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Human-machine System Scheduling According to Fatigue and Learning Effects

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KEYWORDS

Maintenance;
Human Resources;
Fatigue;
Recovery;
learning Process

ABSTRACT

Nowadays, factories are established based on two important factors: human resources and machines. Most manufacturers attempt to provide an optimal production schedule to use machines efficiently, but few of them pay attention to human resources. In this paper, we propose a mathematical model that optimizes the production schedule considering the human fatigue and learning-forgetting process. The proposed model aims to minimize the machines and human resources idleness cost and decreases the human resources fatigue. The main results show that human-machine system scheduling considering the fatigue and learning–forgetting process increases the quality of products and decreases the human fatigue. On the other hand, the model can efficiently provide an optimal scheduling for human resources and machines to improve the total productivity..

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1. Introduction

The market environment is constantly changing through global competition. This fact imposes pressures on manufacturer to produce quality products at competitive prices more frequently, requiring them to be efficient and agile. To confront these pressures, manufacturers have started to provide optimal schedules to use their resources, such as machines and human resources, more productively and efficiently. They also tried to reduce work-in-process inventory level and lead-time and improve customer service performance [1].

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Many researchers have investigated machines' productivity and proposed several methods and models to optimize the production plan in order to decrease the completion time, work in process, earliness and tardiness, and the common cost components related to production systems [2-5].

Each factory is based on two important factors: human and machine. These two factors influence the production system and should be considered to have an effective and flexible production system.

Similar to the proposed paper on machines' effect, there are useful papers that have investigated the human effects on the production systems [6-7]. Godwin and Aniekan studied the human factors affecting the success of advanced manufacturing systems [8]. Azizi et al. [9] proposed a mathematical model and a probabilistic framework for human boredom at work.

Although many researchers have investigated the humans and machines' effects on the production systems, few of them have studied the interaction between human and machine in manufacturing systems such as MacCarthy and Wilson [10]. They edited a book considering human factors in scheduling and planning, but did not really consider the interaction between human and manufacturing factors and interpretation of factors affecting human performance.

Human resources can influence the production system by their learning process and fatigue factors. In this regard, many researchers have studied human learning-forgetting effect as an important human factor that influences manufacturing system. Carlson and Row [11], Globerson and Levin [12], Elmaghraby [13], and Sikström and Jaber [14] investigated the forgetting curve and categorized this curve in different situations. On the other hand, learning effect is also one of the important factors that has attracted researchers' attention to develop conceptual and mathematical models that capture these phenomena; for example, Inman [15] proposed a training strategy in which workers are trained to perform a second task according to learning curve. Jaber and Kher [16] proposed a dual-phase learning-forgetting model.

Fatigue effects have been also studied by many researchers to improve the production systems. Fatigue can affect the judgment, product quality, efficiency, and productivity [17–20]. When fatigue becomes chronic or excessive, it increases the errors and stresses and reduces a person's quality of thinking and working [21–23]. Rest times can alleviate fatigue and allow for human resources to recover their normal strength and capacity. Jamshidi and seyyedesfahani [24] studied the effect of human fatigue on production quality. They proposed that if worker fatigue increases to a predefined value, their work quality decreases and production system can confront quality cost. Nader Azizi et al. [9] focused on the effect of fatigue on human performance and proposed the best work-rest schedule for each human resource. In some production systems, human resources implement different works that require various workloads. While a task is implemented, force capacity of muscle is reduced over time to a predefined value (maximum endurance time) due to fatigue [25]. This fatigue is either alleviated by a rest time or by moving to do another task that has less and different workloads.

Some researchers believed that the rest time should not be very long since forgetting process can counteract the learning effect, and it may impede the worker's productivity [26].

In this paper, we have focused on scheduling the human resources and production considering the fatigue and learning-forgetting processes. Work and rest for human resources and production plan for machines are scheduled based on humans' fatigue and forgetting process. We have proposed a mathematical model to provide the optimal production plan for machines and the best work and rest schedule for each worker. We used some examples to show that the model can obtain the optimal results effectively.

The rest of the paper is organized as follows: Section 2 presents the models of fatigue and recovery. Section 3 describes the learning-forgetting process. Section 4 proposes the problem statement and its assumptions. Section 5 presents some instances along with computational results to validate and verify the proposed model; finally, section 6 concludes the paper.

2. Fatigue and Recovery Models

Fatigue is a loss of efficiency and a disinclination for any kind of effort [27]. Based on this definition, manufacturer should propose a proper work-rest schedule to maintain human fatigue in standard level since fatigue leads to a reduction of force generating, lower performance, increasing of reaction times and slowing of the sensory abilities [28].

Maximum endurance time

There are some models to quantify the fatigue value. These models use several factors to calculate the amount of fatigue for humans according to work type and its duration. Maximum Endurance Time (MET) is one of these factors that represents the maximum time in which a muscle can tolerate a specific charge during an isometric impressment [29]. If human resource reaches MET level, he has also reached 100% level of fatigue and unable to continue his work without rest. MET is derived from Maximum Voluntary Contraction (MVC) that shows the maximum force produced by a muscle.

Rest allowance

With respect to fatigue definition, we can propose a definition of recovery. Recovery is an action that reduces the work-induced fatigue. Insufficient recovery may accelerate the fatigue process [30]. Rest Allowance (RA) was proposed to calculate the needed recovery after performing a specific work. RA is "the time needed for adequate rest following a static exertion" [31].

Many researchers proposed models to calculate the RA such as those of Rose et al. [32] and Rohmert [33]. Table 1 presents the formulation for RA and MET proposed by Rose et al. [32].

Tab. 1. The MET general and Rest Allowance model presented by Rose et al

	MET	RA
Rose	$7.96 * e^{-4.16.fmvc}$	$3 * MET^{(-1.52)}$

The *fmvc* is the fraction of MVC when performing a specific work. Relation (I) is used to calculate the fatigue caused by a specific work. This relation calculates the fraction of fatigue reached by the muscle after doing a specific work using the work duration and MET value. If the work duration is equal to MET, the workers reach 100% of fatigue.

$$ff = \frac{work\ duration}{MET} \quad (I)$$

Similarly, the fraction of recovery received by a worker can be calculated based on rest duration and the needed rest (R) caused by doing a specific work, as shown in Relation (II).

$$fr = \frac{rest\ duration}{R} \quad (II)$$

The value of R is calculated as follows.

$$R = RA * (work\ duration) \quad (III)$$

Since worker cannot rest exactly after working time, other parameters are defined to calculate the accumulated fatigue and the accumulated needed rest; these parameters are calculated as follows [25].

$$f = pf + ff - fr \quad (IV)$$

$$ar = par + R - fr \quad (V)$$

In Relation (IV), f is the accumulated fatigue and pf is the primary accumulated fatigue. Also, ar refers to the accumulated needed rest and par is the primary accumulated needed rest in Relation (V).

3. Learning and Forgetting Models

Wright [34] proposed that the time to perform a task decreases by a constant rate. The implementation time of a task can be formulated as follows:

$$T_x = T_1 . x^{-b} \quad VI$$

Where T_x is the operation time of the xth product, T_1 is the production time of the first product, x is the cumulative production, b is the learning exponent calculated by (b=-*log (LR)/log(2)*), and LR is the learning rate measured in percentage. On the other hand, forgetting effect can be formulated as follows:

$$T'_x = T'_1 . x^{f} \quad VII$$

In this formula, T'_x is the time for the xth unit of lost experience, T'_1 is the intercept of the forgetting curve, x is the amount of task that could be done if rest did not occur, and f is the forgetting exponent. Figure 1 shows the learning and forgetting processes.

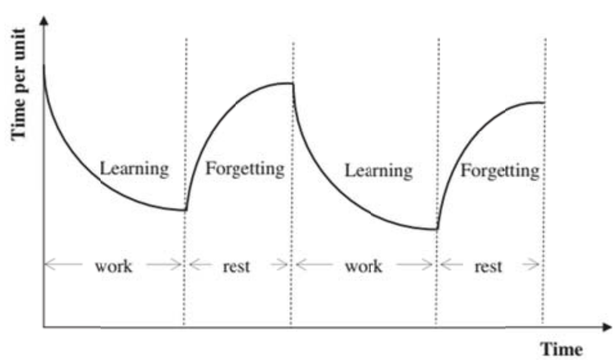

Fig. 1. The behavior of the learning–forgetting process over time

In this paper, the forgetting effect has been considered to justify the rest time. Ideally, the length of a rest time would not exceed the total forgetting time (B). That is to say, the total of consecutive rest times or human idle times must be smaller than a predetermined value (B). On the other hand, the rest time should be long enough to alleviate a significant amount of the physical and mental fatigue caused by doing task. This fact has been considered in the proposed model by considering fatigue-recovery process and learning-forgetting process.

To illustrate the forgetting process, assume that f and T'_1 are equal to 0.05 and 1, respectively. If human resource does not work (rest or idle), then process time T'_x can be calculated based on the rest time. Figure 2 shows T'_x according to rest time of the human resources.

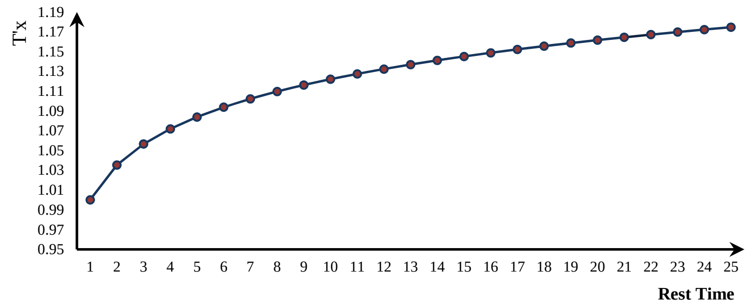

Fig. 2. The effect of forgetting process on work time

Figure 2 shows that if human resource does not work for 25 consecutive time positions, his implementation time increases from 1 to 1.2, considering this fact the proposed model prevents human resource from excessive idleness or rest time. The detail of proposed model is proposed in the next section.

4. Problem Statement

In this section, we formally describe the considered problem and its assumption. The aim of the proposed model is to obtain an optimal maintenance plan for machines and the best work-rest schedule for human resources based on fatigue and learning-forgetting process. The reliability of machines, fatigue, and learning-forgetting process of human resources are the important factors used to determine the scheduling policy. The operation horizon is divided into unit time positions; at each time position, we calculate the machines' reliability to determine whether the machines should be repaired or not. It holds true for human's rest based on fatigue and learning-forgetting process value.

4-1. Objective function

The objective function of the proposed model consists of four cost components as mentioned below.

- Idleness cost of machines
- Idleness cost of human resources
- Cost of corrective maintenance

Since the manufacturer confronts machines and human's idleness, objective function aims to minimize the cost of idleness of humans and machines. Also, cost of corrective maintenance is another cost component considered in the objective function.

4-2. Assumptions

- Each task has a predetermined MET
- RA for each task is calculated based on formulation of Rose et al. [32]
- The reliability of the machine must be greater than a predetermined value (R_{min}) in each time position
- The fatigue of human resources decreases in proportion with rest duration and RA value for each task
- The value of B (allowed consecutive rest time) is known for the worker
- The maintenance actions decrease the failure rate of machine.
- The worker cannot rest if his accumulated needed rest is lower than the amount of rest he receives in the current time position.

The machine has an exponential failure rate.

4-3. Notations

4-3-1. Subscripts

I	Index for task i (i =1, 2,…I)
K	Index for time position (k =1, 2,…K)

4-3-2. Input parameters

P_i	Processing time of task i
WID	The unitary cost of worker idleness

MID	The unitary cost of machine idleness
CR	The unitary maintenance cost of machine
MET_i	The maximum endurance time for task *i*
RA_i	The rest allowance coefficient of task *i*
DF	The primary fatigue of worker
B	The allowed consecutive rest time for human resource
DR	The primary reliability value of machine
DAR	The primary accumulation needed recovery of worker
TI	The time amount of each position time
R_{min}	The minimum reliability the machine should be repaired if its reliability is less than this value.
F_{max}	Maximum allowed fatigue of worker
μ	The worker recovery rate caused by rest in each time position
λ	The machine failure rate

4-3-3. Decision variables

$x_{i,k}$	1 if task *i* is done in position *k* ; =0 otherwise
m_k	1 if the machine is repaired in position *k* ; =0 otherwise
re_k	1 if the worker rests in position *k* ; =0 otherwise
rel_k	The reliability of machine in position *k*
ff_k	The amount of work-related fatigue produced in position *k*
fr_k	The fraction of recovery received in position *k*
r_k	The needed rest time caused by working in position *k*
ar_k	The accumulation of needed recovery in position *k*
f_k	The accumulation of fatigue in position *k*
rr_k	The amount of worker rest in position *k*
fs_i	The finish time of task *i*
ss_i	The start time of task *i*

Considering the above notations, the mathematical model can be formulated as mentioned in the next subsection.

4-4. The mathematical model

$$\min Z: \sum_{k=1}^{K} m_k . CR + \sum_{k=1}^{K} (1-m_k).(1-\sum_{i=1}^{I} x_{i,k}).MID + \sum_{k=1}^{K}(1-re_k).(1-\sum_{i=1}^{I} x_{i,k}).WID \tag{1}$$

S.t.

$$\sum_{k=1}^{K} TI.x_{i,k} = P_i \qquad \forall i; \qquad (2)$$

$$x_{i,k} \leq (1-m_k).(1-re_k) \qquad \forall i,k; \qquad (3)$$

$$\sum_{i=1}^{I} x_{i,k} \leq 1 \qquad \forall k; \qquad (4)$$

$$fs_i = \max_k\{k.x_{i,k}\} \qquad \forall i \qquad (5)$$

$$ss_i = min\{k.x_{i,k}\} \qquad \forall i \qquad (6)$$

$$fs_i - ss_i = P_i + 1 \qquad \forall i \qquad (7)$$

$$rel_k = DR \qquad \forall k \leq 1; \qquad (8)$$

$$rel_k = e^{-\lambda}.rel_{k-1}.\sum_{i=1}^{I} x_{i,k-1} + e^{\lambda}.rel_{k-1}.m_{k-1} + rel_{k-1}.(1 - \sum_{i=1}^{I} x_{i,k-1}).(1-m_k) \qquad \forall k \geq 2; \qquad (9)$$

$$ff_k = \sum_{i=1}^{I} \frac{TI.x_{i,k}}{P_i.MET_i} \qquad \forall k; \qquad (10)$$

$$fr_k = \frac{rr_k}{DAR} \qquad \forall k \leq 1; \qquad (11)$$

$$fr_k = \frac{rr_k}{ar_{k-1}} \qquad \forall k \geq 2; \qquad (12)$$

$$r_k = \sum_{i=1}^{I} \frac{TI.x_{i,k}.RA_i}{P_i} \qquad \forall k; \qquad (13)$$

$$ar_k = DAR + r_k - rr_k \qquad \forall k \leq 1; \qquad (14)$$

$$ar_k = ar_{k-1} + r_k - rr_k \qquad \forall k \geq 2; \qquad (15)$$

$$f_k = (DF + ff_k).(1-fr_k) \qquad \forall k \leq 1; \qquad (16)$$

$$f_k = (f_{k-1} + ff_k).(1-fr_k) \qquad \forall k \geq 2; \qquad (17)$$

$$rr_k = TI.\mu.re_k \qquad \forall k; \qquad (18)$$

$$\sum_{K=k}^{k+B} \sum_{i=1}^{I} (1-x_{i,K}) \leq \text{B} \qquad K = 1,2,..,K-B; \qquad (19)$$

$$m_k \geq R_{min} - rel_k \qquad \forall k; \qquad (20)$$

$$re_k \geq f_k - F_{max} \qquad \forall k; \qquad (21)$$

$$rr_k \leq ar_{k-1} \qquad \forall k \geq 2; \qquad (22)$$

$$R_{min} \leq rel_k \leq 1 \qquad \forall k; \qquad (23)$$

As we mentioned in section 3.1 Relation (1) shows the objective function with three cost components. The first component provides the corrective maintenance cost. The second component calculates the machine idleness cost. If a machine does not work on any task and it is not under maintenance in each time position, the cost of idleness is imposed on manufacturing system. Similar to the second component, the third component provides the idleness cost for worker.

Relation (2) assures that the time spent by a machine to perform a task is equal to the task processing time. Relations (3) shows that tasks cannot be performed when machine is under maintenance or when the worker rests. Relation (4) indicates that only one task can be performed by the machine in each time position. Relations (5-6) calculate the start and finish times for each task. Relation (7) assures that machine works on each task without interruption. Relation (8) shows that the reliability of machine in first time position is equal to a predetermined reliability value. Relation (9) calculates the machine reliability in each time position based on its status in prior time position. If machine works in prior time position, its reliability decreases; if machine goes under maintenance, its reliability increases. If machine is idle in prior time position, its reliability does not change. Relation (10) provides the fatigue fraction of the worker caused by task implementation. Relations (11-12) calculate the recovery fraction received by the worker in each time position based on the amount of rest and accumulated needed rest. Relation (13) calculates the needed rest time caused by implementation on a task in each time position. The needed rest time should be considered if the worker performs one task. Needed rest is calculated based on rest allowance of implemented task. Relations (14-15) provide the accumulated needed rest in each time position. Relations (16-17) obtain the fatigue of the worker in each time position. If the worker can rest as much as accumulated needed rest time, *fr* will be equal to 1 and worker can recover himself totally. Relation (18) shows that if the worker rests in a position time, he receives a rest that is equal to time amount of the position. Relation (19) prevents worker from excessive idleness or rest time in order to restrict the forgetting effect. Relation (20) assures that if machine reliability is lower than minimum required reliability, maintenance should be done. Similarly, Relation (21) assures that human should rest if his fatigue is greater than maximum allowed fatigue. Relation (22) shows that the worker cannot rest if his accumulated needed rest is lower than the amount of rest he receives in the current time position. Relation (23) shows the desirable interval for machine reliability.

5. Numerical Illustration

In this section, we use the proposed mathematical model to determine the optimal schedule for human resources and machines. We propose three instances with different task numbers, processing time, machine failure rate, forgetting ratio, and MET. The main parameters of each instance are shown in Table 2.

Tab. 2. The parameters of instances

		Task1	Task2	Task3	Task4	Task5
instance 1	processing time	3	4	6		
	FMVC(percent)	3	11	5		
instance2	processing time	8	7	14	12	
	FMVC(percent)	5	11	15	9	
instance3	processing time	6	10	11	15	8
	FMVC(percent)	3	14	8	5	2

Other required parameters, such as failure rate, maintenance cost, machine idleness cost, human idleness cost, are selected from the proper distribution function as shown in Table 3.

Tab. 3.Cost, fatigue, and reliability parameters for the proposed instances

Input variables	Distribution
Cost of worker idleness (*WID*)	U(51,60)
Cost of machine idleness(*MID*)	U(25,40)
Primary fatigue of worker(*DF*)	U(0.3,.45)
Primary reliability of machine(*DR*)	U(0.6,.85)
Primary accumulation of fatigue recovery need (*DAR*)	U(1,4)
The time amount of each position(*TI*)	{1,2,3}
Failure rate of machine(λ)	U(0.02,0.05)
The recovery rate caused by rest in each time position(μ)	U(0.3,0.6)
Unitary cost repair for machine(*CR*)	U(40,60)
Minimum required reliability for machine(R_{min})	U(0.4,0.6)
Forgetting coefficient (f)	0.05
Maximum allowed fatigue of worker (F_{max})	U(1)

Using the proposed model to solve these instances, we can obtain the optimal schedule for machines and humans, respectively. Table 4 shows the objective function value for each instance.

Tab. 4. The result of proposed model

	Objective function value	Machine maintenance cost	Machine idleness cost	Worker idleness cost
Instance 1	271.66	128.71	32.31	110.64
Instance 2	290.32	142.05	30.97	117.30
Instance 3	352.36	187.40	40.40	124.56

To illustrate the result of the proposed model, the optimal policy of instance 1 is shown in Figure 3. In this scheduling policy, we have 24 time positions, and the value of variables M and re is proposed.

Time position	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
M	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
re	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1
Task	2	2	2	2					3	3	3	3	3	3			1	1	1					

Fig. 3. The optimal schedule of human and machine for instance 1

As could be seen in Figure 3, Task 2 is done in time positions 1-4; moreover, human and machine are idle in time position 5, since they are available, but do not work on a task. Human-machine system begins to work on Task 3 in position 9 and keeps at it until time position 14; the human rests in positions 15-16. Since Task2 has a greater FMVC than Task3, the human resource rests more time after doing Task2. Finally, Task1 implementation is started in position 17 and continued to position 19. During this period, the reliability of machine and the fatigue and the forgetting effect of worker are maintained in a predetermined value.

6- Conclusions

This paper presents a novel mathematical model to optimize the scheduling policy for machines and human resources, respectively. The main factor for machines maintenance is reliability, while fatigue-recovery and learning-forgetting processes are important factors in human resource scheduling. We combined the concept of reliability, fatigue-recovery, and learning-forgetting for a comprehensive study of human-machine systems, since a separate investigation of human resources scheduling and machines scheduling is not consistent with the actual situation of human-machine systems. The performance of the proposed model was examined by 3 instances as shown in Table 2. The provided results indicate that the model can obtain efficient and effective work- rest schedule and maintenance schedule.

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