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Energy-aware reactive flexible job shop scheduling with timely delivery under uncertainty: A case study

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Abstract

This paper aims to confront the uncertainties in the flexible job shop scheduling (FJSS) problem by considering the tax regulations of energy consumption and timely delivery. Uncertainties include all unexpected disruptions such as machine breakdowns, modifications or cancellation of the orders, and receiving new orders that lead to failure in initial scheduling. Two strategies with the energy-saving approach have been proposed based on scheduling repair. Two considered objective functions are to minimize the tax cost on surplus energy consumption and to minimize total cost of jobs tardiness. The problem is described with the parameters and decision variables clearly in the form of MIP model. Moreover, the proposed model is investigated using data of a real case study in a company based on casting processes. Since the problem is well known strongly NP-hard, a new approach is introduced based on the Non-dominated Sorting Genetic Algorithm (NSGA-II) to find proper solutions for decision-makers. The computational results show that the proposed model and solution approach repairs properly the original scheduling and could improve the Pareto front comparing with the original scheduling. Due to the result, two proposed strategies could reduce total cost of jobs tardiness more than 47.56% compared with the original scheduling in eight different cases. It could also improve the second objective more than 56.91%. This approach will help the manufacturing industry managers, especially in make-to-order (MTO) systems with high-powered machines to respond rapidly to unexpected disruptions with the lowest energy consumption and tardiness penalty.

Keywords: flexible job shop; reactive scheduling; energy-saving; tardiness.

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1. Introduction

Job shop scheduling is one of the most popular scheduling problems in make-to- order (MTO) systems. In the nowadays-competitive environment, the effect of uncertainties on MTO production systems with high-powered and multi-speed machines is more notable than the other systems. The MTO systems based on casting almost use high-powered machines and technology such as induction melting furnaces. Such industries usually are facing some challenges such as high penalty costs of jobs tardiness and high tax costs on surplus energy consumption. Therefore, minimizing these costs is two important objectives for such manufacturing industries.

Unexpected disruptions during running the original predictive scheduling lead to failure in original scheduling. Even minor disruptions in original scheduling will have high impacts on production costs due to the high costs of tardiness penalties and using high-powered and multi-speed machines. The rapid growth of industries has dramatically increased the demand for energy (Chan et al.,2014) and so, governments of developed countries have adopted tax policies to prevent greenhouse gas emissions and to ensure more energy-saving. However, manufacturing industries play an important role in the progression of the economy, and it is responsible for over 40% of the total energy consumption of the industry (Li et al., 2016). Reducing energy consumption under current conditions, especially in developed countries with high-energy costs, is a serious issue that should be considered quickly (Cassettari et al., 2017). Energy-saving and greenhouse gas emissions are some of the most important issues of concern to governments and researchers. For example, china’s “13th Five-Year plan” required energy consumption in 2020 to be reduced by 15% as compared with 2015 (Plan in china, 2016). In addition to governments’ concern, customers ‘awareness about the natural environment has increased and people buy products when natural environment protection factors such as energy-saving and greenhouse gas emissions are respected (Moon et al., 2002). For example, the population ratio of the European who tends to buy expensive products but they were environmentally friendly in 2008 to be increased by 44% as compared with 2005 (Zhang et al., 2015). Since the government and consumers have made a lot of efforts to save energy, many manufacturers have made products with energy-saving (Howes et al., 2013). Therefore, uncertainties during running original predictive scheduling lead to increase costs of energy consumption. Studies of such industries show that uncertainties during production are mainly because of the following factors (Herroelen et al., 2005): job and resource inaccessibility, lack of skilled manpower, inadequate estimation of processing time, machines breakdowns, modifications or cancellation of the orders, changing of the delivery dates, and recording new orders.

In this paper, uncertainties have been investigated in the flexible job shop scheduling problem with the nature of casting in the MTO systems. We tackle the uncertainty parameters with no well-known probability distribution in this study such as machine breakdowns, modification or cancellation of the orders, changing of the delivery dates, and receiving important new orders. These kinds of uncertainties occur as unexpected disturbances and lead to failure in initial scheduling. For this purpose, scheduling repair as reactive scheduling will be useful to deal with these kinds of disruptions. Reactive scheduling is divided into two types (Herroelen et al., 2004): the first type is rescheduling, and the second is scheduling repair. In this paper, we use a scheduling repair for responding to disruptions during running the original predictive scheduling. The best scheduling repair strategies for responding to disruptions are applied in two ways: firstly, the system can allocate multiple machines with different speed level into each operation of jobs, and secondly, the system can select the best alternative process from other jobs when disruptions occur in the process of a job.

The main purpose of this study is to propose a proper approach for responding to different uncertainties to minimize the costs related to surplus energy consumption and the total cost of jobs tardiness. Energy-saving in switching machine modes has considered adjusting the status and speed level of machines in two of the three modes including processing, idle, and standby. The conceptual model of the considered reactive scheduling for disruptions in this study has been shown in Figure (1) as a bi-objective approach.

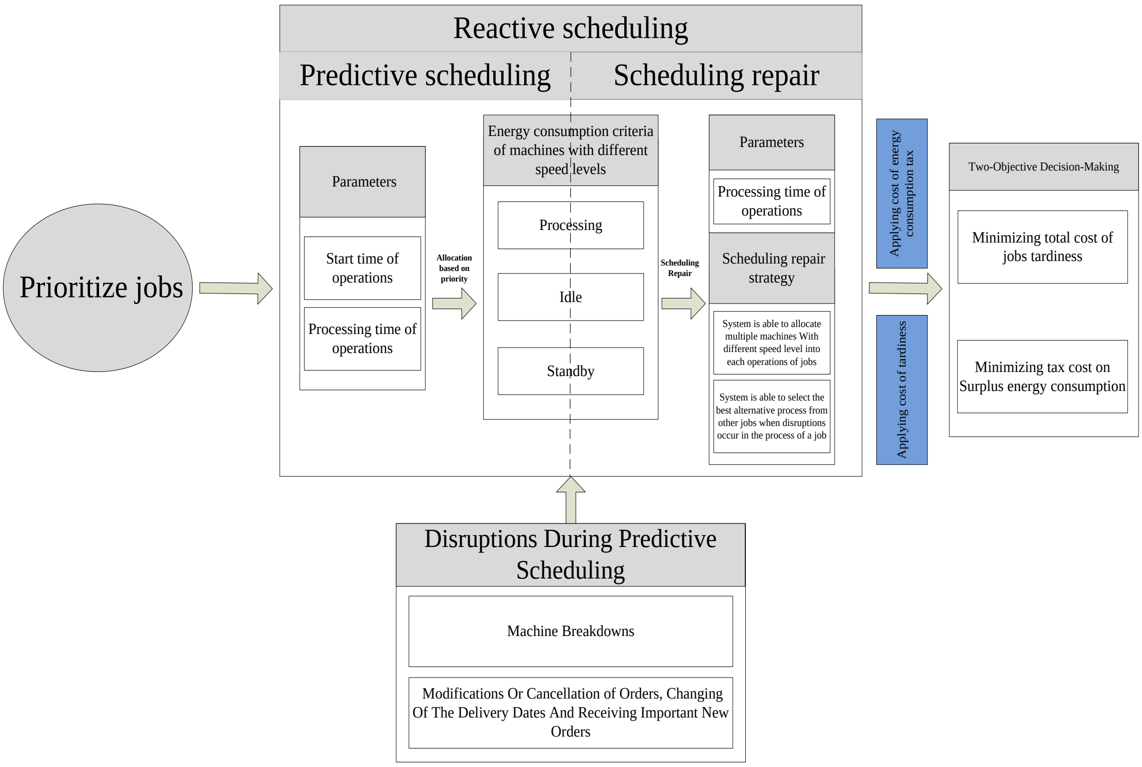


Figure 1. An illustration of the proposed approach in this research

In general, this study tries to answer the following question: "How can industry owners balance between tax cost on surplus energy consumption and total cost of jobs tardiness in faced with uncertainties?". For this purpose, the remaining sections of this paper are organized as follows: section 2 is devoted to the survey of works related to this article. The mathematical model of the problem at hand is presented completely in section 3. We present a numerical example in section 4 based on a case study and solve it to investigate the performance of the proposed model Section 5 provides the solution approach with details. Section 6 shows the computational result and sensitivity analysis for two objective functions. Finally, section 7 presents a summary of this study, a conclusion, and some suggestions for future studies.

2. Literature review

In this section, a comparison of the last studies in flexible job shop reactive scheduling with emphasis on energy-saving is presented. To his end, Table (1) shows a summary of the literature review related to this study.

Table 1. List of papers published in the relevant fields

Authors Name	Refrence Number	Type of model		Type of problem		Type of scheduling		Objective Function							Single/multi machines	
		Simulation	Mathematical	Job shop	Flow shop & etc.	Reactive	Other	Completion time	Energy-Saving	Fatigue	Tardiness & etc.	Efficincy & stability	Makespan	other	Multi	single
Sabuncuoglu & Bayiz	10	√		√		√					√		√			√
Hatami et al.	11		√		√		√				√			√	√	
Ayyoubzadeh et al.	12		√	√		√			√			√			√	
Rahmani et al.	13		√		√	√					√	√			√	
Kim et al.	14	√		√		√					√				√	
Minguillon et al.	15	√		√		√								√	√	
Goli et al.	16		√		√		√	√							√	
Ayough et al.	17		√		√		√							√	√	
Mouzon et al.	18		√		√		√		√							√
Yildirim &Mouzon	19		√		√		√		√		√					√
Che et al.	20		√		√		√		√							√
Dai et al.	21		√		√		√		√							√
Che et al.	22		√		√		√		√		√					√
Mansouri et al.	23		√		√		√		√				√		√	
Tirkolaee et al.	24		√		√		√		√						√	
Fang et al.	25		√		√		√		√						√	
Dai et al.	26		√		√		√		√						√	
Zhang et al.	27		√	√			√		√	√			√		√	
Zhang et al.	28		√		√	√			√				√		√	
Pach et al.	29	√			√	√			√							√
Shrouf et al.	30		√		√		√		√							√
Cheng et al.	31		√	√			√		√							√
This research			√	√		√			√		√				√	

In order to better comparison, we can compare factors of previous studies in Table (1) with related factors of this study considering four different subjects as stated in Table (2).

Table 2. Comparison related works with this study

Subjects	Factors of previous studies	Related factors of this study
Energy-saving	According to the references (11) and (17) to (30) we have four groups studies in this area as follows: • To turn off the machine in idle time (single-machine, flow shop, multi-objective). • Slow down the speed level without affecting Makespan (flow shop, single-machine, and two-machine with different speed levels, multi-objective). • Energy-saving in peak consumption (flexible job shop, single-machine, different rates of electricity cost, multi-objective). • Energy-saving considering government tax regulations (supply chain, multi-objective).	There are a few studies in flexible job shop considering some parallel machines with different speed levels in a multi-objective. It is also notable that, a few researchers have conducted on energy consumption in switching machine modes in scheduling considering government tax regulations. Each machine needs specified energy to switch from standby to idle mode. This amount of energy consumption is notable in MTO systems with high-powered machines.
Reactive scheduling	Due to the references (10) to (14), (27), and (28) disruption during production that lead to reactive scheduling can be considered with four fields in simulation without mathematical model and flow shop as follows: • Breakdowns or access restrictions to machines. • Changing of the delivery dates. • Conducting as a new order. • Cancellation of the orders.	Reactive scheduling is considered in this study to investigate as a mathematical model for flexible job shop scheduling problems. However, these studies have conducted on the problem using the simulation method and no mathematical model has been presented considering all of these issues simultaneously. -Reactive scheduling: Machine breakdowns, changing of the delivery dates and conducting as a new order.

In Figure (2), the percentage of papers published in the four main groups of energy-saving is examined.

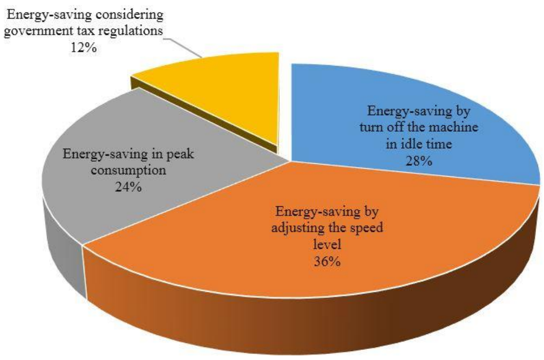


Figure 2. Percentage of papers published in four main groups of energy-saving

By comparing previous studies with the current research, the main contributions of the current study can be stated as follows:

- A realistic flexible job shop scheduling is proposed under uncertainty and timely delivery.

- A novel optimization mathematical model is developed to formulate the considered problem.
- A reactive approach with energy conservation is presented to make a trade-off between the tax cost of energy consumption and tardiness penalties.
- Observe energy-aware during production by using switching control and adjusting the best speed level in the machines.
- Introducing a solution approach based on NSGA-II algorithm using a new two-part structure of chromosomes.

3. Problem formulation

In this section, a new mathematical model is introduced for the FJSS problem to respond to unexpected disruptions and uncertainties during productionscheduling repair. Two considered objective functions are minimizing tax cost on surplus energy consumption and total cost of jobs tardiness. At first, to more clarify the problem, the main assumptions are presented as follows:

1. The precedence relation between operations is determined and won't change.
2. Each operation of each job is assigned just to one machine with one speed.
3. Each machine can only process one operation of a job at a certain moment
4. Sequences of job operations are prioritized.
5. Sequences of jobs on machines are prioritized.
6. Once started, the process cannot be interrupted.
7. Setup times are independent and considered as a section of processing time.

In addition, the following notations are used to formulate the considered problem:

Indices

i, h, b	Indices for jobs, $i, h, b \in \{1,2,\dots,J\}$
k, j, t	Indices for operations, $k, j, t \in \{1,2,\dots,N_i\}$
m	Index for machines, $m \in \{1,2,\dots,B\}$
f, g, a	Indices for speeds, $f, g, a \in \{1,2,\dots,F\}$

General parameters

J	The number of total jobs.
B	The number of total machines.
N_i	The number of total operations for the i^{th} job.
F	The number of total speeds.
O_{ij}	The j^{th} operation of the i^{th} job.
R_{fm}	The processing power of m^{th} machine in the f^{th} speed.
I_m	The idle power of m^{th} machine.
G_m	The standby power of m^{th} machine.
H_m	The power of m^{th} machine to switch from standby to idle mode.
$\propto_{mij}$	A binary parameter that takes value 1 if the j^{th} operation of the i^{th} job requires to the m^{th} machine; 0, otherwise.
V_i	Penalty for delivery later than the specified time of i^{th} job

E	The tax rate on surplus energy consumption
L	The maximum allowed for energy consumption according to the government tax regulation.
M	A large number.

Parameters for the original scheduling before disruptions (τ)

J^{τ}	The set of jobs in the original scheduling(τ).
p^{τ}_{fijm}	Processing time of O_{ij} on the m^{th} machine with the f^{th} speed in the original scheduling (τ)
d^{τ}_{i}	Delivery date of i^{th} job in the original scheduling (τ).
t^{τ}_{ij}	Start time of O_{ij} in the original scheduling (τ)
D^{τ}	Occurrence time of disruption in the original scheduling (τ).
b^{τ}_{fijm}	A binary parameter that takes value 1 if the m^{th} machine with the f^{th} speed is allocated to the O_{ij} in the original scheduling (τ); 0, otherwise.
s^{τ}_{ijhk}	Distance between O_{ij} and O_{hk} in the original scheduling(τ).

Parameters for the reactive scheduling after disruptions (γ)

J^{γ}	The set of corrected jobs in the reactive scheduling (γ).
p^{γ}_{fijm}	Processing time of O_{ij} on the m^{th} machine with the f^{th} speed in the reactive scheduling (γ)
d^{γ}_{i}	Correction of delivery date of the i^{th} job in the reactive scheduling (γ).
T^{γ}_{m}	Duration of inaccessibility to the m^{th} machine in the reactive scheduling (γ).

Decision variables

v^{τ}_{ij}	Binary variable takes value 1 if start time of O_{ij} occurs sooner than disruption time in the original scheduling (τ); 0, otherwise.
x^{γ}_{fijm}	Binary variable that takes value 1 if the m^{th} machine with the f^{th} speed is allocated to O_{ij} in the reactive scheduling (γ); 0, otherwise.
t^{γ}_{ij}	Start time for O_{ij} in reactive scheduling (γ)
z_{mih}	Binary variable taking value 1 if the i^{th} job is the precedence of the h^{th} job and both of them requires to be process on the m^{th} machine; 0, otherwise.
U_{ijhk}	Binary variable taking value 1 if the machine is idle mode between O_{ij} and O_{hk}; 0, otherwise.
WTT_{ij}	Binary variable taking value 1 if O_{ij} is complete before disruption time in the original scheduling (τ); 0, otherwise.
WT_{ij}	Binary variable taking value 1 if O_{ij} is complete before disruption time and inaccessible to machine in the original scheduling (τ); 0, otherwise.

Objective functions

Q	Tax cost on surplus energy consumption.
Y	Total cost of jobs tardiness.
T_i	Tardiness cost of the i^{th} job.
$QTF1_{fgmijhk}$	The Energy consumption of the m^{th} machine between two successive operations O_{ij} with the f^{th} speed and O_{hk} with the g^{th} speed in the original scheduling (τ).
$QTF2_{fgmijhk}$	The Energy consumption of the m^{th} machine between two successive operations O_{ij} with the f^{th} speed and O_{hk} with the g^{th} speed in reactive scheduling (γ).
$QTF3_{fgmijhk}$	The Energy consumption of the m^{th} machine between two successive operations O_{ij} with the f^{th} speed and O_{hk} with the g^{th} speed while one of them is in the original scheduling (τ) and the other is in reactive scheduling (γ).
$Q_{R_{(m)}}$	The energy consumption of the m^{th} machine in the processing mode.
$Q_{I_{(m)}}$	The energy consumption of the m^{th} machine in the idle mode.
$Q_{I_{(fgmijhk)}}$	The energy consumption of the m^{th} machine in the idle mode between two successive operations O_{ij} with the f^{th} speed and O_{hk} with the g^{th} speed.
$Q_{G_{(m)}}$	The energy consumption of the m^{th} machine in the standby mode.
$Q_{G_{(fgmijhk)}}$	The energy consumption of the m^{th} machine in the standby mode between two successive operations O_{ij} with the f^{th} speed and O_{hk} with the g^{th} speed.

The proposed mathematical model

$$Y = \sum_{i=1}^{J} T_i \tag{1}$$

$$T_i \geq 0 \qquad ,\forall\, i \tag{2}$$

$$T_i \geq (t^{\gamma}_{iN_i} + \sum_{m=1}^{B}\sum_{f=1}^{F} p^{\gamma}_{fiN_im}.x^{\gamma}_{fiN_im} - d^{\gamma}_i).V_i \qquad ,\forall\, i \tag{3}$$

According to equations (1), (2), and (3) of the mathematical model, the total cost of jobs tardiness is minimized as the first objective function.

$$Q \geq 0 \tag{4}$$

$$Q \geq \left(\sum_{m=1}^{M} (Q_{R_{(m)}} + Q_{I_{(m)}} + Q_{G_{(m)}}) - L\right).E \tag{5}$$

Equations (4) and (5) aims to minimize tax cost on surplus energy consumption as the second objective function.

$$Q_{R_{(m)}} = \sum_{f=1}^{F} R_{fm}.(\sum_{i=1}^{J}\sum_{j=1}^{N_i} p^{\gamma}_{fijm}.x^{\gamma}_{fijm} + p^{\tau}_{fijm}.b^{\tau}_{fijm}.v^{\tau}_{ij}) \qquad ,\forall\, m \tag{6}$$

$$Q_{I_{(m)}} = I_m . \sum_{f=1}^{F}\sum_{g=1}^{F}\sum_{i=1}^{J}\sum_{j=1}^{N_i}\sum_{h=1}^{J}\sum_{k=1}^{N_h} Q_{I_{(fgmijhk)}} \qquad ,\forall m \tag{7}$$

$$Q_{G_{(m)}} = G_m \,. \sum_{f=1}^{F}\sum_{g=1}^{F}\sum_{i=1}^{J}\sum_{j=1}^{N_i}\sum_{h=1}^{J}\sum_{k=1}^{N_h} Q_{G_{(fgmijhk)}} \quad ,\forall m \tag{8}$$

Equations (6), (7), and (8) calculate the energy consumption of each machine with each speed in the processing, idle, and standby modes respectively.

$$Q_{I_{(fgmijhk)}} = (QTF1_{fgmijhk} + QTF2_{fgmijhk} + QTF3_{fgmijhk}).U_{ijhk}$$
$$,\forall\, f,g,m,i,j,h,k \tag{9}$$

Equation (9) present the energy consumption of each machine with each speed in the idle mode between two successive operations O_{ij} and O_{hk} in three statuses: both of them in the original scheduling, both of them in reactive scheduling, and one of them in the original scheduling and the other in reactive scheduling.

$$Q_{G_{(fgmijhk)}} = (QTF1_{fgmijhk} + QTF2_{fgmijhk} + QTF3_{fgmijhk}).(1 - U_{ijhk})$$
$$,\forall\, f,g,m,i,j,h,k \tag{10}$$

Equation (10) present the energy consumption of each machine with each speed in the standby mode between two successive operations O_{ij} and O_{hk} in three statuses: both of them in the original scheduling, both of them in reactive scheduling, and one of them in the original scheduling and the other in reactive scheduling.

$$QTF1_{fgmijhk} = s^{\tau}_{ijhk}.\propto_{mhk}.\propto_{mij}.b^{\tau}_{fijm}.b^{\tau}_{ghkm}.\upsilon^{\tau}_{ij}.\upsilon^{\tau}_{hk}$$
$$,\forall\, f,g,m,i,j,h \neq i,k \tag{11}$$

Equation (11) estimate the energy consumption of each machine with each speed between two operations O_{ij} and O_{hk} in status: both of them in the original scheduling.

$$QTF2_{fgmijhk} = \left(t^{\gamma}_{hk} - t^{\gamma}_{ij} - p^{\gamma}_{fijm}\right).\propto_{mhk}.\propto_{mij}.x^{\gamma}_{fijm}.x^{\gamma}_{ghkm}.(1 - \upsilon^{\tau}_{ij})$$
$$.(1 - \upsilon^{\tau}_{hk}).z_{mih}.\prod_{(b|b \neq i, b \neq h)}^{J}\prod_{t}^{N_b}\prod_{a}^{F}(1 - z_{mbh}.z_{mib}x^{\gamma}_{abtm}.$$
$$(1 - \upsilon^{\tau}_{bt}).\propto_{mbt}) \qquad ,\forall\, f,g,m,i,j,h \neq i,k \tag{12}$$

Equation (12) estimate the energy consumption of each machine with each speed between two operations O_{ij} and O_{hk} in status: both of them in reactive scheduling.

$$QTF3_{fgmijhk} = (\left(t^{\gamma}_{hk} - t^{\tau}_{ij} - p^{\tau}_{fijm} - T^{\gamma}_{m}\right).WT_{ij}.WTT_{ij} + \left(t^{\gamma}_{hk} - T^{\gamma}_{m} - D^{\tau}\right)$$
$$.WT_{ij}.\left(1 - WTT_{ij}\right) + \left(t^{\gamma}_{hk} - t^{\tau}_{ij} - p^{\tau}_{fijm}\right).\left(1 - WT_{ij}\right).\left(1 - WTT_{ij}\right)).\propto_{mhk}.\upsilon^{\tau}_{ij}$$
$$\propto_{mij}.b^{\tau}_{fijm}.(1 - \upsilon^{\tau}_{hk}).x^{\gamma}_{ghkm}.\prod_{(b|b \neq i, b \neq h)}^{J}\prod_{t}^{N_b}(1 - z_{mbh}.z_{mib}.\propto_{mbt})$$
$$,\forall\, f,g,m,i,j,h \neq i,k \tag{13}$$

Equation (13) estimate the energy consumption of each machine with each speed between two operations O_{ij} and O_{hk} in three statuses: one of them in the original scheduling and the other in reactive scheduling. Change the mode of machines from idle to standby with the aim of energy-saving is considered via equations (14) to (23).

$$H_m \leq \left(t^{\gamma}_{hk} - t^{\tau}_{ij} - p^{\tau}_{fijm} - T^{\gamma}_{m}\right).\propto_{mij}.\propto_{mhk}.b^{\tau}_{fijm}.I_{fm} + M.\left(1 - \propto_{mij}\right) + M.$$
$$(1 - \propto_{mhk}) + M.U_{ijhk} + M.\left(1 - b^{\tau}_{fijm}\right) + M.\left(1 - x^{\gamma}_{ghkm}\right) + M.\left(1 - \upsilon^{\tau}_{ij}\right)$$

$$+M.\upsilon_{hk}^{\tau}+M.\left(1-WT_{ij}\right)+M.\left(1-WTT_{ij}\right) \quad ,\forall\, f,g,m,i,j\,,h\neq i,k \tag{14}$$

$$\left(t_{hk}^{\gamma}-t_{ij}^{\tau}-p_{fijm}^{\tau}-T_{m}^{\gamma}\right).\propto_{mij}.\propto_{mhk}.b_{fijm}^{\tau}.I_{fm}\leq H_m+M.\left(1-\propto_{mij}\right)+M.\left(1-\propto_{mhk}\right)+M.\left(1-U_{ijhk}\right)+M.\left(1-b_{fijm}^{\tau}\right)+M.\left(1-x_{ghkm}^{\gamma}\right)+M.\left(1-\upsilon_{ij}^{\tau}\right)+M.\upsilon_{hk}^{\tau}+M.\left(1-WT_{ij}\right)+M.\left(1-WTT_{ij}\right) \quad ,\forall\, f,g,m,i,j\,,h\neq i,k \tag{15}$$

Based on equations (14) and (15) it is identified that machine mode between two successive operations O_{ij} and O_{hk} must be idle or standby in the following conditions: one of them in the original scheduling and the other in reactive scheduling and the O_{ij} is complete before disruption time in the original scheduling.

$$H_m\leq\left(t_{hk}^{\gamma}-T_{m}^{\gamma}-D^{\tau}\right).\propto_{mij}.\propto_{mhk}.b_{fijm}^{\tau}.I_{fm}+M.\left(1-\propto_{mij}\right)+M.\left(1-\propto_{mhk}\right)+M.U_{ijhk}+M.\left(1-b_{fijm}^{\tau}\right)+M.\left(1-x_{ghkm}^{\gamma}\right)+M.\left(1-\upsilon_{ij}^{\tau}\right)+M.\upsilon_{hk}^{\tau}+M.WTT_{ij}+M.\left(1-WT_{ij}\right) \quad ,\forall\, f,g,m,i,j\,,h\neq i,k \tag{16}$$

$$\left(t_{hk}^{\gamma}-T_{m}^{\gamma}-D^{\tau}\right).\propto_{mij}.\propto_{mhk}.b_{fijm}^{\tau}.I_{fm}\leq H_m+M.\left(1-\propto_{mij}\right)+M.\left(1-\propto_{mhk}\right)+M.\left(1-b_{fijm}^{\tau}\right)+M.\left(1-x_{ghkm}^{\gamma}\right)+M.\left(1-\upsilon_{ij}^{\tau}\right)+M.\upsilon_{hk}^{\tau}+M.\left(1-WT_{ij}\right)+M.WTT_{ij}+M.\left(1-U_{ijhk}\right) \quad ,\forall\, f,g,m,i,j\,,h\neq i,k \tag{17}$$

Based on Equations (16) and (17) it is identified that machine mode between two successive operations O_{ij} and O_{hk} must be idle or standby in the following conditions: one of them in the original scheduling and the other in reactive scheduling and the O_{ij} is complete before disruption time and inaccessible to machine in the original scheduling.

$$H_m\leq\left(t_{hk}^{\gamma}-t_{ij}^{\tau}-p_{fijm}^{\tau}\right).\propto_{mij}.\propto_{mhk}.b_{fijm}^{\tau}.I_{fm}+M.\left(1-\propto_{mij}\right)+M.\left(1-\propto_{mhk}\right)+M.U_{ijhk}+M.\left(1-b_{fijm}^{\tau}\right)+M.\left(1-x_{ghkm}^{\gamma}\right)+M.\left(1-\upsilon_{ij}^{\tau}\right)+M.\upsilon_{hk}^{\tau}+M.WT_{ij}+M.WTT_{ij} \quad ,\forall\, f,g,m,i,j\,,h\neq i,k \tag{18}$$

$$\left(t_{hk}^{\gamma}-t_{ij}^{\tau}-p_{fijm}^{\tau}\right).\propto_{mij}.\propto_{mhk}.b_{fijm}^{\tau}.I_{fm}\leq H_m+M.\left(1-\propto_{mij}\right)+M.\left(1-\propto_{mhk}\right)+M.\left(1-U_{ijhk}\right)+M.\left(1-b_{fijm}^{\tau}\right)+M.\left(1-x_{ghkm}^{\gamma}\right)+M.\left(1-\upsilon_{ij}^{\tau}\right)+M.\upsilon_{hk}^{\tau}+M.WT_{ij}+M.WTT_{ij} \quad ,\forall\, f,g,m,i,j\,,h\neq i,k \tag{19}$$

Based on equations (18) and (19) it is identified that machine mode between two successive operations O_{ij} and O_{hk} must be idle or standby in the following conditions: one of them in the original scheduling and the other in reactive scheduling and the O_{ij} is complete after disruption time and inaccessible to machine in the original scheduling.

$$H_m\leq\left(t_{hk}^{\gamma}-t_{ij}^{\gamma}-p_{fijm}^{\gamma}\right).\propto_{mij}.\propto_{mhk}.I_{fm}+M.\left(1-\propto_{mij}\right)+M.\left(1-\propto_{mhk}\right)+M.U_{ijhk}+M.\left(1-x_{fijm}^{\gamma}\right)+M.\left(1-x_{ghkm}^{\gamma}\right)+M.\left(1-z_{mih}\right)+M.\upsilon_{ij}^{\tau}+M.\upsilon_{hk}^{\tau} \quad ,\forall\, f,g,m,i,j\,,h\neq i,k \tag{20}$$

$$\left(t_{hk}^{\gamma}-t_{ij}^{\gamma}-p_{fijm}^{\gamma}\right).\propto_{mij}.\propto_{mhk}.I_{fm}\leq H_m+M.\left(1-\propto_{mij}\right)+M.\left(1-\propto_{mhk}\right)+M.\left(1-U_{ijhk}\right)+M.\left(1-x_{fijm}^{\gamma}\right)+M.\left(1-x_{ghkm}^{\gamma}\right)+M.\left(1-z_{mih}\right)+M.\upsilon_{ij}^{\tau}+M.\upsilon_{hk}^{\tau} \quad ,\forall\, f,g,m,i,j\,,h\neq i,k \tag{21}$$

Based on equations (20) and (21) it is identified that machine mode between two successive operations O_{ij} and O_{hk} must be idle or standby in the following conditions: both of them in reactive scheduling.

$$H_m \leq \left(t_{hk}^{\tau} - t_{ij}^{\tau} - p_{fijm}^{\tau}\right).\propto_{mij}.\propto_{mhk}.b_{fijm}^{\tau}.b_{ghkm}^{\tau}.I_{fm} + M.\left(1 -\propto_{mij}\right) + M.\left(1 -\propto_{mhk}\right) + M.U_{ijhk} + M.\left(1 - b_{fijm}^{\tau}\right) + M.\left(1 - b_{ghkm}^{\tau}\right) + M.(1 - \upsilon_{ij}^{\tau}) + M.(1 - \upsilon_{hk}^{\tau}) \quad ,\forall f,g,m,i,j\ ,h \neq i,k \tag{22}$$

$$\left(t_{hk}^{\tau} - t_{ij}^{\tau} - p_{fijm}^{\tau}\right).\propto_{mij}.\propto_{mhk}.b_{fijm}^{\tau}.b_{ghkm}^{\tau}.I_{fm} \leq H_m + M.\left(1 -\propto_{mij}\right) + M.\left(1 -\propto_{mhk}\right) + M.(1 - U_{ijhk}) + M.\left(1 - b_{fijm}^{\tau}\right) + M.\left(1 - b_{ghkm}^{\tau}\right) + M.(1 - \upsilon_{ij}^{\tau}) + M.(1 - \upsilon_{hk}^{\tau}) \quad ,\forall f,g,m,i,j\ ,h \neq i,k \tag{23}$$

Based on equations (22) and (23) it is identified that machine mode between two successive operations O_{ij} and O_{hk} must be idle or standby in the following conditions: both of them in original scheduling.

$$D^{\tau} + T_m^{\gamma} \leq t_{ij}^{\tau} + p_{fijm}^{\tau}.b_{fijm}^{\tau} + M.\left(1 - b_{fijm}^{\tau}\right) + M.WT_{ij} + M.\left(1 -\propto_{mij}\right) \quad ,\forall f,m,i,j \tag{24}$$

$$t_{ij}^{\tau} + p_{fijm}^{\tau}.b_{fijm}^{\tau} \leq D^{\tau} + T_m^{\gamma} + M.\left(1 - b_{fijm}^{\tau}\right) + M.\left(1 - WT_{ij}\right) + M.\left(1 -\propto_{mij}\right) \quad ,\forall f,m,i,j \tag{25}$$

Based on equations (24) and (25) it is identified that which the O_{ij} is complete before disruption time and inaccessible to the machine in the original scheduling in the following conditions: one of them is done in the original scheduling and the other in reactive scheduling considering the assumption (6) of the proposed model.

$$D^{\tau} \leq t_{ij}^{\tau} + p_{fijm}^{\tau}.b_{fijm}^{\tau} + M.\left(1 - b_{fijm}^{\tau}\right) + M.WTT_{ij} + M.\left(1 -\propto_{mij}\right) \quad ,\forall f,m,i,j \tag{26}$$

$$t_{ij}^{\tau} + p_{fijm}^{\tau}.b_{fijm}^{\tau} \leq D^{\tau} + M.\left(1 - b_{fijm}^{\tau}\right) + M.\left(1 - WTT_{ij}\right) + M.\left(1 -\propto_{mij}\right) \quad ,\forall f,m,i,j \tag{27}$$

Based on equations (26) and (27) it is identified that which the O_{ij} is complete before disruption time in the original scheduling in the following conditions: one of them is done in the original scheduling and the other in reactive scheduling considering the assumption 6 of the proposed model.

$$t_{ij}^{\tau} \leq D^{\tau} + M.\left(1 - \upsilon_{ij}^{\tau}\right) \qquad ,\forall i,j \tag{28}$$

$$D^{\tau} \leq t_{ij}^{\tau} + M.\upsilon_{ij}^{\tau} \qquad ,\forall i,j \tag{29}$$

$$D^{\tau} + T_m^{\gamma} < t_{ij}^{\gamma} + M.\upsilon_{ij}^{\tau} + M.(1 - x_{fijm}^{\gamma}) \qquad ,\forall i,j,m,f \tag{30}$$

Equations (28) to (30) indicate which operation of each job is starting to process in original scheduling and which of them will start in reactive scheduling.

$$\sum_{m=1}^{B}\sum_{f=1}^{F} \propto_{mij}.x_{fijm}^{\gamma} = 1 - \upsilon_{ij}^{\tau} \qquad ,\forall i,j \tag{31}$$

According to equation (31), each operation of each job can be processed by only one machine with one speed.

$$\left(t_{ij}^{\tau}+p_{fijm}^{\tau}.b_{fijm}^{\tau}\right).\propto_{mij}\leq t_{hk}^{\gamma}.\propto_{mhk}+M.(1-\propto_{mhk})+M.\left(1-x_{ghkm}^{\gamma}\right)+M.\left(1-b_{fijm}^{\tau}\right)+M.\left(1-v_{ij}^{\tau}\right)+M.v_{hk}^{\tau}+M.(1-z_{mih}) \quad ,\forall\, h,j,i\neq h,k,f,g,m \tag{32}$$

Equation (32) emphasize that the start time in reactive scheduling is always larger than the end time in the original scheduling in the condition such as one of them is done in the original scheduling and the other in reactive scheduling.

$$\left(t_{hk}^{\gamma}+p_{ghkm}^{\gamma}.x_{ghkm}^{\gamma}\right).\propto_{mhk}\leq t_{ij}^{\gamma}.\propto_{mij}+M.\left(1-\propto_{mij}\right)+M.\left(1-x_{fijm}^{\gamma}\right)+M.\left(1-x_{fhkm}^{\gamma}\right)+M.z_{mih}+M.v_{ij}^{\tau}+M.v_{hk}^{\tau} \quad ,\forall\, f,g,m,i,j,h\neq i,k \tag{33}$$

$$\left(t_{ij}^{\gamma}+p_{fijm}^{\gamma}.x_{fijm}^{\gamma}\right).\propto_{mij}\leq t_{hk}^{\gamma}.\propto_{mhk}+M.(1-\propto_{mhk})+M.\left(1-x_{gijm}^{\gamma}\right)+M.\left(1-x_{fhkm}^{\gamma}\right)+M.v_{hk}^{\tau}+M.(1-z_{mih})+M.v_{ij}^{\tau} \quad ,\forall\, f,g,m,i,j,h\neq i,k \tag{34}$$

In equations (33) and (34) are emphasized on prioritizing between two operations of O_{ij} and O_{hk} in the condition such as both of them in the reactive scheduling.

$$z_{mih}\leq Max_{j=1}^{N_i}\{\propto_{mij}\}.Max_{k=1}^{N_k}\{\propto_{mhk}\} \quad ,\forall\, h\neq i,i,m \tag{35}$$

When two operations of O_{ij} and O_{hk} achieve a common speed simultaneously, which of them is the priority? so this is expressed as equation (35).

$$x_{fijm}^{\gamma}\leq\propto_{mij} \quad ,\forall\, i,j,f,m \tag{36}$$

According to equation (36), each machine with each speed is assigned to the operation of O_{ij} when the operation mentioned requires the same machine.

$$t_{ij}^{\tau}+\sum_{m=1}^{B}\sum_{f=1}^{F}p_{fijm}^{\tau}.b_{fijm}^{\tau}\leq t_{i(j+1)}^{\gamma}+M.\left(1-v_{ij}^{\tau}\right)+M.v_{i(j+1)}^{\tau} \quad ,\forall\, i,j=\{1,2,\dots,(N_i-1)\} \tag{37}$$

$$t_{ij}^{\gamma}+\sum_{m=1}^{B}\sum_{f=1}^{F}p_{fijm}^{\gamma}.x_{fijm}^{\gamma}\leq t_{i(j+1)}^{\gamma}+M.v_{ij}^{\tau}+M.v_{i(j+1)}^{\tau} \quad ,\forall\, i,j=\{1,2,\dots,(N_i-1)\} \tag{38}$$

The sequences of operations on the jobs are determined via equations (37) and (38).

$$t_{ij}^{\gamma},Q_{I_{(fmijhk)}},Q_{G_{(fmijhk)}},QTF1_{fmijhk},QTF2_{fmijhk},QTF3_{fmijhk}\ \geq 0\ \ and\ \ integer \quad ,\forall\, c,m,i,j,h,k \tag{39}$$

$$Q_{R_{(m)}},Q_{I_{(m)}},Q_{G_{(m)}}\geq 0,\quad v_{ij}^{\tau},WT_{ij},WTT_{ij},x_{fijm}^{\gamma},U_{ijhk},z_{mih}\epsilon\{0,1\} \quad ,\forall\, f,m,i,j\ ,b\neq i,t,h\neq i,k,h\neq b \tag{40}$$

$$Q,Y \quad ,free\ variable \tag{41}$$

Equations (39) to (41) represent the decision variables and their possible values. The proposed model is a nonlinear model due to equations (9) to (13). So, we linearized the mathematical model using the method suggested by Chen et al., (2010).

4. A numerical study

This section addresses a case study in a casting industries company and solves it using the proposed model. A casting industry including melting furnace, molding, and casting that is usually followed by a machining process. The considered manufacturing company produces turbochargers, ball bearings, helical turbochargers, brake discs, clutch plates, etc. for a car manufacturing firm. In the first half of November 2020, the company received orders to build two parts and repair three parts in the automotive sector. The company is going to produce the five aforementioned parts through four main workstations including machining, milling, pressing, and casting stations. The production planning department is going to allocate resources and job scheduling with a uniform probability distribution of the start and processing time of operations. The delivery date and tardiness penalty of jobs are as Table (3). We want to present a proper schedule with a minimum of total tax cost on surplus energy consumption and total cost of jobs tardiness per hour for this case.

Table 3. Delivery date and tardiness penalty of the jobs based on original scheduling (τ)

i	1	2	3	4	5
d_i^{τ}	20	42	18	72	43
V_i	120	250	300	150	50

The company has seven machines in which the machining speed has three parallel machines with different energy consumption and the casting speed has two parallel machines with different energy consumption and the milling and pressing speeds each has one machine. The power consumption of the machines at each speed as well as the power consumption for machine switching based on the energy label in kw/h are illustrated in Table (4).

Table 4. Machine parameters in energy consumption for three speed levels (kw/h)

B_m	Processing Power			Idle Power	Standby Power	H_m
	speed1	speed2	speed3			
B_7	843	967	1220	953	20	5000
B_6	2483	2820	2930	2150	80	6123
B_5	3112	3120	3329	2950	120	6123
B_4	1000	1239	1428	605	22	3421
B_3	980	1027	1100	805	32	3421
B_2	1500	1714	1809	1205	52	3421
B_1	2302	2437	2532	2102	80	5345

For example, it can be found from Table (4) that the power consumption of machine 7 (B_7) in the processing mode for three-speed levels is 843 kw/h, 967 kw/h, and 1220 kw/h, respectively. It can be seen that the power consumption in the idle mode for the same machine is 953 kw/h. It should be noted that the energy consumption of the same machine in standby mode is reduced to 20 kw/h. In addition, the power consumption of the mentioned machine is equivalent to 5,000 kw/h to switch from standby to idle modes. According to calculations based on government tax regulations, the maximum amount of power consumption is 200,000 kw/h to produce 5 parts and surplus energy consumption causes a tax cost of 3$ per hour. The real-time occurrence of the original predictive scheduling is shown in Table (5) based on the scheduling of the company's production planning department.

Table 5. The real-time occurrence of the original scheduling for three speed levels

	Operation1	Operation2	Operation3	Operation4
Job1	1;(8,6,5) ;(13,11,10) B_1	8;(6,5,4) ;(12,11,9) B_7	16;(4,3,1) ;(4,3,1) B_2 , B_3, B_4	-
Job2	3;(8,5,2) ;(8,5,2) B_5 , B_6	8;(9,7,6) ;(17,14,13) B_1	20;(13,12,11) ;(15,14,13) B_7	33;(11,10,9) ;(10,9,8) B_2 , B_3, B_4
Job3	2;(11,9,7) ;(14,12,10) B_2 , B_3, B_4	13;(9,8,5) ;(14,11,9) B_7	-	-
Job4	4;(14,12,10) ;(10,7,5) B_5 , B_6	16;(12,10,7) ;(12,10,7) B_1	48;(15,10,9) ;(12,8,6) B_2 , B_3, B_4	66;(9,7,6) ;(7,5,4) B_7
Job5	2;(11,8,6) ;(15,13,12) B_7	28;(11,10,8) ;(12,11,9) B_1	38;(5,3,2) ;(6,4,3) B_2 , B_3, B_4	-

According to the information in Table (5), operation 1 of job 3 can be assigned to any of machines B_4, B_3 and B_2. The process starts at 2 o'clock, and the processing can take three values of 11, 9, and 7 hours depending on the speed levels of the machines. In addition, the processing can take three values of 14, 12, and 10 hours after breakdowns and repairing the machines. The scheduling and allocation of the jobs and their operation have been presented in Figure (3) as a Gant chart.

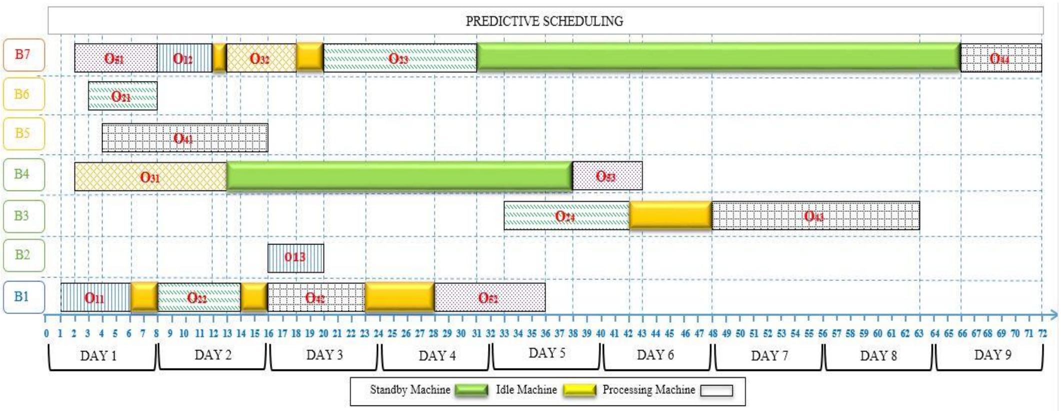


Figure 3. The real-time occurrence of the original predictive scheduling

However, two kinds of disruptions happen at 10 o'clock during the real-time occurrence of the original predictive scheduling. The first disruption happens because some preventive maintenance modifications were not implemented on some machines; the machines are damaged and are out of the production circuit for a certain period. The inaccessibility time of each machine based on the first disruption is shown in Table (6).

Table 6. Duration of inaccessibility on machines with each speed (T_m^γ)

B_m	B_1	B_2	B_3	B_4	B_5	B_6	B_7
T_m^γ	3	-	2	5	-	-	5

The second disruption is that the customers called and asked the company to change delivery dates instead of paying the company according to Table (7).

Table 7. Delivery date and tardiness penalty of the jobs based on reactive scheduling (γ)

i	1	2	3	4	5
d_i^τ	16	35	15	32	38
V_i	120	250	300	150	50

However, the company does not respond to two aforementioned unexpected disruptions and continues the process based on the original scheduling without revising after repair the machines. The obtained result of continuing the original scheduling without considering reactive scheduling is presented in Figure (4) in terms of tardiness and power consumption. As can be observed in Figure (4), due to two kinds of disruptions in the production system without any reactive scheduling, both tardiness cost and power consumption cost have been significantly increased. Based on this result, the total cost of tardiness penalties for all jobs increased to 14080$, and power consumption increased to 107343$ because of the tax cost on surplus energy consumption.

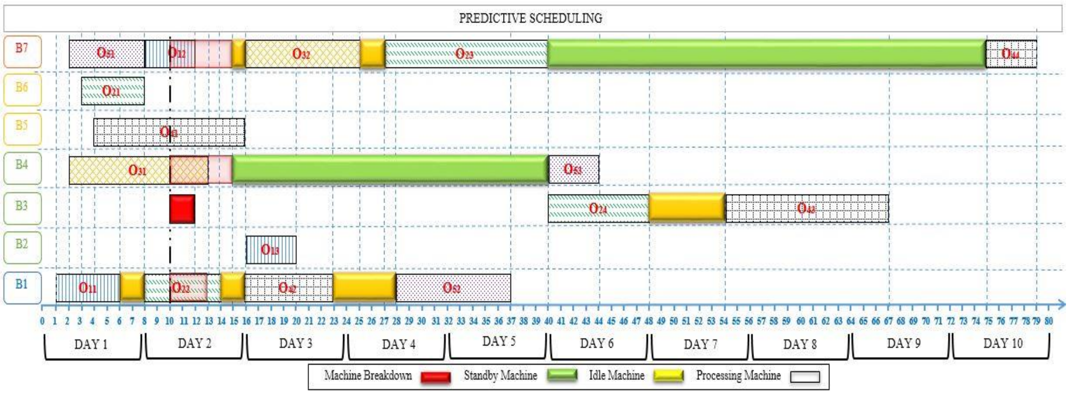


Figure 4. The effect of disruptions on the real-time occurrence of the original scheduling (Without the proposed model scheduling)

We want to have the best response to the two disruptions that the company faces with them through proper reactive scheduling in order to minimize the total cost of jobs tardiness and tax cost on surplus energy consumption. For this purpose, this problem has been solved with the new proposed model applying the GAMS software. The result will be valuable in answer to the basic question of the study as "How can industry owners balance between tax cost on surplus energy consumption and total cost of jobs tardiness in faced with uncertainties?". To answer this question, the Pareto Front obtained from augmented ϵ-constraint that has been presented in Figure (5) is investigated. In the Pareto Front of the proposed model, the cost of tardiness has been indicated on the horizontal axis that changes from 6550$ to 8710$. However, the tax cost on energy surplus consumption changes from 40524$ to 39024$ as is shown on the vertical axis. Therefore, several points have been provided for the related managers to make the best decision according to their preferences. Therefore, the best point on the Pareto Front in Figure (5) is the point where the cost of total tardiness is in the minimized state of to 6550$ and the tax cost on energy surplus consumption is 40524$, which total cost of 47074$ is the lowest possible cost if there are no preferences on two objective functions.

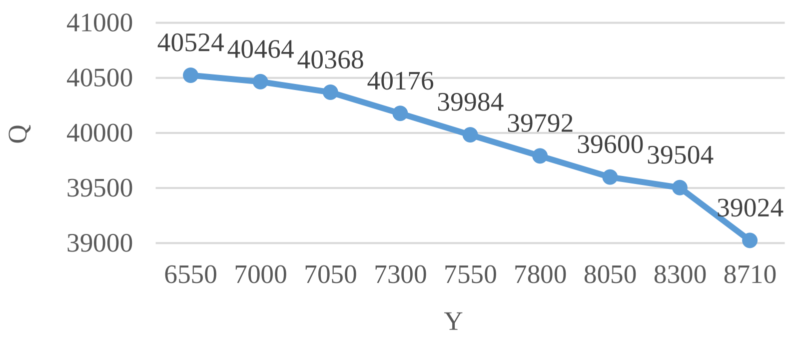


Figure 5. The Pareto front of two objectives based on reactive scheduling

As it is obvious from Figure (5), the proposed reactive scheduling model can provide a proper response to two major disruptions during running the original scheduling in the production system. This model could reduce the total cost of jobs tardiness by up to 54% and tax cost of surplus energy consumption up to 63%. Figure (6) shows the new Gant chart of production after doing the reactive scheduling. This result indicates how the proposed model responding to the unexpected disruptions during the real-time occurrence of the original predictive scheduling with the best results are achieved in the new status.

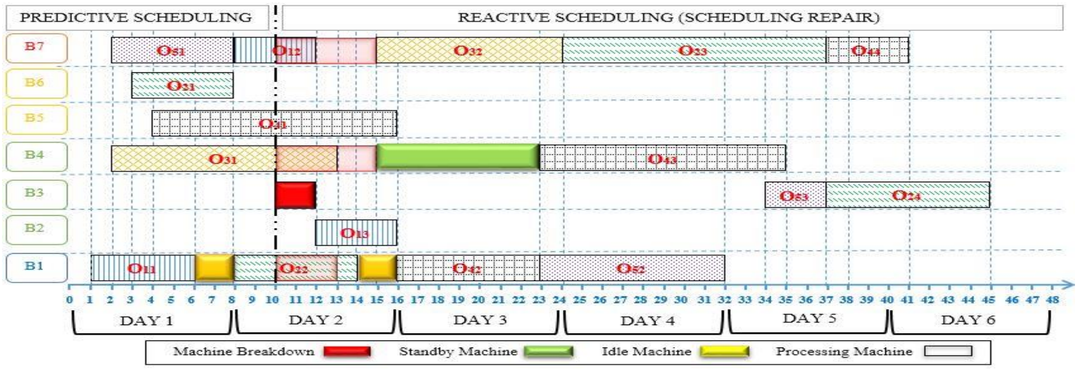


Figure 6. The effect of disruptions on the real-time occurrence of the original scheduling (Using the proposed model scheduling)

A comparison of the best result of the original scheduling and reactive scheduling after disruptions is presented in Figure (7). This result again emphasizes the notable impact of reactive scheduling in the reduction of bi-objective functions value.

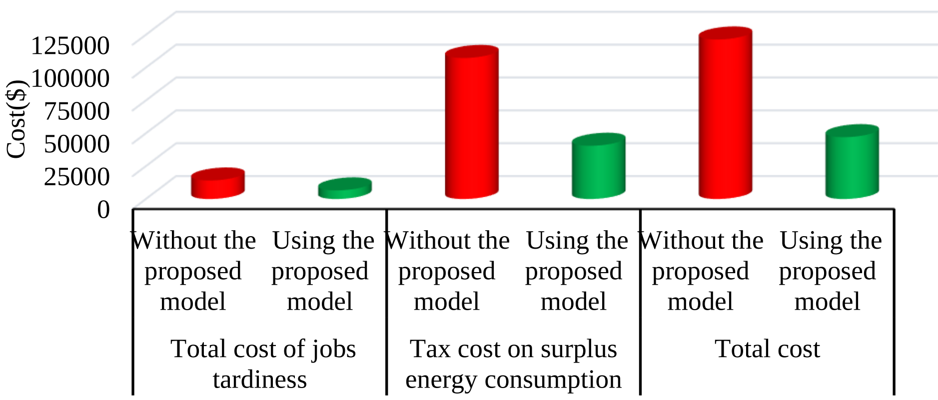
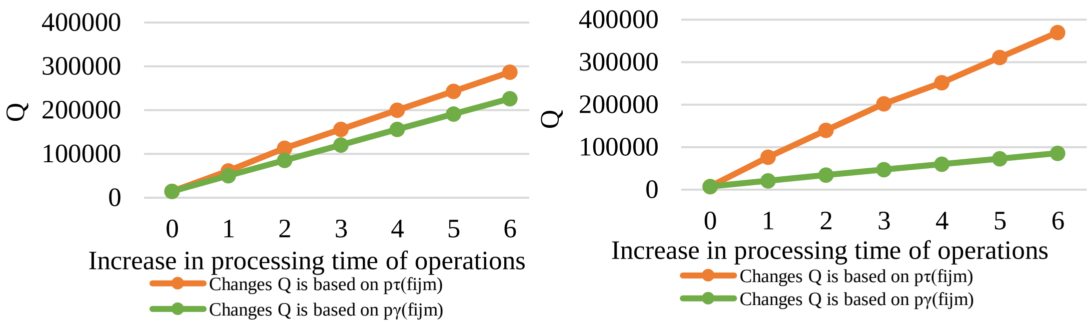


Figure 7. Comparison the result of the proposed model with the obtained result in company

More analysis of the result emphasizes the proposed model validity and its application solutions. Due to another analysis, sooner disruptions in early of execution the original scheduling, have less sensitivity to increasing the processing time of operations of jobs p_{fijm}^{τ} in original scheduling on tax cost of surplus energy consumption and more sensitivity to increasing the processing time of operations of jobs p^{γ}_{fijm} in reactive scheduling on tax cost of surplus energy consumption. This will be vice versa if disruptions happen near the end of the original scheduling. Figure (8) shows changes in tax cost on surplus energy consumption proportion to increasing 1 to 6 hours in the processing time of operations. As we can see in this figure, the rate of change in the tax cost of surplus energy consumption for jobs p^{τ}_{fijm} is more than jobs p^{γ}_{fijm}. On the other hand, we can see a less rate in increasing the tax cost of surplus energy consumption for jobs $p^{\gamma}_{fijm}$when disruption occurs in time 30 in comparison to this happened in time 15.



A. Disruption occurs in time 15. **B. Disruption occurs in time 30**

Figure 8. Rising in tax cost on energy surplus consumption by increasing the p^{τ}_{fijm} and p^{γ}_{fijm}

Figure (9) presents the influence of increasing the H_m on tax cost of energy surplus consumption. As this result emphasizes, the exception in low values the next increasing in $H_m$has a notable effect on the tax cost on energy surplus consumption.

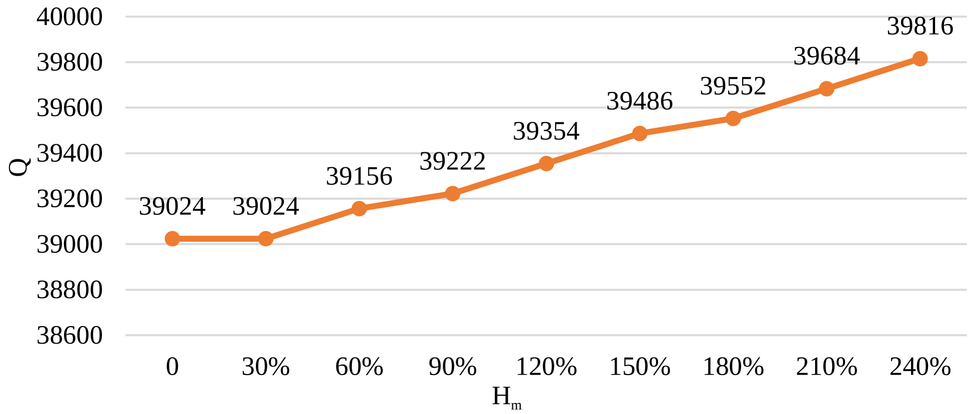


Figure 9. The changes in tax cost on energy surplus consumption by increasing the H_m

Table (8) indicates the role of the proposed model in improving two considered objectives for eight different cases. Due to this result, the proposed method could improve both of the two considered objectives in all eight cases. It is worth mentioning that in these eight cases, the total number of machines is 7 and the total number of speeds is 3.

Table 8. Improvement two objectives in the environment uncertainty of FJSS

# of case	Specification		Total cost of jobs tardiness			Tax cost on surplus energy consumption		
	Number of jobs	Number of operations	Without the proposed model	Using the proposed model	Improvement %	Without the proposed model	Using the proposed model	Improvement %
Case 1	5	16	14080	6550	53.48	107343	40524	62.25
Case 2	7	22	18753	9188	51.01	132031	53045	59.82
Case 3	9	29	24030	10664	55.62	165448	69945	57.72
Case 4	11	34	28004	14264	49.06	204014	78945	61.30
Case 5	13	38	32518	15764	51.52	231168	95903	58.51
Case 6	15	44	53119	24664	53.56	250093	99945	60.03
Case 7	17	53	64273	33699	47.56	322620	139012	56.91
Case 8	19	60	79414	37420	52.87	376465	143884	61.78

As the result indicates in Table (8), the proposed model could reduce significantly both of the two objective functions comparing to the classic scheduling. Investigating the considered case study in eight conditions shows a 51.83% improvement in the total cost of jobs tardiness on average. Similarly, the tax cost on surplus energy consumption as the second objective function demonstrates more than 59.79% improvement by using the proposed model.

5. Solution algorithm

The problem at hand (FJSP) is recognized as a classic Non-deterministic Polynomial hard (NP-hard) problem due to the complex process constraints (Ho & Tay, 2004). So, we have to use approximation methods to provide proper solutions for real-sized instances in a reasonable time. Many researchers have shown that NSGA-II is highly effective in optimizing multi-objective problems (Deb et al., 2002). Therefore, we tuned and used this algorithm to solve the considered problem in different conditions. A meta-heuristic implementation needs to decide how to represent solutions in an efficient way to the searching space. Representation should be easy to decode and calculated to reduce the run time of the algorithm. For the considered problem, the structure of the chromosome is divided into two parts: the first part consists of the main chromosome and the second part consists of a sub chromosome that is created based on the main chromosome. For more explanation, this structure is implemented on a case study presented in section 4. Solution representation of the main chromosome structure consists of a row vector with $\sum_{i=1}^{J} N_i$ number of gens. Genes are encoded based on the corresponding number of jobs. Moreover, the structure of the main chromosome is divided into two parts as the original scheduling and the reactive scheduling. For the aforementioned numerical example, as detailed in Table (5), job 5 is received by the factory. Therefore, the start time of those operations of jobs has been done before 10 o'clock according to the initial scheduling and this part is always constant in all main chromosomes.

While the second part of these main chromosomes is different. In this part, a random number is selected from the set of jobs for each gene. For this purpose, if the i^{th} selected number is repeated less than or equal to N_i in previous genes. Then, the i^{th} job number will be encoded in the relevant gene, otherwise, another random number is generated. The method of encoding of the main chromosome structure is shown in Figure (10).

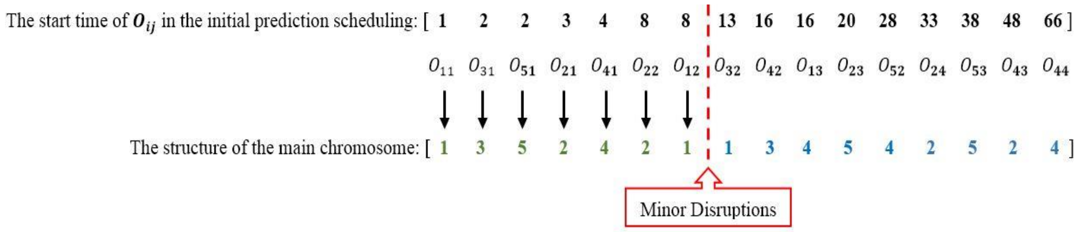


Figure 10. Encoding of the main chromosome structure

As Figure (10) demonstrates, the start time of seven genes from the structure of the main chromosome is less than 10 o'clock. Therefore, the numbers of jobs are transferred exactly to the corresponding gene. It should be noted that the blue genes are not executed according to the initial predictive scheduling. The encoding of such genes is based on a random selection of i^{th} job from the J^{γ} set with respect to the allowable repetition limit N_i.

Similar to the main chromosome, the structure of sub chromosomes consists of two parts including the original scheduling and the reactive scheduling. Each row of this matrix shows a series of codes, which are described as follows: in row one, the number of operations is encoded based on the number of jobs in the main chromosome. It is shown that the number of speeds in the second row is based on the encoding of row one related to the sub chromosome and the main chromosome. The third row depends on the encoding of the previous two rows of the sub chromosome and main chromosome, which indicates the allocation number of the machines. In the speeds where there are parallel machines, the machine numbers are randomly selected and placed in the corresponding gene. The iteration number of the machine allocation number is shown in the fourth row, which is encoded based on the third row. The codes in the fifth row indicate the scheduling period of the operations of jobs. Therefore, operations of jobs receive code 1 that is in the original scheduling. The sixth row is the start time of operations if they have received code 1 in the fifth row. Therefore, their start time is based on the initial predictive scheduling. Otherwise, the start time will be generated by observing the constraints of the mathematical model. Genes take value 1 if the machine is in an idle mode between O_{ij} and O_{hk} in the seventh row. Sequential operations assigned to a machine are identified using the fourth row. The interval between two consecutive operations is calculated based on the sixth row and the parameter of processing time. Thereupon, the status of machines between them is defined as standby mode and idle mode. In the eighth row, genes take value 1 if the o_{ij} is complete before disruption time in the original scheduling (τ). In the ninth row, genes taking value 1 if the $o_{ij}$is complete before disruption time and inaccessible to the machine in the original scheduling (τ). In this way, rows 8 and 9 are calculated based on the sixth row considering processing time. Figure (11) represents a schematic view of the proposed structure for the sub chromosome using the real data of the abovementioned case study.

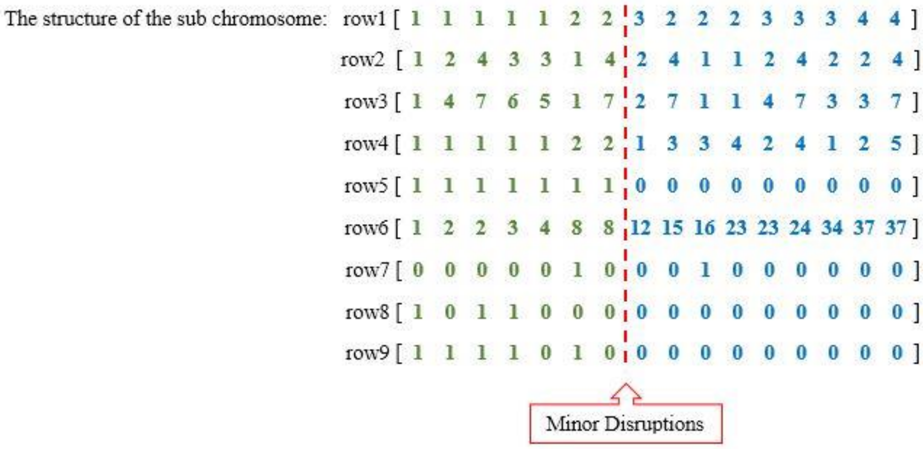


Figure 11. Encoding of the sub chromosome structure

NSGA-II is a population-based metaheuristic that starts with a number of solutions as the first population for solving a problem. The considered procedure for generating the first population is as follows. First, the main chromosomes are created as many as defined. After that the population of sub chromosomes is generated for each of the main chromosomes and the best sub chromosome for the main chromosome is selected considering values of the objective functions. Then, the dominate matrix is created and the rank of the Pareto front is determined for each chromosome with the computing of the crowding distance. Eventually, the next generation is selected through tournament selection. The population of feasible main chromosomes of offsprings is created using the crossover of main chromosomes of parents' population and generate new main chromosome of offsprings through mutation operator using swap between two random genes. Finally, the best sub chromosome is selected for the main chromosome of each offspring and a new population is being produced. The algorithm is iterated until the termination condition is satisfied. Remain steps of the solution algorithm are presented below.

5.1. Selection

To determine proper chromosomes as parents and the new generation, the best chromosomes are indicated through the Parto Front ranking criteria and crowding distance criteria.
The steps of tournament selection can be summarized as follows:
Step 1: Calculate the value of two objective functions for all chromosomes
Step 2: Determine the rank of the Pareto front through the dominate matrix. It is worth noting that, among the values of the different functions of a chromosome, at least one function has a lower value than the other chromosomes.
Step 3: Calculate the crowding distance for each of the chromosomes within a Pareto front. For this purpose, we arrange the chromosomes within a Pareto front from the lowest to the highest based on the first objective function. Set the value of the first and last points of the Pareto front to infinity. The crowding distance between the middle points of the Pareto Front is calculated based on equation (42).

$$CD_p = \frac{(OFV1_{p+1} - OFV1_{p-1}) + (OFV2_{p-1} - OFV2_{p+1})}{(OFV1_{lp} - OFV1_{ep}) + (OFV2_{ep} - OFV2_{lp})} \tag{42}$$

In the equation mentioned, the value of CD_p is the crowding distance of point p. $OFV1_{lp}$ is the value of the first objective function at the last point of the Pareto front and $OFV1_{ep}$ is the value of the first objective function at the first point of the Pareto front. Finally, the same definitions apply to $OFV2_{lp}$ and $OFV2_{ep}$ for the value of the second function.

Step 4: Determine two chromosomes considering the order of lower ranking. Whenever the rank of the Pareto Front is the same for two required chromosomes, the selection operator is done randomly.

5.2. Crossover operator

The crossover operator is used to combine the parent's chromosomes and create new solutions as a child. In the proposed algorithm, the crossover is applied just for the parent's main chromosomes. There exist a variety of crossover operators for recombination that are suitable for scheduling problems. We tested some of them and finally selected the two-point crossover. For this purpose, two points of the selected parent's chromosomes are considered randomly. It should be noted that the first point must be set on the first gene of reactive scheduling after the occurrence of disruptions. Then, the second point is randomly selected between the first point and the last gene. Figure (12) represents a sample of the proposed crossover operator.

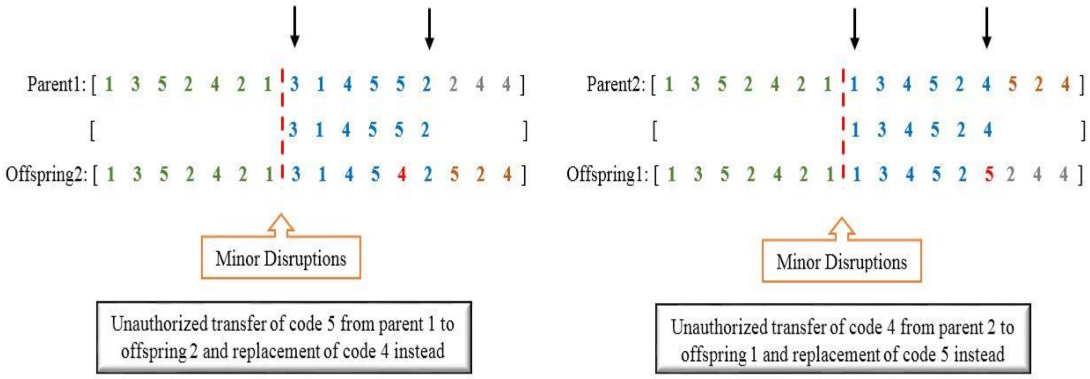


Figure 12. A sample of the crossover operator for the considered problem

5.3. Mutation operator

The mutation operator is usually applied to prevent premature convergence of the algorithm. Different various were examined and the swap between two genes was selected finally as the proper mutation operator. According to this method that has been shown in Figure (13), first, two genes are selected randomly from the main chromosome of the offspring between the first gene of reactive scheduling after the occurrence of disruptions and the last gene. After that, the swap operation is done between two genes from the main chromosome of the offspring.

Figure 13. A sample of the mutation operator for the considered problem

The steps of creating a new two-part chromosome structure and how to apply operators based on the NSGA-II algorithm are shown in Figure (14).

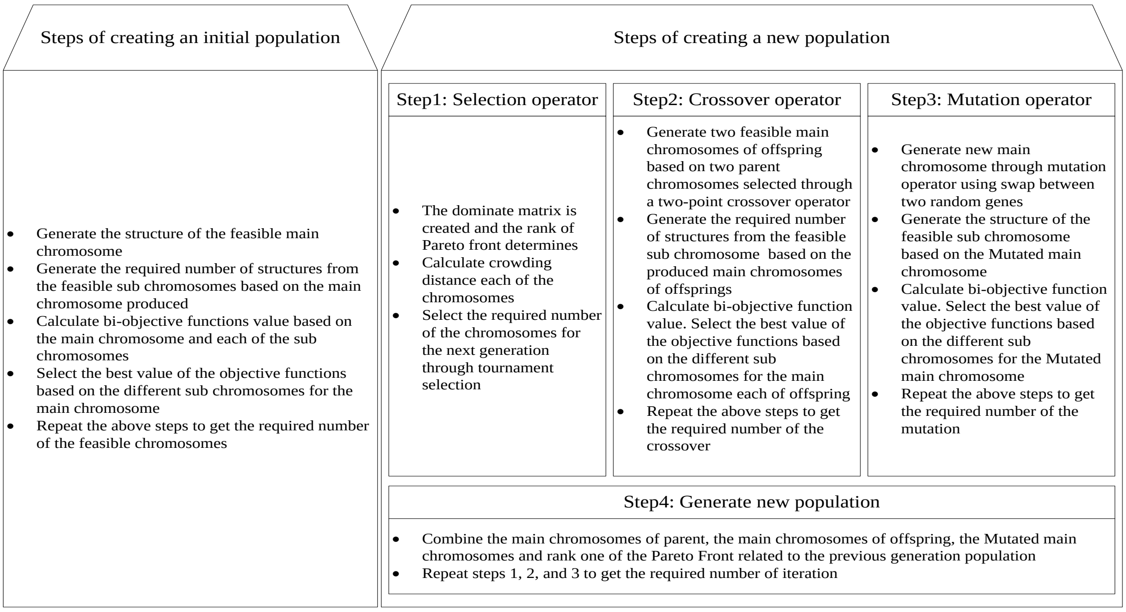


Figure 14. The solution approach based on the NSGA-II algorithm

In the next section, a numeric example is investigated to be solved using the solution approach. Moreover, the exact method has been compared with the NSGA-II.

6. Experimental comparisons and discussions

All the experiments are performed on a PC with the following specifications: Intel Core (TM) 2 Duo CPU, T6570 @ 2.10 GHz, 2.00G RAM, Win7 32 bit. Moreover, Matlab software is used for coding the proposed solution algorithm. Required data for parameters of the problem were taken from a real case study described in Section 4. To tune the parameters of the proposed solution algorithm, each of them was tested at three levels: low, medium, and high by the Taguchi analysis method. The performance of the NSGA-II as Pareto-based evolutionary algorithms is strongly dependent on its parameters. We tried to tune the algorithm parameters by the Taguchi method in the design of the experiment. So, for each parameter, three different levels are defined to evaluate the influence of relevant parameters on algorithm performance. Test values and the final value of each parameter have been presented in the appendix.

To evaluate the meta-heuristic algorithm, the Pareto front extracted by the meta-heuristic algorithm and an exact solution approach has been evaluated based on three important indicators. The first indicator used in this evaluation is the Error Ratio (ER). The number of solutions matched from the final Pareto front PF_{final} to the real Pareto front PF_{real} has been evaluated through ER indicator. The ER indicator is calculated based on equation (43).

$$ER = \frac{\sum_{f=1}^{F} error_f}{F} \quad (43)$$

In the equation above, the total number of solutions on the PF_{final} is shown with F. Also, error solutions are expressed on the PF_{final} with $error_f$. If the f^{th}solution from the PF_{final} coincides with the solution of the PF_{real}. In this case, the $error_f$ is 0. Otherwise, its value is equal to one. The closer the value of ER is to zero. It means that the PF_{final} obtained from the meta-heuristic algorithm has less error than the PF_{real} obtained by the exact method.
The second indicator used in this evaluation is the Generational Distance (GD). The distance of each solution from the PF_{final} is calculated from all RE^{th} solutions of the PF_{real} and the sum of the shortest distances is obtained by equation (44).

$$GD = \frac{\sqrt{\sum_f^F \min_{\forall RE} \left(\left(OFV1_f - OFV1_{RE}\right)^2 + \left(OFV2_f - OFV2_{RE}\right)^2\right)}}{F} \quad (44)$$

According to this indicator, the closer the GD value is to zero, which indicates a shorter distance between the PF_{final} and the PF_{real}. In other words, decreasing the value of the GD indicator represents the increase in the quality of the solutions on the PF_{final}. The third important indicator for evaluating the NSGA-II proposed algorithm is the Overall Non-Dominated Vector Generation Ratio (ONVGR). The ratio of the total number of non-dominated solutions the PF_{final} compared to the PF_{real} has been investigated. The GD indicator is calculated as follows:

$$ONVGR \triangleq \frac{F}{RE} \quad (45)$$

In the equation above, the total number of solutions on the PF_{final} and PF_{real} are shown with F and RE respectively. When ONVGR=1, this states only that the same number of solutions have been found in both PF_{final} and PF_{real}.It does not infer that $F = RE$. This metric requires that the researcher knows RE. In Table (9), the evaluation output is reported based on the CPU time and value of the objective function. In Table (9), the evaluation output is reported based on the CPU time and value of the indicators for 4 cases of small size and 4 cases of medium size. By default for all cases, the total number of machines and the total number of speeds are 7 and 3, respectively.

Table 9. Results obtained for different cases by comparing exact method and NSGA-II

# of case	Specification		Method	CPU Time	Indicators		
	Number of jobs	Number of operations			ER	GD	ONVGR
Case1	5	16	Exact	295	0	0	1
			NSGA-II	321	0	0	1
Case2	7	22	Exact	354	0	0	1
			NSGA-II	386	0	0	0.95
Case3	9	29	Exact	402	0	0	1
			NSGA-II	427	0.05	53	0.95
Case4	11	34	Exact	481	0	0	1
			NSGA-II	454	0.05	73	0.90
Case5	13	38	Exact	499	0	0	1
			NSGA-II	473	0.10	91	0.90
Case6	15	44	Exact	563	0	0	1
			NSGA-II	491	0.10	115	0.80
Case7	17	53	Exact	641	0	0	1
			NSGA-II	508	0.10	133	0.80
Case8	19	60	Exact	712	0	0	1
			NSGA-II	529	0.10	148	0.80

As you can see in Table (9), the results obtained from the NSGA-II are very close to the exact method in terms of CPU time and performance indicators. All experiments are conducted 30 runs and the best results have been reported for 8 cases. In order to better demonstrate the performance of the NSGA-II algorithm, we solved 6 cases of large size. The percentage of improvement of objective functions in the last generation compared to the first generation has been evaluated for each case in Table (10).

Table 10. Percentage of the NSGA-II improvement in creating generations' solutions

# of case	Specification		Total cost of jobs tardiness			Tax cost on surplus energy consumption		
	Number of jobs	Number of operations	generationFirst	Last generation	%Improvement	generationFirst	Last generation	%Improvement
Case 9	40	86	81394	50391	38.09	254874	146093	42.68
Case10	50	113	105343	65080	38.22	404267	226995	43.85
Case11	60	142	129985	80239	38.27	481581	270262	43.88
Case12	70	182	142977	88488	38.11	676086	380095	43.78
Case13	80	199	220894	135584	38.62	736171	411004	44.17
Case14	90	213	289551	177871	38.57	810862	454731	43.92

7. Conclusion

Scheduling in a flexible job shop under uncertainty was investigated in this study with a bi-objective approach. Governmental tax regulations and energy-saving in setting modes and speed levels of machines were also considered in this research. At first, the problem was described clearly with the parameters and decision variables and then, a new mathematical model was developed. The non-linear model was modified to a linear model as MIP. This model has developed aims to use in make-to-order (MTO) production systems with high-powered machines under uncertainty for energy-saving and cost reduction. Two strategy scheduling repair were used in the proposed model responding to different kinds of uncertainties (machine breakdowns, modification or cancellation of the orders, changing of the delivery dates, and receiving new important orders without any known probability distribution).

The approach of H_m was used in the scheduling to reduce the total cost of energy consumption. Based on this approach, each machine has an energy label that indicates the need energy for switching the machine from standby to idle mode. This label emphasizes that if need idle power of a machine between two consecutive operations is less than H_m it should keep in the idle mode and do not switch to standby mode. The issue that has been not conducted in the last related studies is an important factor in controlling total energy consumption. Another innovation of this study is investigation this subject and determining the best choice of machines modes in order to energy-saving. Because of the energy-saving conflicts the complete the jobs, we studied this problem considering two objectives simultaneously to reduce total cost. These two objectives were defined as tax cost on surplus energy consumption, and cost of tardiness penalties.

To evaluate and validate the performance of the proposed model, data of a real case study based on the casting process was used. The proposed model with energy consumption in switching machine modes is able to provide a good response to uncertainties on MTO production systems. Consequently, the proposed strategies, which have been derived from the scheduling repair with energy consumption in switching machine modes have been a good approach to adapt the original scheduling to the new status. Then, a solution approach was introduced based on the NSGA-II algorithm. It was shown that the proposed NSGA-II algorithm provided a set of solutions on the Pareto front close to the result of the exact method that was obtained using the augmented ε-constraint method. Finally, the result indicated that the proposed approach can improve the first and the second objective function by more than 38.3% and 43.7% respectively during iterations.

Two managerial insights can be mentioned in this study. First, managers of such industries should note that a high number of switches from standby mode to idle mode on machines leads to high-energy consumption during production scheduling. Therefore, the energy-saving in switching machine modes allows operations of jobs to be assigned to machines, which has less H_m than other machines because machines with less H_m tend to stabilize in standby mode to reduce energy consumption while the machines with more H_m tend to stabilize in idle mode to reduce energy consumption. The computational results in the case study displayed that the total costs can be reduced up to 56% on average. Second, industry managers pay attention to adjusting the speed level of high-consumption machines during processing time. If the speed level of the machines increases. In that case, the total cost of jobs tardiness should be reduced. However, the tax cost on surplus energy consumption should increase and vice versa. In such cases, the proposed model adjusts the machines to the best status from the speed level during processing time. Using the proposed model is recommended to industry managers.
As interesting future research, it is worthwhile to develop the problem by adding some practical assumptions such as restriction on buffer capacity and transportation between workstations. Furthermore, it is recommended to investigate the peak power consumption constraints in this problem.

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Appendix A

Introduction of pNSGA-II algorithm parameters:
A: The population size of the main chromosomes
B: The population size of the sub chromosomes
C: The probabilities of selection (P_s)
D: The probabilities of crossover (P_c)
E: The probabilities of mutation (P_m)
F: The iteration

Table A1. Design summary

Taguchi array	L27(3^6)
Factors	6
Runs	27
Columns of L27 (3^13) array: 1 2 3 4 5 6	

Table A2. Parameters setting of NSGA-II algorithm

Parameters	Test value			NSGA-II
	Level1	Level2	Level3	
A	185	245	305	245
B	12	22	34	34
C	0.60	0.70	0.80	0.60
D	0.52	0.72	0.92	0.72
E	0.20	0.50	0.80	0.50
F	7	12	17	7

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