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Opportunistic maintenance management for a hybrid flow shop scheduling problem

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Abstract *– In this article, an approach to optimize opportunistic maintenance policies was presented to examine the use of opportunities created in preventive maintenance activities. After the operation, maintenance, and repair, a component never gets back to the status of a new one. Hence, assuming that the replacement case is not approached, a maintenance activity is referred to as an imperfect type. In this article, assuming the existence of the imperfect maintenance type, an opportunistic approach based on age threshold values of components is proposed. The maintenance activities in this research focus on the hybrid flow shop problem. Different threshold values are also introduced in this article for failure conditions for a machine. A harmony search algorithm is used to provide optimized values for this proposed approach. The simulation approach is used to calculate the average cost of maintenance. The cost analysis indicates that the proposed approach is better than the corrective policy widely in literature; otherwise, the proposed approach with about 25 percent saving is the best performance.*

Keywords*– Opportunistic maintenance, Imperfect maintenance actions, hybrid flow shop, Harmony search Algorithm, simulation.*

I. INTRODUCTION

In real-world cases, we rarely find a shop with a single machine at each stage. Generally, machines are duplicated in parallel at stages. The purpose is to balance the capacity of stages, improve the overall shop floor capacity, reduce, if not eliminate, the impact of bottleneck stages, and so forth Behnamian et al. (2011), and Naderi and Ruiz (2010). The shop with multi machines at its stages (or at least one stage with more than one machine) is called a hybrid flow shop (HFS). One can find the applications of HFS in food processing, ceramic tile manufacturing, the processing of wood, and the manufacture of furniture.

From the production scheduling point of view, most literature assumed that machines are always available during the planning time horizon. However, this assumption is unreasonable in real manufacturing systems because some unavailability periods, like maintenance activities, cause the machines not to be available for processing (Schmidt, 2000).

Production scheduling and preventive maintenance (PM) planning are two areas that have received tremendous attention from both the industry and the academic community. Similarly, most of the maintenance models ignore the

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production requirements. However, the maintenance effectiveness cannot be measured in a totally meaningful way without taking into account whether the maintenance function is meeting the production requirements (Mohammadi, 2010).

The impact of the costs of the maintenance operations on the reduction of the cost of production planning projects has attracted the attention of many governments, investors, and researchers so that for the successful development of this industry in the future, it needs to study maintenance operations strategies accurately. In fact, the purpose of the maintenance management system is to enhance accessibility and, at the same time, reduce the cost of maintenance. Current methods for the maintenance of the hybrid flow shop machines can be used in three categories: corrective maintenance, preventive maintenance, and condition-based maintenance (Najid et al., 2011). Now, corrective maintenance and preventive maintenance based on time are widely used in the literature review. However, there are few studies about optimizing preventive maintenance activities in the production planning industry. Since each stage consists of a number of machines, we can say that there is a kind of economic relationship in the machines of a stage. In fact, when a group of the repairman is sent to the shop floor, based on a series of predetermined decision conditions, the opportunity to do group maintenance activities is more economical (Xiao et al., 2016). In this approach, when a failure occurs in the shop, the maintenance activities are forwarded to the implementation of the corrective actions. In addition, the team has the opportunity to conduct preventive maintenance on the failed machines.

This article aims to minimize the total cost of corrective maintenance, preventive maintenance, and common costs associated with the entire system. The common assumption in most studies in the maintenance of the hybrid flow shop problem is that maintenance activities are generally considered interchangeable. It is assumed that machines will reach maintenance activities in their best situation. But in practice, the maintenance activities are not always conducive to returning machines to their best. Researchers at the source about this issue (imperfect maintenance activities) for a flow shop machine have developed an opportunistic approach (Aghezzaf et al., 2016). Researchers have attempted to study the introduction of a threshold of life for all machines under the management of their perfect and imperfect maintenance activities. Most studies in this field have been developed based on corrective maintenance. This means that researchers consider their economic dependence on corrective maintenance to reduce the cost of maintenance. Feng et al. (2018) make an imperfect PM policy for hybrid flow shop manufacturing cells working under group-varying machining conditions considering sequence-dependent group scheduling that minimizes PM cost, minimal repair cost, and job tardiness cost. Simulated annealing embedded genetic algorithm is considered to solve the problem. Bakhtiary et al. (2021) presented an opportunistic maintenance threshold policy is implemented for tamping scheduling on a ballasted railway track over a 3-year planning horizon. Results show that machine preparation costs will be reduced by approximately 46%. Also, the track quality of the studied track section is increased by up to 12.2%.

In Aghezzaf and Najid (2008), the problem was investigated with several production lines, each production line producing one product. Two types of maintenance were considered preventive and corrective. Preventive maintenance is done periodically and occurs in a state of perfect repair. The corrective maintenance is minimal repair, and the job returns to its pre-damaged condition. Each line has a specific capacity to produce products. Doing the maintenance reduces the production capacity. In this study, the Lagrange method was used. Nourelfath and Châtelet (2012) examined the problem of similar planning for a production system consisting of a set of parallel machines in which the economic dependence of machines and failures of common cause were considered.

Xiao et al. (2016) considered the problem of group maintenance of the flow-shop system and production schedule. The objective is to minimize total costs, including production costs, preventive maintenance, minimum repairs for accidental breakdowns, and delays. In this article, any machine failure will result in the stop of the entire production line. The proposed maintenance strategy is performed simultaneously on all machines, which is a perfect repair. The two results obtained from this study include determining the optimal group threshold of preventive maintenance for machines and assigning each job. One of the assumptions of this problem is to perform a minimal repair in case of failure in the non-preventive group interval, in which the machine with this type of repair will reach the state before failure.

This article attempts to consider the economic dependence opportunistic preventive maintenance approach for production machines in a flow shop arrangement. So that, at the same time, the advantage of opportunistic maintenance method and imperfect maintenance analysis method is considered on maintenance activities. Opportunistic maintenance policies are considered based on reliability limits values of life threshold of machines so that imperfect maintenance assumption for preventive maintenance activities is satisfied with threshold limits values related to each disabled or healthy machine. A simulation approach is considered to evaluate the costs of the proposed policy maintenance.

Our motivation for doing this research is applying new maintenance strategies in a hybrid flow shop environment is important and commonly encountered in real-world situations. Examples of such applications of this problem can be found in the automotive industry, the furniture industry, and house stuff manufacturing. The main contribution of our work is the development of opportunistic maintenance policies based on reliability limits values of life threshold of machines so that imperfect maintenance assumption for preventive maintenance activities is satisfied with threshold limits values. And the presentation of a new methodology by a hybrid of harmony search algorithm and simulation approach for solving the proposed model. The structure of this article is organized as follows. In the next part of the article, the general model of the flow shop scheduling problem is presented opportunistically. The third section deals with the simulation model and the optimization of the maintenance activities. The fourth part of the article is dedicated to evaluating and analyzing the proposed maintenance strategy. Finally, the last section of this article is devoted to the article's conclusion.

Table I. A summary of literature review

Authors	***environment***	***objective***	***Solution***	***Constraint***	***Maintenance***	***repair type***	***maintenance strategy***
Aghezzaf et al. (2007)	Single	total cost	Solver Cplex	capacity	PM+CM	-	minimal repair+ replacement
Aghezzaf et al. (2008)	parallel	Cost	LR	capacity	PM+CM	-	cyclic pm
Najid et al. (2011)	Single	total cost	Solver xperss	capacity	PM+CM	-	time window
Fitouhi et al. (2012)	Single	Cost	ensormous	capacity	PM+CM	-	cyclic pm and non-cyclic pm
Nourelfath and Châtelet (2012)	Single	Cost	ensormous	capacity	PM+CM	-	t-age group pm+cm
Fitouhi et al. (2014)	Flow-shop	Cost	software, SA	-	PM+CM	-	noncyclic pm replacement
Yalaoui et al. (2014)	Single	Cost	fix and relax heuristic-relaxation	capacity	PM+CM	-	cyclic pm and non-cyclic pm
Jamali et al. (2015)	Flow-shop	Cost	Cplex	-	PM+CM	-	non-cyclic pm+ minimal repair
Gan et al. (2015)	Flow-shop	total cost	GA	-	PM+CM	replacement	minimal repair
Xiao et al. (2016)	Flow-shop	total cost	RKGA	-	PM	perfect	Opportunistic maintenance threshold
Purohit et al. (2016)	Single	total cost	GA+SIM	SDST+ production limit	PM+CM	new+ continue	-
Junfang et al. (2016)	Flow-shop	tardines+ maintenance cost	GA+lowerbound	-	PM	-	flexible+diverse

Continue Table I. A summary of literature review

Authors	***environment***	***objective***	***Solution***	***Constraint***	***Maintenance***	***repair type***	***maintenance strategy***
Aghezzaf et al. (2016)	Flow-shop	Cost	MIP-heuristic	-	PM	imperfect	non-cyclic
Feng et al. (2018)	Hybrid flow-shop	tardines+ maintenance cost	SA+GA	sequence-dependent group scheduling	PM	imperfect PM	Minimal repair
Bakhtiary et al. (2020)	-	Maintenance cost	GA	-	PM	-	opportunistic maintenance threshold
This research	Hybrid flow-shop	Cost+availibity	SIM+harmony searh algorithm	availability+ SDST	PM+CM	replacement+ imperfect	Opportunistic maintenance threshold

II. THE INTRODUCTION OF AN OPPORTUNISTIC MODEL ON HYBRID FLOW SHOP MACHINES

Opportunistic maintenance is a systematic method of collecting, investigating, preplanning, and publishing a set of proposed maintenance tasks and acting on them when there is an unscheduled failure or repair “opportunity” (Ding and Tian, 2012). In this strategy, preventive maintenance activities are combined with corrective ones when certain technical and economic conditions are satisfied. An opportunity-based maintenance strategy involves several nonlinear variables that affect the cost of maintenance that should be optimized to result in a cost-effective decision on maintenance actions.

Suppose that there are M stages in a production environment so that each stage has K machines. This article examines the maintenance strategies in a parallel-series system. In addition, it is assumed that the failure of any machine doesn’t impact other machines. In this article, maintenance activities are divided into two categories: perfect and imperfect activity. Perfect maintenance activities are preventive maintenance activities that return the machine to its best possible condition by doing repairs. On the other hand, imperfect maintenance activities transfer the machine to a position between perfect failure and the best possible situation. In this article, the same article Aghezzaf et al. (2016), the age or the age of the machine is the machine that reflects the state or quality of performance. Thus, in association with imperfect maintenance activity, a Life ratio (percent) q is defined. The life of a machine of imperfect maintenance operations is reduced to about q ($0 \leq q \leq 1$). For example, if the technical and economic reasons for imperfect repair are q=0/6 on the transmission of a machine, and it’s done on one of the machines of the stage with eight years old, then the new life of the machine after the imperfect repair is 8(1-0.6) =3.2 Years. It can be concluded that the maintenance and collection deal with a machine of 3.2 years. In other words, if maintenance operations with q=1 are done on each machine (perfect maintenance), it means that machines have been replaced because they work part-time (age =0). It is against a new machine. In addition, the operating cost function related to imperfect maintenance with the value of q is defined as follows:

‘

$$C_P = \begin{cases} q^2 \times CPV + CPF & 0 < q \leq 1 \\ 0 & q = 0 \end{cases} \tag{1}$$

‘

Where CPV is the variable cost of preventive maintenance and CPF is maintenance fixed cost. For example, the total cost of replacing the declining age of 100 percent ($q = 1$) is equal to $CPF + CPV$. Thus, if the life percentage of a machine is reduced more, more cost is paid.

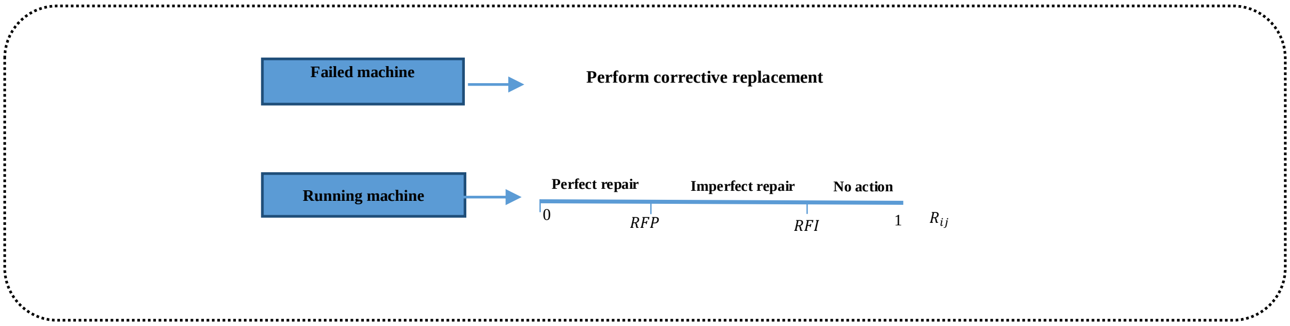

Fig. 1. Overview of maintenance operations

In addition, in the event of failure of one machine, CF (Corrective maintenance cost) is paid to replace the corrective machine. Dispatch costs can be a fixed cost of preparing and deploying the group to the shop floor (C_{fix}).

According to the concepts presented above, it is necessary to define the life threshold limits of each machine at each stage for maintenance operations. In this article, the threshold limits for the life of a machine are defined as a percentage of the average failure time so that if it is more than the life, a series of maintenance operations must be done on it. Source threshold of life to provide three opportunistic maintenance strategies is used. Regardless of the stage, this threshold is presented, and the issue is whether the machine in a stage is healthy or not. While, certainly, these two issues have an important role in the quality of the proposed strategies. Hence, in this article, two percent thresholds RFP, RFI to running machine type k ($\mathrm{k} = 1, \cdots, \mathrm{K}$) are considered.

PM_k is the percentage threshold of dispatch preventive maintenance group machine k. Overall, in this article, it is assumed that the maintenance group is sent when a machine caused the failure or life segment machine k ($k = 1, \cdots, K$) passed the threshold $PM_k \times MTTF_k$. After deployment, maintenance groups to the floor shop (preventive or corrective), if any, the failed machine must be replaced with the new machine. Then, the imperfect maintenance operations are done when the life of the machine is more than $RFP_k \times MTTF_k$. That $MTTF_k$ is the meantime to failure machine k. After imperfect maintenance, the life of the machine is reduced to size q_k ($k = 1, \cdots, K$). There is always a machine with the following relations.

$$PM_k < RFP_k \qquad k = 1, \cdots, K \tag{2}$$

$$RFP_k < RFI_k \qquad k = 1, \cdots, K \tag{3}$$

Overall, Figure (1) shows the maintenance of the group's activities by the machine. Based on the presented, the model will be as follows:

$$\min C_E(RFP, RFI, PM, q) \tag{4}$$

$s.t.$

$$PM_k < RFP_k \qquad k = 1, \cdots, K$$

$$RFP_k < RFI_k \qquad k = 1, \cdots, K$$

C_E is the total expected maintenance cost of a machine per unit of time. PM, RFP, RFI and q to denote the vector of design variables associated with the machines are as follows. Determining the optimal amount is about in a way that minimizes the maintenance expected total cost.

III. THE SIMULATION MODEL AND OPTIMIZATION MAINTENANCE

A. Simulation Approach

One of the main advantages of simulation is the ability to control the speed of passing a test. The General manager uses different methods to simulate the flow of time, including discrete events and the next event. One of the simplest ways to control the timing, method, and time slice is included in the assessment and update of the model at regular intervals (Pidd, 1984). The challenge of this approach is to determine the value of the interval. The maximum time this approach is reviewed and updated is when a status change or a hazard is created. Transition management from time to time by the movement of one event to the next event and the next event is called technique. This approach is very good when its performance is better than the discrete method. In this article, the simulation approach is used to calculate the average cost of maintenance (Dinwoodie et al., 2015). As explained in the previous section, based on system characteristics described, generally following two events will be a change in the status of a stage:

- There was a failure of a machine
- occurring preventive maintenance

Table II. simulation Table of opportunistic maintenance strategy

Stage	*Machine*	*age*	*failure of age (FA)*	*Total times of fail (TA)*
1	1	0	300	300
	2	0	270	270
	⋮	⋮	⋮	⋮
	K	0	450	450
⋮	⋮	⋮	⋮	⋮
M	1	0	305	305
	2	0	268	268
	⋮	⋮	⋮	⋮
	K	0	420	420
clock simulation ($Clock_i$) = 0			total cost Expected (C_T)= 0	

Each of these events is created several times during the simulation in the system. In the next event technique, at the time of each event, the model is analyzed and updated by considered maintenance policy. Therefore, the status of each machine of each stage is stored separately and continuously. Table II shows the designed simulation to supply the required information. The first and second columns indicate the number of stages and machines number. Besides, in every K row of the table, the information of each stage is represented. Change time simulation (Clock_i) in the last row of the table is to show the duration of the simulation of the system to the i-th iteration ($i = 1,2,\dots,I$). Thus, based on the simulation time in Table I, this table shows the start of the simulation. As mentioned in the second part, the machine's life means operation times and is considered an indicator of the machine's performance. At the start of a simulation, the life of all machines is zero ($age_m = 0$).

The third column shows the life of a machine failure. Life is the time in which failure occurs to fail a machine for a given stage. At the start of each simulation, by sampling the distribution failure, failure is predicted lifetime. For example, machine 1 of stage M in Table II will be disabled after three hundred and five days. The fifth column represents the total downtime of a machine. In addition, in order to calculate the total expected cost of each machine per unit of time, all costs that are generated during the simulation run are kept in memory. C_T Represents the total cost of maintenance during simulation ($Clock_i$) and certainly, at the start of a simulation, its value will be zero.

Table III. maintenance opportunistic strategy simulation table

Stage	*Machine*	*Age*	*failure of age (FA)*	*Total times of fail (TA)*
1	1	268	300	300
	2	268	270	270
	⋮	⋮	⋮	⋮
	K	268	450	450
⋮	⋮	⋮	⋮	⋮
M	1	268	305	305
	2	268	268	268
	⋮	⋮	⋮	⋮
	K	268	420	420
clock simulation ($Clock_i$) = 268			total cost Expected (C_T) = 0	

Records associated with each of the constituent parts of the shop floor (various lines by simulation) constitute the core of the simulation approach. The simulation engine manages maintenance policy on the machines and stages via the control of information stored in the records. Simulated engine for three-phase information is controlled as follows:

Phase A: in i-th iteration simulation, simulation time and life-to-date components are as follows:

$$Clock_i = \min\left(TA_{k,m}, \left(Clock_{i-1} + PM_k \times MTTF_k - age_{k,m}\right)\right) \tag{5}$$

$$age_{k,m} = age_{k,m} + Clock_i - Clock_{i-1} \tag{6}$$

Equation (5) specifies which of two machine failure events occur or the next event will happen as preventive maintenance. In this equation, $Clock_{i-1} + PM_k \times MTTF_k - age_{k,m}$ represents the threshold limit of preventive maintenance for machine k of stage m .This equation (6) is the time of dispatch maintenance in the repeated group i-th garnering. For example, suppose that the next event by (1) is the failure event of the second machine at stage m. Thus, the simulation time to transfer time is 268, and Table II shows that the changes are made.

Phase B: after the deployment of Group maintenance, a series of maintenance activities should be based on the maintenance strategy. maintenance activities can be divided into three categories based on the nature of the operation:

- ***Swap reform***

Replacement parts are replaced on disabled machines. Thus, the life of the part in the simulation will be zero. Also, the failure-to-day life is determined by sampling the failure distribution function. The value of parameter Ta in the fifth column of Table III is obtained according to equation (8).

$$FA_{k,m} = TL_{k,m} \tag{7}$$

$$TA_{k,m} = Clock_i + TL_{k,m} \tag{8}$$

In the above equation, $TL_{k,m}$, is the life failure generated from the component failure distribution. For example, to simulate corrective replacement of machine M in stage 2, a random number is generated from the failure distribution function ($TL_{2,M} = 292$). The life of this machine is zero, and the machine is set to modify the simulation in table IV.

Table IV. maintenance opportunistic strategy simulation table

Stage	***Machine***	***age***	***failure of age (FA)***	***Total times of fail (TA)***
1	1	0	310	578
	2	268	270	270
	⋮	⋮	⋮	⋮
	K	160.8	442	549.2
⋮	⋮	⋮	⋮	⋮
M	1	0	295	563
	2	0	292	560
	⋮	⋮	⋮	⋮
	K	160.8	418	525.2
clock simulation ($Clock_i$) = 268			total cost Expected (C_T) = 0	

- ***Perfect Preventive maintenance***

In the shutdown machines, if the life of the machine of a perfect overhaul threshold is higher ($age_{k,m} \geq MTTF_k \times PFH_k$), the switch will be preemptive. a new breakdown TL_k is generated, and life segments will be returned to zero. Also, failure life is obtained by $FA_k = TL_k$. According to equation (9), the total time of the failure life will be updated. If each machine in each stage satisfies the relation $age_k \geq MTTF_k \times PMH_k$, then the machine will be healthy. For example, according to Table IV, in stages 1 and M, if the threshold limit of each machine is 300, the change of at least one of the machines is necessary.

- ***Imperfect Preventive maintenance***

For each disabled machine, if their life is more than the threshold limit of imperfect repairs ($MTTF_k \times PFH_k \geq age_k \geq MTTF_k \times PFL_k$), maintenance operations will be imperfect. As mentioned in the second part, a percentage or proportion of life Q is defined for imperfect repairs. In fact, after carrying out the imperfect repair, the life of a machine adds up to $age_k \times (1 - q_k)$. Thus, in the simulation, the life of a machine follows this relation:

$$age_k = age_k \times (1 - q_k) \tag{9}$$

After performing maintenance, it's possible to change the time of machine failure. In fact, at q_k% of the maintenance time, the life of a machine failure changes (the new failure $TL_{k,m}$ occurs using failure distribution). On the other hand, it is possible that a failure repair does not have any effect on life. Thus, life and total destruction in the fourth and fifth columns of the table is updated as follows:

$$FA_k = q_k \times TL_k + (1 - q_k) \times FA_k \tag{10}$$

$$TA_k = Clock_i + FA_k - age_k \tag{11}$$

The process of updating the information stored in the simulation for the imperfect repairs of each machine will be the same as the previous notes except that the relation $MTTF_k \times PMH_k \geq age_k \geq MTTF_k \times PML_k$ must be satisfied.

For example, suppose that the lifetime of machine type k is 268 days with a percent $q_K = 0.4$. If two randomly generated numbers 430 and 415 are the failure age of machines one and M, related records in Table IV show that the update has been made.

Phase C: the total cost of the maintenance activities carried out for the following day.

$$C_T = C_T + \sum_{k=1}^{K} (CP_k \times IP_k + Cf_k \times IC_k) + C_{Access} \times IA \quad + C_{fix} \tag{12}$$

Where $IP_k = 1$, if it is a preventive maintenance activity on a machine of K and otherwise, it is zero. It should be noted that CP_k for various values of q is variable. $IC_k = 1$, if the machine is disabled and corrective replacement is needed.

Three phases A, B, and C to end up repeating the simulation are done in tandem. When the maximum number of simulation steps is taken ($i = I$). The total expected cost per machine per unit of time is calculated as follows:

$$C_E = \frac{C_T}{M * Clock_I} \tag{13}$$

B. harmony search algorithm

Based on the different values that can only be introduced in the threshold limits, different strategies of maintenance are created. For example, when $q_k = 1$, imperfect maintenance activities will not take place on machine k. When $RFI_k = RFP_k$ and $0 \leq q_k < 1$ are satisfied for all machines, imperfect maintenance operations are done. When the preparation cost and little access of infinite amounts of threshold limits $RFP, RFI, PM,$ maintenance are considered, maintenance cannot be opportunistic. According to the proposed approach, the solution of the problem, even for the average number of sub-systems, may be very large. Thus, a convenient and efficient optimization method to obtain the optimal threshold is required. In the literature on meta-heuristic algorithms (such as genetic algorithm and ant colony algorithm), the answer sheet is used to deal with very large optimization problems. In this article, the harmony search algorithm is used to solve the problem defined above. The harmony search algorithm was first developed by Gem et al. (Geem et al., 2001). This algorithm has been created on the model of musician orchestra behavior. In this method, a musician is considered as part of a vector solution, and the value is determined by three lows.

Harmony search (HS) algorithm was recently developed in an analogy with the music improvisation process where music players improvise the pitches of their instruments to obtain better harmony. The steps in the procedure of harmony search are shown in Figure 2.

- Step 1. Initialize the problem and algorithm parameters.
- Step 2. Initialize the harmony memory.
- Step 3. Improvise a new harmony.
- Step 4. Update the harmony memory.
- Step 5. Check the stopping criterion.

A New Harmony vector $X_i = [RFP_1, \dots, RFP_k, RFI_1, \dots, RFI_k, PM_1, \dots, PM_k,]$ is generated based on three rules: (1) memory consideration, (2) pitch adjustment, and (3) random selection. Generating a new harmony is called 'improvisation'.

Improvise a new solution $[x_1^/, x_2^/, x_3^/ \dots, x_n^/]$ from the *HM*. Each component of this solution, $x_j^/$Is obtained based on the *HMCR*. The *HMCR* is defined as the probability of selecting a component from the members of the present *HM*, and 1-*HMCR* is, therefore, the probability of generating it randomly. If $x_j^/$comes from the *HM*, it is chosen from the j-th dimension of an *HM* random member, and it can be further mutated according to the *PAR*. The *PAR* determines the probability of a candidate from the HM to be mutated. Obviously, the improvisation of $[x_1^/, x_2^/, x_3^/ \dots, x_n^/]$ is rather similar to the production of the offspring in the genetic algorithm (GA) with the mutation and crossover operations (Mohammadi et al., 2011). However, the GA creates fresh chromosomes using only one (mutation) or two (simple crossover) existing ones, while the generation of new solutions in the HS method makes full use of all the *HM* members.

The answer is a candidate for optimizing maintenance strategies developed, including a combination of thresholds for the life of machines which are shown below.

$$X_i = [RFP_1, \dots, RFP_k, RFI_1, \dots, RFI_k, PM_1, \dots, PM_k,] \tag{14}$$

every element of a vector solution i-th in t-th step of the algorithm related to one of the thresholds defined in opportunistic maintenance strategy is presented. Problem-solving includes searching for a solution vector of optimal threshold limits with the lowest maintenance cost per machine per unit of time. The harmony search structure is displayed in Figure 2.

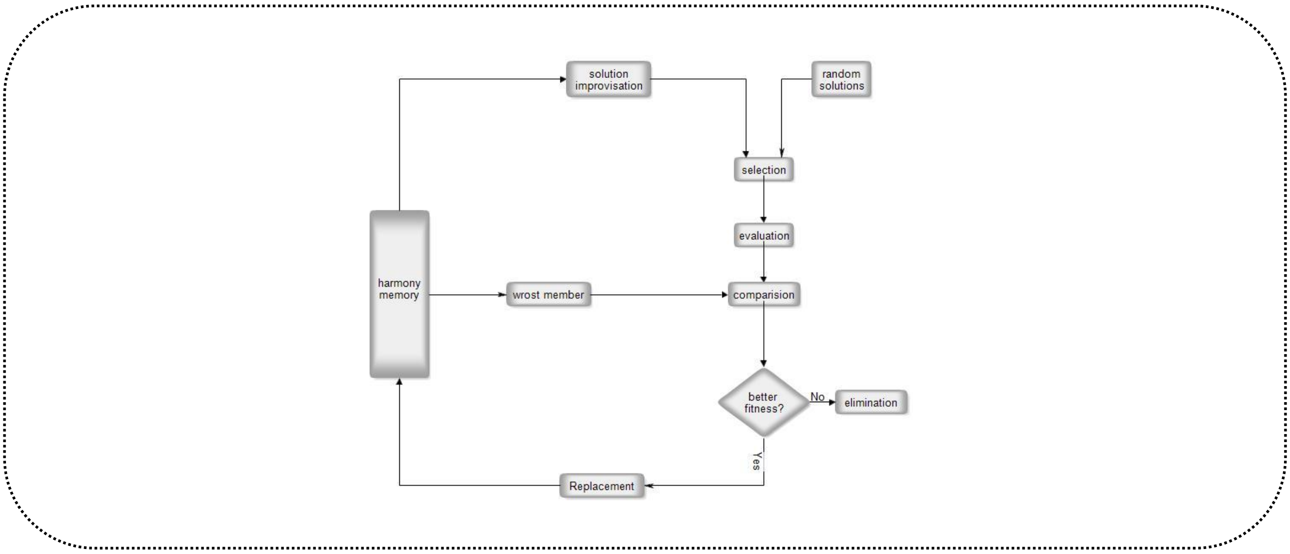

Fig. 2. Harmony search algorithm flowchart (Rastgar and Sahraeian, 2017)

As shown in figure 2, the algorithm starts with the initial population of solution vectors. Then, the memory is updated by three rules until the termination condition is satisfied. For example, the element associated with the value of q that is outside the range $[0,1]$-will be unforgettable. So, elements that are outside the allowed scope must be modified as follows:

```
for (j=1 to n) do
    if ($r_1$< HMCR) then
      $X_{new(j)} = X_{a(j)}$ where a ∈ (1,2,…,HMS)
      if ($r_2$< PAR) then
        $X_{new(j)} = X_{new(j)} \pm r_3 \times BW$ where $r_1,r_2,r_3 \in (0,1)$
      end if
    else
      $X_{new(j)} = LB_j + r \times (UB_j - LB_j)$, where r ∈ 0,1)
    end if
end for
```

In the last step, the fitness value (the value that calculates maintenance cost per machine per unit of time) is calculated based on the number of stops and then examined. The time-stopping condition could be the number of repetitions.

IV. EVALUATION AND ANALYSIS OF MAINTENANCE STRATEGY

To evaluate and analyze the performance of the maintenance strategy presented, an example of a shop floor environment is given. A shop floor consists of two stages and each stage consists of four machines. It is assumed that the distribution of downtime for each of the machines is Weibull distribution. Failure distribution parameters of each of the four machines are shown in Table V.

Table V. Breakdown time distribution parameters Components

Machine	*Parameter scale α (Day)*	*Parameter shape β (Day)*
a	3000	3
b	3750	2
c	2400	3
d	3300	2

The second and third columns of this table represent the Weibull distribution parameters of scale (x) and shape (y) for each of the machines. All costs, including corrective replacement cost, fixed and variable preventive maintenance costs, and the costs of deployment and access groups in Table VI are estimated.

The total cost of maintenance of a specific strategy can be calculated using the simulation. This algorithm has been implemented in MATLAB software. The results show that the group of maintenance will not be applied when the machine's average life is greater than the average time between two events. Repair is generally done on an old machine, while there is a tendency for imperfect repair work done on the newer machine. In general, there are three types of thresholds; two types of thresholds for healthy machines and one type for disabled machines. The optimal policy is shown in Table VII. The average maintenance cost per machine per day to 186 units is obtained.

Table VI. costs of machines

Machine	(CF_k)	(CPV_k)	(CPF)	(C_{fix})	(C_{Access})
a	112	28	15	50	7
b	60	15			
c	152	38			
d	100	25			

The costs considered are based on 1/000 currency.

Table VII. optimal policy opportunistic

Machine	*q*	*RFP*	*RFI*
a	0.46	3.5	2.7
b	0.4	1.2	0.92
c	0.59	1.1	0.98
d	0.51	1.8	1.2

In this article, at the same time, economic dependence and imperfect maintenance activities are considered. Hence, the importance of taking into account the economic dependence and maintenance activities should be considered imperfect. If the economic interdependence between the machines is not considered (corrective maintenance policy), the total cost of the system for a machine will be 246 currencies. To investigate the effect of imperfect maintenance operations, opportunistic maintenance policy based on the source (Aghezzaf et al., 2016) is defined as follows:

maintenance opportunistic policy about perfect activity: Took the opportunity to deployment group maintenance that the preventive replacement operations for machines $k\ (k = 1, \cdots, K)$ of the stage $m\ (m = 1, \cdots, M)$ are done if $age_{k,m} \geq MTTF_k \times P$, ($P = P_1$ for disabled machines and $P = P_2$ for healthy machines).

maintenance opportunistic policy only imperfect with regard to the activities: At the time of group maintenance that these opportunity preventive maintenance operations for the machines $k\ (k = 1, \cdots, K)$ of the stages $m\ (m = 1, \cdots, M)$ are done if $age_{k,m} \geq MTTF_k \times P$, ($P = P_1$ for disabled machines and $P = P_2$ for healthy machines).

Table VIII shows the optimal cost per machine per day. Optimization results indicate that the maintenance cost for a machine with a day for two opportunistic maintenance politics, by taking action against 210 and 192 perfect and imperfect educations is currency. Thus, significant cost savings in using three opportunistic maintenance strategies compared with corrective maintenance policy are 63/14, 9/21, and 3/24 percent, respectively. In the meantime, the proposed approach with about 25 percent saving is the best performance.

Table VIII. Comparison of cost strategies explained

Corrective maintenance		***monetary units per day***	
	strategy 1	strategy 2	The proposed approach
Minimum cost	210	192	186
Cost savings	/%14.63	%21.9	%24.3

V. CONCLUSION

Production and maintenance planning are two areas that have received tremendous attention from both industry and the academic community. Most of the production models assume that machines are available all the time. However, in real situations, machines do fail or need to be maintained and hence may become unavailable during certain periods. In this article, an optimization approach has been introduced to maintenance policies to take advantage of opportunities created by opportunistic preventive maintenance. The approach proposed in this article was solved using simulation and analysis of harmony search algorithm. Numerical examples presented in the article show that the opportunistic maintenance policy can reduce the cost of maintenance of machines to be acceptable. Extension of the novel metaheuristic algorithms and the model in other production environments may be taken into consideration by researchers interested in this field.

REFERENCES

Aghezzaf, E.-H., Khatab, A. and Le Tam, P., "Optimizing production and imperfect preventive maintenance planning′ s integration in failure-prone manufacturing systems", *Reliability Engineering & System Safety*, Vol. 145, No., (2016), 190-198.

Aghezzaf, E.-H. and Najid, N.M., "Integrated production planning and preventive maintenance in deteriorating production systems", *Information Sciences*, Vol. 178, No. 17, (2008), 3382-3392.

Bakhtiary, A., Zakeri, J.A. and Mohammadzadeh, S., "An opportunistic preventive maintenance policy for tamping scheduling of railway tracks", *International Journal of Rail Transportation*, Vol. 9, No. 1, (2021), 1-22.

Behnamian, J., Zandieh, M. and Ghomi, S.F., "Bi-objective parallel machines scheduling with sequence-dependent setup times using hybrid metaheuristics and weighted min–max technique", *Soft Computing*, Vol. 15, No. 7, (2011), 1313-1331.

Ding, F. and Tian, Z., "Opportunistic maintenance for wind farms considering multi-level imperfect maintenance thresholds", *Renewable Energy*, Vol. 45, No., (2012), 175-182.

Dinwoodie, I., Endrerud, O.-E.V., Hofmann, M., Martin, R. and Sperstad, I.B., "Reference cases for verification of operation and maintenance simulation models for offshore wind farms", *Wind Engineering*, Vol. 39, No. 1, (2015), 1-14.

Feng, H., Xi, L., Xiao, L., Xia, T. and Pan, E., "Imperfect preventive maintenance optimization for flexible flowshop manufacturing cells considering sequence-dependent group scheduling", *Reliability Engineering & System Safety*, Vol. 176, No., (2018), 218-229.

Geem, Z.W., Kim, J.H. and Loganathan, G.V., "A new heuristic optimization algorithm: Harmony search", *simulation*, Vol. 76, No. 2, (2001), 60-68.

Mohammadi, M., "Integrating lotsizing, loading, and scheduling decisions in flexible flow shops", *The International Journal of Advanced Manufacturing Technology*, Vol. 50, No. 9-12, (2010), 1165-1174.

Mohammadi, M., Ghomi, S.F. and Jafari, N., "A genetic algorithm for simultaneous lotsizing and sequencing of the permutation flow shops with sequence-dependent setups", *International Journal of Computer Integrated Manufacturing*, Vol. 24, No. 1, (2011), 87-93.

Naderi, B. and Ruiz, R., "The distributed permutation flowshop scheduling problem", *Computers & Operations Research*, Vol. 37, No. 4, (2010), 754-768.

Najid, N.M., Alaoui-Selsouli, M. and Mohafid, A., "An integrated production and maintenance planning model with time windows and shortage cost", *International Journal of Production Research*, Vol. 49, No. 8, (2011), 2265-2283.

Nourelfath, M. and Châtelet, E., "Integrating production, inventory and maintenance planning for a parallel system with dependent components", *Reliability Engineering & System Safety*, Vol. 101, No., (2012), 59-66Schmidt, G., "Scheduling with limited machine availability", *European journal of operational research*, Vol. 121, No. 1, (2000), 1-15.

Pidd, M., "Computer simulation in management science–john wiley & sons", *Inc. New York, NY, USA ISBN 0-471-97931*, Vol., No., (1984).

Rastgar, I. and Sahraeian, R., "New formulation and solution in pcb assembly systems with parallel batch processors", *Journal of Quality Engineering and Production Optimization*, Vol. 2, No. 1, (2017), 27-46.

Xiao, L., Song, S., Chen, X. and Coit, D.W., "Joint optimization of production scheduling and machine group preventive maintenance", *Reliability Engineering & System Safety*, Vol. 146, No., (2016), 68-78.