An Efficient Approach for Flattening the Electricity Consumption Profile at Small and Medium Enterprises

Gheorghe Grigoras, Bogdan-Constantin Neagu, Ovidiu Ivanov
Power Systems Department
”Gheorghe Asachi” Technical University of Iasi, Iasi, Romania
ggrigor@tuiasi.ro

***Abstract*— Production scheduling represents a significant tool for reducing the cost of electricity bills, flattening the consumption profile, energy conservation, improving the energy efficiency and economic performance, and strengthening competitiveness at small and medium enterprises (SMEs). Considering these aspects, an efficient approach for flattening the electricity consumption profile based on the production scheduling at SMEs was proposed. The optimal solutions were obtained using combinational optimization. The approach was tested at an industrial consumer (a small enterprise in the automobile repair activity domain). The obtained results led at a decrease of peak values of the electricity consumption with 15.87 %.**

Keywords— ***flattening; electricity consumption profile; small and medium Enterprises; production scheduling; combinational optimization***

I. INTRODUCTION

Production scheduling is the process of achieving some specific objectives (minimization of electricity consumption, maximization of efficiency, maximization of profits, or minimization of electricity costs) by optimal allocating the equipment / installations to the technological activities/flows.

Because the minimization of electricity costs and the flattening the electricity consumption profile represent today important challenges of small and medium enterprises (SMEs), the optimal planning of activities/technological flows as the main direction in which enterprises can be geared towards electricity conservation and reduction of consumption, will become one of the issues that attract attention.

In the literature, there are many references on the topic of production scheduling at SMEs in order to minimize the electricity consumption. In [1], the authors proposed a mathematical model to optimize energy consumption in manufacturing companies with the aim of generating alternatives for illumination and air conditioning systems. The obtained results led to annual savings with direct impact on the company’s overhead costs. An analysis was presented in [2] to investigate the energy conservation potential in the cashew processing industry. The optimization model reduced the usage of process heat energy and electricity over the maximum demand, being an efficient tool to solution the related problems regarding this industry. A method of production scheduling oriented to energy consumption optimization based on self-adaptive differential evolution algorithm was proposed in [3]. The simulation results indicated that the proposed algorithm has the advantages of shorter solution time and quicker operation. An agent-based approach was developed in [4] to flatten the demand load by optimally scheduling the usage times for appliances held by a single or multiple agents. In this context, a mathematical model to determine an optimal energy consumption by changing the equipment operation scheduling was proposed. The approach presented in [5] is focused on an energy consumption scheduling scheme to meet the peak load demand and reduce the cost. The assumptions of this approach considered the use of an energy consumption controlling inside of the smart meter from each consumer to minimize the peak load by transferring the shiftable equipment from peak hours to off-peak hours. In [6], a load management program basically optimized the equipment which reduced the peak demand of an enterprise. This approach had as result an optimal rescheduling of electricity consumption which caused to reduce the electricity consumption bill. Another approach is presented in [7] where a mixed integer non-linear programming model is developed to specify the product mix in order to maximize a sustainability index for a manufacturing facility. Based on this model, the identification of the prospective improvements of manufacturing sustainability is allowed. A research focused on the development and evaluation of an optimization model to optimally schedule water-cooled chillers in industrial applications was made in [8]. The proposed optimization model allows minimizing energy and/or peak demand costs associated with normal operation of chillers, depending on the priority of the industrial consumer, while meeting the demand-supply balance, process, peak demand constraints, and operating limits at the same time. Also, a practical demand side management scenario where the selfish consumers compete to minimize their individual energy cost through scheduling their future energy consumption profiles is proposed in [9]. The analysis of all approaches has highlighted the fact that there is no common approach in terms of the production scheduling, many of which are approaches that are customized on a particular type of consumer.

In this context, the main objective of this paper is to determine the optimal solutions for production scheduling at

978-1-7281-0750-9/19/$31.00 ©2019 IEEE

SMEs (whatever the branch of activity) in order to obtain the flattening of the electricity consumption profile. To achieve this objective, a combinational optimization method is proposed and tested, characterized by the fact that it quickly explores the set of admissible solutions (the region of interest) in order to find the optimal solution, represented by the time intervals in which the equipment will work, with the aim to obtain a total cost minimum energy consumed. The method can find solutions in very large search regions for which other classical optimization algorithms cannot be applied, providing a useful tool for decision making in the task of optimally choosing the energy suppliers and improving the energy efficiency actions. The remaining sections of the paper are structured as follows: Section II presents the proposed mathematical model for flattening the electricity consumption profile based on production scheduling. Section III details the combinational optimization methodology used for flattening the electricity consumption profile. Section IV presents the testing of the proposed methodology at an industrial consumer. Section V shows the conclusions.

II. THE MATHEMATICAL MODEL FOR FLATTENING THE ELECTRICITY CONSUMPTION PROFILE

In order to build the mathematical model and develop the algorithm that will find the optimal solution, the electricity consumption will be considered as being the recorded amount from starting up to stopping all necessary equipment / installations to perform any activity in an technological process. This recorded amount represents the total electricity consumption between the times when an equipment / installation was started until it is stopped after the task has been accomplished within a technological process [1].

Also, the equipment/installation can be divided into two categories: programmable and non-programmable. The programmable equipment has a working time that can be shifted to the hours where the electricity consumption is small, with a minimum loss of performance for the industrial consumer. Differently, non-programmable equipment has a working regime which can be delayed and, also, can be reduced in intensity.

If the work schedule is very intensive in the peak hours, it is intended to flattening the electricity consumption profile:

$$\min \sum_{h=1}^{T} C^h \cdot \left| \sum_{j=1}^{N_a} \sum_{k=1}^{N_e} w^h_{i,j,k} - \frac{\Delta}{T} \right| \tag{1}$$

where:

$$\Delta = \sum_{j=1}^{N_a} \Delta_j = \sum_{j=1}^{N_a} \sum_{k=1}^{N_e} C^h \cdot w^h_{i,j,k}\ ,\ i = 1, \ldots, N_p \tag{2}$$

C^h - the cost of electricity at hour h; T - analysis interval, $w^h_{i,j,k}$ - electricity consumption of equipment/ installation k necessary for the activity j to obtain the finished product i; N_p - the total number of finished products; N_a - the total number of activities to obtain the finished product i, N_e - the number of equipment/installations necessary for the activity j.

In the mathematical optimization model, various technical constraints necessary for the production scheduling with referring the minimization of objective function (1) are considered: allocation constraint, time constraint, constraint on the phase sequences belonging to technological processes, balance electricity consumption constraint.

a. Allocation constraints

Any equipment / installation can work within a single technological process and for the same task:

$$X_{i,j,k} = \begin{cases} 0 & \text{if } k \text{ does not work} \\ 1 & \text{if } k \text{ works} \end{cases} \tag{3}$$

$$k = 1, 2 \ldots, N_e,\quad i = 1, 2, \ldots N_p,\ j = 1, 2, \ldots N_a$$

where: $X_{i,j,k}$ represents a variable on the basis of which the decision is made. When this variable takes value 1, the equipment/installation k performs the activity j to get the finished product i. Otherwise, the equipment/installation k does not work.

b. Time constraint

The work interval of an equipment/installation k:

$$H^{Start}_{i,j,k} - H^{Stop}_{i,j,k} \geq T_{i,j,k} \tag{4}$$

$$k = 1, 2 \ldots, N_e,\quad i = 1, 2, \ldots N_p\ ,\ j = 1, 2, \ldots N_a$$

where: $H^{Start}_{i,j,k}$ and $H^{Stop}_{i,j,k}$ - the start and stop working hours of the equipment/installation k to perform the activity to get the product i; $T_{i,j,k}$ – the working time of the equipment/ installation k to perform the activity j to get the product i;

c. Phase sequence constraint.

This constraint takes into account that for any equipment / installation, all the activities necessary to finish the current product i should be completed before starting the processing of the the next finished product (i+1):

$$H^{Stop}_{(i+1),j,k} - H^{Stop}_{i,j,k} \geq T_{i,j,k} \tag{5}$$

$$k = 1, 2 \ldots, N_e,\quad i = 1, 2, \ldots N_p\ ,\ j = 1, 2, \ldots N_a$$

d. Balance electricity consumption constraint.

The restriction takes into account that at any time the total electricity consumption corresponding with the sum of the total electricity consumption of all equipment/installations k corresponding each activity j associated to the finished product i must be equal to the total electricity consumption recorded by the measuring equipment.

$$W^h_{meter} = \sum_{j=1}^{N_a} \sum_{k=1}^{N_e} w^h_{i,j,k} \quad h = 1, \ldots, T \tag{6}$$

where: $w_{i,j,k}$ - the electricity consumption of equipment k which work inside the activity j at time t; T – is the hour when the work schedule is finished.

III. THE PROPOSED APPROACH FOR FLATTENING THE ELECTRICITY CONSUMPTION PROFILE

The steps of the proposed methodology for production scheduling are as follows:

Step 1. Enter the input data

The input data is represented by the information contained into a matrix associated to the activities j =1, …, N_a, with the following data about each equipment k = 1,…, N_e: working/not working (using the decision variable E with values 1 or 0), the number of working cycles, the working time, programmable/ non-programmable (as a binary variable 1 or 0), and dependency (indicating the equipment which will work only together to obtain the finished product i), the start/stop working hours of the equipment, and hourly average electricity consumption absorbed in normal operation).

Step 2. Determining the working characteristics of each equipment

The working characteristic of each equipment will be determined considering the working time, sampled per hour and multiplied with the hourly electricity consumption. If two equipment work together, the resulting characteristic of both equipment will contain the cumulative working times.

Step 3. Determining the optimal solution for production scheduling with the purpose flattening the electricity consumption profile

In this step, flattening the electricity consumption profile represents the goal of the production scheduling. The combinatorial optimization has been used to solve the mathematical model (1 - 6).

Generally, a combinatorial problem is solved by Total or Partial Enumeration of the set of its solutions (noted with Ω) [10]. In the Total Enumeration method, finding the optimal solution $x^* \in A$, where A is the set of admissible solutions, requires the generation of all possible combinations of values given to the variables, for all elements from the set Ω. The Partial Enumeration approach is characterized by finding the optimal solution x^* by generating the some part from the Ω and adopting the assumption that in the remained part does not contain the optimal solutions.

Regardless of the enumeration scheme, once an element $x \in \Omega$ is generated, the following steps are performed:

1. It is investigated if element $x \in A$; if NO another element in Ω is generated. If YES, go to the next step.
2. Compare the current value of the objective function with the obtained value for the best element found in step 1; if the value of the objective function is improved (in the optimal sense), x is retained as the best item found in the set A. Otherwise, x is dropped and a new element of Ω is generated.

It is very important to highlight that the generation of the set Ω or even a part of this set does not mean the memorization of the generated elements for two reasons: there are many and then unnecessary (except the best element found in a certain iteration of the enumeration).

IV. CASE STUDY

The methodology presented in the above paragraph was applied at a small enterprise with the activity domain - auto repairs [11]. For this consumer, the working schedule is between 8 a.m. and 5 p.m. The rated power for each equipment/ installation related to all activities is indicated in Table I.

TABLE I. THE RATED POWER OF ALL ELECTRIC EQUIPMENT/INSTALLATIONS

No.	Electric Equipment/Installations		Rated Power [kW]
1	Dyeing Machine (dyeing and drying)		15
2	Air Compressor		11
3	Welding machine		6
4	Lighting system	Tinsmithing and Repair Hall	1.2
5		Dyeing Cabine	0.72
6	Reception Office		0.35
7	Various electric equipment		10
8	Vehicle Elevator		2
9	Electric Heat Installation	Tinsmithing Hall Repair Hall	2x3

The objective of the optimization process is flattening the electricity consumption profile. Using the steps described in Section III, the optimal production schedule will be determined in order to flatten the consumption profile. In this respect, the electricity consumption was recorded for a month (August 2018), and the information about the activities carried out and the equipment which works, were analysed. For this study period the daily electricity consumptions for each equipment was determined (see Fig. 1).

The activities that can be scheduled in every day and the equipment which works were identified. The finished products are represented by cars which have undergone mechanical, tinsmithing and dyeing interventions. For each equipment, the rated power, operating time for various types of operations, and maximum number of operating cycles were identified. In Fig. 2, the variation of electricity consumption as a function of the activities performed on a day from the study period (August 2018) is presented. The values equal with 0 correspond to weekend days when the consumer does not work. It can be observed that the maximum values of electricity consumption were obtained for the Dyeing Machine which has more working cycles with one or both phases (dyeing and drying). These phases can be encountered together or only one (dyeing, because the drying can be natural and not with hot air). Using the data from Table II, representing the input data and technical characteristics (the decision variable (X), working time (T), number of working cycles (N_C), dependency between equipment (D), the start and stop working hours (H^{Start} and H^{Stop}) of each equipment/installation), the optimal solution for production scheduling with the purpose flattening the electricity consumption profile is obtained using combinatorial optimization.

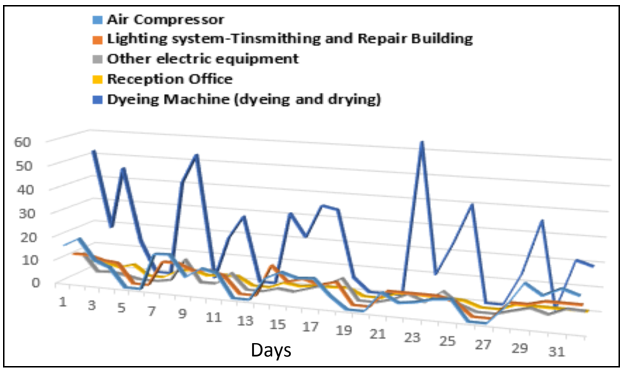

Fig. 1. The daily electricity consumptions for each equipment in analysed period, [kWh]

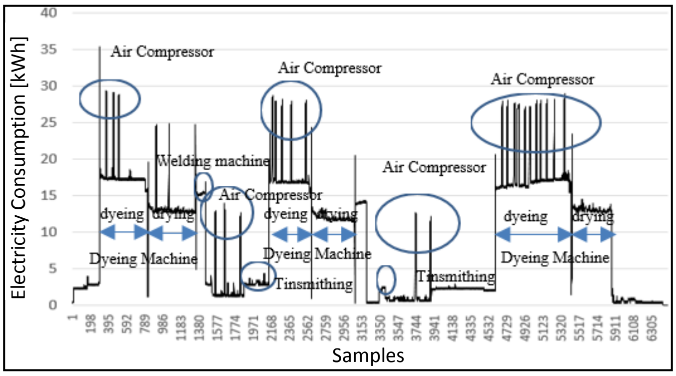

Fig. 2. The electricity consumption for each equipment/installation for a day from the study period (august 2018)

The results for a day (21.08.2018) from the analysed period are presented in Fig. 3 and Table III.

TABLE II. THE INPUT DATA MATRIX

No.	Equipment/Installation	X_k	$T\ [h]$	N_C	D	H^{Start}	H^{Stop}
1	Dyeing Machine - Dyeing Phase	1	1.5	1	2	8	17
2	Dyeing Machine - Drying Phase	1	1	1	1	8	17
3	Dyeing Machine - Dyeing Phase	1	1	1	0	8	17
4	Air Compressor	1	9	1	0	8	17
5	Lighting system -Tinsmithing Building	1	9	1	0	8	17
6	Lighting system -Repair Building	1	9	1	0	8	17
7	Lighting system -Dyeing Machine	1	1	2	0	8	17
8	Reception Office	1	9	1	0	8	17
9	Various electric equipment	1	3	1	0	8	17
10	Vehicle Elevator	1	1	1	0	8	17
11	Pneumatic equipment	1	4	2	4	8	17

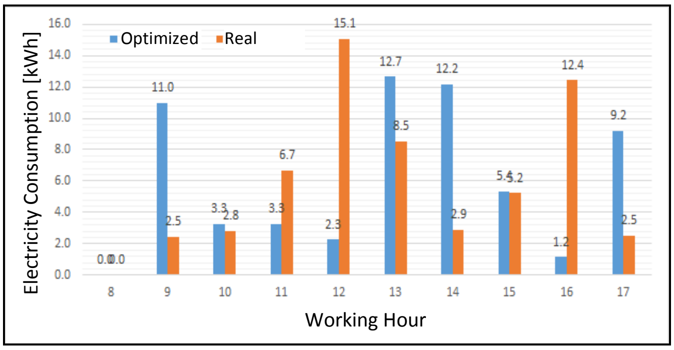

Fig. 3. The real and optimized electricity consumption profile

TABLE III. OPTIMAL SCHEDULING OF EQUIPMENT

Programmed Equipment	Start Hour	End Hour
Vehicle Elevator	8	9
Air Compressor	8	17
Lighting system-Tinsmithing Building	8	17
Lighting system-Repair Building	8	17
Reception Office	8	17
Various electric equipment	8	11
Tinsmith Activity - pneumatic equipment	8	12
Lighting system-Dyeing Machine	11	12
Dyeing Machine - (both phases)	12	15
Tinsmith Activity - pneumatic equipment	13	17
Lighting system-Dyeing Machine	15	16
Dyeing Machine - Dyeing Phase	16	17

Following the use of the proposed approach, it can be observed that the peak value of electricity consumption was reduced with 2.7 kWh (15.87%) from 15.1 kWh to 12.7 kWh.

V. CONCLUSIONS

A mathematical model has been developed to determine the solutions for optimal production scheduling for SMEs in order to minimize costs and flatten the electricity consumption profile. The optimal solutions were obtained using the combinational optimization method based on the total enumeration. The method is characterized by a quick exploration of the set of admissible solutions (the region of interest) in order to obtain the optimal solution, represented by the time intervals in which the equipment will work. The approach was tested at an industrial consumer with activities in the auto service domain. The peak electricity consumption was reduced in a day with 15.87 %. It has been demonstrated that the method finds solutions in very large search environments, providing a useful management tool for making decisions about the optimal choice of energy suppliers and increasing the energy efficiency.

REFERENCES

[1] M. Méndez-Piñero and M. Colón-Vázquez, "Mathematical Model to Optimize the Energy Consumed by a Semiconductors Manufacturing Industry – An Application," Journal of Mathematical Modelling and Application, vol. 1, no. 8, pp. 78-83, 2013.

[2] V. Huddar and M. Kamoji, "An Optimization Model for Energy Saving Opportunities in Cashew Processing Industry," The International Journal of Research in Mechanical Engineering and Technology, vol. 5, no 1, pp. 10 – 14, 2015.

[3] L. Zhang, Y. Luo, Y. Zhang, and G. Song, "Production Scheduling Oriented to Energy Consumption Optimization for Process Industry Based on Self-adaptive DE Algorithm," International Journal of Control and Automation, vol. 8, no. 2, pp. 31-42, 2015.

[4] Y. Hong, S. Wang, and Z. Huang, Efficient Energy Consumption Scheduling: Towards Effective Load Leveling, Energies, vol. 10, no.105, 2017, Available online: http://cs.iit.edu/~yhong/pub/energies17.pdf.

[5] A. Mahmood, M. N. Ullah, S. Razzaq, A. Basit, U. Mustafa, M. Naeem, and N. Javaid, "New Scheme for Demand Side Management in Future Smart Grid Networks," Procedia Computer Science, vol. 32, pp. 477 – 484, 2014.

[6] N. A. Chaudhry, S. S. Chaudhry, A. Junaid, J. Ali, and Q. A. Chaudhry, "Minimization of Electricity Consumption Cost of a Typical Factory," Pakistan Journal of Science, vol. 66, no. 3, pp. 252 – 256, 2014.

[7] N. Galal, and A. Abdul Moneim, "A Mathematical Programming Approach to the Optimal Sustainable Product Mix for the Process Industry," Sustainability, vol. 7, 2015, Available online: https://www.mdpi.com/2071-1050/7/10/13085/htm.

[8] J. F. O. Girón, "Optimal Load Management Application for Industrial Customers," University of Waterloo, Ontario, Canada, 2015, Available online: https://uwspace.uwaterloo.ca/handle/10012/9564.

[9] H. Chen, Y. Li, R. Louie, and B. Vucetic, "Autonomous Demand Side Management Based on Energy Consumption Scheduling and Instantaneous Load Billing: An Aggregative Game Approach," IEEE Transactions on Smart Grid, vol. 5, no. 4, pp. 1744 – 1754, 2014.

[10] T. Munakata, R. Barták, "Logic Programming for Combinatorial Problems," Artificial Intelligence Review, vol. 33, no. 1 -2, pp. 135 – 150, 2010.

[11] G. Grigoras, B.C. Neagu, and Fl. Scarlatache, "Influence of Sampling Size in Profiling Process of Electricity Consumption at Small and Medium Enterprises," 10th International Conference and Exposition on Electrical and Power Engineering, Iasi, Romania, pp. 743 – 748, 2018.