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Developing simulation based optimization mechanism for a novel stochastic reliability centered maintenance problem

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Condition-Based Maintenance (CBM);
Shocking mechanism;
Biogeography Based Optimization (BBO).

Abstract. This research investigates joint scheduling of maintenance and production planning. This novel integrated problem takes benefit of Reliability-Centered Maintenance (RCM) for monitoring and managing maintenance function of a stochastic complex production-planning problem, namely, Flexible Job Shop scheduling Problem (FJSP). The developed RCM works based on stochastic shocking of machines during their process time. In fact, it implements condition based maintenance approach regulated according to stochastic reliability concept. Comparison of the system reliability with critical levels determines the failure status of the machines. It activates two main types of reaction called preventive and corrective maintenance. Considering breakdown of the system between inspection intervals makes the proposed model more realistic. Moreover, maintenance activity times and their duration are considered stochastically. Because of the high complexity level of this joint system, Simulation-Based Optimization (SBO) approach is proposed for solving the problem. This SBO searches the feasible area through Genetic Algorithm (GA) and Biogeography Based Optimization (BBO) algorithm. Different test problems, statistical methods, and novel visualizations are used to discuss the problem and the algorithm, explicitly.

1. Introduction

Production plans and the maintenance activities are joint concepts in real world. However, most of the production and scheduling problems assume all times machine availability [1]. In contrast to this assumption, real world problems face many situations in which machines break down or need maintenance. [2]. Moreover, inefficient maintenance can cause one third of maintenance costs being wasted due to unnecessary or improper maintenance activities [3]. Nonetheless, maintenance issues are not a considerable portion of the literature on production and manufacturing problems.

On the other hand, maintenance and reliability have a significant share of the literature on modeling and optimization [4-9]. Thus, taking benefit of this opportunity to realize and reinforce production-planning problems is of interest. One of these opportunities is a method called Reliability Centered Maintenance (RCM). Actually, the main goal of this paper is consistent introducing of RCM to production problem because of its importance in real environment. RCM has various industrial applications in the maintenance and reliability literature, including power distribution systems, subsea pulpiness, steel plants, chemical indus-

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try, transportation, water distribution, and concrete bridge decks inspection [10-15].

RCM functionally controls the systems to reach a desired level by monitoring their reliability [16]. Moreover, it prioritizes maintenance activities by ranking the failures according to their effects on system reliability. In fact, RCM continuously monitors the reliability of the system and determines type of the required maintenance activities according to the levels of reliability [16]. Condition-Based Maintenance (CBM), in many cases, conducts the task of monitoring. CBM development owes to the recent emerging technologies such as radio frequency identification (RFID), Micro-Electro-Mechanical System (MEMS), wireless telecommunication, and Product Embedded Information Devices (PEID) [17]. In the next subsection, the literature on joint scheduling of maintenance and production planning is reviewed.

1.1. Integration of maintenance and general production problems

Graves and Lee [18] developed a single-machine scheduling problem. They assumed certain intervals for maintenance activities. Lee [19] studied the two-machine flow shop scheduling problem under availability constraint and developed dynamic programming algorithm and heuristic solutions. Lee and Chen [20] considered a scheduling model for parallel machines in which jobs could be maintained only once during the planning horizon. They also assumed two strategies: machines could be maintained simultaneously or separately. Schmidt [21] reviewed deterministic scheduling problems with availability constraints. Espinouse et al. [22] and Cheng and Liu [23] investigated a two-machine flow-shop problem in a no-wait environment with availability constraint. Liao and Chen [24] considered several maintenance periods in their single-machine scheduling problem, which minimized the maximum tardiness of jobs.

Aggoune [25] in a flow shop problem considered two variants of the non-preemptive jobs. Allaoui and Artiba [26] integrated hybrid flow shop scheduling problem and maintenance constraints minimizing the flow time. Cassady and Kutanoglu [27] proposed a mixed model of single-machine model with periodic or preventive maintenance, which was followed by Sortrakul t al. [28]. Liao et al. [29] developed a two-parallel-machines problem considering preventive maintenance. Mauguiere et al. [30] studied unavailability in job-shop scheduling problem and single-machine model. Allaoui and Artiba [31] investigated one-machine flow shop with availability constraints. Lin and Liao [32] studied hybrid parallel machine problem and maintenance affairs. Ruiz et al. [33] studied a permutation flow shop problem with preventive maintenance. Chen [34] implemented flexible and periodic maintenance in his models. Liao and Sheen [35] considered parallel machine scheduling with availability and eligibility constraints, simultaneously. Berrichi et al. [36] studied parallel machines focusing on makespan and unavailability, simultaneously. Zribi et al. [37] integrated job-shop scheduling problem with availability constraints.

Naderi et al. [38] scheduled a sequence-dependent setup time job-shop with preventive maintenance. Mellouli et al. [39] developed an integrated parallel machine scheduling problem with preventive maintenance. Chen [40] studied a single machine with several maintenance periods and minimized the maximum tardiness of jobs. Mati [41] focused on the integration of job-shop scheduling problem and availability constraints. Pan et al. [42] considered variable maintenance time subjected to machine degradation to make their single machine compatible with preventive maintenance. Low et al. [43] considered single machine with periodic maintenance. Safari et al. [44] developed CBM for flow shop scheduling problem. They did not develop mathematical model and only simulated the concept. Moreover, their simulation did not assume the possibility of breakdown between inspection times. Ben Ali et al. [45] proposed a multi-objective job shop problem that optimized maintenance cost in addition to makespan. Ramezanian and Saidi-Mehrabad [46] developed parallel machine with rework process. Zhou et al. [47] proposed a multi-component system under changing job shop with preventive maintenance consideration. Ozkok [48] investigated hull structure production process in a fixed-position shipyard company with machine breakdown consideration.

Chouikhi et al. [49] integrated a single-unit system with CBM and optimized the cost of maintenance and inspection time by determining the optimal inspection. They assumed that both corrective and preventive maintenance actions were perfect, which means after such actions, the system became as good as the new one. Besides, they assumed that durations of inspection, corrective maintenance, and preventive maintenance could be negligible. Kim and Ozturkoglu [50] developed a joint scheduling of single machine problem with multiple preventive maintenances. They proposed ant colony optimization and particle swarm optimization in order to solve this problem. Ying et al. [51] introduced different SMPSs considering maintenance activity between two sequential jobs. Lin et al. [52] evaluated reliability of a multistate FLexible FSSP with stochastic capacity. Huang and Yu [53] developed a two-stage multiprocessor FSSP with maintenance and clean production aims. Cui and Lu [54] investigated flexible maintenance in SMPS and solved their problem through the Earliest Release Date-Longest Processing Time (ERD-LPT), and Branch and Bound (B&B) algorithm.

1.2. Integration of maintenance and Flexible Job Shop scheduling Problem (FJSP)

Flexible job shop scheduling problem is a popular and complex flexible manufacturing problem [55,56]. In classical FJSP, most researches assume that all machines are available during their working process. Both areas of the optimization problems, i.e., model development [57-61] and solving method extension [62-76], can be found in the classical literature on FJSP. Demir and Isleyen [77] performed a comprehensive evaluation of the various mathematical models presented for the FJSP.

Zribi and Borne [78] assumed unavailability of machines due to preventive maintenance. Gao et al. [79] proposed preventive maintenance for FJSP in which the period of maintenance tasks was non-fixed and should be determined during the scheduling procedure. Wang and Yu [80] developed FJSP considering maintenance activities either flexible in a time window or fixed beforehand. Moradi et al. [81] integrated FJSP and preventive maintenance by optimizing unavailability and makespan. Mokhtari and Dadgar [82] introduced a joint FJSP and PM model that assumed the failure rates were time varying. In their model, the duration of PM activities was fixed. Ahmadi et al. [83] studied random machine breakdown in FJSP with simulation considerations. The related important studies are summarized in Table 1.

1.3. Gap analysis

According to the literature, a rare portion of the production studies is devoted to FJSP, CBM, and RCM. Therefore, this research reinforces FJSP problem through RCM concept. Real world assumptions, rarely considered in the literature, are assumed in the developed RCM. For instance, breakdown possibility is assumed between inspection intervals. Also, this study considers maintenance occurrence and duration time stochastically. In addition, it stochastically assumes recovery level of the system after preventive maintenance. Moreover, we use both types of maintenance strategies, called Corrective Maintenance (CM) and Preventive Maintenance (PM). CBM is used to detect the level of reliability [84].

The structure of the paper is as follows. Section 2 presents the related literature review of the problem. Section 3 discusses the elements of the proposed joint problem. The simulation-based approach related to the proposed RCM is developed in Section 4. Section 5 presents the proposed problem and its solving methodology through numerical examples. Finally, Section 7 concludes the paper.

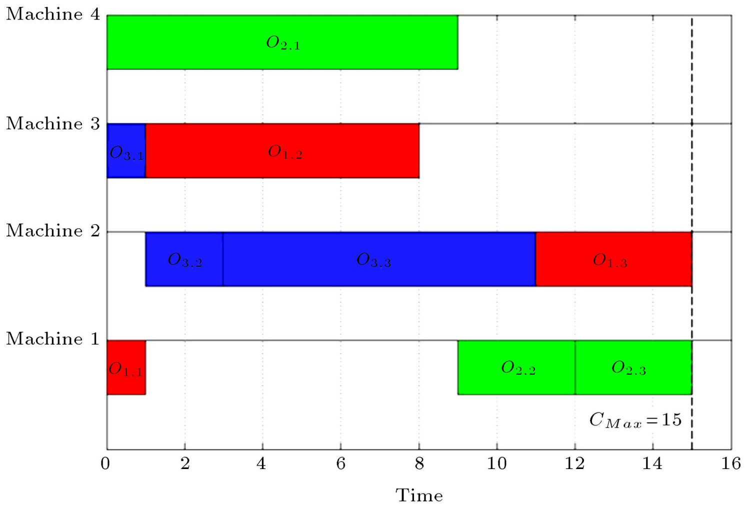
2. Preliminaries of the developed joint problem

The considered production problem is a stochastic version of the simple FJSP. FJPS has two tasks, namely, allocating operations to machines and determining the sequence of allocated operations to each machine [72,79]. Simple FJSP consists of n jobs, J $(J_i, i \in \{1, 2, ..., n\})$; each job, i $(J_1, ..., J_n)$, includes n_i operations, $O(O_{ij}, j \in \{1, 2, ..., n_i\})$, that are processed on m machines, $M(M_k, k \in \{1, 2, ..., m\})$. The FJSP objective function of this paper is makespan (C_{max}) given below:

$$C_{max} = max\{C_k | k = 1, ..., n\}, \tag{1}$$

where C_k denotes complementation time of machine k [74].

Figure 1 illustrates the FJSP example with 3 jobs, 4 machines, and 9 operations. This figure includes a table and a related Gant chart. In the table, the numbers present the processing times of operations on machines in addition to their sets of capable machines. The



Jobs	Operations	Processing time of the operations on machines			
		*M*1	*M*2	*M*3	*M*4
J1	O11	1	15	2	4
	O12	inf	6	7	8
	O13	21	4	inf	inf
J2	O21	inf	inf	inf	9
	O22	3	4	12	8
	O23	3	inf	inf	inf
J3	O31	inf	13	1	6
	O32	inf	2	4	inf
	O33	inf	8	inf	inf

Figure 1. The machine capability table and Gant chart of a related feasible solution.

Table 1. Literature review of the integration of scheduling and maintenance.

Ref. #	Year	Scheduling types	Objectives	Types of maintenance				Solving methodologies		
				CM	PM	CBM	RCM	Meta-heuristics	Exact	SBO
Grave and Lee [18]	1999	Single machine	C_{max} Lateness		*				DP	
Cassady and Kutanoglu [27]	2005	Single machine	TWCT		*			Heuristic	TE	
Sortrakul et al. [28]	2005	Single machine	TWCT		*			GA		
Mauguiere et al. [30]	2005	Single machine & job shop	C_{max}		*				B&B	
Chen [34]	2008	Single machine	C_{max}		*			Heuristic		
Chen [40]	2009	Single machine	C_{max}		*			Heuristic	B&B	
Pan et al. [42]	2010	Single machine	MWT		*			Heuristic		
Low et al. [43]	2010	Single machine	C_{max}		*			Heuristic		
Kim and Ozturkoglu [50]	2013	Single machine	C_{max} TCT TWCT		*			GA		
Ying et al. [51]	2016	Single machine	T, ML, TFT, MT		*			Heuristic		
Cui & Lu [54]	2017	Single machine			*				B&B, ERD-LPT	
Lin and Liao [32]	2007	Parallel machine	C_{max}		*			Heuristic		
Liao and Sheen [35]	2008	Parallel machine	C_{max}		*				BSA	
Berrichi et al. [36]	2009	Parallel machine	C_{max} Unavailability		*			NSGAII		
Mellouli et al. [39]	2009	Parallel machine	TCT		*				DP, B&B	
Lee [19]	1999	Flow shop	C_{max}	*				Heuristic	DP	
Espinouse et al. [19]	2001	Flow shop	C_{max}		*			Heuristic		
Cheng and Liu [20]	2003	Flow shop	C_{max}		*			Heuristic		
Aggoune [25]	2004	Flow shop	C_{max}		*			TS GA		
Allaoui and Artiba [26]	2004	Flow shop	Flow time		*			Heuristic		*
Ruiz et al. [33]	2007	Flow shop	C_{max}		*			Random, NEH, SA, GA, ACO		
Safari et al. [44]	2010	Flow shop	$C_{\max}$	*	*	*		SA-TS		*
Naderi et al. [38]	2009	Flexible flow shop	C_{max}		*			AIS, GA		
Huang & Yu [50]	2016	Flow shop	C_{max}		*			PSO, ACO		

Table 1. Literature review of the integration of scheduling and maintenance (continued).

Ref. #	Year	Scheduling types	Objectives	Types of maintenance				Solving methodologies		
				CM	PM	CBM	RCM	Meta-heuristics	Exact	SBO
Zribi et al. [34]	2008	Job shop	C_{max}		*			Heuristic GA		*
Mati [38]	2010	Job shop	C_{max}		*			Heuristic		
Ben Ali [45]	2011	Job shop	C_{max} Cost		*			MOEA		
Zhou et al. [47]	2012	Job shop	C_{max} Cost		*				DP	
Zribi and Borne [78]	2005	FJSP	C_{max}		*			Hybrid GA		
Gao et al. [72]	2006	FJSP	C_{max} TWL CWL		*			GA		
Wang and Yu [73]	2010	FJSP	C_{max}							
Moradi et al. [74]	2015	FJSP	C_{max} Unavailability		*			NSGAII		
Mokhtari, and Dadgar [82]	2015	FJSP	C_{max}		*			SA		*
Ahmadi et al. [83]	2016	FJSP	C_{max} Stability	*				NSGAII NRGA		
This Study		FJSP	C_{max}	*	*	*	*	BBO & GA		*

symbol 'inf' implies that the machine cannot operate the corresponding operation. The Gant chart depicts combination of the sequence and the assignment for a sample solution.

This research realizes the basic FJSP production-planning problem through considering the real stochastic nature of the maintenance function. The main concept of the proposed approaches is RCM. RCM determines and classifies the failure modes and tries to keep the reliability of the system in a level that the occurrence of these modes is prevented [16]. In fact, it monitors the system status predictively to recognize the mode and do the required qualified actions in consequence [85-87].

The monitoring mechanism of the proposed RCM is based on the CBM approach. CBM determines the maintenance activities according to the actual condition of the systems [85]. In addition, the developed RCM mimics the shocking process [86] that degrades the considered reliability function of the machines, stochastically. In other words, CBM monitors the reliability degradation caused by stochastic shocking process. Simultaneously, it predicts and determines the appropriate maintenance actions according to the reliability status of the machines [16,85]. The failures considered in the research are of both types of CM and PM. Now, in case the reliability status falls beneath the first critical threshold, L, CBM suggests to have PM, and if it gets inferior to failure rate LL, a failure or breakdown occurs [87].

Figure 2 illustrates reliability deteriorating and failure modes, schematically. This figure plots the manner of reliability from two aspects. In the upper part, it introduces the stochastic variables of the problem, while in the lower part, on a generally similar figure, it focuses on the maintenance activities according to the state of reliability. The S values in the figure denote the shock times that reduce machine reliability within simulation process. This example encompasses seven shocks, i.e., $S1$ to $S7$, presented on the horizontal axis. The M values, i.e., $M1$ and $M2$, denote the time of the jth maintenance activity on the machine.

After shocks $S1$ to $S3$, reliability of the machine is still higher than L. Therefore, the machine does not require maintenance activity. Then, the fourth stochastic shock ($S4$) decreases the reliability of machine to the preventive maintenance bound L. Therefore, on the inspection time of $2T$, the PM maintenance activity is recognized. The PM maintenance activity recovers and improves the degradation level in $M1$. The machine works at this level of reliability until $S5$ occurs. Since the reliability level of machine after

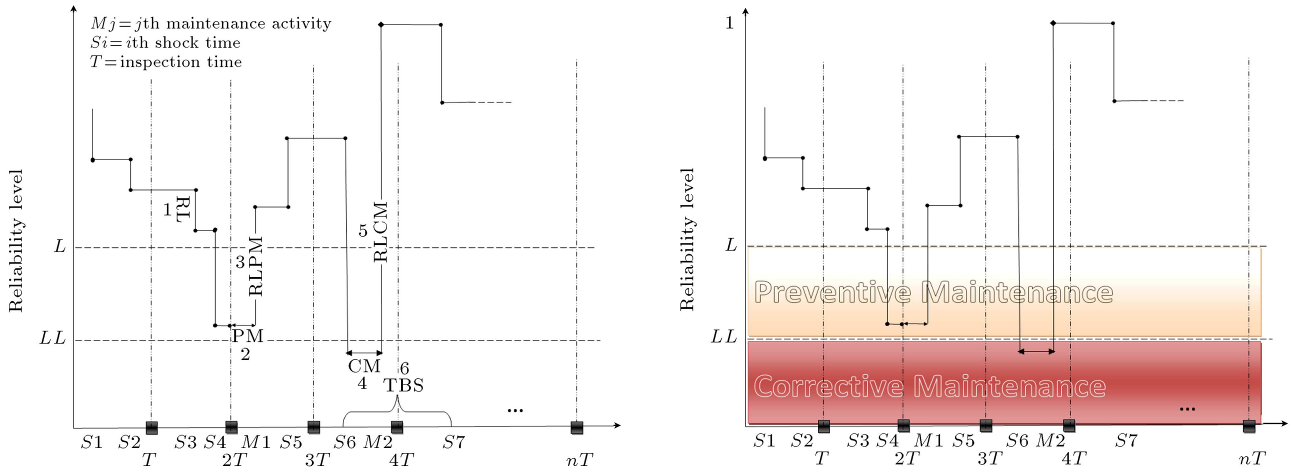


Figure 2. The maintenance activities due to the degradation level.

Calculate the reliability level of machines $\mathrm{Rel}(m)$ **in each new sample time**
  If $\mathrm{Rel}(m) \geq L$
    $\mathrm{Rel}(m)_{\mathrm{new}} = Rel(m)_{\mathrm{old}}$
  Else if $LL \leq \mathrm{Rel}(m) \leq L$
    $\mathrm{Rel}(m)_{\mathrm{new}} = \mathrm{Rel}(m)_{\mathrm{old}} + \mathrm{RLPM}$
  Else
    $\mathrm{Rell}(m)_{\mathrm{new}} = Rel(m)_{\mathrm{old}} + \mathrm{RLCM} = 1$
  End
End

Figure 3. The proposed reliability modification model.

shock $S5$ is higher than L, no maintenance activity is required. However, $S6$ degrades the machine to even less than LL; thus, corrective maintenance should be done. This corrective maintenance has two main distinctive differences with PM, namely 1) happening between the inspection intervals that cause breakdown of the machines, and 2) improving the reliability to a new machine reliability level or reliability zero in $M2$.

In Figure 2, the number represents the stochastic event types that occur during the working process of the machine as follows.

Number 1 is a stochastic variable that denotes machine reliability level (Rel_m) or rel and follows exponential distribution with parameter ($RL \sim Exp(\eta)$). In fact, this number is a function of degradation of machine at each time ($D_m(t)$) according to the function in Eq. (2). In this equation, β_0 and β_1 are reliability deterioration rates and weighted average of critical levels, i.e., $DM = (L + 4^* LL)/5$. Machine degradation (DL_m) or $D_m(t)$ follows exponential distribution with parameter ($DL_m \sim Exp(\eta)$). It should be noticed that in the equations of this paper, DL_m and $D_m(t)$ denote machine degradation and RL_m and $\mathrm{Rel}_m(t)$ denote machine reliability.

$$\mathrm{Rel}_m(t) = \frac{e^{-\beta_0 D_m(t)}}{1 + e^{\beta_1 (D_m(t) - DM)}}. \tag{2}$$

Number 2 denotes PM Duration (PMD) and it follows lognormal distribution (PMD $\sim$ log normal(μ_{PM}, σ_{PM})).

Number 3 represents the improving or recovery level through PM (RLPM) activity, calculated through Eq. (3), and it follows lognormal distribution (RLPM$-$ log normal$(\mu_{PM'}, \sigma_{PM'})$).

$$\mathrm{Rel}_{new} = \mathrm{Rel}_{old} + RLPM;$$

$$\mathrm{LL} < \mathrm{Rel}_{old} \leq L. \tag{3}$$

Number 4 denotes the CM Duration (CMD) and it follows lognormal distribution (CMD $\sim$ log normal (μ_{CM}, σ_{CM}).

Number 5 represents the improving or Recovery Level through CM (RLCM) activity, calculated through Eq. (4), that either entirely removes the reliability of machine or makes it one.

$$\mathrm{Rel}_{new} = \mathrm{Rel}_{old} + RLCM; \quad \mathrm{Rel}_{old} \leq LL. \tag{4}$$

Number 6 denotes the stochastic time between two shocks (TBS) and it follows an exponential distribution (TBS $\sim \mathrm{Exp}(\lambda)$).

Figure 3 illustrates a brief explanation of the explained reliability modification process.

Habitat sequence	O_{31}	O_{32}	O_{21}	O_{33}	O_{11}	O_{22}	O_{12}	O_{23}	O_{13}
Habitat machine assignment	M_3	M_2	M_4	M_2	M_1	M_1	M_3	M_1	M_2

Figure 4. The proposed solution habitat (solution) vector of the example in Figure 1.

```
/Generate a random number between 1 and 3 and call it Rand1/
/Generate a random permutation with TNOP and call it Randperm1/
 If Rand1 = 1
   /Execute swap operator/
   a1=Randperm1(1)
   a2=Randperm1(2)
   SSV1=SSV
   SSV1(a1)=SSV(a2)
   SSV1(a2)=SSV(a1)
Else if Rand1 = 2
   /Execute reversion operator/
   b1=min{Randperm1(1), Randperm1(2)}
   b2=max{Randperm1(1), Randperm1(2)}
   SSV1=SSV
   /Reverse the order of the objects placed between the b1 and b2
   in SSV1 or SSV1 (b1:b2)=SSV1(b2:-1:b1)/
Else Rand1 = 3
   /Execute insertion operator/
   c1=Randperm1(1)
   c2=Randperm1(2)
   if C1<C2
     SSV1=[SSV(1:c1) SSV(c2) SSV(c1+1:c2-1) SSV(c2+1:end)]
   else
     SSV1=[SSV(1:c2-1) SSV(c2+1:c1) SSV(c2) SSV(c1+1:end)]
End
```

Figure 5. The proposed hybrid SSV operator of the habitat.

3. Simulation-Based Optimization (SBO) algorithm

The proposed SBO has two main elements, namely, optimization algorithm and simulation process. Two different meta-heuristic algorithms, namely, GA and BBO, conduct the optimization algorithm. Accordingly, this section is classified into three parts. The first two parts introduce the mentioned elements, respectively, and the third one integrates the whole elements and operators with each other.

3.1. Optimization algorithm of the SBO

Before developing the optimization algorithms, separately, let us explain them, comparatively. GA and BBO, as population-based algorithms, have many similarities. Both algorithms include a set of individuals, called chromosomes and habitats, respectively. The fitness values of the individuals are called fitness and High Suitability Index (HSI), respectively. Other detailed comparisons of the algorithms are provided in [84].

3.1.1. The BBO algorithm

BBO mimics the migration term of biogeography science [88,89]. The solution or habitat structure in this paper is a vector equal in length to the number of operations or total number of operations (TNOP). Each cell of this vector is an ordered pair in which the upper object is the operation name and the lower object is the assigned machine to that operation. Moreover, the first row of the solution structure shows the sequence of operations for operating on machines. Figure 4 illustrates a sample of solution structure related to the Gant chart of Figure 1.

BBO implements different strategies in its mutation operator. In Sequencing Sub-Vector (SSV), it applies a hybrid strategy, including swap, reversion, and insertion, through a random process, as shown in Figure 5.

For the assignment sub-vector (MASV), BBO performs through machine changing from the capable table of each operation as in Figure 6.

For executing the migration, in sequencing part, permutation operator conducts the migration as in

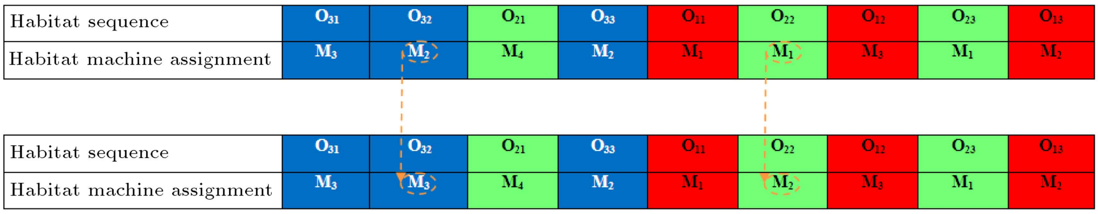


Figure 6. MASV operator of BBO.

Permutation crossover

Generate an integer number [1-2] and denote it by *Rnd*

EH = emigrated habitat; IH = immigrated habitat; MH = migrated habitat

RI = Generate an integer number $[1 : (TNOP - 1)]$

$x11 = EH(1 : RI)$

$x12 = EH(RI + 1 : end)$

$x21 = IH(1 : RI)$

$x22 = IH(RI + 1 : end)$

$MH = [x11\ x22]$

$MH = [x21\ x12]$

Figure 7. Proposed migration of sequencing.

```
/Create a random mask vector with binary values as long as TNOP/
/EH = emigrated habitat; IH = immigrated habitat; MH = migrated habitat/
For i = 1 : TNOP
    If Mask(i) = 0
        MH(i) = EH(i)
    Else
        MH(i) = IH(i)
    End
End
```

Figure 8. Proposed migration of assignment.

Figure 7, and in assignment part, mask operator plays the role as in Figure 8.

3.1.2. The Genetic Algorithm (GA) operators

GA implements reproduction, mutation, and crossover as the conductive operators for searching the search space. Reproduction operator copies a set of elite chromosomes to the next generation [90].

3.2. The simulation agent of the algorithm

As mentioned in the developed scheduling model, the proposed FJSP contains different stochastic components, such as RL, PMD, RLPM, CMD, RLCM, or TBS, to encompass a realistic version of the RCM. These variables change the states of the solutions dynamically.

SBO, as a powerful tool of optimization, is involved in almost every aspect of stochastic programming [84]. Two general classes of stochastic optimization problems exist in the literature, namely, the parametric (static) and the control (dynamic) ones. The static optimization includes a set of static parameters for all states. However, in the control optimization, solutions change according to dynamic states [84]. Here, because of the stochastic nature of problem, dynamic strategy controls the simulation process. Figure 9 plots the general structure of the proposed SBO.

The input to Figure 8 is a solution from the optimization process and its output is the simulated version of the objective function. This SBO conducts a loop of simulation runs (*Numsim*) to obtain average and standard deviation of solutions for reporting a more robust solution. In this flowchart, *dt* regulates sample time of the simulation. Moreover, VT and LVT denote predetermined length between visit times and the obtained last visit time, respectively. Besides, the terms $IJS\{j\}(i)$, $IJF\{j\}(i)$, and $IMB(m)$ in Figure 10 to Figure 12 are binary logical variables that represent 'is operation j of job i started,' 'is operation j of job i finished,' and 'is machine m busy,' respectively.

The reliability updating function of Figure 10 determines the level of reliability for machines and the

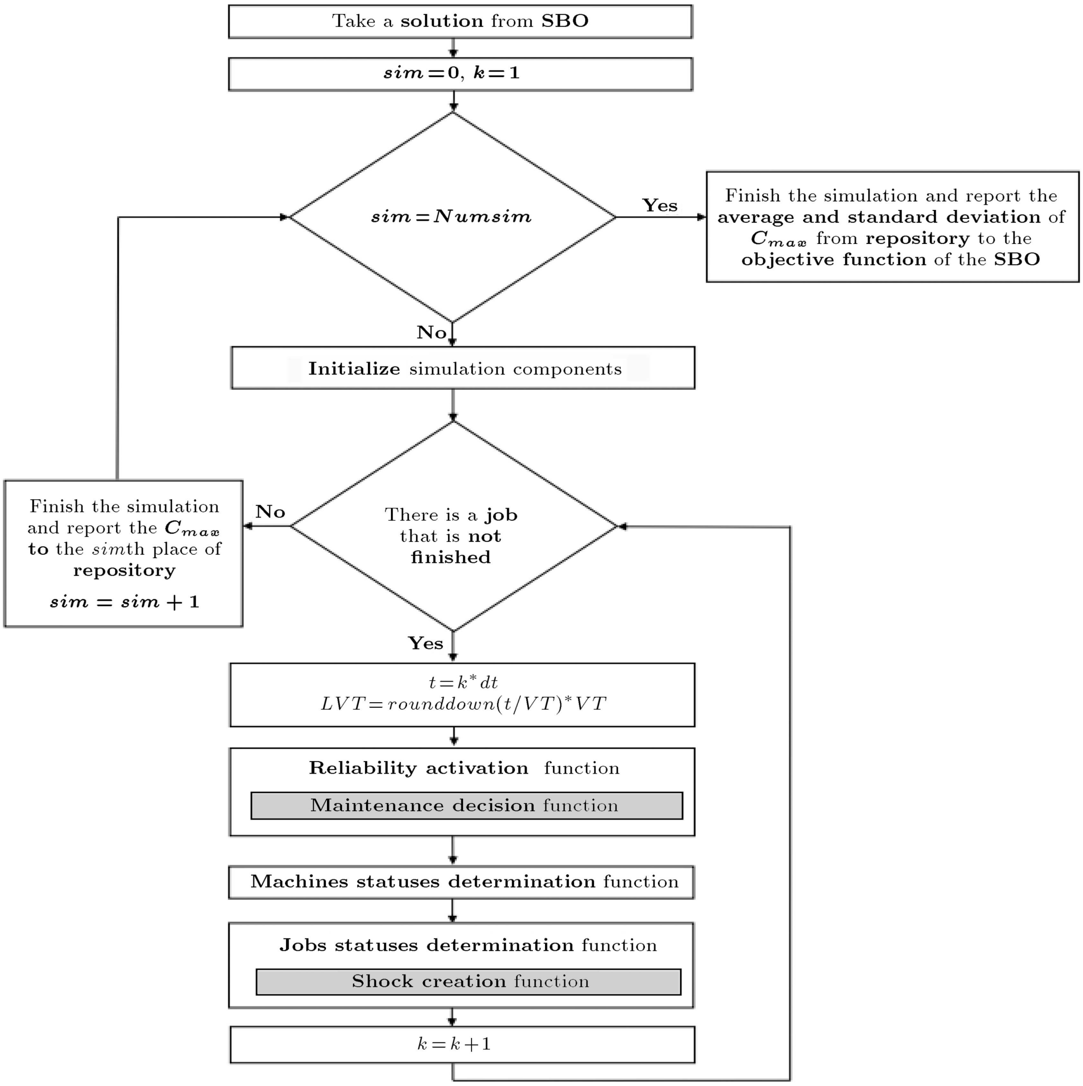


Figure 9. The overall flowchart of the proposed simulation part of SBO.

maintenance decision. Figure 11 includes the logic of the maintenance decision determination.

According to schedules, machine and job status determination functions are activated as given in Figure 12 and Figure 13, respectively. These functions determine the start and finish status of jobs plus the business status of machines at each moment of simulation.

The job status function includes the shocking time determination functions. Figure 14 illustrates the proposed shocking logic. SBO at these shock times updates the reliability level of machines during the operating times for the related assigned operations. Certainly, they have impact on the types of the maintenance decisions according to the reliability level obtained after the shock times.

4. Computational results

This section provides us with the numerical examples of the problem to have a detailed view of the developed stochastic problem and the simulation based algorithms. The general information of these test problems is provided in Section 2 and their detailed descriptions are in a file, called RCM, placed in *ResearcheGate site* of the first two authors. In this section, the proposed SBO is compared with Genetic Algorithm (GA).

4.1. Parameter tuning

Parameters of the algorithms are tuned through Taguchi method [91].

Tables 2 and 3 show the determined levels of parameters of BBO and GA.

4.2. Outputs of the algorithms

Tables 4 and 5 present the outputs of the algorithms for the developed stochastic problem for GA and BBO, respectively. Moreover, these tables include the results of the algorithms for simple version of the problem as

for $\boldsymbol{m = 1 : M}$
if $\boldsymbol{t = 0}$
Reliability level (RL) of machine m is zero i.e. $\boldsymbol{RL\{m\} = 1}$
end
if t is not shock time of the machine m i.e. $\boldsymbol{t \neq shocktime\{m\}}$
/**Note**: Shock times are obtained from shock creation function/
go to the next machine of the loop i.e. $\boldsymbol{m = m + 1}$
else
The final $DL\{m\}$ of machione m is cumulated with a random number of exponential distribution with η mean i.e. $\boldsymbol{RL_{new}\{m\} = RL_{old}\{m\} - exp(\eta)}$
end
According to the update reliability **determine the maintenance decision**
/**Note**: through maintenance creation function/
end

Figure 10. Proposed reliability updating function.

if reliability level of machine m ($RL\{m\}$) is less than reliability bound (L) i.e. $\boldsymbol{RL\{m\} \leq L}$
if t is visit time or $RL\{m\}$ is less than reliability bound (H) i.e. $\boldsymbol{t = LVT}$ **&** $\boldsymbol{RL\{m\} \leq LL}$
Call the index of the started job and its related operation on machine m as $\boldsymbol{i}$ and $\boldsymbol{j}$ respectively
Breakdown of **the operfation** j of jon i on machine m to **start** one type of **maintenance acitivity** on that i.e. $\boldsymbol{IJS\{i\}(j) = 0}$
if $\boldsymbol{RL\{m\} > LL}$
Conduct preventive maintenance activity on machine m with stochastic duration number from lognormal distribution i.e. $PMD \sim \log normal(\mu_{PM}, \sigma_{PM})$
Increase the reliability level of machine m with a random from lohnormal distribution i.e. $RLPM \sim \log normal(\mu_{PM'}, \sigma_{PM'})$ and $\mathrm{Rel}_{new} = \mathrm{Rel}_{old} + RLPM; LL < \mathrm{Rel}_{old} \leq L$
Set the start time of PM job on machine m ($STJ\{m\}$) and start time of machine m ($STM\{m\}$) to t i.e. $\boldsymbol{STJ\{m\} = t}$ & $\boldsymbol{STM\{m\} = t}$
Set the finish time of PM job on machine m ($FTJ\{m\}$) and finish time of machine m ($STM\{m\}$) to $t + PMD$ i.e. $\boldsymbol{FTJ\{m\} = t + PMD}$ **&** $\boldsymbol{STM\{m\} = t + PMD}$
else if $\boldsymbol{RL\{m\} \leq LL}$
Conduct corrective maintenance activity on machine m with stochastic duration number from lognormal distribution i.e. $CMD \sim \log normal(\mu_{CM}, \sigma_{CM})$
Improve the reliability level of machine m entirely and set it to one i.e. $\mathrm{Rel}_{new} = \mathrm{Rel}_{old} + RLCM; \mathrm{Rel}_{old} \leq LL$
Set the start time of CM job on machine m ($STJ\{m\}$) and start time of machine m ($STM\{m\}$) to t i.e. $\boldsymbol{STJ\{m\} = t}$ **&** $\boldsymbol{STM\{m\} = t}$
Set the finish time of CM job on machine m ($FTJ\{m\}$) and finish time of machine m ($STM\{m\}$) to $t + CMD$ i.e. $\boldsymbol{FTJ\{m\} = t + CMD}$ **&** $\boldsymbol{STM\{m\} = t + CMD}$
end
end
Make the machine m busy i.e. $\boldsymbol{IMB\{m\} = 1}$ /**Note**: This business lasts to the end of $\boldsymbol{FTM\{m\}}$/
end

Figure 11. The proposed maintenance decision function.

for $\boldsymbol{m = 1 : M}$
if Machine m is busy i.e. $\boldsymbol{IMB\{m\} = 1}$
if $\boldsymbol{t \geq FTM\{m\}}$
Relax machine and change its status to no busy i.e. $\boldsymbol{IMB\{m\} = 0}$
if Type of the job on machine is not maintenance activity
Call the index of the started job and its related operation on machine m as $\boldsymbol{i}$ and $\boldsymbol{j}$ respectively
/**Note:** The index of the maintenance activities does not require calling in this part and they are simply finished/
Change the status of j of job i on machine m to finish i.e. $\boldsymbol{IJF\{i\}(j) = 1}$
end
else
Go to the next machine i.e. $\boldsymbol{m = m + 1}$
end
end
end

Figure 12. The proposed machine status determination function.

```
1 for m = 1 : M
2     if Machine m is busy i.e. IMB{m} = 1
3         Go to the next machine i.e. m = m + 1
4     end
5     for op = 1 : TNOP
6         Call the job and operation index of the opth ordered operation
          from the sequence harmony sub vector that is assigned to machine m as i and j respectively
          /Note: Assignment are determined according to assignment sub part of harmony solution/
7         if The called operation is started i.e. IJS{i}(j) = 1
8             Go to the next operation i.e. op = op + 1
9         else if Called operation is not started and it's all precedence operations are finished
                  i.e. IJS{i}(j) = 0 & all[IJF{i}(1 : j − 1)] = 1
10                Called operation can be started i.e. IJS{i}(j) = 1
11                Start time of this operation is maximum of the existing simulation time,
                  its final precedence finish time, and the finish time of the final operated job on machine m
                  i.e. STJ{i}(j) = Max[t, FTJ{i}(j − 1), FTM{m}]
12                Finish time of the operation is it's start time added to it's processing time on machine m
                  i.e. FTJ{i}(j) = STJ{i}(j) + PTJ{i}(j){m}
13                Start and finish times of the machine m should also be updated
                  i.e. STM(m) = STJ{i}(j) & FTM(m) = FTJ{i}(j)
14                Shock times should also been determined in this stage through shock creation function
15        end
16    end
17 end
```

Figure 13. The proposed job status determination function.

```
1 The starting time of the shoching is equal to start time of the called operation
  on machine m and is inserted in shock time set of machine m
  i.e. S1 = STJ{i}(j) & Shocktimeset(m) = [S_1]
2     while S is less than the finished time of the called operation i.e. S ≤ FTJ{i}(j)
          l = l + 1
3         Determine the next shock time through exponential distribution with λ mean i.e. S_l = S_{l−1} + exp(λ)
4         Insert S_l in shock time set of machine m i.e. Shocktimeset_new(m) = [Shocktimeset_old|S_l]
5     end
6 end
```

Figure 14. The proposed shock creation function.

Table 2. The factor levels of BBO.

A: Iteration size	B: Population size	C: Mutation rate	D: E rate	A: I rate
10	10	0.1	0.8	0.8
30	30	0.2	1	1
50	50	0.3	1.2	1.2

Table 3. The factor levels of GA.

A: Iteration size	B: Population size	C: Crossover rate	D: Mutation rate
10	10	0.5	0.1
30	30	0.6	0.2
50	50	0.7	0.3

Table 4. Outputs of the algorithms for test problems.

Problem #	GA			BBO		
	$C_{maxMean}$	Time 1	C_{maxSTD}	$C_{maxMean}$	Time 1	C_{maxSTD}
FJSP1	108	440.02	0	108	873.81	0.0011
FJSP2	193	924.09	15.202	173.5	1907.36	98.005
FJSP3	93	683.67	0	93	1429.61	0
FJSP4	146.75	728	13.22	141.05	1365.07	16.97
FJSP5	167.7	1255.8	25.243	212.35	2871.43	30.759
FJSP6	76	690.4	0	76	1222.08	0
FJSP7	261.9	1277.74	4.596	265	2347.27	21.637
FJSP8	169.2	1197.9	12.727	183.1	2200	3.889
FJSP9	266.95	2702	30.193	252.8	5244.42	47.16
FJSP10	204.05	2496.35	8.414	203.09	4550.73	21.99
Average	**168.655**	**1239.597**	10.959	170.789	2401.178	**26.14111**

Table 5. Outputs of the algorithms for test problems.

Problem #	GA		BBO	
	C_{max}	Time 2	C_{max}	Time 2
FJSP1	108	2.17	108	8.36
FJSP2	149	2.65	147	14.03
FJSP3	93	2.67	93	13.57
FJSP4	133	2.73	118	14.79
FJSP5	154	3.66	146	19.09
FJSP6	76	6.02	76	19.15
FJSP7	203	6.82	194	20.51
FJSP8	139	7.45	120	20.07
FJSP9	167	11.37	167	28.72
FJSP10	154	11.7	139	30.64
Average	137.6	**5.724**	**130.8**	18.893

a lower bound validation. The lower bound model is the simple version of the FJSP with any stochastic parameter or maintenance consideration. Obviously, in such situation, both C_{max} and execution time of the algorithm present lower bound values for the developed stochastic problem. The simple problem does not encounter PM, CM, or breakdown. Moreover, it does not need inspection. Therefore, C_{max} values are only dependent on the main operations and are in the worst case equal to the stochastic version. In terms of execution time, low time is required for processing only some operations in comparison with the case in which different maintenance components are also inserted besides the operations.

In each table, for the main developed problem, because of the stochastic nature of the problems, each test problem is run several times and the average ($C_{maxMean}$), standard deviation of C_{max} (C_{maxSTD}) values, and average execution times (Time) are reported. In the simple model part of the tables, *Diff1* is difference value of C_{max} in stochastic model and simple lower bound model (i.e., $Diff1 = C_{max_{Mean}} - C_{max}$). Similarly, *Diff2* shows difference of time values of the models (i.e., $Diff2 = Time\ 1 - Time\ 2$).

In both Tables 4 and 5, the last columns represent the average values of the columns. Since C_{max}, standard deviation, and time objective functions are all to be minimized, the smallest values are the best ones.

Figure 15 compares the algorithms regarding three metrics of average C_{max} ($C_{maxMean}$), average time, and average standard deviation for the obtained simulated solutions. As it is clear, GA is better than BBO only in time metric. Figure 16 carries out the comparison of the obtained outputs from the

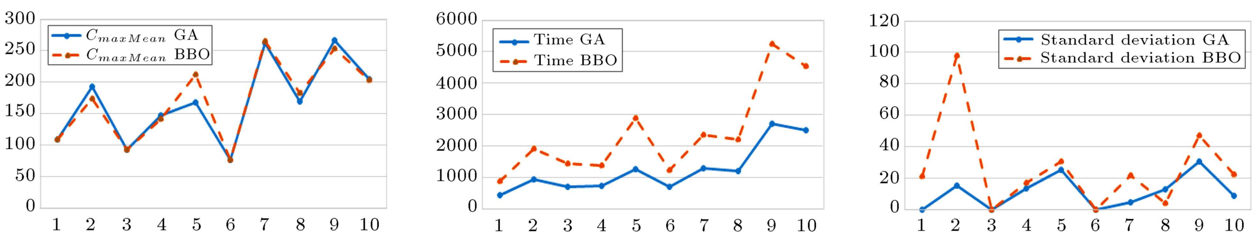


Figure 15. Comparison of algorithms for the stochastic problem with maintenance considerations.

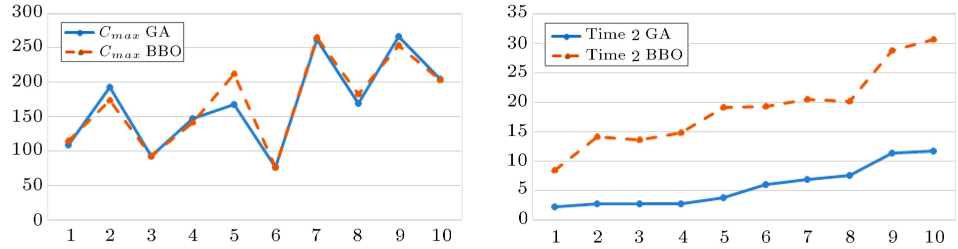


Figure 16. Comparison of algorithms for the simple problem without maintenance considerations.

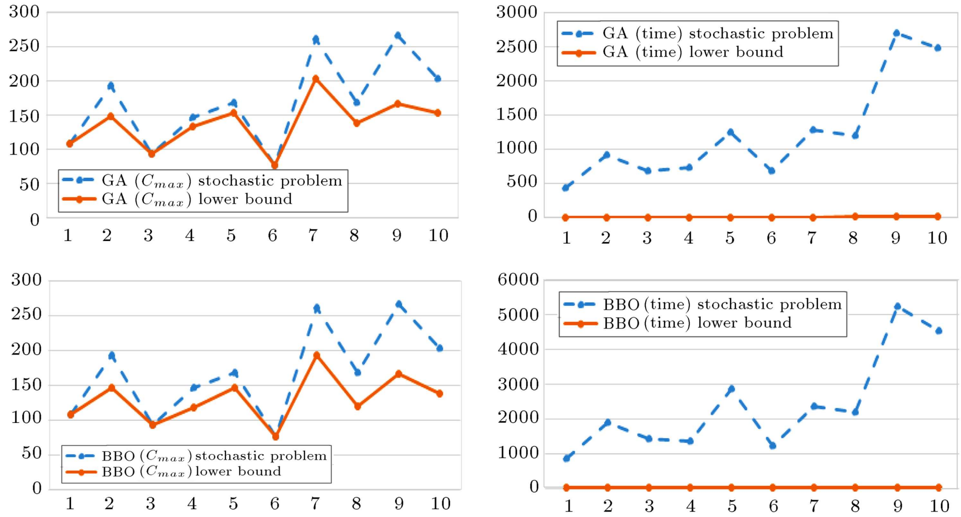


Figure 17. Comparison of algorithms regarding their obtained lower bounds.

algorithms for the deterministic version or the lower bound problem.

As can be seen in Figure 17, algorithms do not have difference on C_{max}. Besides, although they have the same trend in time, the vertical dimensions of the outputs of algorithms are different.

Tables 6 and 7 conduct the statistical tests for the simple and stochastic versions. In fact, they prove that the algorithms in terms of C_{max} are non-dominated and in terms of time, GA is superior.

Figures 18 compares the convergence plots of GA and BBO for the stochastic and simple problems regarding the mentioned metrics. Moreover, the real-time novel reliability monitoring illustration is presented in Figure 19 for problem FJSP9. GA is used for drawing these figures. This developed and innovative figure illustrates the developed reliability-centered maintenance approach in detail. In this figures, whenever a task is assigned to a machine, its reliability decreases during the task operation. Then, according to the mentioned logic behind the PM and CM, suitable maintenance reaction is taken.

Table 6. T-test for comparing GA and BBO regarding the metrics of Table 4.

Metric name	*P*-value	Description
C_{max} ($C_{max_{Mean}}$)	0.943	They are not considerably different
Time 1	0.044	GA outperforms BBO
Standard deviation ($C_{max_{STD}}$)	0.150	They are not considerably different

Table 7. T-test for comparing GA and BBO regarding the metrics of Table 5.

Metric name	*P*-value	Description
C_{max}	0.926	They are not considerably different
Time 2	0.000	GA outperforms BBO

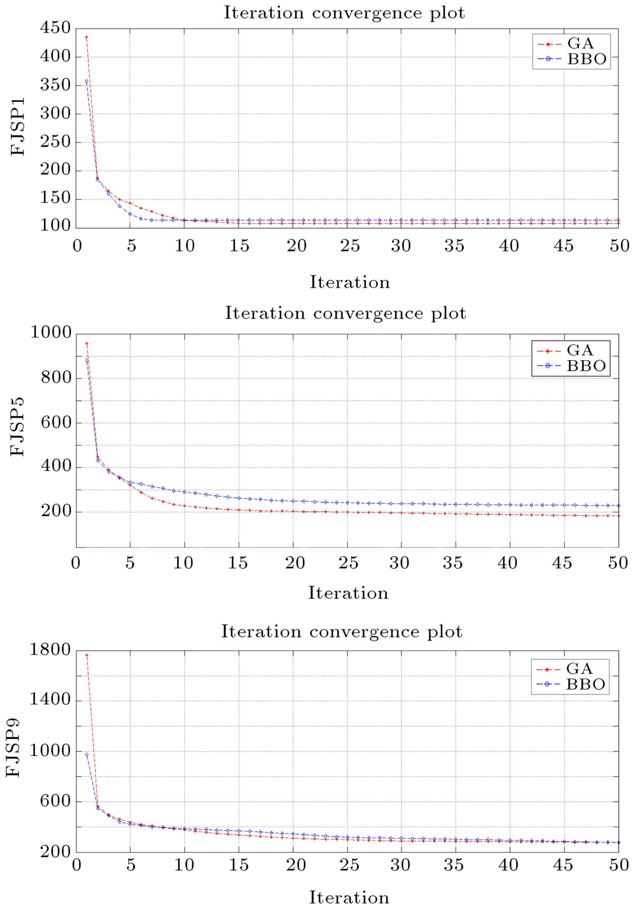


Figure 18. Comparison of convergence plots of GA and BBO for three problems.

4.3. Discussion

As mentioned in Figure 2, our RCM problem assumes two determining levels, i.e., L and LL. These levels are tuned to 0.81 and 0.11, respectively. According to this figure, 6 stochastic components are considered in the proposed RCM to make it realistic. These components and variables are also shown in Figure 20 for the main selected problem of FJSP9. In fact, this figure is same as Figure 19, but in reliability part, it only reports the outputs of Machine 2 for presentation simplicity.

Number 1 or RL and number 6 or TBM in Figure 20 depict a set of reliability degradations and set of shocks, respectively, due to activation of operation 1.1 on Machine 2. However, since the values of these variables are very small, the associated values are presented all together for a specific operation. RL is regulated according to the function in Figures 3 and 10. Shock times of TBM are generated according to Figure 14. Besides, the (3) values show the effect of PM ($RLPM$) on the reliability level of machine and they cause PM with duration denoted by number 2. The PM occurs when the degradation level goes less than the L level at the inspection times or before them. Inspection times are presented in Gant chart part of the figure. CM recovery levels ($RLCM$) and their durations are pointed by numbers 5 and 4, respectively. CM happens when the reliability level violates LL level. Activation of PM or CM and their durations are denoted by the maintenance decision function given in Figure 11. In the Gant chart part of the figure, machines and jobs

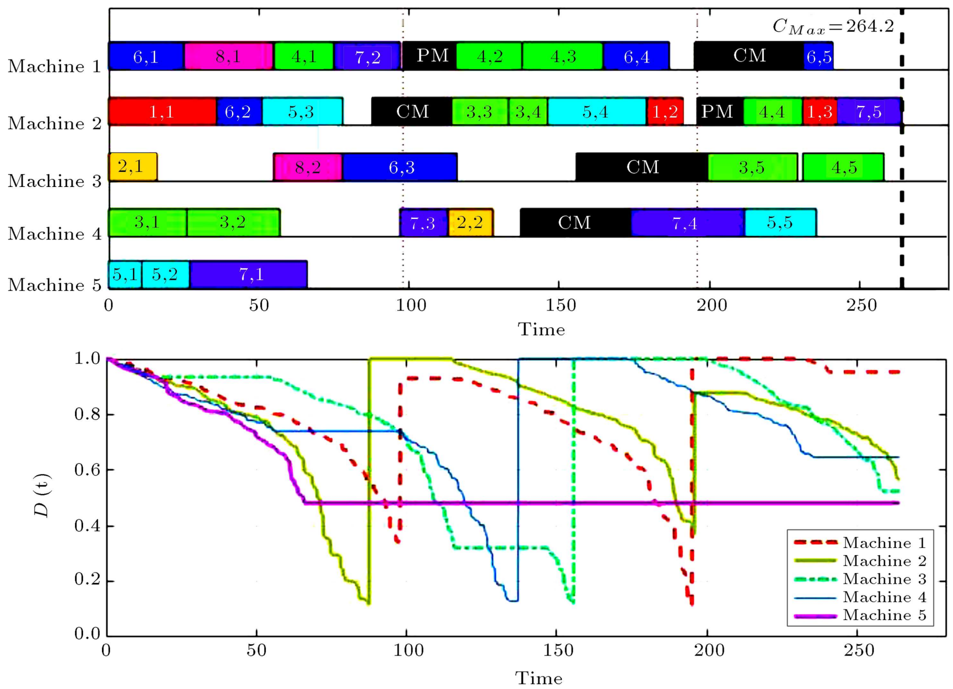


Figure 19. Real-time reliability level according to the Gant chart evolution for FJSP9.

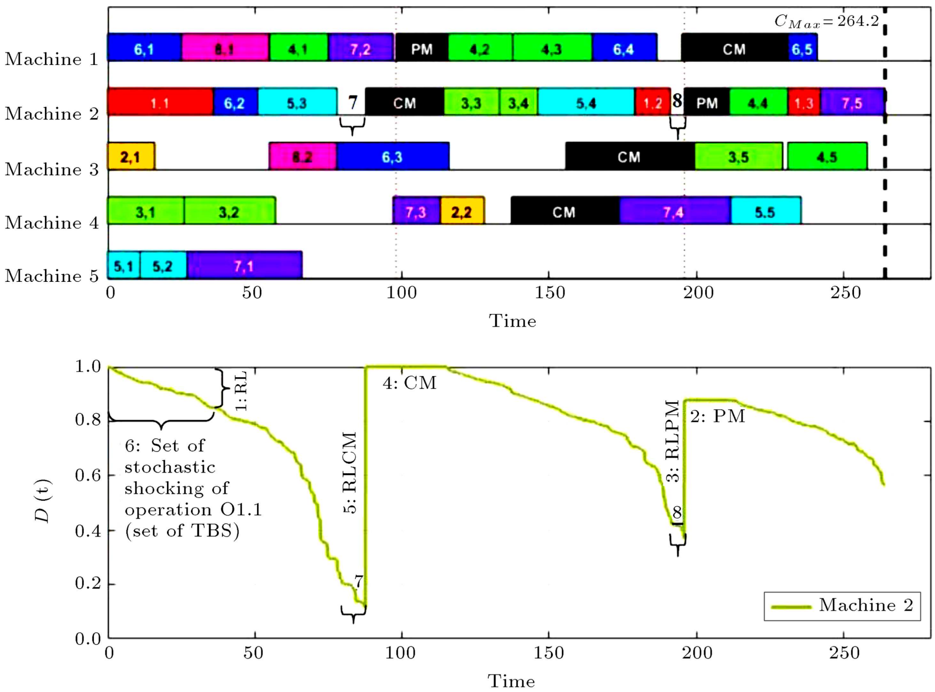


Figure 20. Description of the main results of the outputs for FJSP9.

are scheduled through Figures 12 and 13, respectively. Figure 9 manages the whole simulation task.

Numbers 7 and 8 in this figure show the wasted time according to the maintenance requirement recognized with the autonomous detection engine of the simulation algorithm. It means that during the periods shown by numbers 7 and 8, operations $O_{3,3}$ and $O_{4,4}$ have been started, respectively, since they were degraded in the reliability figure. However, since their reliability levels have become less than LL and L, respectively, they require CM and PM. Therefore, their main operations are interrupted and the maintenance operations are started. Certainly, since the jobs are not resumable in our problem, they are started from the beginning after their maintenance activities. To sum up, these figures prove that the designed algorithm can control the process autonomously.

5. Conclusion

This research focused on the maintenance consideration in production problems. A stochastic FJSP was developed by considering a modern maintenance system called RCM. This autonomous RCM monitored reliability level permanently and decided which maintenance activity should be done. Since the developed problem needed real-time checking of stochastic events, it was so complicated. Therefore, two SBO mechanisms, namely, GA and BBO, were developed to conduct the optimization problem. The required main and sub functions of the proposed algorithms were described in detail with sufficient examples. According to the results, the proposed RCM took benefit from its considered CBM concept properly. Moreover, it handled the considered assumptions and constraints during the optimization process completely. Moreover, different innovative and novel visualization techniques illustrated the proposed logics of the stochastic problem explicitly. Future work following this research may control the cost term of the maintenance within a multi-objective problem or develop other stochastic techniques, based on decomposition, to handle the same problem.

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