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# Energy-aware production scheduling of continuous slurry ball mills in tile industries with stirring time consideration

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## Abstract

In this paper, a bi-objective mixed-integer model for energy-aware production scheduling of continuous slurry ball mills is proposed. Slurry ball mills are considered as the main consumer of electrical energy and impose high energy costs on tile factories. Hence, minimizing the energy costs associated with slurry production through implementation of peak-load minimization strategy and optimal assignment of orders to ball mills is the main goal which is considered in this study. On the other hand, the quality of slurry has a significant effect on the quality of produced tiles. An increase in time which slurry has left in rotating slip tanks, i.e. stirring time, helps improve its quality. Thus, the second goal which is pursued in this scheduling is compliance with the stirring time standards. The effectiveness of the proposed model is illustrated on a small-scale case study with a saving of above 15% in energy costs.

**Keywords:** Ceramic tile industry, slurry ball mills, energy-aware scheduling, stirring time

## 1-Introduction

Energy-efficiency in manufacturing can be improved through two main approaches, i.e. technological and managerial (Rager et al. 2015). Technological changes such as upgrading existing machines usually require allocating a large budget. Thus, especially in the presence of high uncertainty in terms of market conditions in coming years, this approach increases managers' resistance to change. In contrast, energy-aware scheduling which does not require initial investment is more easily accepted by managers.

Energy-aware, energy-efficient or green scheduling refers to a category of sustainability-related aware scheduling problems in which, unlike classic scheduling problems, the objective functions are not limited to those such as maximizing the company's service level or income (Liu et al. 2017) But, energy and environmental consideration is also involved in scheduling. The study by Mouzon et al. (2007) is the most famous one in the literature.

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The numerical results of this study confirm that some strategies for energy-aware scheduling, such as turning off non-bottleneck machines when they will be idle for a certain amount of time, can even reduce energy costs by up to 80%. According to review paper of Gahm et al. (2016) the most common strategies for energy-aware scheduling problems are as follows:

- Shifting electricity load during periods of high demand and cost, i.e., on-peak hours to periods of low demand and cost, i.e., off-peak or relatively average demand and cost, i.e., mid-peak hours in order to reduce energy cost in terms of time-of-use (TOU) pricing,
- Adjusting the processing speed of machines,
- Turning machines off or putting them into standby mode during their idle intervals,
- Leveling the workload on working machines,
- Regular maintenance of machines and keeping them in the optimum state,
- Assigning more energy-intensive jobs to higher energy-efficient machines.

To reduce energy costs, we benefit from the first strategy, i.e., peak-load minimization strategy and an energy-aware framework for production scheduling under TOU electricity pricing is proposed.

Tile production is an energy-intensive industry (Monfort et al. 2010); about 30% of its costs is associated with energy (Monfort et al. 2010, Ye et al. 2018) and the global average energy consumption per square meter of its production is about 40 kWh (Ros-Dosdá et al. 2018).

Tile production process consists of five main stages. Figure 1, shows the diagram of production process of tile and forms of energy which are consumed in these main stages.

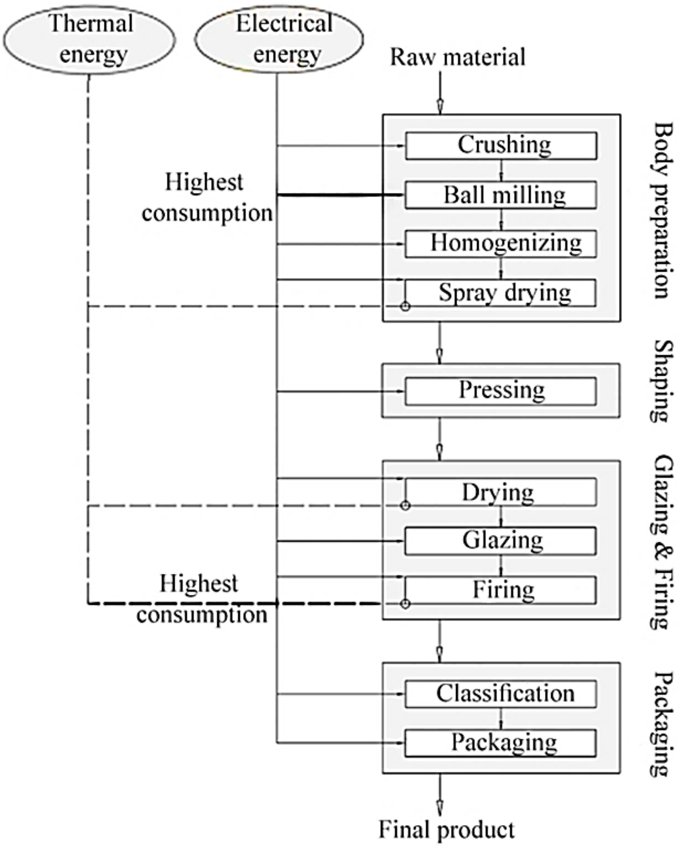

**Fig 1.** Various forms of energy used in the main stages of tile production process

According to (Ciacco et al. 2017) the highest thermal energy consumption occurs in firing stage while ball milling stage consumes the highest electrical energy. So that, for improvements in electricity efficiency, the body preparation stage, especially slurry ball mills play a vital role. Moreover, the quality of slurry which produced at body preparation stage considerably affect the quality of produced tiles. But, adequate stirring time of produced slurry in rotating slip tanks as a controllable quality factor in scheduling has been neglected in the literature.

Finally, this study seeks to answer the following research question: How much energy cost reduction is possible through using the proposed energy-aware production scheduling which benefits from peak-load strategy while the stirring time standards of all slurry orders are met?

The reminder of this paper is organized as follows. In section 2, a brief literature review for production scheduling in tile industry is presented. In section 3, the problem is formulated using Mixed-integer programming. Section 4, illustrated the effectiveness of the proposed model on a small-scale case study. Finally, the paper is concluded in section 5.

## 2-Literature review

Nowadays, in need of significant variety of products, the production scheduling in tile industry become more complex and competition among tile factories over their market share has increased (Ruiz and Maroto, 2002). However, the number of studies that specifically address production scheduling for this industry is limited, and even these limited studies has often neglected production scheduling of ball mills in body preparation stage. In table 1, for each study, the production stages which are considered is outlined.

**Table 1.** Literature classification – tile production scheduling

| Studied stages | Tabucanon & Kongrit | Mirghafuri | Ruiz & Maroto | Durate et al. | Davoli et al. | Deghatian | Abbasi | Ramezanian | This research |
|---|---|---|---|---|---|---|---|---|---|
| Body preparation | | | | * | | | | | * |
| Pressing and glazing | * | * | | | | | | * | |
| Firing | * | * | | | | * | | * | |
| packaging | | * | | | | | | * | |
| Ignorance of the details of production process | | | * | | * | | * | | |

Tabucanon and Kongrit (1991) developed production schedule only for pressing and firing stages. Mirghafuri (1998) presented a mathematical model for production planning and resource allocation of the whole tile manufacturing process except body preparation stage and stated that no restrictions are imposed on tile factories by the pre-press processes. This Justification cannot be accepted as a rational one especially when energy cost is significant, because energy-efficient scheduling of ball mills can play a crucial role in reducing energy cost associated with slurry production. In Ruiz and Maroto (2002), mixed integer modeling and Evolver (a Genetic Algorithm Solver for Excel) was used to plan and schedule the production of a tile plant, but this work did not elaborate on any of the tile production stages. Davoli et al. (2010) presented a stochastic simulation approach for production scheduling and investment scheme in tile industry. They studied the impact of managerial decisions on key performance indicators of this industry, but the details of the tile manufacturing process were not examined in any of its stages.

In order to minimize the stopping time of furnaces in tile production line, Daghatian (2014), optimized the way buffers were allocated to each line and they used simulation and genetic algorithm to solve it. Therefore, this study also does not deal with scheduling of body preparation stage and focuses solely on firing stage. Ramazanian et al. (2017) presented a mixed integer model for simultaneous lot sizing and multi-product production scheduling in flexible job shop environment, and in their case study they considered all tile production stages except body preparation stage. Abbasi et al. (2017) studied the problem of lot sizing and production scheduling for complementary products in tile industry. Each package of complementary product contains tiles of different sizes, colors, and designs, and if the product is not available in a specified number, the package will not be complete. In their study, different parallel lines were considered for producing different types of tiles with different properties and processing times, but details of production stages were not considered in optimization. Their proposed model may be applicable to automation-based stages after body preparation.

To our best knowledge, the research carried out by Duarte et al. (2009) is the only study that has proposed a mathematical model for ball mills in tile industry. This study pursued three different goals simultaneously: 1) identifying the optimal number and net capacity of the mills to install in the grinding section, 2) selection of the best shift policy, and 3) determining the optimal plant schedule taking into account the workforce and equipment resources constraints. Duarte et al. (2009) considered a single product production environment and one-week planning horizon, while in reality customers' demands are often not a single product and has a variety of production processes. They also assumed that demand to be cyclical and it would remain constant for all the next weeks, whereas, according to market fluctuations, this assumption cannot be valid. Moreover, they assumed that paying attention to production scheduling in the factory configuration phase cam cause significant reduction in costs. In fact, they proposed integrated model to achieve an optimal exchange between operating and installation costs. However, oftentimes it is not logical to consider decisions from strategic level (the number and size of ball mills), tactical level (optimal shift policy), and the operational level (production scheduling), simultaneously in an integrated model. Therefore, our research attempts to address the mentioned shortcomings. In our research, the design and capacity of the ball mills are predetermined and only production scheduling is taken into account.

Finally, proposing an energy-aware scheduling model which is more adapted with the characteristic of tile industry in comparison to the literature is the main contribution of this study.

## 3-Problem description and formulation

Ball mills of body preparation stage are uniform parallel machines (Ma et al. 2017) i.e., each one is capable of producing any slurry orders, but they may differ in terms of some technical characteristics. To produce slurry with a specific formulation, several kinds of mineral soils, are mixed with water and some additives in ball mills. The slurry color of different formulations is either white or red. To process new order in a ball mill, if the color of the new order is the same as that of the previous one, it is only necessary to adjust the ball mill input settings, thus the setup time is about zero. But, if the color of the next order changes, the ball mill must be washed before pouring raw material for next processing (figure 2). In equation (1), the value of setup time parameter ($s_{ii'm}$) is calculated, when processing of order $i$ precedes order $i'$on machine $m$. Binary parameters ($c_i$) determine the color of order $i$. If $c_i = 1$, the slurry color is red, otherwise it is white. For the cleaning operation of each machine, an approximately fixed time required ($\pi_m$). $s_{ii'm}$ is equal to zero when order $i'$ is the same color as order $i$, otherwise it is equal to the time required for the cleaning operation.

$$s_{ii'm} = |c_i - c_{i'}| \times \pi_m \tag{1}$$

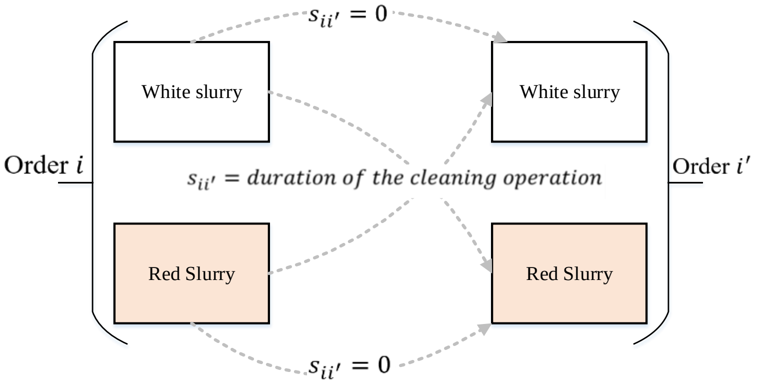

**Fig 2.** Sequence-dependent setup time according to the color of orders

The ball mills are connected to all the crusher silos and soil can be poured from each crusher silo according to the required slurry formulation. Each ball mill is also connected to one or more rotating slip tanks that the produced slurry enters them.

Ball mills are continuous or discontinuous. In discontinuous type, the ball mill is switched off before processing each order and the raw material is loaded. Then, after completing each order the ball mill is again switched off and the order is unloaded. However, in continuous type, loading and unloading are done gradually during processing time while the ball mill stays on. In this study, only the continuous ball mills are considered. During the slurry processing, at least one quality sampling is needed. In continuous ball mills, sampling occurs during slurry processing, Thus, does not cause extra processing time. The produced order is gradually unloaded and stored in rotating slip tanks stirred continuously (Zeng et al. 2019). The rotating slip tanks are big enough and in rather all cases, there is no capacity constraint for storage.

At the beginning of the scheduling horizon, all slurry orders with their delivery times to the next stage, i.e., spray dryers are known. Each order has only one operation and preemption is not allowed. Orders can be processed on any ball mills and they must be processed separately. Also, each ball mill can process only one order at a time.

To improve the quality of the produced slurry, it must be homogenized in rotating slip tanks for a certain period of time, i.e., stirring time ($\Delta_i$). Therefore, the deadlines of slurry orders ($dd_i$) in ball mills are equal to their delivery to spray dryers ($D_i$) minus ($\Delta_i$) (see figure 3).

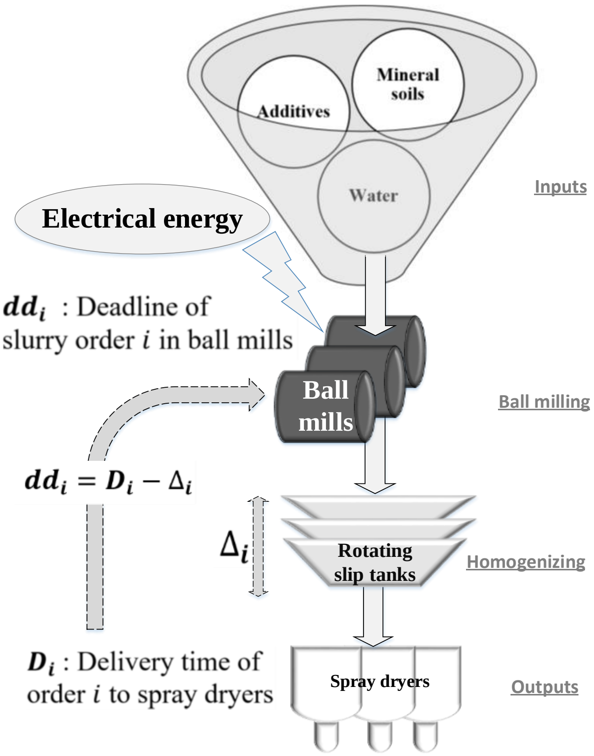

**Fig 3.** Relationship between completion time of ball milling and next operations

Ball mills may differ in terms of speed of processing and energy consumption rate. Moreover, energy cost is time-dependent and comprises costs of off-peak ($\alpha$), mid-peak ($\beta$) and on-peak periods ($\gamma$). In this study a bi-objective model is proposed. The main goal of this model is minimizing the total production energy costs. Afterwards, if the first objective function exhibits multiple optimal solutions, the second objective function, i.e., minimization of negative deviation of stirring time is taken into account.

To provide a formal description of the developed model, some notations are introduced as follows:

**Sets and parameters:**

| | |
|---|---|
| $T$ | time periods={1,2,…,\|T\|} |
| $M$ | ball mills={1,2,…,\|M\|} |
| $I$ | orders={1,2,…,\|I\|} |
| $\alpha_t^{bin}.\beta_t^{bin}.\gamma_t^{bin}$ | Binary parameters, equal to one if period $t$ is in off-peak, mid-peak or on-peak hours respectively |
| $e_m$ | Energy consumption rate of ball mill $m$ in production intervals |
| $\alpha.\beta.\gamma$ | Cost of using one unit of energy for a period of processing at off-peak, mid-peak or on-peak hours respectively |
| $\mathrm{D}_i$ | Delivery time of order $i$ to the next stage |
| $\Delta_i$ | Minimum necessary delay between the completion of order $i$ and its delivery to the next stage |
| $p_{im}$ | Processing time of order $i$ on machine $m$ |
| $s_{ii'm}$ | Sequence-dependent setup time, duration of the cleaning operation required to switch from order $i$ to $i'$ on machine $m$ |
| $G_i$ | Ideal delay between the completion of order $i$ and its delivery to the next stage |
| $\rho_i$ | Penalty of negative deviation of $i$-th order's stirring time from its ideal value |

**Decision variables:**

| | |
|---|---|
| $x_{itm}$ | Binary variable, equal to one if processing of order $i$ starts at period $t$ on machine $m$ |
| $y_{itm}$ | Binary variable, equal to one if machine $m$ is involved in the processing of order $i$ at period $t$ |
| $z_{ii'}$ | Binary variable, equal to one if processing of order $i$ precedes order $i'$ $(i < i')$. |
| $dp_i.dn_i$ | Amount of positive and negative deviation of $i$-th order's stirring time from its ideal value respectively |

The mathematical formulation of the proposed model is as follows:

$$Min(f) = \sum_{n\in N}\sum_{t\in T}\sum_{m\in M}(\alpha_t^{bin}\alpha + \beta_t^{bin}\beta + \gamma_t^{bin}\gamma)e_m y_{itm} \tag{2}$$

$$Min(G) = \sum_{i\in I}\rho_i dn_i \tag{3}$$

Subject to:

$$x_{itm} \le M\left(\sum_{t'=t}^{t+p_{im}-1} y_{it'm} - (p_{im}-1)x_{itm}\right);\ \forall i.t.m \tag{4}$$

$$\sum_{t\in T}\sum_{m\in M}(t+p_{im})x_{itm} \le D_i - \Delta_i;\ \forall i \tag{5}$$

$$\sum_{t\in T}\sum_{m\in M}(t+p_{im})x_{itm} = D_i - G_i''' + dn_i''' - dp_i''';\ \forall i \tag{6}$$

$$\sum_{t\in T} tx_{i'tm} \ge \sum_{t\in T} tx_{itm} + p_{im} + s_{ii'm} - M(1-z_{ii'}) - M(2 - \sum_{t\in T} x_{itm} - \sum_{t\in T} x_{i'tm});\ \forall m.i.i';i' > i \tag{7}$$

$$\sum_{t\in T} tx_{itm} \ge \sum_{t\in T}(tx_{i'tm} + p_{i'm}) + s_{i'im} - M(z_{ii'}) - M(2 - \sum_{t\in T} x_{itm} - \sum_{t\in T} x_{i'tm});\ \forall m.i.i';i' > i \tag{8}$$

$$\sum_{t\in T}\sum_{m\in M} x_{itm} = 1; \forall i \tag{9}$$

$$\sum_{i\in I} y_{itm} \le 1;\ \forall t.m \tag{10}$$

$$x_{itm}.y_{itm} \in \{0.1\};\ \forall i \in I.\forall t \in T.\forall m \in M \tag{11}$$
$$z_{ii'} \in \{0.1\};\ \forall i.i' \in I.i' > i \tag{12}$$
$$dp_i, dn_i \geq 0;\ \forall i \in I \tag{13}$$

This model consists of two objective function. Its first objective function, as shown in (2), is to minimize the total energy costs of producing all slurry orders. While, the second objective which shown in (3) tries to minimize the sum of the weighted negative deviation of orders' stirring time from their ideal values as much as possible. In (4), for each order, the production variables are set to one from the beginning to the end of its production. In (5), satisfaction of all orders before their deadlines are guaranteed. In (6), the positive and negative deviations of orders' stirring time from their ideal values are calculated. Constraints (7) and (8) are precedence constraints which identify the sequence of orders on each machine. In (9), it is guaranteed that each order produced on exactly one machine. In (10), It is ensured that each machine at each period not be involved in production of multiple orders, simultaneously. Constraints (11) and (12) ensure binary condition for the production variables. Constraints (13) ensure non-negativity condition for the variables related to negative and positive deviations of orders' stirring time from their ideal values.

## 4-Case study

In this section, the behavior and effectiveness of the proposed model is examined through a small-scale illustrative case over a three-day scheduling horizon.

Firstly, in section 4.1, the scheduling which was done by the factory in the case of not using the proposed mathematical model is given. Next, in section 4.2, the proposed model is applied to it and to evaluate the performance of the model, a comparison between the results of this section and the previous section is drawn.

### 4-1- Experience-based scheduling

The scheduling horizon is considered to be three days, i.e. 3×24 hours. Moreover, for the sake of simplicity of illustrating the results through graphs, only three continuous ball mills of the factory are considered. The speed of these three ball mills is almost the while their energy efficiency is different. $e_m$ for ball mill 1 and 2 is 341 kWh, for ball mill 3 is 322 kWh. The industrial electricity tariffs of the considered energy source vary from off-peak to mid-peak and on-peak periods. These tariffs in winter-weekdays is given in figure 4.

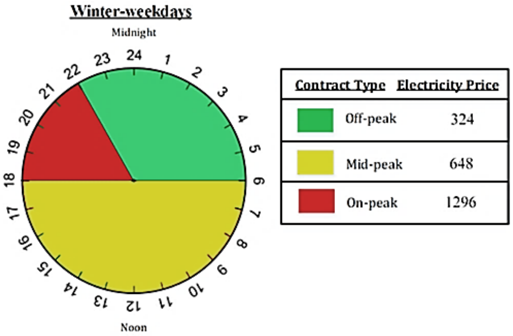

**Fig 4.** The industrial electricity tariffs in winter-weekdays

Figure 5 (a) shows the scheduling which was done by the factory without using the proposed mathematical model. The row which is labeled by "Shifts" categorizes the hours of every day which is shown in the row labeled by "Time" to three 8-hour shifts. Row "Time" identifies the contract type at each time through colors which are defined in figure 4. In next rows of figure 5 (a), the numbers which are shown after letter D and B indicate the day of scheduling horizon and the ball mill number respectively, e.g. row D3B1 is related to the third day of the scheduling horizon and the first ball mill.

The status of each ball mills at each time interval is shown through different colors. Gray indicates the intervals in which the ball mill is idle. The intervals in which the ball mill is not available for production for some reason is shown in black. The production intervals are shown in white and bright red which are related to the color of slurry order, e.g. the color of order 7 (name as o7) is red and the color of order 8 (o8) is white. Moreover, the set up intervals (name as S) are shown in blue, e.g. ball mill 3 required a one-hour cleaning operation to produce o8 after o7.

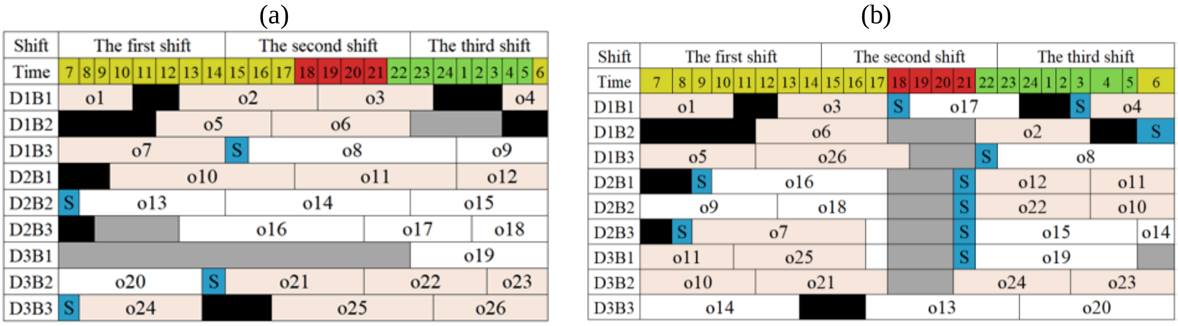

**Fig 5.** The schematic of production scheduling: (a) experience-based, (b) model-based

## 4-2-Model-based scheduling

To solve the proposed problem, ILOG CPLEX 12.8 is used on a 64-bit computer benefits from Intel Core i7 2.70 processor and 12 GB of RAM. Moreover, to handle the bi-objective problem, a lexicographic approach is applied. For this purpose, energy cost reduction gets the highest priority and minimization of the sum of the weighted negative deviation of orders' stirring time from their ideal values is put in the second priority. The model with the first objective function is solved within 319 seconds. While, the model with the second objective function and the lexicographic constraint related to optimal energy cost exceeds a two-hour time limit without any feasible solution. Thus, we only report the solution of the first objective function in figure 5 (b). In the scheduling which was done by the factory, 88% of available on-peak periods are used for production. While, benefiting from peak-load minimization strategy, this value is decreased to 17%. Moreover, this model-based scheduling is able to achieve a saving of above 15% in energy costs.

## 5-Conclusion

This paper proposes an energy-aware scheduling model with stirring time consideration on uniform parallel continuous ball mills under time-of-use electricity tariffs, where electricity price may change hourly. To formulate this problem a bi-objective MIP model is proposed and lexicographic method is used. The computational results on the model with the first objective function indicated an optimal solution with above 15% saving in energy cost. While, no feasible solution is found within a reasonable time limit for the model with lexicographic constraint related to optimal energy cost and the stirring time objective function. Due to the complexity of the proposed model, this work can be extended by proposing an effective solution method. Moreover, providing an energy-aware framework for both production and maintenance operations may result in higher saving in energy costs. Work is in progress to address these extensions.

## Acknowledgments

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## References

Abbasi Hafshejani, N., Lotfi, M. M., Honarvar, M. (2017). A Hierarchical Approach for Lot-sizing and Production Scheduling of Complementary Product Packages, Journal of Advances in Industrial Engineering, Volume 51(2), 207-222.

Ciacco, E. F., Rocha, J. R., & Coutinho, A. R. (2017). The energy consumption in the ceramic tile industry in Brazil. Applied Thermal Engineering, 113, 1283-1289.

Davoli, G., Gallo, S. A., Collins, M. W., & Melloni, R. (2010). A stochastic simulation approach for production scheduling and investment planning in the tile industry. International Journal of Engineering, Science and Technology, 2(9).

Deghatian, M. (2014). Optimization of production program simulation using genetic algorithm (Case study: Goldis Tile Company), Master Thesis, Yazd University.

Duarte, B. P., Santos, L. O., & Mariano, J. S. (2009). Optimal sizing, scheduling and shift policy of the grinding section of a ceramic tile plant. Computers & Operations Research, 36(6), 1825-1834.

Gahm, C., Denz, F., Dirr, M. and Tuma, A., 2016. Energy-efficient scheduling in manufacturing companies: a review and research framework. European Journal of Operational Research, 248(3), 744-757.

Liu, G. S., Zhou, Y., & Yang, H. D. (2017). Minimizing energy consumption and tardiness penalty for fuzzy flow shop scheduling with state-dependent setup time. Journal of cleaner production, 147, 470-484.

Ma, Y., Chu, C., & Zuo, C. (2010). A survey of scheduling with deterministic machine availability constraints. Computers & Industrial Engineering, 58(2), 199-211.

Mirghafoori, H. (1998). Designing a mathematical model for production planning in tile industry, Master Thesis, Tarbiat Modares University.

Monfort, E., Mezquita, A., Granel, R., Vaquer, E., Escrig, A., Miralles, A., & Zaera, V. (2010). Analysis of energy consumption and carbon dioxide emissions in ceramic tile manufacture. Boletin De La Sociedad Espanola De Ceramica Y Vidrio, 49(4), 303-310.

Mouzon, G., Yildirim, M. B., & Twomey, J. (2007). Operational methods for minimization of energy consumption of manufacturing equipment. International Journal of production research, 45(18-19), 4247-4271.

Rager, M., Gahm, C., & Denz, F. (2015). Energy-oriented scheduling based on evolutionary algorithms. Computers & Operations Research, 54, 218-231.

Ramezanian, R., Sanami, S. F., & Nikabadi, M. S. (2017). A simultaneous planning of production and scheduling operations in flexible flow shops: case study of tile industry. The International Journal of Advanced Manufacturing Technology, 88(9-12), 2389-2403.

Ros-Dosdá, T., Fullana-i-Palmer, P., Mezquita, A., Masoni, P., & Monfort, E. (2018). How can the European ceramic tile industry meet the EU's low-carbon targets? A life cycle perspective. Journal of Cleaner Production, 199, 554-564.

Ruiz, R., & Maroto, C. (2002). Flexible manufacturing in the ceramic tile industry. In Eight International Workshop on Project Management and Scheduling, PMS 2002. (pp. 301-304).

Tabucanon, M., & Kongrit, A. (1991). Hierarchical approach to production planning and scheduling: the case of a mosaic tile plant. In Modern Production Concepts (pp. 114-145). Springer, Berlin, Heidelberg.

Ye, L., Hong, J., Ma, X., Qi, C., & Yang, D. (2018). Life cycle environmental and economic assessment of ceramic tile production: A case study in China. Journal of Cleaner Production, 189, 432-441.

Zeng, C., Tang, J., Fan, Z., & Yan, C. (2019). Auction-based approach for a flexible job-shop scheduling problem with multiple process plans. Engineering Optimization, 1-18.