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Determining Maintenance Opportunity Window (MOW) in Job-Shop Systems by Considering Manpower of Maintenance

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Abstract– *Nowadays, production systems seek to integrate production and maintenance activities. An effective maintenance plan can improve maintenance stability and system performance. Machines that stop for repairing operation impose a high cost on the system. On the other hand, there are always some intangible situations during a production process in which repairing activities can be carried out. If they are detected, system productivity can be improved. The main purpose of this study is specifying Maintenance Opportunity Window (MOW) in job-shop production systems. For this purpose, mathematical models and formulae were developed in order to determine the MOW in a way that they could provide maximum repairing time for the machine and, as a result, the lowest disturbance occurring in production. This model also determines the number of lost products during PM. Considering the manpower of maintenance and M/M/1//k queueing model, the terms required for repairs are addressed. Finally, numerical experiments on and sensitivity analysis of critical parameters of the model, such as the initial level of the buffers and processing rates of the machines, are considered. Model validation is carried out by comparison of the results with a simulation model. In this study, some suggestions for improving the system are proposed.*

Keywords– *Job-shop systems, Maintenance opportunity window, Maintenance optimization, MOW.*

I. INTRODUCTION

Nowadays, there is a tendency to combine maintenance activities with production activities in a production system in order to increase the productivity of the system. Given to the fact that production systems are getting more complex, arranging how to integrate these activities is a tough task (Chang et al., 2007). Maintenance plays an important role in the manufacturing activities and covers about 60 percent of production costs (Keith, 2002). There are several maintenance strategies, two of which can be expressed as follows: Corrective Maintenance (CM) that is utilized to deal with unexpected failures; and Preventive Maintenance (PM) that is planned for renovations and restoration of a machine to keep it in proper state and prevent failures. In practice, due to the cost considerations, PM is preferred to CM (Gu et al., 2017). Traditionally, PM activities are performed at times outside production period, e.g., during weekends or shifts of the shutters (Li et al., 2009). For the first time, preventive maintenance policy was introduced by Barlow and Hunter (1960). In some studies, e.g., Coolen-Schrijner et al. (200), Doyen and Gaudoin (2011), and Sheu et al. (2006), the main focus is on opportunities investigation for maintenance performance time and some studies, e.g., Keizer et al. (201) and Liu et al. (2017), have focused on the condition investigation. Traditional planning of PM activities has some

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disadvantages including increase in the salary costs of maintenance staff because of the activity during the weekends or shifts of shutters. Increases in salaries can vary from one and a half to twice the amount of salaries in normal hours. In addition, in large-scale manufacturing systems, because of numerous PM-related activities, a queue of PM activities is formed. In this kind of circumstances, encountering time shortage is inevitable. Therefore, a comprehensive plan is required to deal with this condition (Keith, 2002).

Maintenance Opportunity Window (MOW) is a kind of strategy in which PM activities are carried out in an opportunity that has arisen deliberately or unintentionally during production time (Cui & Li, 2006). Most of the maintenance strategies focus on only one component of the system; but in the MOW, several components of the system are considered and, regarding different components of the system, different results are achieved (Cui & Li, 2006). Various models have been introduced to determine the performance of a production system with unreliable components and limited capacity buffers. Most of them are based on a steady-state analysis and focused on evaluation of the system in a limited period (Gershwin, 1994; Buzacott & Shanthikumar, 1993; Koochaki et al., 2012). We also need a mechanism for completing maintenance activities in short intervals (Yang et al., 2007; Guo et al., 2013; Ni & Jin, 2012; Li & Meerkov, 2008). The main purpose of utilizing MOW is the integration of production and maintenance activities in a manner that they do not influence the functionality of other machines and, in general, the production scheme. Some studies define MOW as the maximum time in which a machine can be stopped for PM during production in a manner that it does not affect the performance of other machines (Chang et al., 2007).

Chang et al. (2007) proposed a systematic approach to determining the appropriate time of conducting PM activity during the production period. The proposed method provided an algorithm for simulating the system. In their study, first, a 2M1B was considered and then, it was expanded to a production line. Gu et al. (2012) discussed the concept of MOW in deterministic systems. Lee et al. (2013) Generalized the concepts of MOW to different systems in the case of deterministic production data and determined MOW to overhaul a group of machines; they considered this state as a new concept and called it GMOW. GMOW is the maximum time in which a group of machines can be stopped for PM activities in a way that they do not affect other machines. Gu et al. (2013) outlined sophisticated production systems that included both assembly and disassembly lines or parallel machines. In this research, the MOW was determined in the case of deterministic problem data; in order to deal with the uncertainties associated, the authors performed a simulation and analyzed the systems in different conditions of the simulation. In order to deal with the uncertainty and probability of machine condition, Lee et al. (2013) calculated MOW in a 2M1B system using the Markov chain. They mainly focused on the minimum buffer level that should be available to complete the PM activities. Gu et al. (2015) introduced and determined a specific type of MOW called Positive MOW (PMOW). PMOW was the time in which a machine could be stopped due to the break-down of other machines. Gu et al. (2017) calculated Active MOW (AMOW), which was the period of time in which each machine could be stopped during the production period without affecting other machines, to perform PM activities at a time when there was no sudden failure due to the stop of a machine in the system. Li et al. (2015) calculated the Energy Opportunity Window (EOW), which was the time during which a machine could be stopped during production to reduce energy consumption. Zou et al. (2015) worked on a production line using the Markov chain and considering MOW. They assumed that data were probabilistic their purpose was to determine AMOW based on the slowest machine (bottleneck) so that the output of the production line did not fluctuate. Ni et al. (2015) also presented some models based on the discrete and continuous Markov chains to confront the probability and uncertainty of the data in systems. A summary of the research in this field is presented in Table I.

Considering the literature on this subject, we can mention manpower and the store building system as two topics not studied in the MOW problem. The question is “when a machine is stopped for the PM activities, is maintenance manpower available to carry out these activities? and if not, how long will the machine wait in the queue?” The production system considered in this study is a job-shop system, which has been neglected in previous studies. The main purpose of this paper is to determine the best time for performing each PM activity during production using the proposed model. MOW and the fluctuations in the machines are also determined by taking into account the manpower of maintenance. Unlike the other studies that have focused only on system output, this paper attempts to control and minimize the fluctuations in the performance of the machine. In addition to the extra costs imposed on the system, these fluctuations can also create an unpleasant feeling among the production staff. Therefore, in this paper, the 3M2B model is considered as the base for determining the MOW in the job-shop in a way that is has the minimum impact on performances of the machines in the previous or subsequent stages in the sequence of the production operation. Also, the fluctuations in the previous and subsequent machines are determined when they are stopped at a particular moment.

Table I. Characteristics of this study and related studies

Study	Probabalistic or deterministic			Production system					Objective of study				Solving approach				
	Probabilistic																
	deterministic	Discrete	Continues	2M1B	3M2B	Production line	Assembly or disassembly	Job-shop	AMOW calculation	PMOW calculation	Best time to overhaul	Lost products calculation	Simulation	Deterministic equations	Heuristic algorithm	Markov chain/queue systems	Considering manpower of maintenance
Chang et al. (2007)			✓	✓		✓			✓				✓				
(Gu et al. (2012)	✓			✓		✓	✓		✓					✓			
Lee et al. (2013)	✓		✓	✓	✓	✓	✓		✓		✓		✓	✓			
Gu et al. (2013)	✓			✓		✓	✓		✓			✓	✓				
Lee et al. (2013)		✓	✓	✓					✓		✓					✓	
Gu et al. (2015)		✓		✓		✓				✓					✓		
Ni et al. (2015)		✓	✓	✓		✓	✓		✓	✓						✓	
Zou et al. (2015)		✓		✓		✓			✓		✓					✓	
Gu et al. (2017)		✓		✓		✓			✓			✓			✓		
This study			✓		✓	✓	✓	✓	✓		✓	✓				✓	✓

The remainder of this study is as follows: in Section II, the problem and its assumptions are described and in Section III, MOW is determined in a 3M2B system. In Section IV, the 3M2B model is generalized to a Job-shop system and in Section V, a numerical sample is solved and then, the proposed model is validated using simulation approach. Finally, in Section VI and Section VII, a discussion and a conclusion are presented, respectively, for this study.

II. ASSUMPTIONS AND PROBLEM DESCRIPTION

The main assumptions of the study are as follows:

1. The MOW determination is done with the purpose of minimizing fluctuations in the activity of the machines. For this purpose, the stop of machines, which may occur in the MOW period, should be minimized for the previous and next machines.
2. Based on the production schematics, each machine can be a prerequisite to the next machines.
3. Each machine has its own buffer and the volumes of the occupied space by various products are equal in buffers.
4. Mean Time Between Failures (MTBF) and Mean Time Between Repairs (MTBR) are similar for all machines.
5. Processing rates for the products are different.
6. Failure rate, repair rate, demand rate, and processing rate for each product follow the Poisson distribution.
7. The maintenance department has only one group of repairers who can repair only one machine at a time.
8. During the repairing process of the machine M_i, the previous and next machines cannot break.
9. During the repairing process of the machine M_i, the previous machines are never blocked and the next machines never starve.

10. A machine will be blocked if the buffer is completed.
11. A machine will starve if the buffer is empty.
12. AMOW determination is one of the aims of the study and only MOW is used to abbreviate it.

The following symbols are used in this study

ρ_m: $Processing\ rate\ of\ machine\ m$

C_b: $Maximum\ capacity\ of\ buffer\ b$

γ: $Repair\ rate\ of\ machine\ m\ eqaul\ to\ \frac{1}{MTBR}$.

μ: $Failer\ rate\ of\ machine\ m\ equla\ to\ \frac{1}{MTBF}$

j_b: $Level\ of\ buffer\ b$

F_m: $Amount\ of\ flactuations\ in\ machine\ m$

t_{max}: $The\ lastest\ moment\ at\ which\ PM\ activity\ can\ start$

$B_{b,0}$: $Level\ of\ buffer\ b\ on\ the\ start\ time$

NB_m: $Set\ of\ machines\ previous\ to\ machine\ m$

NA_m: $Set\ of\ machines\ next\ to\ machine\ m$

K_m: The population of the system equal to

$Total\ Machines(the\ number\ of\ machines\ associated\ with\ the\ machine\ m\ that\ are\ previous\ or\ next\ to\ it)$

w_m: The time of waiting or PM activities for machine m

The following elements should be calculated to solve the problem.

1. Potential SMOW, BMOW a, d MOW (Given the buffer capacity of the previous and next machines M_i at the moment of stop).
2. The time required to perform repairs on machine M_i.

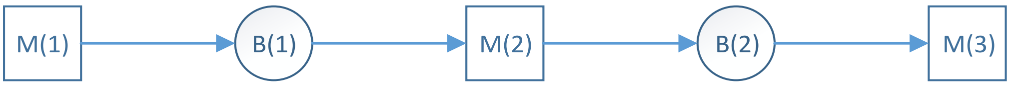

Fig. 1. Schematics of the 3M2B system

3. Duration of blockage of machines previous to machine M_i and duration of starvation of machines after machine M_i.
4. The optimum moment to start repairing machine M_i based on the levels of its pre- and post-buffers with the aim of maximizing the MOW.

III. DETERMINING MOW IN 3M2B SYSTEM

A. Problem description

As shown in *Fig.* (1), there are three machines and two buffers in this system. In order to illustrate the problem, it is assumed that the PM activities are planned for machine 2 during the production period. For this purpose, the available

MOW and the required MOW as well as the number of fluctuations in the machines previous to and after machine 2, and the optimal start time of PM activities should be determined.

For better understanding of the testing in this step, some definitions are provided below:

Definition 1. The amount of fluctuations is equal to the amount of time that each of the previous and next machines is lost due to blocking or starving during the PM activities on machine 2.

Definition 2. The MOW value, which is obtained by examining the blocking of machine number one, is shown with the symbol BMOW.

Definition 3. The MOW value, which is obtained by examining the starving of machine number three, is shown with the symbol SMOW.

B. Calculations

Machine 2 will be stopped at the moment t for PM activities. At this moment, there are i parts in buffer one and j parts in buffer 2. As the processing rate of each machine follows the Poisson distribution, it can be concluded that the lengths of the processing time for the two parts follow the exponential distribution and the lengths of the processing time of several parts follow the Erlang distribution; accordingly,

SMOW = E (the amount of time taken to consume parts in buffer 2)

$$\text{SMOW} = \frac{j_2}{\rho_3} \quad (1)$$

BMOW = E (the amount of time taken to complete the capacity of buffer 1)

$$\text{BMOW} = \frac{C_1 - j_1}{\rho_1} \quad (2)$$

As MOW is defined in such a way that there is no fluctuation in the system,

MOW = min {SMOW, BMOW}

$$\text{MOW} = \min \left\{ \frac{j_2}{\rho_3}, \frac{C_1 - j_1}{\rho_1} \right\} \quad (3)$$

Now, considering that the maintenance manpower is always free in this case, the fluctuation durations for machines 1 and 3 are determined as follows:

for machine 1: $T_1 = \max \{0, 1/\lambda - \text{BMW}\}$,

for machine 3: $T_3 = \max \{0, 1/\lambda - \text{SMOW}\}$,

$$\text{N1} = \text{E (number of pieces produced on machine 1 at T1)} = \text{T1} * \rho_1 \quad (4)$$

$$\text{N2} = \text{E (number of pieces produced on machine 3 at T3)} = \text{T3} * \rho_3 \quad (5)$$

Now, the best moment of time for stopping machine 2 should be calculated; for this purpose, a model is presented as follows:

$$\text{Max-min} \left\{ \frac{C_1 - j_1}{\rho_1}, \frac{j_2}{\rho_3} \right\}$$

S.t.

$j_1 \leq \rho_1 t - \rho_2 t + B_{b,0}$ (6)

$j_2 \leq \rho_2 t - \rho_3 t + B_{b,0}$ (7)

$0 \leq t \leq t_{max}$ (8a)

$0 \leq j_1 \leq c_1$ (8b)

$0 \leq j_2 \leq c_2$ (8c)

j_1, j_2 integer (9a)

t continues (9b)

In this model, the objective function maximizes the minimum SMOW and BMOW. *Eqs.* (6 & 7) calculate the maximum levels of buffers. *Eqs.* (8a-8c) specify bounds of decision variables. *Eqs.* (9a & 9b) determine types of variables.

IV. EXPANDING 3M2B TO JOB-SHOP SYSTEMS

A. Developing 3M2B to job-shop systems

Job-shop layouts are classified in product-base layouts; in this kind of layout, a machine can interact with several machines. Therefore, each machine may receive inputs from several machines and provide inputs to several machines. Thus, the machines before and after the machine M_i are specified. The formulae presented in Section III are generalized as follows:

SMOW = $min_{l \in NA_m}\{\frac{j_l}{\rho_l}\}$ (10)

SMOW = $min_{k \in NB_m}\{\frac{c_k - j_k}{\rho_k}\}$ (11)

MOW = $min_{k \in NB_m, l \in NA_m}\ \{\frac{j_l}{\rho_l}, \frac{c_k - i_k}{\rho_k}\}$ (12)

As we deal with several machines, when a machine is stopped for PM, a queue of machines waiting for maintenance may form. The waiting time and time of PM activities for the machine can be considered as an M/M/1//K queueing theory model; the Little's law is as follows:

$$w_m = \frac{L}{\gamma(c - L)} + \frac{1}{\mu}$$

Suppose that during the repairing activity on the machine m, the previous and next machines do not break down:

$(K_m - L)$= Average of healthy machines (13a)

Z_m=$(K_m - L)$ = $\sum_{i=0}^{(K_m} i * \frac{e^{-\gamma}\gamma^{(K_m - i)}}{(K_m - i)!}$ (13b)

$w_m = \frac{K_m - Z_m}{\gamma Z_m} + \frac{1}{\mu}$ (13c)

For machine $k \in NB_m$:

T_k= max $\{0, w_m - \frac{c_k - j_k}{\rho_k}\}$ (14)

For machine $l \in NA_m$:

$$T_l = \max \{0, w_m - \frac{j_l}{\rho_l}\} \quad (15)$$

$$N_k = E(\text{number of parts produced by machine k at } T_k) = T_k * \rho_k \quad (14a)$$

$$N_l = E(\text{number of parts produced by machine l at } T_1) = T_l * \rho_l \quad (15a)$$

For determining optimal stopping time, the model is proposed as follows:

$$\text{Max} - \min_{k \in K_m, l \in L_m} \{ \frac{j_l}{\rho_l}, \frac{c_k - i_k}{\rho_k} \}$$

S.t.

$$j_k \le \rho_k t - \rho_m t + b_{k,m,0} \quad \forall\, k \in NB_m \quad (16)$$

$$j_l \le \rho_m t - \rho_l t + b_{m,l,0} \quad \forall l \in NA_m \quad (17)$$

$$0 \le t \le t_{max} \quad (18a)$$

$$0 \le j_k \le c_k \quad \forall\, k \in NB_m \quad (18b)$$

$$0 \le j_l \le c_l \quad \forall l \in NA_m \quad (18c)$$

$$j_k, j_l \text{ integer} \quad \forall l \in NA_m, k \in NB_m \quad (19a)$$

t continues (19b)

where, the objective function maximizes the minimum SMOW and BMOW. *Eqs.* (16 & 17) calculate the maximum levels of buffers. *Eqs.* (18a-18c) specify bounds of decision variables. *Eqs.* (19a &19b) determine types of variables.

B. Calculation of processing rate with respect to the demand for the products

Given the assumption that each machine processes different products and there are different demands for these products, a specific machine works on a specific product at each moment of production period with a specific probability. Then, with respect to this probability, the processing rate is calculated for different products on each machine as follows:

$$Processing\ rate\ for\ the\ product\ = (probability\ of\ work\ on\ product\ x\ ) * (processing\ rate\ of\ the\ particular\ machine) \quad (20)$$

Table II. Production sequence and demand rate for products

Product	Production sequence	Demand rate (per day)
X1	M10<-M8<-M5<-M3<-M2<-M1	20
X2	M10<-M9<-M8<-M7<-M2	18
X3	M10<-M8<-M6<-M3<-M1<-M4	14
X4	M10<-M7<-M9<-M6<-M5<-M4<-M3	12
X5	M10<-M9<-M7<-M4<-M3<-M1	22

Table III. Characteristics of machines

Machine	MTBF	MTBR	Processing rate
M1	7200	180	0.125
M2	7200	180	0.2
M3	7200	180	0.2
M4	7200	180	0.125
M5	7200	180	0.2
M6	7200	180	0.25
M7	7200	180	0.25
M8	7200	180	0.125
M9	7200	180	0.125
M10	7200	180	0.5
*Times are in minutes			

Table IV. Characteristics of buffers

	Maximum capacity for each product	Level of each product				
Buffer		X1	X2	X3	X4	X5
B1	10	2				1
B2	8	2	2			
B3	8	7		2	1	1
B4	10			1	9	2
B5	12	1			1	
B6	14			1	3	
B7	10		3		2	3
B8	16	2	1	3		
B9	15		2		1	3
B10	-	-	-	-	-	-

Table V. The processing rate of machines in relation to machine 5

Machines before M5	Process rate
M3	0.0588
M4	0.03125
Machines after M5	
M8	0.048125
M6	0.11525
Products processed on machine 5	
X1	0.3125
X4	0.1875

V. NUMERICAL EXPERIMENT

A. Problem description and solving

A numerical example is presented to evaluate the performance of the proposed model in the calculation of the best opportunity to start PM and MOW as well as the rates of fluctuation in the machines. Then, the result is compared with the simulation result.

Suppose that there is a workshop with 10 machines and 9 buffers located one after the other. This workshop produces 5 products $X1, X2, \dots, X5$. Production sequence for each product is presented in Table II, characteristics of machines are presented in Table III, and characteristics of buffers are presented in Table IV. Based on *Eq.* (20), the processing rates of these machines should be calculated by considering product demands. Results of these calculations are shown in Table V.

Table VI. Level of buffers in the optimum overhaul time

Optimum stopping time	14
	Buffer level in optimum stopping time
X1 in buffer 3	0
X4 in buffer 4	5
X1 in buffer 5	8
X4 in buffer 5	4

Table VII. Fluctuations and lost products during PM activities on machine 5

Machine	Without fluctuation time	With fluctuation time	Lost products
M3	136	136	4
M4	160	160	1
M8	166	166	2
M6	35	35	20

Based on *Eqs.* (13a-13c), the required time for PM on machine 5 is calculated

Waiting time in maintenance queue = 36 minutes

MTBR= 180 minutes

Total required time = 216 minutes

The best opportunity to shut down machine 5 and start PM according to the suggested model is presented in Section IV. Solution results of this model are shown in Table VI. Also, on the basis of *Eqs.* (14, 15, 14a, &15a), fluctuations of each machine and the lost products on each machine are calculated, the results of which are presented in Table VII.

B. Validating the model using simulation

In this section, the example proposed in Section V.A is simulated by Rockwell Automation Arena 14.0 software; also, OptQuest software is used to apply parameters of the model to the optimization of simulation results. Then, the results are analyzed to validate the proposed model. For this purpose, the confidence interval for the results of the model was calculated using 100 simulation iterations, which are shown in Table VIII. The confidence interval is considered equal to 95%. The simulation has been used to clarify the states of the system in several iterations and each of the problem variables can be estimated based on the achieved statistics; moreover, their upper and lower bounds can be calculated.

Table VIII. Statistical analysis of simulation results

		Average of simulation	Variance	Lower bound of confidence level	Upper bound of confidence level
	Optimum stopping time	28	7	28	29
Buffer level in stopping time	X1 in B3	0	0	0	1
	X4 in B4	5	2	4	5
	X1 in B5	8	2	8	9
	X4 in B5	4	2	4	5
Time without fluctuation	M3	139	61	136	141
	M4	164	55	162	166
	M8	166	78	164	169
	M6	37	45	35	39
Average of lost products	X1 in M3	4	0	4	4
	X4 in M4	1	0	1	1
	X1 in M8	2	0	2	2
	X4 in M6	20	1	20	20

Based on the results in Table VIII, by comparing the confidence interval and results of the proposed model, it can be inferred that the model has high reliability and it can be utilized in real situations.

C. Sensitivity analysis

Based on the results in Table VI, machine 6 acts as a bottleneck. This machine has the maximum fluctuations and lost products. The proposed model relies on the processing rate of the machine and level of buffer in the moment of the start of PM. In this section, the sensitivity analysis of MOW is presented by changing the level of product X4 in buffer 5, reducing the rate of processing of machine 6, and increasing the rate of machine 5. The results of these sensitivity analyses are shown in *Figs*. (2-4).

VI. DISCUSSION

This paper advances the literature by integrating maintenance activity and production activity as well as eliminating wastes, which have a significant impact on the performance and productivity of the production system. One of the wastes is the lost time, which can be reduced by performing the PM activity when it has the lowest impact on production and fluctuations in machines. In this study, considering job-shop production systems instead of the production line, a mathematical model was proposed for the first time in Sections III and IV in order to calculate items related to MOW concept. Also, maintenance manpower was considered to calculate the required time for PM using an M/M/1//K queueing theory model. To deal with the bottleneck machine, two strategies can be adopted. If the bottleneck machine is after the proposed machine, then increasing the initial buffer level of the proposed machine is the first strategy. As shown in *Fig.* (2), MOW can be increased linearly by considering this strategy. However, this strategy cannot be efficient if the buffers are wasted in production systems. Another strategy that can be used is increasing the processing rates of the other machines or decreasing the processing rate of the bottleneck machine. To decrease the processing rate of the machine, for example, more jobs can be allocated to it. As shown in *Fig.* (3), this strategy can be useful to increase MOW in the best possible way.

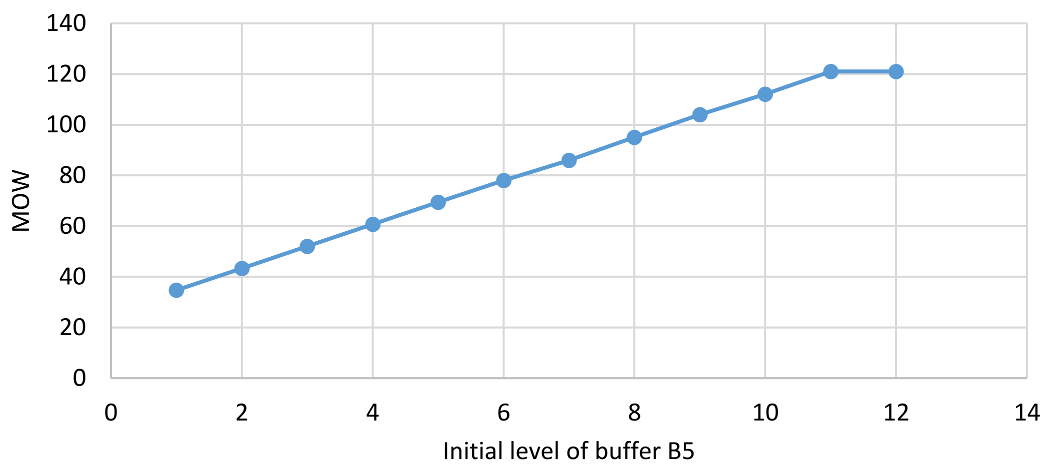

Fig. 2. Change in MOW by changing the initial level of product x4 in buffer 5

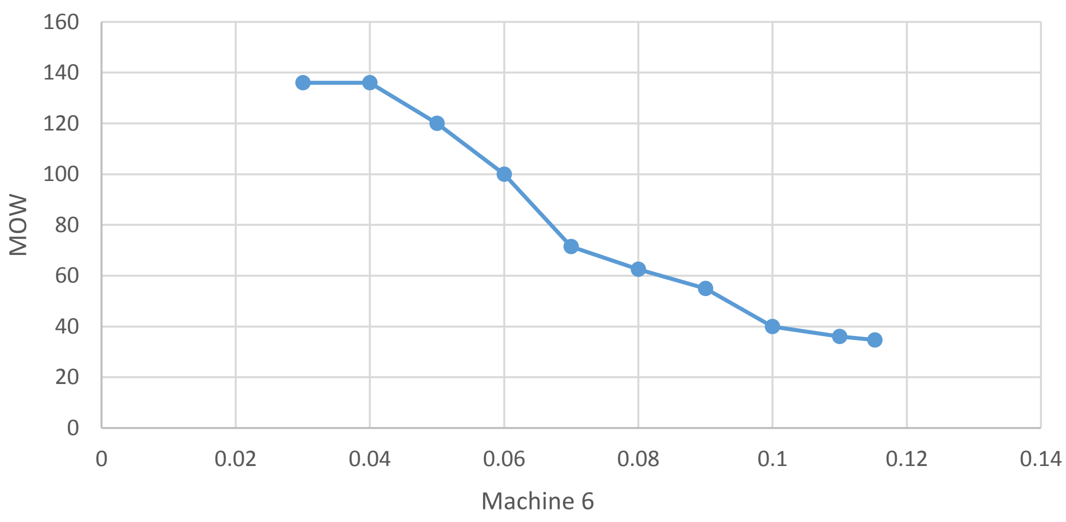

Fig. 3. Change in MOW by changing the machining rate of machine 6 for product x1

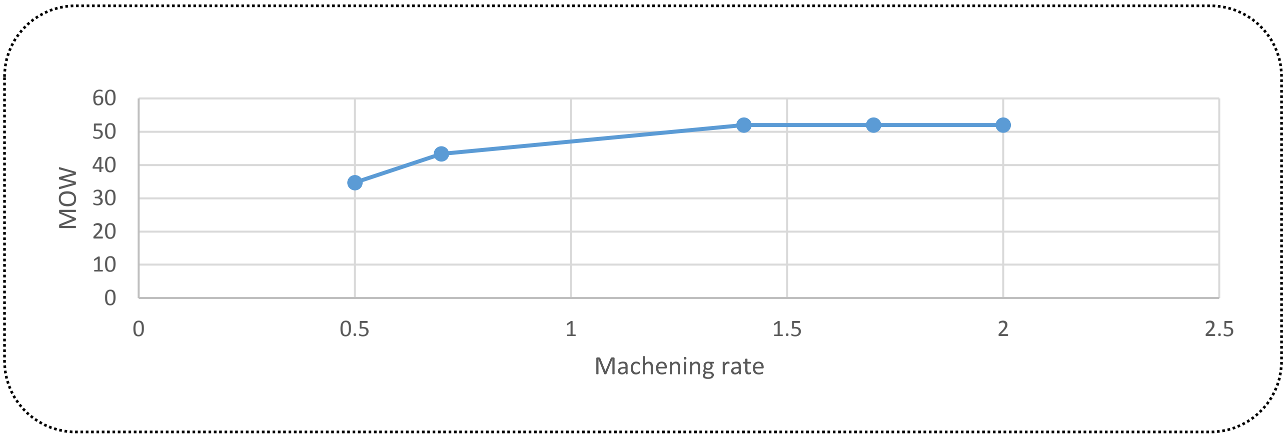

Fig. 4. Change in MOW by changing the machining rate of machine 5

Since several parameters are not deterministic in this study, some limitations emerge for the problem. They are explained along with their solving approaches in the following. First, the proposed model is based on the expected values of parameters. Another limitation we encounter is the assumption that machines are dependent on the previous and subsequent machines in calculating MOW and they cannot stop in the PM period. Moreover, MTBF and MTBR are considered similar for all machines, while they can be taken different for machines in the future research in order to increase applicability of the model. One more limitation is the objective of minimizing the fluctuations between machines. The suggestion of this study for future studies is changing the objective of the model or considering different repair rates and machines maintenance. Also, as the aim of this study was calculating the MOW, the future studies can focus on calculating POW. Moreover, as the proposed model in this study was a non-linear one, the problem was NP-HARD; solving the problem in large scales with continues evolutionary algorithms like Particle Swarm Optimization (PSO) or Simulated Annealing (SA) can be an attractive scope for new researchers.

VII. CONCLUSION

This study calculated the maintenance opportunity window in job-shop production systems. Considering 3M2B as the basic model, MOW, the best time to start PM, and fluctuations in buffers of machines in PM time wre calculated. Then, the proposed model was extended to a job-shop production system consisting several machines. Each machine could be related to other machines considering different products. Then, MOW, the best time to start PM, and fluctuations in the buffers of machines in PM time again as well as lost products on each machine were calculated. This model, maintenance manpower, and M/M/1//K queue model were considered for calculating the required time for PM. Finally, the model was validated using simulation and some critical production parameters, such as production fluctuation, were improved.

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References

Barlow, R., & Hunter, L. (1960). Optimum preventive maintenance policies. *Operations Research*, *8*(1), 90–100.

Buzacott, J. A., & Shanthikumar, J. G. (1993). *Stochastic models of manufacturing systems* (Vol. 4). Prentice Hall Englewood Cliffs, NJ.

Chang, Q., Ni, J., Bandyopadhyay, P., Biller, S., & Xiao, G. (2007). Maintenance opportunity planning system. *Journal of Manufacturing Science and Engineering*, *129*(3), 661–668.

Coolen-Schrijner, P., Shaw, S. C., & Coolen, F. P. (2009). Opportunity-based age replacement with a one-cycle criterion. *Journal of the Operational Research Society*, *60*(10), 1428–1438.

Cui, L., & Li, H. (2006). Opportunistic maintenance for multi-component shock models. *Mathematical Methods of Operations Research*, *63*(3), 493–511.

Doyen, L., & Gaudoin, O. (2011). Modeling and assessment of aging and efficiency of corrective and planned preventive maintenance. *IEEE Transactions on Reliability*, *60*(4), 759–769.

Gershwin, S. B. (1994). *Manufacturing systems engineering*. Prentice Hall.

Gu, X., Jin, X., Guo, W., & Ni, J. (2017). Estimation of active maintenance opportunity windows in Bernoulli production lines. *Journal of Manufacturing Systems*, *45*, 109–120.

Gu, X., Jin, X., & Ni, J. (2015). Prediction of passive maintenance opportunity windows on bottleneck machines in complex manufacturing systems. *Journal of Manufacturing Science and Engineering*, *137*(3), 031017.

Gu, X., Lee, S., Liang, X., Garcellano, M., Diederichs, M., & Ni, J. (2013). Hidden maintenance opportunities in discrete and complex production lines. *Expert Systems with Applications*, *40*(11), 4353–4361.

Gu, X., Lee, S., Liang, X., & Ni, J. (2012). Extension of maintenance opportunity windows to general manufacturing systems. In *Proc. of ASME 2012 International Manufacturing Science and Engineering Conference, Nortre Dame, IN.(MSEC2012-7346).*

Guo, W., Jin, J. J., & Hu, S. J. (2013). Allocation of maintenance resources in mixed model assembly systems. *Journal of Manufacturing Systems*, *32*(3), 473–479.

Keith, M. R. (2002). *An introduction to predictive maintenance*. Butterworth-Heinemann.

Keizer, M. C. O., Teunter, R. H., Veldman, J., & Babai, M. Z. (2018). Condition-based maintenance for systems with economic dependence and load sharing. *International Journal of Production Economics*, *195*, 319–327.

Koochaki, J., Bokhorst, J. A., Wortmann, H., & Klingenberg, W. (2012). Condition based maintenance in the context of opportunistic maintenance. *International Journal of Production Research*, *50*(23), 6918–6929.

Lee, S., Gu, X., Garcellano, M., Diederichs, M., & Ni, J. (2013). Discovery of hidden maintenance opportunities in automotive assembly lines: MOW and GMOW. *The International Journal of Advanced Manufacturing Technology*, *68*(9–12), 2611–2623.

Lee, S., Gu, X., & Ni, J. (2013). Stochastic maintenance opportunity windows for unreliable two-machine one-buffer system. *Expert Systems with Applications*, *40*(13), 5385–5394.

Li, J., Blumenfeld, D. E., Huang, N., & Alden, J. M. (2009). Throughput analysis of production systems: recent advances and future topics. *International Journal of Production Research*, *47*(14), 3823–3851.

Li, J., & Meerkov, S. M. (2008). *Production systems engineering*. Springer Science & Business Media.

Li, Y., Chang, Q., Jin, X., & Ni, J. (2015). Stochastic energy opportunity windows in advanced manufacturing systems. *ASME Paper No. MSEC2015-9257.*

Liu, B., Wu, S., Xie, M., & Kuo, W. (2017). A condition-based maintenance policy for degrading systems with age- and state-dependent operating cost. *European Journal of Operational Research*.

Ni, J., Gu, X., & Jin, X. (2015). Preventive maintenance opportunities for large production systems. *CIRP Annals-Manufacturing Technology*, *64*(1), 447–450.

Ni, J., & Jin, X. (2012). Decision support systems for effective maintenance operations. *CIRP Annals-Manufacturing Technology*, *61*(1), 411–414.

Sheu, S. H., Lin, Y. B., & Liao, G. L. (2006). Optimum policies for a system with general imperfect maintenance. *Reliability Engineering & System Safety*, *91*(3), 362–369.

Yang, Z., Chang, Q., Djurdjanovic, D., Ni, J., & Lee, J. (2007). Maintenance priority assignment utilizing on-line production information. *Journal of Manufacturing Science and Engineering*, *129*(2), 435–446.

Zou, J., Chang, Q., Lei, Y., Xiao, G., & Arinez, J. (2015). Stochastic Maintenance Opportunity Windows for Serial Production Line. In *ASME 2015 International Manufacturing Science and Engineering Conference* (p. V002T04A007–V002T04A007). American Society of Mechanical Engineers.