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Procedia Manufacturing 42 (2020) 538–541

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

International Conference on Industry 4.0 and Smart Manufacturing (ISM 2019)

Job shop scheduling model for a sustainable manufacturing

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Abstract

Technological development was not always environmental-friendly but it led to problems that affect the entire population, such as climate change and the depletion of non-renewable resources. In recent years, we are trying to change the concept of industrialization, with a more prudent and focused view to environmental issues. In this perspective, the setting of the fourth industrial revolution, called Industry 4.0, seeks to make technological development sustainable with the crucial aim of resource saving firstly.

Starting by this issue, this study aims at introducing a smart tool, based on the application of a mathematical model, already proposed in literature, for the job scheduling from an energy saving perspective into a real company IT system. After a preliminary introduction on the concepts of sustainability and industry 4.0, and how they are connected to each other, and a second part that will deal with Smart Factory, smart factories oriented to customization and flexibility, the mathematical model of activity scheduling will be discussed and than applied to a specific IT system. This model, in fact, properly implemented into a Manufacturing Execution System (MES) will represent a powerful tool oriented to the efficient use of energy resources.

Keywords: Sustainable manufacturing; job scheduling; energy saving.

1. Introduction

The increase of global industrialization, the population growth, the development of new products, the high levels of production and extreme consumption have contributed to an economic development but contemporary have produced negative impacts on the ecosystem. The new paradigm of Industry 4.0 seems to take care about these aspects and tries to develop a new manufacturing paradigm based firstly on the combination of virtual and physical, represented by Cyber Physical System, Internet of Thing, robotics, Big Data, Cloud, augmented reality, etc., but also on sustainable manufacturing [1].

The term *"sustainable development"* was coined for the first time in 1972 [2], at the UN Conference on the Human Environment in Stockholm, to seek a mediation between economic development and environmental protection. Economic development, in fact, defined itself as "sustainable" if not only the purely financial aspects are considered but also its social and environmental effects. This definition, a few years later, was then expanded and specified by the World Commission for the Environment and Development (Commission Brundtland) [3], which defined sustainable as the "economic and social development that meets the needs of the current generation without compromising the ability of future ones to respond to their own”. So, a correct sustainable development is achieved by balancing three aspects: economic sustainability (profit); environmental sustainability (planet); social sustainability (people) [4].

In this paper, a mathematical model [5] have been implemented into a real production system to solve the production scheduling problem with a new perspective that takes into account also environmental issues such as the energy consumption required for performing the single activity. The main goal of the model, in fact, is to propose the better scheduling for the jobs not only for the makespan reduction, as usually done, but also balancing them from a sustainable perspective.

10.1016/j.promfg.2020.02.034

2. Beyond the Industry 4.0 concept

The development of new technologies has allowed us to identify over the years four different industrial revolutions, each of them characterized by a technology.

One of the main objectives of Industry 4.0 is to link resources, services and humans in real time throughout the production based on Physical Cyber Systems (CPS) with the help of the Internet of Things (IoT) [6].

In Industry 4.0 the physical components of any industrial system are completed and enhanced by sensors, actuators and embedded systems, which give it the ability to process and communicate data.

An embedded system is a combination of hardware and software components, integrated in a technical context where it often performs predefined tasks in real time. It is able, through the use of sensors, to carry out specific data monitoring actions and to control, through the actuators, physical processes. In addition to CPS and IoT, two other fundamental pillars are Big Data analytics and Cloud Computing. Big Data analytics is the process by which large amounts of data are examined to discover hidden patterns, unknown correlations, marketing trends, customer preferences and other useful company information. Analytical results can lead to more effective marketing, new revenue opportunities, better customer service, better operational efficiency, competitive advantages over rival organizations and other business benefits. Cloud computing is a term generally used to identify the provision of Internet hosting services. It allows companies to use IT resources and services on the internet rather than having to build and maintain infrastructures on-site [1,7].

The paradigm of industry 4.0 aims to create more sustainable value, compared to previous industrial revolutions, in all three dimensions of sustainability: social, economic and environmental.

From an economic point of view, the approach to the design of sustainable products in Industry 4.0 essentially focuses on the generation of optimal life cycles, allowing the reuse and regeneration of a given specific product. Other approaches, instead, are based on the achievement of the degree of satisfaction of the consumer, setting a lower bound as a reference point below which it is not convenient to go down.

As regards the environmental context, development methods for Cleaner Production (CP) are developed. These systems offer an alternative for waste reduction through their implementation [8].

New technologies allow the creation of production systems that are not only integrated, but also flexible, which makes it possible to cope with the variability of real-time market demand [9].

The complexity of the operations has determined, for all the companies that approach industry 4.0, the introduction of a Manufacturing Execution System (MES).

The MES is used to detect all information related to the production cycle and monitor production in real time. It is generally described as the implementation of a highly integrated management information system that uses modern concepts and technologies to reduce costs, improve business processes and standardize the sector, thanks to the integration of best technological practices. It can optimize a process, simulate it and verify the results in the different departments managing to manage any alerts. The MES is inserted between the ERP systems and the PLC, SCADA machine control systems. With the inclusion of this system you can have management, visibility and control of everything that happens between the input and output factors. The MES, as mentioned, deduces useful information to integrate the control and the progress of production, collects data in real time and, based on these, makes decisions.

Thanks to the ERP it is possible to plan the production and therefore the theoretical times of machine inactivity. The MES, on the other hand, returns the actual production data, information on material flows and actual times of machine inactivity. The MES is able to simultaneously perform data collection within even complex systems and constant and punctual monitoring of the production processes connected to them, always guaranteeing greater efficiency and control [10].

From the knowledge of the planned and the actual, the new MES, integrated with the sustainable scheduling function, will be able to decide for instance when to shut down a specific machine to save energy. Having taken this decision, the MES will transmit the information to the control unit which in turn will translate it into a signal to switch off the machine in question.

All this will bring some considerable advantages from an economic point of view, due to a reduction in costs that can be achieved thanks to better management of energy consumption but, above all, to much more interesting and important advantages from the environmental sustainability point of view, thanks to the proficient use of energy resources.

3. Mathematical model

With the growing economic, social and scientific developments, the claim for energy is rapidly increasing, as a result all non-renewable resources are running out and it is necessary to be aware of energy saving problem, assuming that manufacturing companies absorb about a third of the energy consumed globally.

A reduction of energy consumption in light of a reduced invested capital could be given by the implementation of scheduling models that take into account the use of energy during the manufacturing process. The objective of these mathematical models is to schedule the production through a selection of the machines and an optimal sequencing of the operations on them, in order to reduce energy consumption. By implementing a model of this type, industries can save a considerable amount of energy, making the processes more competitive and eco-friendly.

Some studies have also shown that the 80% of the energy spent during manufacturing operations is used to keep the machines in an idle state time and therefore they show that there is a large margin of savings and efficiency. An efficient way to reduce idle times is to set up an On / Off strategy on the machine so that it is turned off when an idle period is long enough. This idea was readily applied to non-linear optimization models, to move on mixed linear programming models on a single machine, until arriving progressively at identical machines connected in parallel and then in line.

The most recent application concerns the so-called "Flexible Job Shop Problem" (FJSP) [5,11]. In this paper the model proposed in [5] has been taken into account as reference for the subsequent industrial application. Generally speaking, about this class of problems, the literature has focused more on time performances (thus on the minimization of Makespan) than on energy consumption. However, the depletion of resources, the consequent rise in energy costs, and stricter laws and regulations on sustainability and environmental protection, have meant that an ever increasing number of authors have placed their attention on energy consumption in FJSPs.

3.1. Problem discussion

The Flexible Job Shop Scheduling Problems are an extension of the standard Job Shop Scheduling Problems. In this class of problems, the machines are flexible and suitable for processing multiple types of operations, thus an operation can be performed on different machines (a subset).

A problem of this type can be broken down into two sub-problems: choosing the machine on which to perform each operation and determining the sequence of operations on the machines [5]. Typically, the following assumptions must be taken into account [5]:

- the operations of the same job must be processed according to a given sequence;
- different job transactions are independent;
- all jobs and machines are available at the beginning of the planning time;
- each machine cannot process more than one operation at a time and each operation cannot be performed by several machines simultaneously;
- all the parameters of the model are deterministic and known with certainty;
- transportation times between different machines and set up times for processing different jobs on the same machine are negligible;
- no preemption.

In a FJSP there are a set I of jobs $(i = 1, \dots, n)$ and a set K of machines $(k = 1, \dots, m)$ on which the jobs are to be processed. Each job i consists of a sequence of operations $J_i = (O_{i,1}, O_{i,2}, \dots, O_{i,S_i})$, $j = 1, \dots S_i$ that can be performed on a subset $Kij \subseteq K$ of machines.

3.2. Parameters

$Ppower_{i,j,k}$ processing power operation $O_{i,j}$ on the machine k
$Ptime_{i,j,k}$ processing time operation $O_{i,j}$ on the machine k
N_k maximum number of times the machine k can be switched on / off
TB_k breakeven value for the machine k, defined as $max\left\{T_k\,,\ {EnergyS_k}/{P_{idle}^k}\right\}$
$EnergyS_k$ energy spent by the machine k for an on / off switch
T_k time spent by the machine k for an on / off switch
P_{idle}^k energy spent by the machine k when it is in idle time
$P_{\text{auxiliary}}$ energy spent for the operation of auxiliary systems (light, air conditioning, ventilation, heating)

3.3. Decision making variables

$$X_{i,j,k} = \begin{cases} 1 \text{ if the operation } O_{i,j} \text{ can be processed} \\ \text{on the machine k} \\ 0 \text{ otherwise} \end{cases}$$

$$Y_{i,j,k,t} = \begin{cases} 1 \text{ if the operation } O_{i,j} \text{ occupies the position t} \\ \text{of the machine k} \\ 0 \text{ otherwise} \end{cases}$$

$$Z_{k,t} = \begin{cases} 1 \text{ if the } \frac{\text{On}}{\text{Off}} \text{ strategy is implemented} \\ \text{between t and t + 1 of the machine k} \\ 0 \text{ otherwise} \end{cases}$$

$B_{i,j} \geq 0$, continuous variable that indicates the instant of the starting of the operation $O_{i,j}$
$E_{i,j} \geq 0$, continuous variable indicating the ending instant of the operation $O_{i,j}$
$F_{k,t} \geq 0$, continuous variable indicating the final instant of occupation of position t on the machine k
$S_{k,t} \geq 0$, continuous variable indicating the initial instant of occupation of position t on the machine k
$C_{max} \geq 0$, Makespan
$Energy_{k,t} \geq 0$, continuous variable indicating the energy consumption of the machine k between the positions t and t+1

3.4. Objective function

The objective of the model is to minimize the total energy consumption (Total Energy) [5]:

$$(1)\ \min Total\ Energy = \sum_{k \in K} \sum_{t \in LL_k} Energy_{k,t} + \sum_{i \in I} \sum_{j \in J} \sum_{k \in K_{i,j}} Ppower_{i,j,k} Ptime_{i,j,k} X_{i,j,k} + P_{auxiliary} C_{max}$$

In the expression (1) the first member represents the total energy spent by all the machines when they are in a state of idleness, while the second and third members respectively represent the energy spent for the processing of all the operations of all the jobs on all the machines and the energy spent for the operation of the auxiliary systems.

3.5. Constraints

According to the paper [5], the constraints ensure the correct processing of the operations $O_{i,j}$ on the machines k, considering sequence of these and the position t occupied.

The constraints ensure that each operation is assigned to a machine position so that each operation is exactly assigned to one of the possible machines, that if the operation $O_{i,j}$ is assigned to the machine k, it will then be exactly assigned to one of the positions of the machine k, otherwise it will not be assigned to any of its positions.

Each position on the machine can be allocated at least one and the position of each machine operations are assigned in sequential order.

The correct sequencing of operations is guaranteed by the combination of the start and end time: the instant of completion of an operation with its instant of beginning and the instant of end of occupation of a position with its instant of beginning.

The beginning of the operation, is equal to the instant in which the position is occupied, if the operation $O_{i,j}$ is assigned to the t position of the machine k and an operation of a job can only be started if the previous operation it has been completed.

A constraint determines the makespan and another one restricts the number of times an On / Off strategy can be implemented on each machine.

If the t_k^{idle}, or the difference between $S_{k,t+1} - F_{kt}$, is not smaller than the value TB_k of breakeven, the machine is turned off, otherwise it will continue to remain in its idle state.

The new ones are added to the constraints represented up to now (taken from paper [5]):

$$(1)\ Energy_{kt} \geq EnergyS_k Z_{kt}, \qquad \forall\, k \in K, t \in LL_k$$
$$(2)\ Energy_{kt} \geq (S_{k,t+1} - F_{kt}) P_k^{idle} - MZ_{kt}, \quad \forall\, k \in K, t \in LL_k$$

For this new mathematical model, the constraints (1) and (2) are used to ensure that if the energy spent by the machine when it is in an idle condition exceeds $EnergyS_k$, or the energy spent by the machine k for an On / Off, then the strategy On / Off will be implemented ($Z_{kt} = 1$) to save energy, and consequently $Energy_{kt} = EnergyS_k$. Otherwise, if the On / Off strategy is not implemented ($Z_{kt} = 0$), we will obtain $Energy_{kt} = (S_{k,t+1} - F_{kt}) P_k^{idle}$, or rather the power spent by the machine in the idle state for the period of time in this condition persists.

3.6. Case study

This model was firstly implemented into a C-plex environment by Java code, and then integrated into a Manufacturing Execution System (MES) of a medium enterprise involved in the planning and production of aircraft components. The production asset of the company adopted as case study is characterized by two type of operations: mainly machining and assisted assembly, so the attention was pointed on the first step. This is performed with 10 large universal CNC work centers that are turned on each morning and then off in the evening. This machines are fully automated and partially supervised by man power. The production rate does not require the whole available working capacity, so according to the daily production plane, any machine could stay in stand by up to hours. However, the energy consumption during the idle time ranges around 2kWh for each machine, while it reaches less than 6kWh for only few seconds during the starting phase. Performing on the MES the previous model starting by the subset of production orders planned to be delivered in one week, the better scheduling was identified with four turn On/Off cycle during the week and customised starting and ending time for each machine per day. Comparing that with the conventional approach a full cost saving of 1.2% was obtained.

4. Conclusion

This work aims to integrate two segments: industry 4.0 and sustainability. In this work, starting by a model available in literature [5], the same was adapted and implemented into a real industrial scenario in order to demonstrate the impact of the same into a SME environment. The application highlighted that it is possible to minimize the energy to use, in the execution of given operations, the related cost associated and therefore also the reduction of CO_2 emissions.

In future, starting from the already available model [5] and by the promising results obtained on a specific case study, new types of FJSP models with new features will be performed, such as the possibility of considering the set-up times of the machines or the transport times between one machine and another.

Further developments may focus on the introduction of new constraints or a new objective function that take into consideration the energy self-produced by the industry through renewable sources and, on this beginning, to schedule operations in a proficient way, introducing the possibility of succeeding in use energy deriving from wind and solar systems belonging to the company itself. By doing that, the smart factory will become more environmental friendly, projecting itself towards sustainable development, and at the same time optimizing and reducing production-related costs.

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