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AN INTEGRATED MODEL OF PRODUCTION SCHEDULING AND MAINTENANCE PLANNING UNDER IMPERFECT PREVENTIVE MAINTENANCE

MODEL ZINTEGROWANY HARMONOGRAMOWANIA PRODUKCJI I PLANOWANIA OBSŁUGI TECHNICZNEJ W RAMACH NIEPEŁNEJ KONSERWACJI ZAPOBIEGAWCZEJ

For a successful company, machines are always required to work continuously to make more profit in a certain period. However, machines can be unavailable due to the scheduled maintenance activities or unexpected failures. Hence, a model connected production scheduling with maintenance planning for a production line which is composed of multiple machines is developed. Suppose preventive maintenance is imperfect and cannot renew all the machines. Age reduction factor and hazard rate increase factor are introduced to illustrate the imperfect character. Aperiodic preventive maintenance policy is adopted. Replacement as perfect maintenance could restore the machine "as good as new". When and whether to perform replacement is based on a cost-time rate function which is defined to judge whether or not the preventive maintenance is economical. The objective of the joint model is to maximize the total profit which is composed of production value, production cost, maintenance cost (including the preventive maintenance cost and replacement cost), and tardiness cost (which is related to the job sequence and maintenance activities). To optimize the objective, immune clonal selection algorithm is utilized. The proposed model is validated by a numerical example.

Keywords: *aperiodic imperfect preventive maintenance; production scheduling; maintenance planning; immune clonal selection algorithm; total profit.*

Aby firma mogła działać z powodzeniem i przynosić większe zyski w danym okresie czasu, zainstalowane w niej maszyny muszą pracować w sposób nieprzerwany. Niestety, z powodu planowych działań obsługowych lub nieoczekiwanych awarii, maszyny są czasami wyłączane z produkcji. Dlatego też w niniejszym artykule opracowano model łączący harmonogramowanie produkcji z planowaniem obsługi technicznej dla linii produkcyjnej złożonej z wielu maszyn. W pracy założono, że konserwacja zapobiegawcza jest niepełna i nie prowadzi do odnowy wszystkich maszyn. Aby zilustrować jej niepełny charakter, wprowadzono pojęcia czynnika redukcji wieku oraz czynnika wzrostu wskaźnika zagrożenia. Przyjęto politykę nieokresowej konserwacji zapobiegawczej. Wymiana jako forma pełnej konserwacji pozwala na przywrócenie maszyny do stanu "fabrycznej nowości". Kiedy i czy należy przeprowadzić wymianę zależy od funkcji wskaźnika kosztu w stosunku do czasu, który pozwala ocenić, czy konserwacja zapobiegawcza jest opłacalna. Model zintegrowany ma na celu maksymalizację całkowitego zysku, który jest wypadkową wartości produkcji, kosztów produkcji, kosztów obsługi (w tym kosztów konserwacji zapobiegawczej oraz kosztów wymiany) i kosztów nieterminowego zakończenia zadania (ang. lateness, związanych z kolejnością wykonywanych zadań i czynności obsługowych). Aby zoptymalizować opisany cel, wykorzystano algorytm odpornościowej selekcji klonalnej Proponowany model zweryfikowano na przykładzie liczbowym.

Słowa kluczowe: *nieokresowa niepełna konserwacja zapobiegawcza; harmonogramowanie produkcji; planowanie konserwacji; algorytm odpornościowej selekcji klonalnej; całkowity zysk.*

1. Introduction

In manufacturing industry, machines' high availability and reliability is the key factor to make companies competitive in fierce business competition. With the increased machine's usage and age, the machine's reliability and performance could decline and result in failure. The unexpected failures could result in not only catastrophic losses but also security event. Preventive maintenance is an effective way to avoid unexpected failures and keep machine in good condition. It is a bridge connected machine's degradation with production process. The machine's degradation can be described and predicted [26]. But in some cases, a machine may become unavailable because of scheduled maintenance activities or unexpected failures [13]. A good production scheduling makes the company complete more order forms in a certain period. This is critical for company to obtain high profit. In addition, high reliability and short breakdown is the goal for managers.So there is a time-conflict problem between production scheduling and maintenance planning. In addition, in some real manufacturing context, the two activities are employed separately [15]. So how to optimize the two activities simultaneously is a problem.

The integrated problem has aroused researchers' interest for many decades. And many works have been published on this issue. Among the existing works, most of them focus on a single machine [24, 4, 8]. Because the single machine problems could be interpreted as fundamental basis for more complex problems [10, 23]. While in practise, many products should be processed on different machines, so, it is more difficult to build the integrated model of production scheduling and maintenance planning for multi-machine system. Hence, this study develops the jointed model in a multi-machine context.

According to the condition of a machine after maintenance in a repairable system, maintenance can be classified into three types [19, 12]. (1) Perfect maintenance. It can renew the machine. (2) Minimal maintenance. It just restores the machine to its prior state before failure. (3) Imperfect maintenance. It just makes the machine less deteriorated. Most of the current models based on the assumption that the preventive maintenance is perfect [9, 18, 5]. Pham and Wang [19] pointed out not all the machines or systems can be restored to “as good as new” status after maintenance, some actions just make them younger. Moreover, not all the damage is thoroughly recovered [1,16]. Therefore, imperfect preventive maintenance should be considered. Wong et al. [25] stressed preventive maintenance tasks included lubrication, cleaning, inspection, adjustment, alignment and/or replacement. In this study, we redefine replacement and preventive maintenance as two different activities. Replacement is replacing the failed system by a brand new one. It makes the machine “as good as new”. Preventive maintenance is imperfect and just undertaken to the key components in a system.

Although many papers optimized preventive maintenance and replacement simultaneously [6, 14, 3], few works considered preventive maintenance, production scheduling and replacement together. Roux et al. [21] considered bloc replacement policy when optimizing preventive maintenance and production scheduling. Ruiz et al. [22] mentioned replacement should be undertaken for longer maintenance, but they didn’t illustrate when to implement concretely. Different with the aforementioned works, in this study, we defined a cost-time function which is used to illustrate when to perform replacement. Meanwhile, the function could evaluate whether or not the preventive maintenance is economical.

The objective of the integrated problem is to maximize the total profit. To construct the objective, production value and production cost of each job, tardiness cost which is impacted by job sequence and maintenance cost including preventive maintenance cost and replacement cost, all the factors should be considered. As proved by Qi et al. [20] the joint optimization of production scheduling and preventive maintenance planning is a NP-hard problem. So one issue appears that how to optimize the objective. Traditionally, enumeration method is used to solve the joint problem [2]. However, when the number of jobs is large, it takes much time and space to calculate and get the optima. Therefore, artificial intelligent research algorithm should be utilized. Hence, in this study, immune clonal selection algorithm is used to optimize the integrated problem.

Overall the analysis above, we focus on the joint problem of production scheduling and maintenance planning in a production line composed of multiple machines. We suppose the preventive maintenance is imperfect and the degradation is accelerated after each preventive maintenance. While replacement can renew the machine. When to implement replacement is based on a cost-time rate function which is also used to evaluate the economy of preventive maintenance. The objective of the integrated model is to maximize the total profit which is impacted by job sequence, production cost, production value, tardiness cost and the cost for preventive maintenance and replacement. To solve the complex problem and obtain the optimal, immune clonal selection algorithm is used.

The rest of the paper is organized as follows: Section 2 describes the development of the integrated model. In Section 3, the optimization methodology based on immune clonal selection algorithm is illustrated. Section 4 reports the validation of a numerical example and the results. Finally, Section 5 concludes the paper and proposes the future research.

2. Development of the integrated model

2.1. Assumption, acronyms and notations

A1: Suppose there are many jobs to be processed on different machines. All jobs are predetermined at the beginning of the production horizon and pre-empting one job for another is not allowed.

A2: Suppose, all the machines are new at the beginning of production horizon. For each machine, there is a key system, if the key system failed, the machine cannot work. If the system is renewed, the machine is renewed. If the system is not “as good as new”, the machine is not “as good as new”. Namely, the machine’s degradation is exactly equal to the corresponding key system’s degradation.

A3: Even though each system’s failure is stochastic, the system’s failure rate function can be described. And after preventive maintenance, the machine begins a new degradation process.

A4: Minimal repair is undertaken upon failure and restores the system “as bad as old”. The time and cost for minimal repair is negligible. Preventive maintenance is imperfect and just makes the system less deteriorated. Replacement is perfect maintenance.

A5: The unplanned failure can be inspected once it occurs.

A6: Time for the machine’s setup and transition is negligible.

A7: The continuum between two sequential preventive maintenance activities is called preventive maintenance cycle.

PM: preventive maintenance

cr: cost-time rate

PMC: the preventive maintenance cost

RC: replacement cost

T_i: the i^{th} preventive maintenance cycle

PMT: the preventive maintenance time

R_f: reliability threshold

λ_i: failure rate in T_i

t: time variable in each T_i

a_i: age reduction factor in T_i

b_i: failure rate increase factor in T_i

RT: replacement time

AIS: artificial immune system

CS: clonal selection

GA: genetic algorithm

ICSA: immune clonal selection algorithm

ST: start time of each job

ET: end time of each job

MTs: the times of maintenance

2.2. Problem description

Suppose there will be many jobs to be processed on a production line which contains multiple different machines. Usually, once the machine’s reliability is lower than the predetermined reliability threshold, then periodic preventive maintenance (PM) is implemented.One issue is how to determine the periodic interval. Traditionally, the periodic interval is determined according to experts’ experience. While this kind of periodic PM is irrational especially under imperfect maintenance system. Because “over maintenance” or “less maintenance” would happen and it is uneconomic and high hazardous.

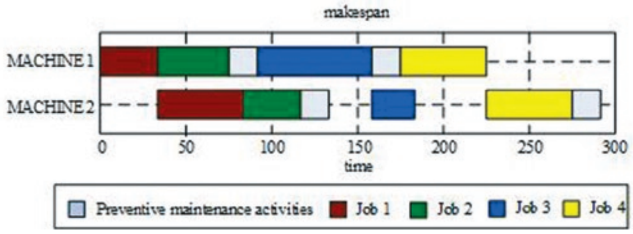


Fig. 1. Information of machine’s service and maintenance with considering production and PM simultaneously

Under the imperfect PM policy, machine's reliability could be restored to a better status, but not to the new status. To illustrate the imperfect character, age reduction factor (Malik [11]) and failure rate increase factor (Nakagawa [17]) is introduced. Hence, machine's failure rate is bigger than the former PM cycle. Figure 2 describes the machine's reliability during the production horizon.

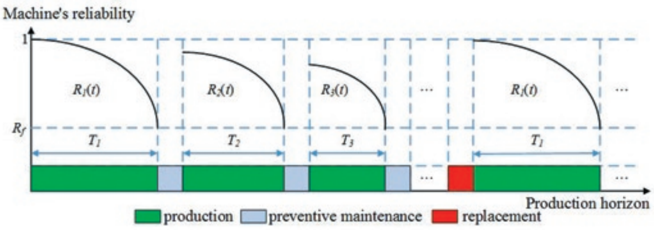


Fig. 2. The illustration of the system's reliability during the production horizon

Suppose preventive maintenance is just undertaken to key components of the key system. Due to the introduction of age reduction factor and failure rate increase factor, the system's failure rate is bigger than in the former PM cycle. So, with the increased machine's usage and maintenance times, the maintenance cost becomes rather high, and the machine's operational time is much less than before preventive maintenance cycle. Thus, when involved in this situation, replacing the key system by a brand new one will be reasonable and economical after certain number of preventive maintenance. However, a new problem is raised that is how to determine the number of preventive maintenance. Namely, how to determine the upper bound of preventive maintenance, because after the certain number of preventive maintenance, it is uneconomical to perform preventive maintenance. This study defines a cost-time rate (*cr*) function to evaluate the economy of preventive maintenance for a new machine.

$$cr = \frac{N \times PMC + RC}{\sum_{i=1}^{N} T_i + N \times PMT} \tag{1}$$

The cost-time rate (*cr*) means maintenance cost per unit time.With the increased number of preventive maintenance, *cr* decreases. After certain number of preventive maintenance, *cr* will increase. The inflection point of *cr* is the most economical number of preventive maintenance. It means in the same unit time, the maintenance cost is lowest at the inflection point. Hence, the inflection point is chosen to regard as the best time to implement replacement. The variation of *cr* with the increased number of preventive maintenance is shown in Figure 3.

Fig. 3. The variation of cr with the increased number of preventive maintenance

Therefore, the machine's usage with considering preventive maintenance and replacement is described in Figure 4.

Step 1. Making a job sequence and organizing production.

Step 2. Predicting the machine's reliability.

Step 3. Comparing the current reliability $R_i(t)$ and reliability threshold R_f. If $R_i(t)$ is bigger than R_f, go to Step 4, otherwise, go to Step 1.

Step 4. Calculating *cr* and judging whether or not the preventive maintenance is economical. If the preventive maintenance is uneconomical, go to Step 5. Otherwise, go to Step 6.

Step 5. Replacement. Replacing the system by a new brand one. After replacement, the machine's status is "as good as new". Then go to Step 1 until the all the jobs are finished.

Step 6. Preventive maintenance. Preventive maintenance is just undertaken to the key components of the key system. After preventive maintenance, go to Step 1 until the all the jobs are finished.

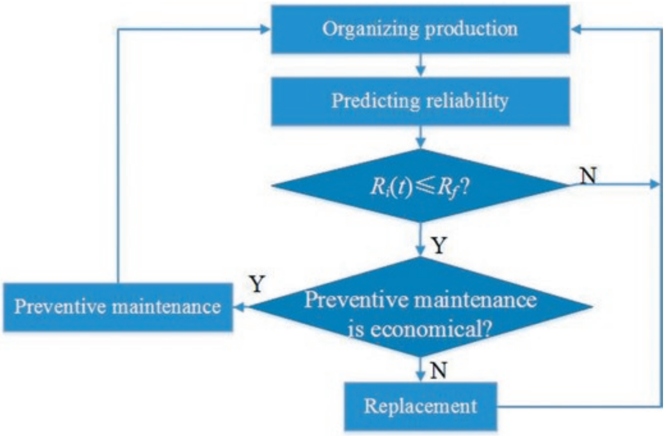


Fig. 4. Usage of a machine

2.3. Model for implementing aperiodic imperfect preventive maintenance

It is obvious that the machine's failure rate will increase with increased usage and age. Age reduction factor and failure rate increase factor is introduced to describe the imperfect character. The age reduction factor is used to illustrate the machine cannot be renewal. Failure rate increase factor is used to represent the failure rate is increased. Therefore, the failure rate function is defined as follows:

$$\lambda_{i+1}(t) = b_i \lambda_i (t + a_i T_i) \tag{2}$$

Where, a_i is the age reduction factor and b_i is the failure rate increase factor in T_i respectively. $0<a_i<1<b_i$ and $1<b_1<b_2<\cdots<b_i$.

According to the theoretical relationship between the failure rate function and reliability, the machine's reliability is shown as Equation 3:

$$R_{i+1}(t) = \exp\left[-\int_0^t b_i \lambda_i (t' + a_i T_i) dt'\right] \tag{3}$$

It is supposed that machine's reliability reaches the reliability threshold (R_f), so the machine's reliability at the end of the current preventive maintenance cycle can be inferred as:

$$R_f = \exp\left[-\int_0^{T_{i+1}} b_i \times \lambda_i \left(t' + a_i \times T_i\right) dt'\right] \tag{4}$$

Rewritten as:

$$\ln R_f = -\int_0^{T_{i+1}} b_i \times \lambda_i\left(t' + a_i \times T_i\right)dt' \tag{5}$$

So, the preventive maintenance cycle (T_{i+1}) can be calculated according to the reliability threshold (R_f), age reduction factor (a_i), failure rate increase factor (b_i) and the failure rate function of the machine ($\lambda_i(t)$) in the current preventive maintenance cycle (T_i).

The current processing job is can be interrupted due to scheduled maintenance even though it is unfinished. Therefore, the machine's service time is related to the status of Job *m* in the current maintenance cycle.

$$wt_j = \begin{cases} \overline{wt}_{j-1} + it_m \\ \overline{wt}_{j-1} + \overline{it_m} \end{cases} \tag{6}$$

Where, $\overline{wt}_{j-1}$ is the service time before the *jth* processing, wt_j is the service time after the *jth* processing. it_m means Job *m* could be just finished in this maintenance cycle. $\overline{it_m}$ is the finished part of Job *m* in this maintenance cycle if the machine is disrupted due to the maintenance. Suppose that the machine is maintained for *k* times (including PM and replacement) before completing Job *m*. The calculated completion time of Job *m* in calendar (t_{cm}) could be got by Equation (7):

$$t_{cm} = \sum_{k'=0}^{k} t_{r,k'} + \sum_{m'=1}^{m} it_{m'} \tag{7}$$

Where, $t_{r,k'}$ is the maintenance time including preventive maintenance time (PMT) and replacement time (RT). $it_{m'}$ is the processing time of Job *m*. Therefore tardiness of Job *m* (θ_m) is as follows:

$$\theta_m = \max\left(0, t_{cm} - dt_m\right) \tag{8}$$

Where, dt_m denotes the delivery time of Job *m*. Suppose the machine is maintained for *K* times (including PM and replacement) before completing all jobs, so the total profit I_{total} of the task should consist four parts: (1) production value of all the jobs, (2) production cost of all the jobs, (3) maintenance cost (including PMC and RC) and (4) total tardiness cost:

$$I_{total} = \sum_{m=1}^{n} it_m \times \left(pv_m - pc_m\right) - \sum_{k=0}^{K} cp_k - \sum_{m=1}^{n} \theta_m \times dc_m \tag{9}$$

Where, pv_m, pc_m and dc_m are production value, production cost and tardiness cost of Job *m* respectively. cp_k denotes the cost of the *kth* maintenance activity including PMC or RC. From Equation (9), maintenance planning and production scheduling is jointed and could be optimized simultaneously.

2.4. Model for implementing periodic perfect preventive maintenance

In other current works, periodic PM activities are generally considered. And another basic assumption is that preventive maintenance could renew the machines. Suppose a machine is always implemented periodic PM without replacement, therefore the calculated completion time of Job *m* in calendar (t^p_{cm}) is Equation (10):

$$t^p_{cm} = \sum_{k'=0}^{k_p} t_{p,k'} + \sum_{m'=1}^{m} it_{m'} \tag{10}$$

Where, $t_{p,k'}$ represents the time for each periodic PM. Thereby, the tardiness of Job *m* is Equation (11):

$$\theta^p_m = \max\left(0, t^p_{cm} - dt_m\right) \tag{11}$$

Subsequently, the total profit is as follows:

$$I^p_{total} = \sum_{m=1}^{n} it_m \times \left(pv_m - pc_m\right) - \sum_{k=0}^{K_p} cp_k - \sum_{m=1}^{n} \theta^p_m \times dc_m \tag{12}$$

Noting that, different from Equation (9), the third monomial in the Equation (12) just includes preventive maintenance cost without replacement cost.

3. Optimization methodology

The joint optimization of production scheduling and preventive maintenance planning has been proved as a NP-hard problem [20]. Artificial immune system (AIS) as a kind of random researching algorithm is usually used to solve optimization problem. Compared with deterministic optimization methods, there are two main characteristics and advantages for AIS. (1) The optimum is searched from a series of points simultaneously in the solution sets rather than from one single point. (2) The objective is used in the iteration process rather than the derivative or other additional information. Clonal selection (CS) is one of the most important theory in AIS. Different from genetic algorithm (GA), CS performs selection based on the rate of affinity between antibodies and antigens. Besides, CS constructs memory cells which contain a group of optima. Moreover, CS could diversify the population by replacing the old antibodies. The basic steps of the immune clonal selection algorithm (ICSA) are illustrated in Figure 5.

Step 1: Problem recognition. The fitness function for ICSA is the objective which is to maximize the total profit. Each chromosome is encoded to represent one job sequence and each gene presents one unique job. For example, chromosome{1, 5,6,9,4,3,7,2,8,10} represents the sequence of all the jobs processed on one certain machine.

Step 2: Initializing parameters. The parameters contain the number of population (*popsize*), the number of antibodies for replacement (*Ar*), the number of iteration (*iteration*), the clonal selection probability (*Ps*), the initial clone number (*Cn*), the clonal inhibited radius (*Cir*), the inspiration parameter (*Ip*), the clonal recombination probability (*Pre*), the gene change probability (*Pc*), the gene shift probability (*Psh*), the inverse probability (*Pi*), and density selection probability (*Pd*).

Step 3: Calculating initial solution sets. Each chromosome's value is calculated based on the objective.

Step 4: Judging whether the terminal condition is met. Here, the terminal condition is the optimum beyond certain value. If met, go to Step 11, otherwise, go to Step 5.

Step 5: Sorting the solution set in descending order.

Step 6: Immune clone. This step contains clonal selection and immune clone. First, the affinity should be calculated, which is as follows:

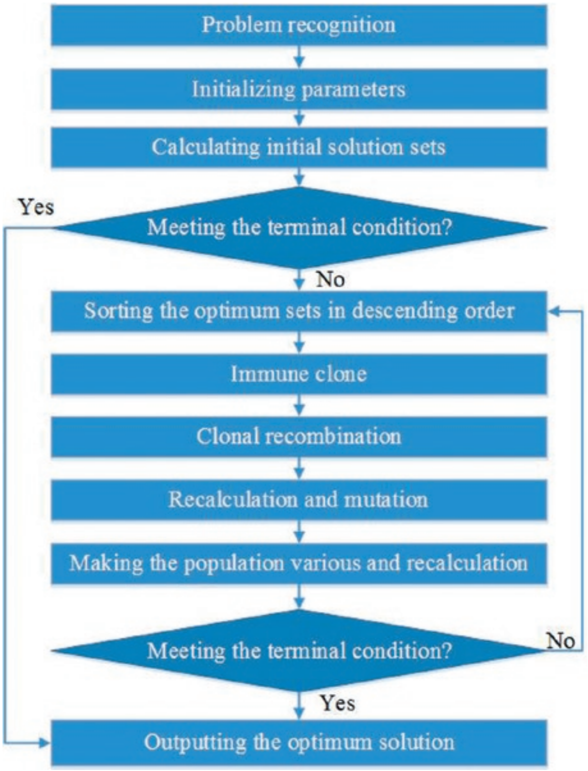


Fig. 5. Process of immune clonal selection algorithm

$$aff = \frac{p - \min p}{\max p - \min p} \tag{13}$$

Where, p is the total profit of each chromosome, $\min p$ is the minimum among p, and $\max p$ is the maximum. In this way, *aff* is in the interval (0,1) which is convenient to be compared. Before calculating similarity of every two chromosomes, a whole zero matrix is set, if the genes from two chromosomes represent the same meaning, the corresponding value is changed into 2, if the selected genes are different, then the value in the zero matrix should be transformed into 1, the unselected genes are still 0. Then the matrix is divided by 2 and named it *hk*. If the value in the matrix is bigger than 0, the calculation should follow Equation (14), otherwise, it is still 0:

$$HK = -hk \times \ln(hk) \tag{14}$$

Then the similarity and antibodies density is calculated respectively:

$$ayy = \frac{1}{1 + HK} \tag{15}$$

$$density = \frac{cumsum}{popsize} \tag{16}$$

Where, *cumsum* means the cumulative sum of all the genes from each chromosome which similarity is bigger than the given *Cir*.

Chromosomes with higher affinity can be regarded as Cell B. To determine the number of clone for each Cell B (*Cnt*), Equation (17) is developed:

$$Cnt = round\left(Cn \times \frac{aff_t}{aff_n} \right) \tag{17}$$

Where, the aff_t and aff_n is the affinity of each Cell B and the cumulative sum affinity of each Cell B respectively.

Step 7: Clonal recombination. Before clonal recombination, all the clones are separated into two parts, the ahead-ranked part and the latter-ranked part. The ahead-ranked part contains the first half of all the clones, and the latter-ranked part includes the rest clones. Recombinants are from the two parts named the first chromosome and the second chromosome respectively. Firstly, the initial cross position is determined according to two random numbers which are between two adjacent jobs. Then cross operation is followed. For the first chromosome, all genes are compared with genes from the second chromosome which are locates the initial cross position. If they are different, the gene from the first chromosome replaces the gene next to the initial cross position from the second chromosome. Next time, the next position is replaced.

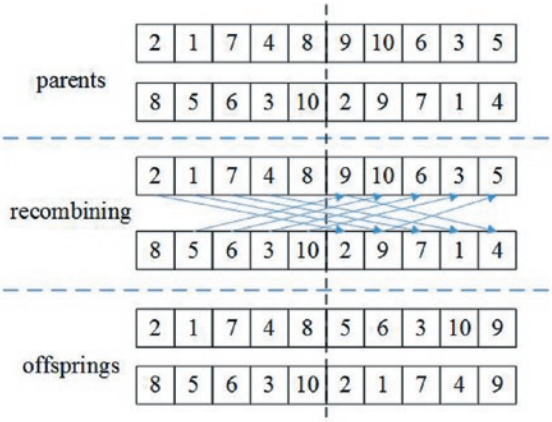


Fig. 6. Illustration of clonal recombination

Step 8: Recalculation and mutation. After clonal recombination, the affinity and the objective should be recalculated. If the affinity of the offspring is smaller than the parents', the offspring are replaced by the parents. Then mutation operation is followed including genetic exchange, genetic inverse and genetic shift. After each operation of mutation operation, the objective and affinity should be recalculated.

Step 9: Population diversification and recalculation. According to *Pd*, the clones with high similarity should be wiped out. The remaining chromosomes and the initial population are combined to form a new matrix named matrix *E*. The formula for inspiration of matrix *E* is Equation (18):

$$act = aff\_E \times e^{\frac{-density\_E}{Ip}} \tag{18}$$

Where, *aff_E* and *density_E* is the affinity and density of matrix *E* respectively.

The chromosomes with high incentive degree are selected to construct a new matrix named *F*. Matrix *F* is sorted according to affinity by descend. To vary samples, *Ar* chromosomes are generated to replace the chromosomes with small inspiration in matrix *F*. Then the new matrix is named matrix *P* and calculated the objective, the affinity, the similarity and density.

Step 10: Judging whether the terminal condition is met. Here the terminal condition is whether the iteration reaches the maximum step. If met, go to Step 11, otherwise, go to Step 5.

Step 11: Outputting the optimum solution.

4. A Numerical example

In this section, a numerical example is designed to validate the integrated model which is proposed in Section 2. Suppose there are 10 jobs to be processed on a production line which is composed of 5 different machines. The jobs' processing time on each machine and the maintenance information for each machine is listed in Table 1.

Table 1. The jobs' processing time and maintenance information on each machine

Machines	Operation Time										PMT	PMC	RT	RC
	J1	J2	J3	J4	J5	J6	J7	J8	J9	J10				
M1	25	17	41	74	37	72	11	31	32	27	2	180	4	2000
M2	15	41	155	12	95	34	77	39	92	114	5	230	8	4000
M3	12	22	83	24	72	62	31	141	42	21	4	170	6	3600
M4	40	36	121	48	52	32	26	56	74	90	3	200	5	2700
M5	60	58	160	78	153	162	32	79	102	52	5	500	7	2000

J1 represents the first job, M1 is the first machine, by such analogy. For each machine, its failure is subject to Weibull distribution. Because, Weibull distribution has been widely used to illustrate system's failure rate, and also usually adopted to study the problem of maintenance policy and production scheduling. The corresponding parameters are listed in Table 2.

Each machine's reliability threshold according to expertise and total operation time (*TOT*) is calculated according Table 1.

Besides, the factors which are important to influence the objective are given including each job's delivery time in calendar (*dt*), production cost (*pc*), production value (*pv*) and tardiness cost (*dc*) in Table 4.

4.1. Validation and results

As analysed, age reduction factor and failure rate increase factor is used to illustrate PM is imperfect and degradation is increased. In order to simplify the calculation, age reduction factor is assumed as a constant, a_i=0.1. Failure rate increase factor b_i is variant according to number of preventive maintenance (i):

$$\begin{cases} b_0 = 1 \\ b_i = b_0 + 0.1 \times (i-1) \end{cases} \tag{19}$$

Meantime, to simplify the calculation, the calculated T_i is processed by Equation (20):

$$T_i = fix(T_i) \tag{20}$$

Some essential parameters for ICSA are set, which is used to optimize the joint problem.

Table 2. Shape parameter and scale parameter of each machine

	M1	M2	M3	M4	M5
Shape Parameter	2	2.2	1.8	1.8	1.2
Scale Parameter	175	225	184	236	318

Table 3. Machines' reliability threshold and total operation time

	M1	M2	M3	M4	M5
R_f	0.6	0.6.	0.7	0.7	0.75
TOT	367	674	510	575	936

Table 4. The basic information about each job

Jobs	*dt*	*pc*	*pv*	*dc*
J1	322	27	98	121
J2	286	40	133	184
J3	1050	39	143	193
J4	645	23	89	127
J5	821	21	90	127
J6	577	34	115	128
J7	446	49	148	190
J8	788	29	118	168
J9	515	37	129	138
J10	751	25	98	152

Table 5. Parameters for ICSA

Popsize	*Ar*	*iteration*	*Ps*	*Cn*	*Cir*	*Ip*	*Pre*	*Pc*	*Psh*	*Pi*	*Pd*
50	30	150	0.7	80	0.7	100	0.6	0.3	0.3	0.3	0.7

Table 6. MTs and revised Ti for aperiodic imperfect PM

Machines	MTs	Ti									
M1	3	125	113	108	103						
M2	4	165	149	144	138	133					
M3	5	103	94	89	85	81	78				
M4	4	133	120	115	109	105					
M5	10	112	107	98	92	86	80	76	72	68	112	107

Table 7. ST and ET under aperiodic imperfect PM

(a) Job sequence is {1,2,6,7,9,4,10,8,5,3}

	J1		J2		J6		J7		J9		J4		J10		J8		J5		J3	
	ST	ET	ST	ET	ST	ET	ST	ET	ST	ET	ST	ET	ST	ET	ST	ET	ST	ET	ST	ET
M1	0	25	25	42	42	114	114	125	127	159	159	233	233	262	262	293	293	330	330	373
M2	25	40	42	83	114	148	148	230	230	322	322	334	334	453	453	492	492	592	592	752
M3	40	52	83	105	148	210	230	265	322	364	364	388	453	478	492	637	637	713	752	839
M4	52	92	105	141	210	242	265	294	364	438	438	489	489	579	637	696	713	765	839	963
M5	92	152	152	215	242	409	409	441	441	553	553	631	631	688	696	780	780	943	963	1135

(b) Job sequence is {2,1,6,7,9,4,10,8,5,3}

	J2		J1		J6		J7		J9		J4		J10		J8		J5		J3	
	ST	ET	ST	ET	ST	ET	ST	ET	ST	ET	ST	ET	ST	ET	ST	ET	ST	ET	ST	ET
M1	0	17	17	42	42	114	114	125	127	159	159	233	233	262	262	293	293	330	330	373
M2	17	58	58	73	114	148	148	230	230	322	322	334	334	453	453	492	492	592	592	752
M3	58	80	80	92	148	210	230	265	322	364	364	388	453	478	492	637	637	713	752	839
M4	80	116	116	156	210	242	265	294	364	438	438	489	489	579	637	696	713	765	839	963
M5	116	174	174	239	242	409	409	441	441	553	553	631	631	688	696	780	780	943	963	1135

Table 8(a)The tardiness for the job sequence {1,2,6,7,9,4,10,8,5,3}

	J1	J2	J6	J7	J9	J4	J10	J8	J5	J3
Tardiness	0	0	0	0	38	0	0	0	122	85

Table 8(b)The tardiness for the job sequence {2,1,6,7,9,4,10,8,5,3}

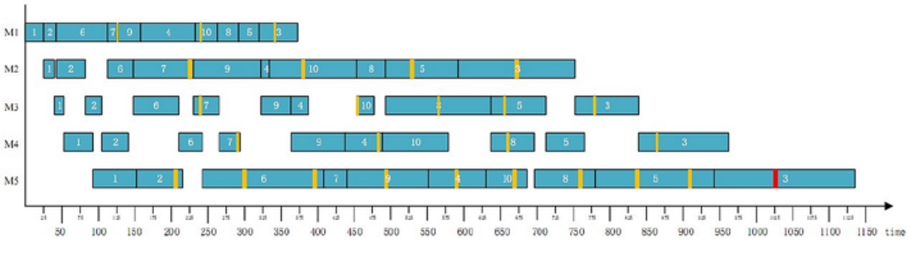
	J2	J1	J6	J7	J9	J4	J10	J8	J5	J3
Tardiness	0	0	0	0	38	0	0	0	122	85

Table 9. Reliability at the end of each maintenance cycleunder aperiodic PM

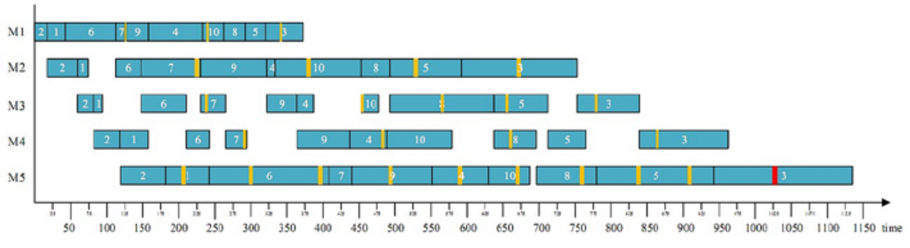
Machines	Reliability (at the end of each maintenance cycle)										
M1	0.6004	0.6010	0.6025								
M2	0.6032	0.6031	0.6011	0.6026							
M3	0.7033	0.7016	0.7037	0.7030	0.7046						
M4	0.7003	0.7033	0.7009	0.7028							
M5	0.7514	0.7506	0.7523	0.7502	0.7503	0.7530	0.7516	0.7517	0.7533	0.7514	0.7506

Table 11. ST and ET of job sequence {2,1,7.6,9,4,10,8,5,3} under periodic perfect PM.

	J2		J1		J7		J6		J9		J4		J10		J8		J5		J3	
	ST	ET	ST	ET	ST	ET	ST	ET	ST	ET	ST	ET	ST	ET	ST	ET	ST	ET	ST	ET
M1	0	17	17	42	42	53	53	125	127	159	159	233	233	262	262	293	293	330	330	371
M2	17	58	58	73	73	150	150	189	189	281	281	293	293	412	412	451	451	551	551	711
M3	58	80	80	92	150	181	189	255	281	323	323	347	412	437	451	596	596	672	711	794
M4	80	116	116	156	181	207	255	290	323	397	397	445	445	538	596	655	672	724	794	918
M5	116	174	174	239	239	271	290	457	457	564	564	647	647	699	699	783	783	941	941	1111



(a) {1,2,6,7,9,4,10,8,5,3}



(b) {2,1,6,7,9,4,10,8,5,3}

Fig. 7. The machine's service time and maintenance information under aperiodic imperfect PM

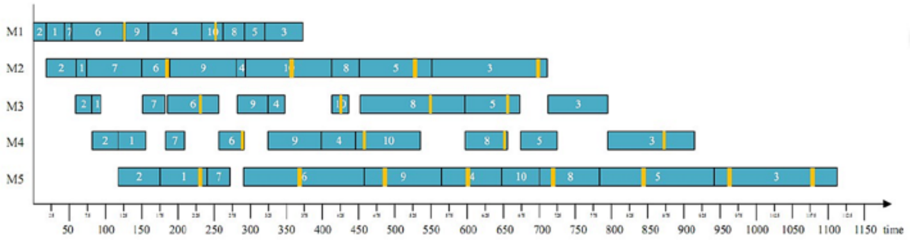


Fig. 8. The machine's service time and maintenance information of job sequence {2,1,6,7,9,4,10,8,5,3} under periodic perfect PM

4.1.1. Scenario 1: Aperiodic imperfect preventive maintenance

For the imperfect preventive maintenance system, the number of maintenance (*MTs*) and PM cycle of each machine is listed in Table 6.

Noting that in Table 6, there is a replacement on M5. Using ICSA, the optimized total profit is 213553 with total tardiness 245. The best job sequences are {1,2,6,7,9,4,10,8,5,3} and {2,1,6,7,9,4,10,8,5,3}. The start time (ST) and end time (ET) is given as follows.

In Figure 7, some jobs are separated into 2 parts by yellow or red lines. The yellow lines mean PM and the red line is replacement. The corresponding tardiness of the two job sequences for each job is listed in Table 8.

At the end of each maintenance cycle, the machines' reliability is listed in Table 9.

To show the better performance of the proposed aperiodic imperfect PM, the periodic perfect *PM* is implemented. Because the age reduction factor and failure rate increase factor is unintroduced, the failure rate in each preventive maintenance is same [7]. Therefore, each preventive maintenance cycle is same. The number of preventive maintenance and PM cycle is listed in Table 10.

By calculating, the total profit is 219517 and the corresponding total tardiness is 232. The proper job sequence is {2,1,7,6,9,4,10,8,5,3}.

The tardiness for each job of best job sequence is given in Table 12.

The machines' reliability at the end of each PM cycle is listed in Table 13.

4.2. Results from ICSA and GA.

To validate the algorithm proposed in Section 3, the traditional GA is used to compare. The compared GA just contains selection operation, crossover operation, and mutation operation. Selection probability is decided by roulette, crossover probability and mutation probability is set as 0.6 and 0.05 respectively. The number of population (*popsize*) and the number of iteration (*iteration*) is same with ICSA's. Considering the random of the initial solution, we test 5 times for each algorithm, the results are listed in Table 14.

Table 10. MTs and revised T_i for periodic perfect PM

Machines	*MTs*	T_i								
M1	2	125	125	125						
M2	4	165	165	165	165	165				
M3	4	103	103	103	103	103				
M4	4	133	133	133	133	133				
M5	8	112	112	112	112	112	112	112	112	112

Table 12. The tardiness for each job under the periodic perfect PM

	J2	J1	J7	J6	J9	J4	J10	J8	J5	J3
Tardiness	0	0	0	0	49	2	0	0	120	61

Table 13. Reliability at the end of each PM cyclefor periodic perfect PM.

Machines	Reliability (at the end of each PM cycle)							
M1	0.6004	0.5421						
M2	0.6032	0.5379	0.5055	0.4751				
M3	0.7033	0.6622	0.6355	0.6098				
M4	0.7003	0.6589	0.6320	0.6061				
M5	0.7514	0.7390	0.7170	0.6956	0.6749	0.6548	0.6353	0.6164

4.3. Results discussion

This study tries to optimize production scheduling and preventive maintenance simultaneously. By comparing with the two scenarios and the results from ICSA and GA, the better performance of the proposed model is validated by comparing with periodic perfect PM. In addition, some conclusions can be gotten:

(1) The proper job sequences with consideration of periodic perfect PM and aperiodic imperfect PM may be the same.However, the correspondingtotal profit is different. Although the aperiodic

Table 14. Results compared ICSA and GA
(a) Results from aperiodic imperfect PM

	Aperiodic imperfect PM			
	No.	The first step to get the optima	Total profit	Total tardiness
ICSA	1	42	213553	245
	2	77	213553	245
	3	75	213553	245
	4	57	213553	245
	5	18	213553	245
	Overall	53.8	213553	245
GA	1	**150**	**204257**	**313**
	2	**150**	**204257**	**313**
	3	23	213553	245
	4	96	213553	245
	5	49	213553	245
	Overall	93.6	209830	272.2

(b) Results from periodic perfect PM

	Periodic perfect PM			
	No.	The first step to get the optima	Total profit	Total tardiness
ICSA	1	41	219517	232
	2	61	219517	232
	3	64	219517	232
	4	32	219517	232
	5	55	219517	232
	Overall	50.6	219517	232
GA	1	86	219517	232
	2	90	219517	232
	3	39	219517	232
	4	**150**	**218886**	**229**
	5	40	219517	232
	Overall	81	219398	231.4

imperfect PM can get less profit and more tardiness, the machine's reliability at each end of the maintenance cycle is always higher than the machine's reliability under periodic perfect PM. (Compared Table 9 and Table 13). More important, the machine's reliability which is under aperiodic imperfect PM policy is always higher than the reliability threshold. While, the assumed periodic perfect PM policy cannot guarantee the machine's reliability is always higher than the reliability threshold.

(2) The best job sequence may not be unique. For some jobs, when the tardiness is sufficient, the job's sequence can be interchanged before the deadline of these jobs which has sufficient tardiness.

(3) Compared with GA, ICSA could get the solution in less iterations for both the aperiodic imperfect PM and periodic perfect PM. ICSA could get more profit with less average iteration steps (compared the overalls in Table 14). Even though, sometimes the optima could be gotten from GA which is in less iteration than from ICSA, the results from GA are not stable. For example, sometimes the iteration has met the terminal condition (for example the terminal condition is maximum step), GA still cannot get the optima. (Table 14).

(4) More factors which impact the objective (to maximize the total profit) are helpful to get the optimum job sequence. Because the more influence of each job is taken into consideration, the difference of jobs is concerned. Some jobs may stress the delivery time and the tardiness cost is high. And some jobs may not be needed in urgent time, therefore, it could be processed later. Therefore, more information about each job should be considered when optimizing the joint scheduling problem.

5. Conclusions and future work

Production scheduling is usually considered to meet certain demands, such as, to minimize total tardiness, the total cost or to maximize total profit etc. Preventive maintenance is an effective way to keep the machine in high availability and reliability. But when maintenance operation is implemented, the machine is disrupted. Moreover, in practice, production scheduling and maintenance planning are optimized and performed separately. Based on this scheme, this study proposed an integrated model to joint production scheduling and maintenance planning in a multi-machine system. In this model, the PM is imperfect. Furthermore, at each end of PM cycle, the cost-time rate function is used to judge the economy of PM. The jointed model aims at maximizing the total profit with considering the factors which could impact the total profit. The proposed model is validated by a numerical example through comparing two scenarios, the results show that the aperiodic imperfect preventive maintenance could ensure the machines in good operational condition in each PM cycle. Meanwhile, the reliability is guaranteed.

In the future, we will focus on more practical situation and take advantages of advanced technology. For example, sensors are used to monitor machine's condition and develop real-time health evaluation model jointed with the production scheduling. To avoid sudden breakdown, the finite preventive maintenance, replacement, inventory and purchasing should be taken into consideration simultaneously.

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