Fig. 4. Production scheduling from 19-Mar 2019 to 25-Mar 2019 with optimization (Case D). **a)** Production scheduling on 19-Mar 2019, **b)** Production scheduling on 20-Mar 2019, **c)** Production scheduling on 21-Mar 2019, **d)** Production scheduling on 22-Mar 2019, **e)** Production scheduling on 23-Mar 2019, **f)** Production scheduling on 24-Mar 2019, **g)** Production scheduling on 25-Mar 2019
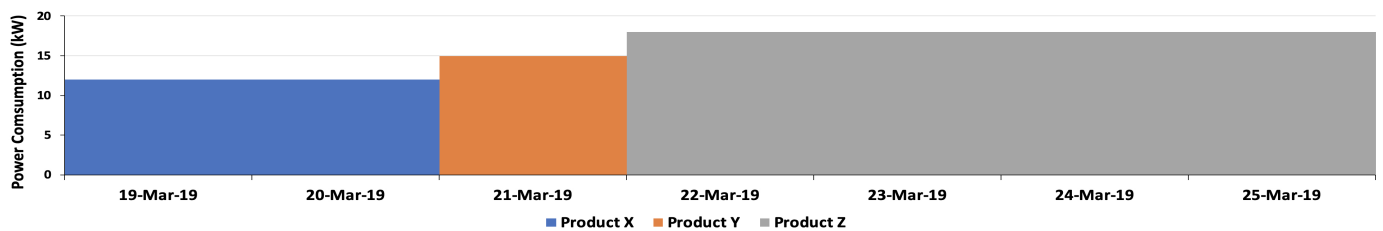

Fig. 5. Power consumption over the week for the reference case without optimization (Case A and Case B)
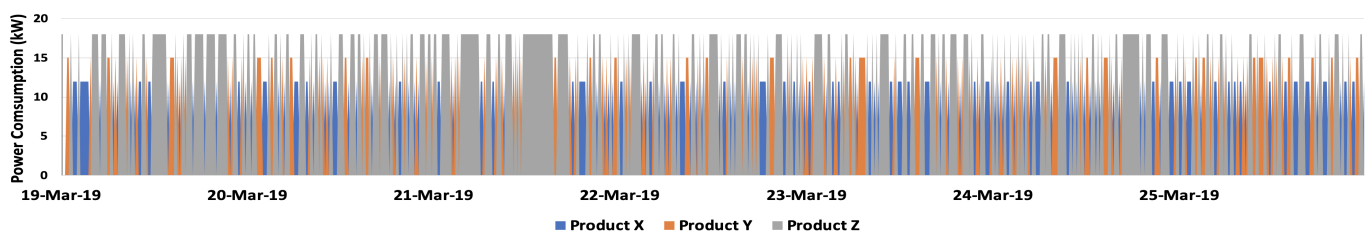

Fig. 6. Power consumption over the week for the optimized production scheduling with lowest cost - Case D

a continuous power consumption of 18 kW in the last 4 days. This is not optimal for the factory and grid, specially if PV generation and dynamic electricity price is available. Fig. 6 represents the power consumption for case D, where dynamic price is considered in the optimization, and where the lowest cost is verified. Since production is shifted between the three different products, the power consumption also shifts continuously in order to adapt to the current price and PV power generation. Thus, the peak power consumption occurs several times in different periods during the considered simulation timespan.

5. CONCLUSION AND FUTURE WORK

The paper presents an optimization model to solve the production scheduling model considering single cell production line with the possibility to manufacture several different products. The work is developed in the context of SPEAR project which aims to develop an optimization platform to improve a broad spectrum of industrial production processes in terms of energy-related aspects. The results obtained with the current model highlight the potential savings by adopting solar power generation and dynamic electricity price in production plants. The energy savings can amount up to 29% when PV and dynamic price is combined, 19% if only PV is considered and 4% if only dynamic price is adopted.

The current model depends on forecast inputs of solar power generation and the knowledge of future electricity price which might not be available in advance. Future work will consider uncertainty in the solar power generation and include more advanced constraints, such as variable product production timespan, tasks of products and sequencing, etc. Authors believe that advanced stochastic methods such as those based on evolutionary computation (HyDE-DF in Lezama et al. (2019)) can suit the proposed optimization in a more detailed level, wich naturally will result in a more complex model.

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