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Maintenance and Work-rest Scheduling in Human-machine System According to Fatigue and Reliability

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ABSTRACT

Most manufacturers use human-machine systems to produce high-quality products. Dealing with human-machine systems is very complicated since not only machines should be utilized in proper condition but also appropriate environment should be provided for human resources. Most manufacturers have a maintenance plan for machines but many of them do not have a proper work-rest schedule for human resources. Considering this fact, we emphasis on human role in human-machine systems maintenance and propose a mathematical model that obtains the optimal work-rest schedule for humans based on fatigue-recovery models and the optimal maintenance policy for machines based on reliability level. The performance of proposed model was examined by some instances and the obtained results indicate this model can provide effective maintenance policy for human-machine systems.

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1. INTRODUCTION

To produce high-quality products we should consider machines and human resources simultaneously and study their interaction in a manufacturing systems. With respect to this fact researchers attempt to study the humans' performance in manufacturing systems and the effects of manufacturing systems on humans' performance.

Many researchers classify human resources in two common categories. In the first category, humans are known as a necessary resource to produce products which have no special difference with other resources such as equipment or raw materials.

Martorell et al. [1] studied the effect of human resources and spare parts on maintenance policy with RAM+C condition. Taylor [2] considered the human as an important resource in maintenance resource management (MRM). He believed that maintenance resources scheduling is a part of maintenance human factors which addresses the issues of management, organization and problem solving. AlsoTavakkoli-Moghaddam et al. [3], Ghodratnama et al. [4] and Miripour Fard et al. [5] investigated the human as a resource in manufacturing systems.

In the second category, human has been considered as an operator that influence the machines and products. Considering this fact many topics such as human factor, human reliability, human error classification, human error recognition, human error rate prediction and human error elimination have been proposed.

Horberry, Burgess-Limerick and Steiner [6] discussed the human factors and investigated the human resources' effects on manufacturing operations and maintenance. Tarakci et al. [7] studied the human factors effects specifically operator learning on maintenance actions. Kim and Park [8] introduced a procedure for a predictive analysis of human error potentials based on a work plan. With respect to human role in manufacturing process, manufacturers have to identify the human errors and propose some models to assess human errors [9]. Liu et al. [10, 11] indicated that human errors diagnostic system such as HED and HECA can help manufacturers to develop their own human errors identification model. Although most papers in the human errors identification proposed conceptual model such as the work proposed by Karaulova and Pribytkova [12], few of them obtained

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mathematical model to quantify human error factors such as fatigue and stress [13, 14].

It is obvious that by considering human like what was mentioned in the second category, the manufacturers confront machines failure and humans errors. Therefore, they have to schedule the machine maintenance and human work-rest time to decrease the machine failure cost, human error cost, human idleness cost and machine idleness cost.

Khalaquzzaman et al. [15] proposed a new method to consider human errors in component failure rate calculation for a digital plant protection systems. Kiassat et al. [16] presented a novel method to quantify the effects of human-related factors on the failure risk in manufacturing industries.Wang and Sheu [17] proposed a mathematical model to decrease the cost of some types of human errorsin production and maintenance policy. Carr and Christer [18] proposed a maintenance policy by considering human errors probability. Mahmoud and Moshref [19] proposed a model to determine maintenance policy, considering human errors in a two-unit cold standby system. Asadzadeh and Azadeh [20] proposed a simulation-optimization algorithm for a condition based maintenance scheduling problem with human errors. Azizi et al. [21] proposed a work-rest scheduling model for human resources based on human errors in a manufacturing system. Jamshidi and Seyyed Esfahani [22] proposed a mathematical model to obtain the proper work-rest time based on reliability of each human resources.

There are many papers in optimization of maintenance policy and human work-rest policy, but few of them tried to optimize the maintenance and human work-rest policy simultaneously. If there is no proper work-rest schedule for all involved human resources in manufacturing system, some human factors such as fatigue can reduce the human performance, on the other hand without an appropriate maintenance policy, the machines' failure rate increases and manufacturers confront poor quality products.

In this paper we investigate the maintenance and work-rest scheduling according to machine reliability and human fatigue-recovery models. We first propose the important fatigue-recovery models and present a mathematical model to provide the optimal work-rest schedule for human resources and optimal maintenance policy. In this model, we aim to maintain the machines reliability and humans fatigue in a proper interval with regard to machines and humans' idleness cost and maintenance cost.We use some examples to show the model can obtain the optimal results effectively.

The remaining of the paper is organized as follows: Section 2 presents fatigue and recovery models. Section 3 proposes the problem statement, assumptions and mathematical model. Section 4 presents some instances with computational results to validate and verify the proposed model. Finally, Section 5 concludes the paper and presents the future works.

2. FATIGUE AND RECOVERY MODELS

Fatigue is a loss of efficiency and a disinclination for any kind of effort [23]. 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, reaction times increasing and slowing of the sensory abilities [24].

2. 1. 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 which a muscle can tolerate a specific charge during an isometric impressment [25]. If human resource reaches to MET level, he has also reached 100% level of fatigue and is unable to continue his work without rest. MET is derived from Maximum Voluntary Contraction (MVC) that shows the maximum force produced by a muscle.

2. 2. Rest Allowance With respect to fatigue definition, we can propose a definition for recovery. Recovery is an action that reduces the work-induced fatigue. Insufficient recovery may accelerate the fatigue process [26]. Rest Allowance (RA) was proposed to calculate the needed recovery after performing a specific work. RA is "time needed for adequate rest following a static exertion" [27]. Many researchers proposed models to calculate the RA such as Rose et al. [13] and Rohmert [14]. Table 1 presentsthe formulation for RA and MET that proposed by Rose et al. [13].

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 (*ff*) 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 reaches to 100% of fatigue.

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

TABLE 1. The MET general and Rest Allowance model presented by Rose et al. [13]

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

Similarly, the fraction of recovery (*fr*) 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).

$$fr = \frac{rest\ duration}{R} \tag{II}$$

The value of *R* is calculated as follows.

$$R = RA * (work\ duration) \tag{III}$$

Since worker cannot rest exactly after working time, other parameters are defined to calculate the accumulated fatigue (*f*) and the accumulated needed rest (*ar*), these parameters are calculated as follows [28].

$$f = pf + ff - fr \tag{IV}$$

$$ar = par + R - fr \tag{V}$$

In Relations (IV-V) *(pf)* is the primary accumulated fatigue and*(par)*is the primary accumulated needed rest.

3. 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. The reliability of machines and fatigue of human resources are the two important factors that used to determine the maintenance and work-rest policy. The operation horizon are divided into unit time positions and at each time position we calculate the machines' reliability to determine whether the machines should be repaired or not. It holds true for humans rest based on fatigue value.

3. 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 unpredictable failure
- Cost of corrective maintenance

Since the manufacturer confronts machines and humans idleness, objective function aims to minimize the cost of humans and machines idleness. Also, cost of unpredictable failure has been considered since the reliability of machines is not always in perfect status (100%) and manufacturer confronts machines unpredictable failure.

3. 2. Assumptions Processing time of each task is known

- Each task has a predetermined MET
- RA for each task is calculated based on Rose et al. [13]
- The reliability of machine must be greater than a predetermined value (Rmin) in each time position
- The worker has a specific maximum fatigue level (Fmax) and cannot work with a fatigue value greater than this fatigue limit.
- The fatigue of human resources decreases in proportion with rest duration and RA value for each task
- The maintenance actions decrease the failure rate of machine.
- The machine is in useful life stage based on bathtub curve [29].
- The worker cannot rest if his accumulated needed rest is lower than the amount of rest he receives at current time position.
- The task interruption is not allowed.
- The machine has exponential failure rate.

3. 3. Notations

3. 3. 1. Subscripts

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

3. 3. 2. Input Parameters

Pi	Processingtime of task i
WID	The unitary cost of worker idleness
MID	The unitary cost of machine idleness
CMA	The unpredictable failure cost of machine
CR	The unitary maintenance cost of machine
METi	The maximum endurance time for task i
RAi	The rest allowance coefficient of task i
DF	The primary fatigue of worker
DR	The primary reliability value of machine
DAR	The primary accumulation needed for recovery of worker
TI	The time amount of each position time
Rmin	The minimum reliability that machine should be repaired, if its reliability is less than this value.
Fmax	Maximum allowed fatigue of worker
μ	The worker recovery rate caused by rest in each time position
λ	The machine failure rate

3. 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 next subsection.

3.4. The Mathematical Model

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

S.t.

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

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

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

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

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

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

$$rel_k=DR \quad \forall k\le 1; \quad (8)$$

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

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

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

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

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

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

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

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

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

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

$$m_k\ge R_{min}-rel_k \quad \forall k; \quad (19)$$

$$re_k\ge f_k-F_{max} \quad \forall k; \quad (20)$$

$$rr_k\le ar_{k-1} \quad \forall k\ge 2; \quad (21)$$

$$R_{min}\le rel_k\le 1 \quad \forall k; \quad (22)$$

As we mentioned in Section 3.1 the Relation (1) shows the objective function with four cost components. The first component calculates the cost of unpredictable failure. The more distance between machine reliability and ideal reliability (100%) leads to an increase in unpredictable failure cost. The second component provides the corrective maintenance cost. Third component calculates the machine idleness cost. If a machine does not work on any task and it's not under maintenance in each time position the cost of idleness is imposed to manufacturing system. Similarly the fourth 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 time 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, but 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 of 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, the 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) assures that if machine reliability is lower than minimum required reliability, maintenance should be done. Similarly, Relation (20) assures that human should rest if his fatigue is greater than maximum allowed fatigue. Relation (21) shows that the worker could not rest if his accumulated needed rest is lower than the amount of rest he receives in current time position. Relation (22) shows the desirable interval for machine reliability.

4. NUMERICAL ILLUSTRATION

In this section we use the proposed mathematical model to determine the optimal work-rest schedule for human resources and maintenance schedule for machines. We propose two instances with different task numbers, processing time, machine failure rate and MET.

Instance 1: in this instance we have 3 tasks that their processing time and FMVC are shown in Table 2.

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

Using the proposed model to solve the instance 1, we can obtain the optimal maintenance and work-rest schedule for machine and human, respectively. Table 4 shows the optimal solution for instance 1.

As could be seen, Table 4 proposed the maintenance and work-rest schedule for machines and workers. When a machine goes under maintenance, its reliability increases. For example since machine goes under maintenance its reliability increases in positions 1-6.

On the other hand by working on tasks the machine's reliability decreases in positions 8-12. This fact holds true for worker fatigue, since the worker rests in positions 1-4 his fatigue decreases but in positions 8-12 his fatigue increases by working on tasks. The objective function of the proposed solution is proposed in Table 5.

Instance 2: in this instance we have 10 tasks that their processing time and FMVC are shown in Table 6. Similar to instance 1 all required parameters are selected from the mentioned distribution function in Table 3. The objective function value and its components are mentioned in Table 7.

TABLE 2. The parameters for instance 1

	Processing time	FMVC
Task 1	3	3%
Task 2	6	17%
Task 3	18	7%

TABLE 3. Cost, fatigue and reliability parameters for proposed instances

Input variables	**Distribution**
Cost of worker idleness (*WID*)	U(45,60)
Cost of machine idleness (*MID*)	U(30,40)
Primary fatigue of worke r(*DF*)	U(0.2,.45)
Primary reliability of machine (*DR*)	U(0.7,.85)
Primary accumulation of fatigue recovery need (*DAR*)	U(2,4)
The time amount of each position (*TI*)	{1,2,3}
Failure rate of machine (λ)	U(0.02,0.04)
The recovery rate caused by rest in each time position(μ)	U(0.3,0.5)
Unpredictable failure cost of machine (*CMA*)	U(20,40)
Unpredictable failure cost of worker (*CH*)	U(20,30)
Unitary cost repair for machine (*CR*)	U(40,60)
Minimum required reliability for machine (R_{min})	U(0.4,0.6)
Maximum allowed fatigue of worker (F_{max})	U(2,5)

TABLE 4. The results of proposed model for instance 1

Time position	Task 1	Task 2	Task 3	Machine		Human						
	x	***x***	***x***	***m***	***rel***	***re***	***r***	***rr***	***fr***	***ff***	***ar***	***f***
1	0	0	0	1	0.8	1	0	0.4	0.2	0	1.6	0.24
2	0	0	0	1	0.82	1	0	0.4	0.25	0	1.2	0.18
3	0	0	0	0	0.85	1	0	0.4	0.33	0	0.8	0.12
4	0	0	0	1	0.85	1	0	0.4	0.5	0	0.4	0.06
5	0	0	0	1	0.88	0	0	0	0	0	0.4	0.06
6	0	0	0	1	0.9	0	0	0	0	0	0.4	0.06
7	0	1	0	0	0.93	0	0.02	0	0	0.04	0.42	0.1
8	0	1	0	0	0.9	0	0.02	0	0	0.04	0.43	0.14
9	0	1	0	0	0.88	0	0.02	0	0	0.04	0.45	0.19
10	0	1	0	0	0.85	0	0.02	0	0	0.04	0.47	0.23
11	0	1	0	0	0.82	0	0.02	0	0	0.04	0.48	0.27
12	0	1	0	0	0.8	0	0.02	0	0	0.04	0.5	0.31
13	0	0	0	1	0.78	0	0	0	0	0	0.5	0.31
14	0	0	0	1	0.8	1	0	0.4	0.8	0	0.1	0.06
15	1	0	0	0	0.82	0	0.03	0	0	0.05	0.13	0.11
16	1	0	0	0	0.8	0	0.03	0	0	0.05	0.17	0.16
17	1	0	0	0	0.78	0	0.03	0	0	0.05	0.2	0.2
18	0	0	1	0	0.75	0	0.01	0	0	0.01	0.21	0.21
19	0	0	1	0	0.73	0	0.01	0	0	0.01	0.21	0.22
20	0	0	1	0	0.71	0	0.01	0	0	0.01	0.22	0.23
21	0	0	1	0	0.69	0	0.01	0	0	0.01	0.22	0.24
22	0	0	1	0	0.67	0	0.01	0	0	0.01	0.23	0.25
23	0	0	1	0	0.65	0	0.01	0	0	0.01	0.23	0.26
24	0	0	1	0	0.63	0	0.01	0	0	0.01	0.24	0.27
25	0	0	1	0	0.61	0	0.01	0	0	0.01	0.24	0.28
26	0	0	1	0	0.59	0	0.01	0	0	0.01	0.25	0.29
27	0	0	1	0	0.58	0	0.01	0	0	0.01	0.26	0.3
28	0	0	1	0	0.56	0	0.01	0	0	0.01	0.26	0.31
29	0	0	1	0	0.54	0	0.01	0	0	0.01	0.27	0.32
30	0	0	1	0	0.53	0	0.01	0	0	0.01	0.27	0.33
31	0	0	1	0	0.51	0	0.01	0	0	0.01	0.28	0.33
32	0	0	1	0	0.5	0	0.01	0	0	0.01	0.28	0.34
33	0	0	1	0	0.48	0	0.01	0	0	0.01	0.29	0.35
34	0	0	1	0	0.47	0	0.01	0	0	0.01	0.29	0.36
35	0	0	1	0	0.45	0	0.01	0	0	0.01	0.3	0.37

TABLE 5. The objective function with its detailed cost for instance 1

Objective function value	Unpredictable failure cost	Machine maintenance cost	Machine idleness cost	Worker idleness cost
803.148	303.148	315	35	150

TABLE 6. The parameters for instance 2

	Processing time	FMVC
Task 1	7	20%
Task 2	10	6%
Task 3	14	7%
Task 4	9	13%
Task 5	10	15%
Task 6	13	8%
Task 7	15	18%
Task 8	4	3%
Task 9	8	11%
Task 10	7	20%

TABLE 7. The objective function with its detailed cost for instance 2

Objective function value	Unpredictable failure cost	Machine maintenance cost	Machine idleness cost	Worker idleness cost
2657.567	903	1089	138	527.567

5. CONCLUSIONS AND FUTURE WORKS

This paper presented a novel integer nonlinear model to optimize the maintenance and work-rest for machines and human resources, respectively. The main factor for machines maintenance is reliability and for humans' work-rest is the amount of fatigue.We combined the concept of reliability and fatigue to consider human and machine as two important factors in human-machine system and proposed the best policy for machine maintenance and human rest in regard to human and machine idleness cost. We tried to synchronize the maintenance and rest schedule to reduce the unnecessary stoppage during production period. The performance of proposed model was examined by 2 instances and the provided results indicated the model can obtain efficient and effective work-rest schedule and maintenance schedule.

We have included several assumptions which simplified the model and limited its applicability on real problems. Our future research will be towards incorporation of more complications in the model to bring it much closer to practical scenario. Several issues which are considered for future research are: (i) Other failure distribution function for machine can be considered. (ii) The continuous time can be considered instead of discrete position. (iii) Since the model is non-linear, for large size instances meta-heuristic can be proposed. (iv) Benchmarking the model in real industrial settings.

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Maintenance and Work-rest Scheduling in Human-machine System According to Fatigue and Reliability

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چکیده

بسیاری از کارخانجات تولیدی به منظور تولید محصولات با کیفیت از سیستم های انسان- ماشین بهره می برند. رویارویی با این سیستم ها به نسبت پیچیده است زیرا نه تنها باید شرایط مناسبی برای فعالیت ماشین آلات فراهم آورد بلکه باید محیط کار را برای منابع انسانی نیز در شرایط ایده آل نگه داشت. گرچه بسیاری از کارخانجات برنامه ای برای نگه داری و تعمیرات ماشین آلات دارند اما بسیاری از آن ها برنامه کار و استراحت مناسبی برای نیروی انسانی خود طرحریزی نکرده اند. با در نظر گرفتن این موضوع ما بر نقش نیروی انسانی در سیستم های انسان- ماشین تاکید کرده ایم و مدلی به منظور دستیابی به زمانبندی بهینه برای تعمیرات ماشین آلات و استراحت نیروی انسانی ارائه نموده ایم. این مدل با استفاده از مثال هایی مورد ارزیابی قرار گرفته و نتایج حاکی از اثر بخشی مناسب آن می باشد.

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