Management and Production Engineering Review
Volume 10 • Number 1 • March 2019 • pp. 89–97
DOI: 10.24425/mper.2019.128247

NEW MODEL OF PLANNING AND SCHEDULING FOR JOB-SHOP PRODUCTION SYSTEM WITH ENERGY CONSIDERATION

Zineb Ibn Majdoub Hassani[1], Abdellah El Barkany[1], Ikram El Abbassi[2]
Abdelouahhab Jabri[1], Abdel Moumen Darcherif[2]

[1] *Mechanical Engineering Laboratory, Faculty of Science and Techniques, Sidi Mohammed Ben Abdellah University, Morocco*
[2] *ECAM-EPMI, France*

Corresponding author:
Zineb Ibn Majdoub Hassani
Mechanical Engineering Laboratory
Faculty of Science and Techniques
Sidi Mohammed Ben Abdellah University
B.P. 2202 – Route d'Imouzzer – FEZ, Morocco
phone: (+212) 667639374
e-mail: zineb.ibn1@gmail.com

Received: 6 December 2018
Accepted: 20 February 2019

Abstract
This paper reports a new multi-item planning and scheduling problem in a job-shop production system with the consideration of energy consumption. A mixed integer linear programming is proposed to integrate planning and scheduling with the consideration of energy aspect. In this study a new operational constraint is considered in the tactical level because of the huge interest given to energy consumption and its strong link existing with production system. To evaluate the performance of this model, computational experiments are presented, and numerical results are given using the software CPLEX and then discussed.

Keywords
production, planning, scheduling, MILP, energy, resolution, CPLEX.

Introduction

Over the last decades management of production systems has received a great attention. It is divided into three levels, on the strategic one, it has been proved how production systems should be designed to maximize the long-term profit [1–3]. On the medium-term level, the literature has studied the possibilities to modernize the production equipment and decrease the setup costs, lead times and expand available capacities of production [4–7]. On an operational level, researchers have developed methods that support companies in utilizing a given production equipment as efficiently as possible [8, 9].

However, the production of a good or service is the stage in life cycle where the ecological footprint is greatest. By producing a good in an environmentally responsible way, the company is able to significantly reduce its ecological footprint, reduce its production costs and increase its productivity, thereby creating sustainable competitive advantages. Environmental management is a framework established by an organization to improve its environmental performance by integrating environmental considerations into strategic decision-making and risk management.

Energy is a daily need that the industry, economy and well-being of any population depends on its safety, durability and accessibility. However, the rising of energy cost is one of the important factors associated with increased production costs at manufacturing facilities, which encourages decision-makers to tackle this problem in different manners. Indeed, manufacturing plants are facing increasing pressure to reduce their carbon footprint, driven by concerns related to energy costs and climate change.

The potential to reduce energy costs can lie in increasing the energy efficiency (EE) of production processes and management approaches [10]. For example, reducing non-production modes to improve energy efficiency [11]. This improvement has a positive effect on ecology [12]. It also has a significant effect on minimizing the total production costs. Although, this reduction is an important factor, it is certainly not the only factor involved. Energy cost reduction can also be achieved by moving from on peak to off-peal energy tariff rates [13]. In fact, production planning defines the production process then it selects the available technologies and equipment needed. Energy is an expensive resource that is becoming scarce and energy consumption is considered a primordial factor that need to be addressed in production planning because of the increasing of population and the variation of demand. Actually, improving production efficiency, minimizing makespan, reducing production costs, and reducing energy consumption according to [8, 14] are among the most important production scheduling problems in the job shop.

Based on this observation, we attach great importance to the energy aspect, which can be translated at each level of decision-making. To do this, we propose a new mathematical formulation that allows us to consider in the objective function the energy cost consumption required for each product during each period. Our main objective is to define a production plan feasible at operational level that minimizes the total production cost with the consideration of energy one.

Model of production planning and scheduling with environmental aspects-literature review

Nowadays, climate change concerns us and environmental protection represents a major and important issue. Indeed, this is reflected in several forms in particular the reduction of energy consumption. Recently, several works and conferences on environment and energy have been held. It was strongly recommended to focus on minimizing energy consumption and greenhouse gas emissions for industries and integrating the energy aspect. Indeed, decisions at the supply chain level are related to the duration of planning horizons, particularly long term, medium term and short term. In this study, we focus on the integration of the energy aspect, more specifically energy consumption in production system. Indeed, there is a classification according to the level of decision-making: strategic, tactical and operational.

Strategic level

The strategic level concerns the location of plants, the creation of a new product, the determination of capacity, the abandonment of a product and the choice of transport modes. Several researchers have focused on three areas: economic, social and environmental. In particular [15] who proposed a Mixed Integer Programming (MIP) to maximize profit and minimize greenhouse gas emissions in order to assess the environmental impact of plant premises and determine the best locations for them.

Similarly, [16] has proposed a model that minimizes greenhouse gas emissions and optimizes the cost generated. The main objective is to determine the optimal number of plants, their capacities and their environmental protection rate. Based on the same objective [17, 18] have also developed models with the goal to minimize gaz emissions and the total production cost. On the other hand [19, 20] have focused on all the three components. The proposed MIP minimize production costs for storage, recycling and distribution, consider greenhouse gas emissions and ultimately aim to improve the quality and standards of supply chain life. For the multi-objective case, [21] proposed a model that calculates the optimal number of warehouses to be opened while minimizing the costs resulting from transport and the opening of new warehouses.

Tactical level

At the tactical level, it is about the allocation of resources, the acquisition of new equipment, lot sizing and recruitment. [22] proposed a model that calculates lots to be produced by limiting the periods of carbon emissions. As for [23, 24], they have added to the same model other different means to integrating this aspect, in particular cumulative, global and over the periods of the production horizon. For [25–27] they added a new constraint on carbon emissions to the previous models. In addition, [28] has integrated the carbon release for lot-sizing into the mathematical model. For the bi-objective case, [29] proposed a model that minimizes greenhouse gas emissions resulting from production and production costs. The classic problem of "Economic Order Quantity (EOQ)" was mentioned by [30] taking into account gas emissions as well as [31] reformulated the same problem for the multi-objective case.

In addition, [32] has added new constraints on gas emission through transport and production start-up and [33] has proposed an extension of the EOQ. The objectives of this model are to minimize the overall cost and emissions of gases.

Operational level

At the operational level, decisions are made regarding the scheduling of tasks, manpower and stock balancing. At this level, several research projects have integrated the energy aspect into their models [34–39]. There are some works that have considered energy in terms of cost and others in terms of consumption.

Integration of energy cost at the operational level

In recent years, consumer and professional demand has increased exponentially. According to several studies, electricity demand in Europe will increase by an average of 56% by 2050 with an annual growth rate of 1.1%. Currently, households consume 12% to 14% of electricity and in 2050 it is estimated at 23%. This represents a remarkable increase and an imminent danger, hence the importance of following well-controlled demand response programs.

Demand response programs are economically and environmentally responsible strategies that aim to balance demand with supply while limiting energy. These programs reduce energy consumption, operating and investment costs, and carbon emissions. [34] has divided the demand response programs into two categories: Price driven and event driven.

Price driven is a strategy used in the industrial sector where the cost of energy consumption is included in the total cost of production, so that an increase in energy costs leads to an increase in total production costs. Indeed, companies organize their production in such a way as to minimize electrical costs. This category is divided into two types: Time Of Use (TOU) and Critical Peak Pricing (CPP).

For TO the electricity costs are fixed in advance at each period and they only change twice a year. To reduce the electricity cost, industries move their energy consumption to the least expensive periods (OFF-PEAK).

For CPP it is similar to the TOU, except that there are a few critical peak days where the electrical cost is very low.

For the 2nd category event driven, companies that aim to minimize their energy consumption in face of climate change, degradation and disruption are rewarded.

The works are classified according to the types of production systems and price driven categories.

- Single machine

[35] has developed a linear model that minimizes the costs associated with the condition of the machine and the electrical cost. The model was solved by genetic algorithms.

- Parallel machine

[36–38] have developed an MIP that reduce energy costs and have been solved by commercial solvers and for good quality solutions a hybrid algorithm has been proposed. For the parallel machine case, [39] also presented a model for scheduling problem under energy constraints with maximum and minimum limits.

- Job shop

For this type of workshop [40, 41] have proposed a Zero-one Nonlinear Programming Problem (ZONLP) program that reduces electricity consumption and costs in the first case and the power demand in the second case at each peak period. The models were solved by metaheuristics and SBB solvers. Other authors have also treated this type of workshop using TOU as a response program such as [42–47]. For the job-shop, [48] have proposed a bi-objective MIP model that reduces carbon emissions and the end date of processing.

- Flow-shop

In the article of [49], the authors proposed a model that takes into account the time and condition of the machine with the variation of the electrical cost. As for [50, 51], they proposed a Mixed Integer Nonlinear Programming (MINLP) that reduces power demand and electrical cost and solved their model by the commercial solver (LINGO).

The Critical Peak Pricing program was also mentioned in some works. Especially for the flow-shop, [14] have developed two models that aim to minimize carbon emissions and task delays. For their resolution, the authors proposed a "Non-dominated Sorting-based Genetic Algorithm II (NSGA-II)". Similarly [52] have proposed a MINLP that integrates energy costs into production costs. The resolution of this model is done with the commercial solver (LINDO).

Integration of energy consumption at the operational level

Several research studies have integrated the energy aspect into their models. In this section we discuss the works that considers energy in terms of energy consumption. For a flow-shop, [53] proposed a MIP with power limitation constraint that aims to minimize makespan and delay. This model was solved by CPLEX and then Randomised Neighbourhood Search.

For a single machine, [54] proposed a MIP with the objective of reducing the end date of treatment and energy consumption. The MIP was solved by genetic algorithms. [14] have developed a model with two different objectives. First, minimize the total processing end time and second, minimize greenhouse gas emissions. The second objective is translated by the product between energy consumption and a parameter that estimate this consumption in terms of carbon quantity. An NSGA-II algorithm has been developed to solve the problem.

Definition and modelling

According to the literature review conducted previously, we note that several researchers have taken an interest in the energy aspect as a component whose economic and environmental impacts are powerful, particularly in terms of energy costs, consumption, carbon emissions, greenhouse gas emissions and so on.

Based on this observation, we plan to integrate this energy aspect into the planning level in order to ensure a compromise between the production plan and scheduling. Because one of the major problems in production system is the consideration of planning and scheduling as independent axes and the recklessness of important operational constraints during planning.

With respect to the breakdown presented previously, which consists of classifying the work according to cost or energy consumption. We are particularly interested in the cost, more precisely the cost of the energy consumption of each resource at each production period.

Thus, our main objective is to propose a mathematical model that integrates the maximum of operational constraints into the planning of the production system for a single-level job-shop production system.

Indeed, the originality of this new model lies in the consideration of the new energy aspect at the tactical level. This means integrating the cost of energy and resource consumption into each production period and implicitly considering the cost of electricity consumption of each machine in periods T.

Contextualization

In this part we consider a planning and scheduling problem for the job-shop system with consideration of the energy cost in the multi-product case. We plan the production of N products on M machines and T periods. We don't allow stock between machines.

Each period T is characterized by a duration, a demand and a consumption cost.

We assume:

- Several products can be produced per period.
- Forecasts are known in advance.
- Machines have finite capacities.
- A machine only produces one product at a time.
- The power required by the system is related to the maximum power, which must not exceed a limit.
- A machine can only start producing a quantity if it already exists at the output of $m-1$.

In order to describe the proposed mathematical model, we use the following notations:

Indices

i: Product indices.
k: Ressources indices.
l: Periods indices.

Decision variables

X_{il}: Quantity to produce from product i in period l.
Y_{il}: A setup variable that is equal to 1 if the product i is made in period l $(Y_{il} > 0)$, 0 otherwise.
$I_{i,l}$: Positive inventory level of product i at the end of the period l.
$E_l^{\max}$: The power required by the system during the period $l = 1...T$.

Parameters

C_i^p: Production cost per unit of product i.
C_i^{inp}: Inventory cost per unit of product i.
C_j^s: Setup cost per unit of product i.
$D_{i,l}$: Demand of product i at period l.
$capa_l$: Length of period l (capacity available).
α_{ik}: resources k consumed by product unit i (machines).
β_{ik}: Consumption of fixed resources k by product unit i.
$capa_l^k$: Available capacity of resource k at period l.
L_i: Lead time of the product i.
O: All operations.
$O_{i,m,l}$: Operation of the product i to be manufactured on the resource m at period l.
$i(o)$: Product associated with operation o.
$l(o)$: Period associated with operation o.
p_o^u: Operating time of the operation O per unit of the product $i(o)$.
S_o: Setup time of the operation O per product unit $i(o)$.
$r(o)$: Availability date of the operation O.
$d(o)$: Desired end date of operation O.
A: Set of operation pairs in the product range $(O, O') \in A$ means that operation O precedes operation O' in the operating range.
L: All the last operations in the operating ranges.
F: All the first operations in the operating ranges.
E: All the pairs of operations that must be produced on the same resource.

$S(y)$: All operations associated with the sequence y.
$(o, o') \in S(y)$: The operation o precedes the operation o' in the sequence of a resource.
M: Number of resources.
θ_l: Power Cost per period $l = 1...T$.

Mathematical modelling

The proposed mathematical model is defined as follows:
Min

$$\sum_{i=1}^{N}\sum_{l=1}^{T}(C_i^p \cdot X_{i,l} + C_i^{inv} \cdot I_{i,l} + C_i^s \cdot Y_{i,l}) + \sum_{l=1}^{T}\theta_l \cdot E_l^{\max}. \tag{1}$$

Subject to:

$$I_{il}^{+} = I_{il-1}^{-} + X_{i,l} - D_{il}\ forall; i, l, \tag{2}$$

$$r(o_c^f) + \sum_{c\in C}(P_o^u X_{i(o),l(o)} + S_o Y_{i(o),l(o)}) \le \sum_{l=1}^{l(o_c^l)} C_l \ \ \forall\, c \in C(y), \tag{3}$$

$$X_{i,l} \le \left(\sum_{l=1}^{T} D_{il}\right) Y_{il}, \tag{4}$$

$$\sum_{i=1}^{N}\alpha_{i,k}X_{i,l} + \sum_{i=1}^{N}\beta_{i,k}Y_{i,l} \le capa_l^k \ \ \forall\, i, l, k, \tag{5}$$

$$X_{i,l}, I_{il}^{+}, I_{il}^{-} \ge 0 \ \ \forall\, i, l, \tag{6}$$

$$Y_{il} \in \{0, 1\} \ \ \forall\, i, l. \tag{7}$$

The objective function (1) minimizes the total cost of production and considers the consumption of electric power at each period. Constraint (2), is the inventory balance equation for the mono level case. Constraint (3), indicates that the sum of the execution and start times of operations on a path must end before the end date of the last operation of the path.

The new variable $r(o)$ is defined as follows:

$$r(o) = \sum_{l=1}^{l(o)-l_{i(o)}} C_l \ \ \forall\, o \in F, \tag{8}$$

$$r(o) = \sum_{l=1}^{l(o)-1} C_l \ \ \forall\, o \in L, \tag{9}$$

$$r(o) = \max\left(\sum_{l=1}^{l(o)-l_{i(o)}} C_l,\ \sum_{l=1}^{l(o)-1} C_l\right) \ \ \forall\, o \in F \cap L, \tag{10}$$

$$r(o) = 0 \ \ \forall\, o \notin F \cup L. \tag{11}$$

Constraint (8), ensures that the first operation of the range must start on a date guaranteeing the respect of the obtaining time. Constraint (9), ensures that the last operation of each range is available from the start date of its associated period.

Constraint (10), defines the available date of transactions as the first and last operations in the manufacturing range. Constraint (11), is added to formalize the definition. Constraint (4), of the model links decision variables (lot size and setup variable).

Constraint (5), relates the variable resource requirements k of reference i to the quantity produced from the item i in period l and the fixed resource requirements k of reference i to the setup variable of product i in the period l. They mustn't exceed the available capacity of resources k at period l. Constraints (6) and (7) define the domain of the decision variables $X_{i,l}$, I_{il}^{+}, I_{il}^{-}, they are continuous, non-negative and Y_{il} is a binary variable.

Resolution approach

Resolution methods found in the literature

In this section we present some of the resolution methods found in the literature to solve this type of problem for a job-shop system.

This kind of problem of integrating planning and scheduling of production system with the consideration is NP-difficult especially for a job-shop.

In comparison, studies on the job shop scheduling problem (JSSP) with energy-saving objectives appear to be limited [14, 55]. In fact, most production systems that allow machine speed scaling belong to the mechanical manufacturing industry and they normally adopt the job shop layout instead of flow shop. In recent years, meta-heuristic algorithms have become popular optimization methods for solving the JSSP [56–61].

[62] proposed a model for a job-shop with an energy consumption threshold not to be exceeded. The objective is to propose the best sequencing by considering the energy threshold, the consumption of operations and the duration of the peak consumption. The objective function minimizes the time required to complete all operations. The resolution of the model was done using the commercial CPLEX solver. [63] studied in their paper a new mathematical model of energy-efficient scheduling that takes in-

to account productivity, energy efficiency and noise reduction with a flexible rotation speed for a job-shop. The proposed model was solved by genetic algorithms. [64] studied a scheduling problem in a job-shop with the energy cost as an objective to minimize, while respecting the traditional constraints of this problem but also a certain power limit. The authors plan to solve this model by approximate methods.

Numerical results

In this section we present the results obtained by solving our mathematical model first by an exact method such as Branch and bond integrated in CPLEX commercial solver in version 12.6. Using an HP PROBOOK Intel CORE i5 personal computer with 8 GB of RAM and 64-bits operating system.

CPLEX is an optimization software tool that was developed by Robert Bixby and then marketed by IBM after its purchase by ILOG in 2009. It allows to develop optimization models and create applications that improve results. It is a development environment capable of creating projects and models as well as accessing data through different sources. It also contains several programming interfaces that help users plan, schedule and manage resources efficiently.

For our resolution, the periods, their duration, the number of products and machines as well as the cost of power for each period are generated randomly. For the rest of the parameters they are generated according to a uniform law. For the cost of power in each period it takes real values $\theta_l \approx U$ (1, 19.8) and is expressed in \$/KW.

The resolution time (CPU) in seconds is limited to one hour and 5 different scenarios have been run for each problem.

Analysis and discussion

We note in Table 1 that for small workshops such as 3×3, 3×5, 3×10, 5×3 and 5×5, CPLEX is able to find optimal solutions before 1 hour of calculation time. And the 5 different scenarios executed were solved without any constraints.

For example, for 3×3, 3×10 and 5×3 job-shops the production costs given in less than 1 second respectively are 8155, 145092 and 9560 monetary units. While for medium and large-scale problems, the commercial solver IBM ILOG CPLEX is no longer able to generate solutions.

Table 1 shows that by increasing the size of the problem, the CPU increases considerably. Indeed, for this type of problem, exact methods remain ineffective because they do not allow optimal solutions to be found within reasonable calculation times, especially for medium and large instances. It therefore becomes necessary to use approached methods.

Table 1
Experimental results.

Job-shop	Number of problems solved on 5	CPU in (s)	Production cost in (Monetary unit)
3×3	5	<1	8155
3×5	5	4	18490
3×10	5	<1	145092
5×3	5	<1	9560
5×5	5	600	59326
5×10	5	>3600	
7×7	0	>3600	
7×10	0	>3600	
10×5	0	>3600	
10×10	0	>3600	
15×5	0	>3600	
15×15	0	>3600	

Conclusion and perspectives

This article proposes a new modulization of planning and scheduling of production system with the consideration of energy cost. We considered a job-shop system for the multi-product case. According to the literature review performed, this study has not been done before. However, the main originality of our model lies in the consideration of a new operational aspect at the tactical level, particularly the energetical one. Because one of the major problems of production system is the consideration of planning and scheduling separately. And the non-integration of the meaningful operational constraints at the tactical level, leads to the incoherence between planning and scheduling. However, the integration of energy cost remains a new operational aspect that has never been considered before. It allows to ensure the feasibility of the production plan at the operational level.

Therefore, we integrated energy cost into each production period and implicitly consider the energy consumption of each machine in periods T. Our main objective is to find a compromise between the production plan and scheduling in order to minimize the total production cost. In the other hand, the resolution review has shown that this NP difficult problem has not been very handled for its complexity.

Thus, first we solved our model using CPLEX that is an optimization software that allows to evaluate the optimality of the problem considered and distinguish its degrees of complexity. It uses exact methods for its resolution as Branch and Bound and

Branch and Cut. The experimental results shown in table 1 demonstrate that it is efficient for short instances as job-shops 3×3, 3×5, 3×10, 5×3 and 5×5. The total production costs given for the 5 cases resolved are very satisfactory. For the job-shop 3×3 the total production cost is 8155 monetary units and by increasing the period from 3 to 5 the production cost become 145092. Also, for the job-shop 5×3, the total production cost found in less than one second is 9560 and for 5×5 it becomes 59326 monetary units found in 600 seconds.

In the other hand, by increasing the problem size and planning horizon of 10 and 20 periods, CPLEX become unable to generate solutions. The only explication for this reaction, is the great demand in terms of memory for solving big size problems.

From this observation, we plan to use approached methods, in order to solve our problem, for their effectiveness in proposing the best possible solution even without any guarantee of optimality, such as genetic algorithm and taboo search. Also, we plan to integrate more operational constraints during planning in order to ensure a good compromise between production plan and scheduling.

References

[1] Melo T.V., Moura A.M.A., *Use of seawed flour in the animal feeding*, Arch. Zoot., 58, 99–107, 2009.

[2] Klibi, W., Martel, A., *Modeling approach for the design of resilient supply networks under disruptions*, International Journal of Production Economics, 135, 2, 882–898, 2012.

[3] Eskandarpour M., Dejax P., Miemczyk J., Péton O., *Sustainable supply chain network design: an optimization-oriented review*, Omega, Elsevier, 54, 11–32, 2015.

[4] Huang H., Guo X., Li D., Liu M., Wu J., Ren H., *Identification of crucial yeast inhibitors in bioethanol and improvement of fermentation at high pH and high total solids*, Bioresour Technol., 102, 16, 7486–93, 2011.

[5] Sarkar S.K., Hazra S.K., Sen H.S., Karmakar P.G., Tripathi M.K., *Sunnhemp in India*, ICAR-Central Research Institute for Jute and Allied Fibres (ICAR), Barrackpore, West Bengal, 2015.

[6] Huizhi Yi., Bhaba R. Sarker, *An operational policy for an integrated inventory system under consignment stock policy with controllable lead time and buyers' space limitation*, Computers & Operations Research, 40, 11, 2632–2645, 2013.

[7] Huang L., Massa L., Karle J., *The Kernel Energy Method: application to a tRNA*, Proc. Natl. Acad. Sci. USA, 103, 5, 1233–7, 2006.

[8] Hassani Z.I.M., El Barkany A., Jabri A., El Abbassi I., Darcherif A., *New approach to integrate planning and scheduling of production system: heuristic resolution*, International Journal of Engineering Research in Africa, 39, 156–169, 2018.

[9] Hassani Z.I.M., El Barkany A., Jabri A., El Abbassi I., Darcherif A., *Models for solving integrated planning and scheduling problem: computational comparison*, International Journal of Engineering Research in Africa, 34, 161–170, 2018.

[10] Weinert N., Chiotellis S., Seliger G., *Methodology for planning and operating energy – efficient production systems*, CIRP Annals – Manufacturing Technology, 60, 1, 41–44, 2011, doi: 10.1016/j.cirp.2011.03.015.

[11] Soroush A., Kadivar M., Mohajerani A., Ganji A., Bazargan A., *Manifesto for Iran's green movement*, New Perspectives Quarterly, 27, 2, 32–33, 2010.

[12] Herrman C., Thiede S., *Process chain simulation to foster energy efficiency in manufacturing*, Proceedings in the 17th CIRP China, pp. 23–28, 2009.

[13] Michalski A., Eugen D., Hauschild J-P., Lange O., Wieghaus A., Makarov A., Nagaraj N., Cox J., Mann M., Horning S., *Mass spectrometry-based proteomics using Q Exactive, a high-performance benchtop quadrupole Orbitrap mass spectrometer*, Molecular & Cellular Proteomics, 10, 9, M111.011015, 2011.

[14] Liu Y., Dong H., Lohse N., Petrovic S., Gindy N., *An investigation into minimising total energy consumption and total weighted tardiness in job shops*, Journal of Cleaner Production, 65, 87–96, 2014.

[15] Feng Li, Tie Liu, Hao Zhang, Rong Zeng Cao, Wei Ding, Fasano J.P., *Distribution center location for green supply chain*, Service Operations and Logistics, and Informatics, IEEE/SOLI 2008, IEEE International Conference, 2, 2951–2956, 2008.

[16] Fan W., Xiaofan L., Ning S., *A multi-objective optimization for green supply chain network design*, Multiple Criteria Decision Making and Decision Support Systems, 51, 2, 262–269, 2011.

[17] Pishvaie A., Jaberipur G., Jahanian A., *Improved CMOS (4; 2) compressor designs for parallel multipliers*, Computers & Electrical Engineering, 38, 6, 1703–1716, 2012.

[18] Mallidis I., Dekker R., Vlachos D., *The impact of greening on supply chain design and cost: a case for a developing region*, Journal of Transport Geography, 22, 118–128, 2012.

[19] Ramudhin A., Chaabane A., Paquet M., *Carbon market sensitive sustainable supply chain network design*, International Journal of Management Science and Engineering Management, 5, 1, 30–38, 2010.

[20] Chaabane A., Ramudhin A., Paquet M., *Design of sustainable supply chains under the emission trading scheme*, International Journal of Production Economics (Advances in Optimization and Design of Supply Chains), 135, 1, 37–49, 2012.

[21] Harris I., Christine L-M., Naim M-M., *A hybrid multi-objective approach to capacitated facility location with flexible store allocation for green logistics modeling*, Transportation Research Part E: Logistics and Transportation Review, 66, 1–22, 2014.

[22] Huizhi Yi., Bhaba R. Sarker, *An operational policy for an integrated inventory system under consignment stock policy with controllable lead time and buyers' space limitation*, Computers & Operations Research, 40, 11, 2632–2645, 2013.

[23] Absi N., Dauzère-Pérès S., Kedad-Sidhoum S., Penz B., Rapine C., *The single-item green lot-sizing problem with fixed carbon emissions*, European Journal of Operational Research, 248, 3, 849–855, 2016.

[24] Absi N., Dauzère-Pérès S., Kedad-Sidhoum S., Penz B., Rapine C., *Lot sizing with carbon emission constraints*, European Journal of Operational Research, 227, 1, 55–61, 2013.

[25] Velázquez-Martínez J-C., Fransoo J-C,. Edgar E-B., Jaime M-V., *The impact of carbon footprinting aggregation on realizing emission reduction targets*, Flexible Services and Manufacturing Journal, 26, 1–2, 196–220, 2014.

[26] Akbalik A., Rapine C., *The single item uncapacitated lot-sizing problem with time-dependent batch sizes: NP-hard and polynomial cases*, European Journal of Operational Research, 229, 2, 353–363, 2013.

[27] Mathijn J. Retel Helmrich, Raf Jans, Wilco van den Heuvel, Albert P.M. Wagelmans, *The economic lot-sizing problem with an emission capacity constraint*, European Journal of Operational Research, 241, 1, 50–62, 2015.

[28] Benjaafar S., Yanzhi L., Daskin M., *Carbon footprint and the management of supply chains: insights from simple models*, Automation Science and Engineering, IEEE Transactions, 10, 1, 99–116, 2013.

[29] Sazvar Z., Javad Mirzapour E-M., Baboli A., Akbari Jokar M.R., *A bi-objective stochastic programming model for a centralized green supply chain with deteriorating products*, International Journal of Production Economics, 150, 140–154, 2014.

[30] Hua G., Cheng T.C.E., Shouyang W., *Managing carbon footprints in inventory management*, International Journal of Production Economics, 132, 2, 178–185, 2011.

[31] Bouchery Y., Ghaffari A., Jemai Z., Dallery Y., *Including sustainability criteria into inventory models*, European Journal of Operational Research, 222, 2, 229–240, 2012.

[32] Dinçer Konur, *Carbon constrained integrated inventory control and truckload transportation with heterogeneous freight trucks*, International Journal of Production Economics, 153, 268–279, 2014.

[33] Bozorgi A., Pazour J., Nazzal D., *A new inventory model for cold items that considers costs and emissions*, International Journal of Production Economics, 155, 114–125, 2014.

[34] Goldman C., Reid M., Levy R., Silverstein A., *Coordination of energy efficiency and demand response*, Ernest Orlando Lawrence Berkeley National Laboratory, Environmental Energy Technologies Division, LBNL-3044E, January 2010.

[35] Shrouf F., Ordieres-Mere J., Garcia-Sanchez A., Ortega-Mier M., *Optimizing the production scheduling of a single machine to minimize total energy consumption costs*, Journal of Cleaner Production, 67, 197–207, 2014.

[36] Mir Saman P., Seyyed A-T., Razmi J., *Credibility based fuzzy mathematical programming model for green logistics design under uncertainty*, Computers & Industrial Engineering, 62, 2, 624–632, 2012.

[37] Moon J-Y., Shin K., Park J., *Optimization of production scheduling with time-dependent and machine-dependent electricity cost for industrial energy efficiency*, The International Journal of Advanced Manufacturing Technology, 68, 1–4, 523–535, 2013.

[38] Castro P., Harjunkoski I., Grossmann I., *New continuous-time scheduling formulation for continuous plants under variable electricity cost*, Industrial & Engineering Chemistry Research, 48, 14, 6701–6714, 2009.

[39] Artigues C., Lopez P., Haït A., *The energy scheduling problem: Industrial case-study and constraint propagation techniques*, International Journal of Production Economics, 143, 1, 13–23, 2013.

[40] Fernandez M., Li L., Sun Z., *Just-for-Peak buffer inventory for peak electricity demand reduction of manufacturing systems*, International Journal of Production Economics, 146, 1, 178–184, 2013.

[41] Wang Y., Li L., *Time-of-use based electricity demand response for sustainable manufacturing systems*, Energy, 63, 233–244, 2013.

[42] Luo H., Du B., Huang Q.G., Chen H., Li X., *Hybrid flow shop scheduling considering machine electricity consumption cost*, International Journal of Production Economics, 146, 2, 423–439, 2013.

[43] Castro P.M., Harjunkoski I., Grossmann I.E., *Optimal scheduling of continuous plants with energy constraints*, Computers & Chemical Engineering, 35, 2, 372–387, 2011.

[44] Xing Y., Yusuf O., Zechun H., Yonghua S., *A review on price-driven residential demand response*, Renewable and Sustainable Energy Reviews, Elsevier, 96(C), 411–419, 2018.

[45] Solding P., Petku D., Mardan N., *Using simulation for more sustainable production systems – methodologies and case studies*, International Journal of Sustainable Engineering, 2, 2, 111–122, 2009.

[46] Brundage M-P., Qing C., Yang L., Guoxian X., Jorge A., *Energy efficiency management of an integrated serial production line and HVAC system*, Automation Science and Engineering, IEEE Transactions, 11, 3, 789–797, 2014.

[47] Castro P., Sun L., Harjunkoski I., *Resource – task network formulations for industrial demand side management of a steel plant*, Industrial & Engineering Chemistry Research, 52, 36, 13046–13058, 2013.

[48] Yu Zheng H., Wang L., *Reduction of carbon emissions and project makespan by a Pareto-based estimation of distribution algorithm*, International Journal of Production Economics, 164, 421–432, 2015.

[49] Moon J.-Y., Park J., *Smart production scheduling with time-dependent and machine-dependent electricity cost by considering distributed energy resources and energy storage*, International Journal of Production Research, 52, 13, 3922–3939, 2014.

[50] Babu C.A., Ashok S., *Peak load management in electrolytic process industries*, Power Systems, IEEE Transactions, 23, 2, 399–405, 2008.

[51] Ashok S., *Peak-load management in steel plants*, Applied Energy, 83, 5, 413–424, 2006.

[52] Bego A., Li L., Sun Z., *Identification of reservation capacity in critical peak pricing electricity demand response program for sustainable manufacturing systems*, International Journal of Energy Research, 38, 6, 728–736, 2014.

[53] Bruzzone A., Anghinolfi D., Paolucci M., Tonelli F., *Energy-aware scheduling for improving manufacturing process sustainability: a mathematical model for flexible flow shops*, CIRP Annals – Manufacturing Technology, 61, 1, 459–462, 2012.

[54] Yildirim M-B., Mouzon G., *Single-machine sustainable production planning to minimize total energy consumption and total completion time using a multiple objective genetic algorithm*, IEEE Transactions on Engineering Management, 59, 4, 585–597, 2012.

[55] May G., Stahl B., Taisch M., Prabhu V., *Multi-objective genetic algorithm for energy-efficient job shop scheduling*, International Journal of Production Research, 53, 23, 7071–7089, 2015, doi: 10.1080/00207543.2015.1005248.

[56] Spanos A.C., Ponis S.T., Tatsiopoulos I.P., Christou I.T., Rokou E., *A new hybrid parallel genetic algorithm for the job-shop scheduling problem*, International Transactions in Operational Research, 21, 3, 479–499, 2014.

[57] Goncalves J.F., Resende M.G., *An extended Akers graphical method with a biased random-key genetic algorithm for job-shop scheduling*, International Transactions in Operational Research, 21, 2, 215–246, 2014.

[58] Zhu Z.C., Ng K.M., Ong H.L., *A modified tabu search algorithm for cost-based job shop problem*, Journal of the Operational Research Society, 61, 4, 611–619, 2010.

[59] Zhang R., Wu C., *A neighbourhood property for the job shop scheduling problem with application to hybrid particle swarm optimization*, IMA Journal of Management Mathematics, 24, 1, 111–134, 2013.

[60] Zobolas G.I., Tarantilis C.D., Ioannou G., *A hybrid evolutionary algorithm for the job shop scheduling problem*, Journal of the Operational Research Society, 60, 2, 221–235, 2009.

[61] ChenGuang L., Jing Y., Jie L., WenJuan L., Evans S., Yong Y., *Sustainable performance oriented operational decision making of single machine systems with deterministic product arrival time*, Journal of Cleaner Production, 85, 318–330, 2014.

[62] Kemmoé S., Lamy D., Tchernev N., *Job-shop like manufacturing system with time dependent energy threshold and operations with peak consumption*, Interventions for the Co-Creation of Inter-Organizational Business Process Change, pp. 617–624, 2015.

[63] Lvjiang Y., Xinyu L., Liang G., Chao L., Zhao Z., *Energy-efficient job shop scheduling problem with variable spindle speed using a novel multi-objective algorithm*, Advances in Mechanical Engineering, 9, 4, 1–21, 2017.

[64] Masmoudi O., Yalaoui A., Ouazene Y., Chehade H., *Multi-item capacitated lot-sizing problem in a flow-shop system with energy consideration*, IFAC-PapersOnLine, 49, 12, 301–306, 2016.