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EXTENSION OF MAINTENANCE OPPORTUNITY WINDOWS TO GENERAL MANUFACTURING SYSTEMS

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ABSTRACT

In manufacturing systems, many maintenance tasks require equipment to be stopped in order to safely perform them. However, such tasks cannot last for a long time since the stoppage of machines might directly result in production losses. In this paper, we investigate how long we can perform maintenance during scheduled operations by strategically shutting down equipment without bringing extra production losses to the system. Using the concept of maintenance opportunity window (MOW) we calculate such time intervals with given information of manufacturing systems. MOWs are analytically derived with various system configurations. Simulations are used to deal with uncertainties in production lines such as random machine failures, starvations, blockages, etc. Moreover, the proposed MOW algorithms are demonstrated through numerical case studies.

1. INTRODUCTION

Manufacturing systems usually consist of machines and material handling systems that are connected in a combination of serial or parallel lines. Since manufacturing systems in today's world are highly complicated and interconnected, reliability is becoming more and more important in operating manufacturing systems which are subject to deterioration with age and usage. In order to achieve a satisfactory level of reliability, maintenance is conducted on the system or its units.

There are large bodies of literature [1-6] discussing maintenance policies, which can be generally classified into reactive maintenance (RM), preventive maintenance (PM), and condition-based maintenance (CBM). RM happens when the units are down, and generally will result in longer time and cost. Therefore, it is necessary to perform PM tasks to reduce the random breakdown of the machines. In other words, machines should be strategically shut down for PM before their failure occurs. In the literature, the relationship between PM and the manufacturing system performance is explored [6, 7], and a number of maintenance models are developed to find the optimal policies [1, 3, 5]. Van der Duyn Schouten *et al*. [8] formulated the problem as a semi-Markov decision process, and found the optimal policy. Yao *et al*. [9] used a Markov decision process to find a joint PM and production policy by minimizing total costs (inventory holding, backlog, and maintenance cost). Riane *et al*. [10] formulated it as a linear programming problem to obtain an optimal policy.

Most PM policies developed are based on statistical parameters of a system (mean time between failure, mean time to repair, availability, etc.), which are collected for long-term, and thus the PM planning is predetermined to improve the system performance in the long run. On the other hand, CBM policies pay more attention to not only machine conditions but also real-time information of current system, concentrating more on the transient behavior of a system rather than production performance in steady state [11, 12].

In manufacturing systems, the buffers are used to mitigate short-term negative effects of the failure of the machine, protect stations from blockages and starvations, thus can have immediate impact on system performance. Gershwin *et al*. [13] used a continuous-flow model to analyze the manufacturing system with a buffer of finite capacity. Peters *et al*. [14] built hybrid models with restricted buffer sizes.

Although many researchers aimed to design lean buffers to keep inventory level low, extra space in buffers can protect the system from production losses for short time even if certain machines are down for maintenance. Then one question arises: how long can a station be idle while keeping throughput rate constant? To answer this question, the maintenance opportunity windows (MOWs) of a specific machine were defined by Chang *et al*. [15] as the maximum time duration that allows maintenance without bringing extra production loss to a system. Chang *et al*. analytically calculated MOWs in serial lines in [15], and accounted for the slowest station in [16]. These papers showed that if the station is idle for time less than or equal to its MOW, the production line will be running without throughput losses.

However, in this work, we consider the MOW as the maximum time window we can shut down one machine without causing the bottleneck machine(s) starved or blocked. The short-term bottleneck machines in manufacturing systems are the one whose sensitivity of the system production rate to a machine's production rate is the highest of all machines in the system. In other words, the production interruption on these short-term bottleneck machines will most likely result in the severest system production losses. Thus we do not want maintenance actions on non-bottleneck machines to introduce unnecessary stoppage of bottleneck machines. The data-driven method to detect such short-term bottleneck machines has been developed in [17, 18]. Furthermore, we extend the MOW calculation from serial lines to assembly and disassembly system, and finally to a general manufacturing system which can be a combination of serial and parallel lines.

The remainder of this paper is organized as follows. In Section 2, we analyze MOWs of machines in serial and assembly/disassembly systems, and then extend them to a general manufacturing system. In Section 3, a simulation-based algorithm is used and two case studies are performed. Finally, Section 4 summarizes our conclusions and future research.

2. MAINTENANCE OPPORTUNITY WINDOWS

2.1. MOW for a two-machine one-buffer system (2M1B)

A 2M1B system shown in Figure 1 is discussed to understand basic ideas of an MOW. This 2M1B model can be used as a building block for longer lines and more complex systems.

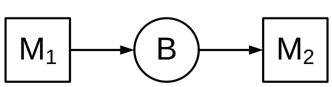


Figure 1: A two-machine one-buffer line (2M1B)

The assumptions and notations for this model are:

- The production rates for machines M_1 and M_2 are denoted as m_1 and m_2, respectively.
- A machine can process only one part at a time. $I_i = 1$ if there is initially a part in machine M_i and $I_i = 0$ if there is no part in machine M_i.
- The buffer level N is continuous and $N(t)$ is a buffer level at time t .
- No machine failure occurs.
- No material travelling time at the buffer is considered.

Assume that at time $t = 0$, machine M_1 is strategically shut down for preventive maintenance. Then the system will be eventually empty at time T as shown in Figure 2. The time duration T depends on the total number of parts in buffer B and machine M_2, and is given by

$$N(0) + I_2 = m_2 T \tag{1}$$

However, after time T, machine M_2 will be starved and cause production losses to the system. Therefore, we can shut down machine M_1 only until buffer B has at least one part at time T,

$$N(T) = 1 . \tag{2}$$

Assuming machine M_1 will be down for MOW_1, we have

$$N(T) - \left(N(0) + I_2\right) = -m_2 \text{MOW}_1 + \left(m_1 - m_2\right)\left(T - \text{MOW}_1\right) . \tag{3}$$

Then, MOW_1 can be calculated as

$$\text{MOW}_1 = \frac{N(0) + I_2}{m_2} - \frac{1}{m_1} . \tag{4}$$

The change in a buffer level over time is shown in Figure 2 to illustrate how to calculate MOW_1 for a 2M1B line. Note that we calculate MOW_1 with the bottleneck machine M_2 ($m_1 \geq m_2$).

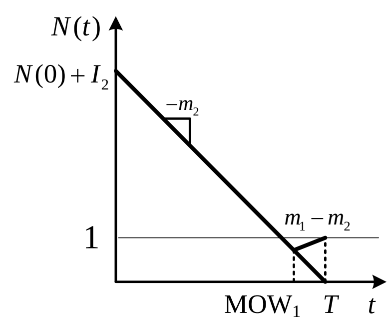


Figure 2: Illustration of MOW_1 calculation of a 2M1B line

On the other hand, if $m_1 < m_2$, the bottleneck is machine M_1 and we can shut down machine M_2 for MOW_2 without bringing system production losses. The illustration is shown in Figure 3, where T is the time that buffer B will become full (i.e., it reaches its capacity, C) if machine M_2 is down during $(0, T]$. After time T, machine M_1 will be blocked and cause production losses to the system. Therefore, we are allowed to shut down machine M_2 only until buffer B has an empty space for at least one part at time T. Similar with Equations from (1) to (3), we have

$$C-\left(N(0)-I_1\right)=m_1 T \quad (5)$$

$$N(T)=C-1 \quad (6)$$

$$N(T)-\left(N(0)-I_1\right)=m_1\mathrm{MOW}_2+(m_1-m_2)(T-\mathrm{MOW}_2) \quad (7)$$

Then, MOW_2 is expressed by

$$\mathrm{MOW}_2=\frac{\left(C-N(0)\right)+I_1}{m_1}-\frac{1}{m_2}. \quad (8)$$

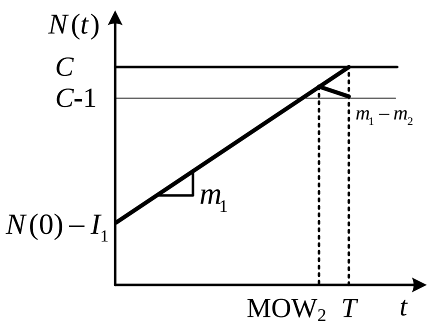


Figure 3: The MOW$_2$ calculation when $m_1 < m_2$

In summary, the MOWs for each machine are given by:

$$\begin{cases}\mathrm{MOW}_1=\dfrac{N(0)+I_2}{m_2}-\dfrac{1}{m_1} & \text{if } m_1\geq m_2\\ \mathrm{MOW}_2=0 & \end{cases}$$
$$\begin{cases}\mathrm{MOW}_1=0 & \\ \mathrm{MOW}_2=\dfrac{\left(C-N(0)\right)+I_1}{m_1}-\dfrac{1}{m_2} & \text{if } m_1< m_2\end{cases}. \quad (9)$$

From Equation (9), we can observe that MOWs depend on the production rates of two machines, initial buffer contents, and part in machines. Furthermore, Equation (9) provides us with insights of a reversibility property.

$$N(0)\leftrightarrow C-N(0)$$
$$I_2\leftrightarrow I_1$$
$$m_2\leftrightarrow m_1$$

The reversed 2M1B line of the original line in Figure 1 can virtually be imagined and given by the following line in Figure 4. Then machine M$_2$ becomes an upstream machine and machine M$_1$ is a downstream one with the same production rates.

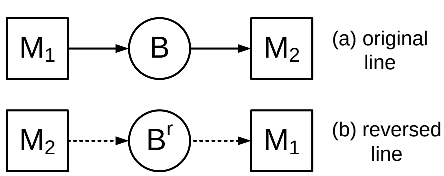


Figure 4: Reversed 2M1B line

Suppose $m_1 < m_2$ and an initial buffer content is $N^r(0)$, then MOW$_2$ for machine M$_2$ in the reversed line can be calculated by Equation (4) as

$$\mathrm{MOW}_2=\frac{N^r(0)+I_1}{m_1}-\frac{1}{m_2} \text{ in the reversed line}. \quad (10)$$

On the other hand, MOW$_2$ in the original line in Equation (8) is given by

$$\mathrm{MOW}_2=\frac{\left(C-N(0)\right)+I_1}{m_1}-\frac{1}{m_2} \text{ in the original line}. \quad (11)$$

Compared with Equations (10) and (11), MOWs are identical if we set $N^r(t)=C-N(t)$. If the bottleneck machine is located upstream, we can reverse a line to have the bottleneck machine downstream with changes of buffer contents from $N(0)$ to $N^r(0)$. Then equivalent MOWs can be achieved. We call it as the reversibility property and use it to calculate MOWs for more complicated manufacturing systems.

2.2. MOW for a Serial Line

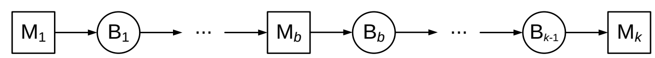


Figure 5: A *k*-machine (*k*-1)-buffer serial line

We consider MOWs of machines in a k-machine (k-1)-buffer balanced serial line in Figure 5. The assumptions are similar to what we have made for the 2M1B model.

- The buffer level N is continuous and $N(t)$ is a buffer level at time t.
- $I_i=1$ if there is an initial part in machine M$_i$, $I_i=0$ if there is no initial part in machine M$_i$.
- Production flow is continuous and the production rate for machine M$_i$ at time t is equal to $m_i(t)$.
- No machine failures.
- No traveling time at buffers is considered.

2.2.1. MOW for a Balanced Serial Line

Suppose that all production rates are the same (i.e., $m_1=m_2=\cdots=m_k$) in Figure 5. We want to calculate the MOW$_1$ of machine M$_1$. By the definition of MOW, the throughput of the system in time interval $(0,\mathrm{MOW}_1]$ will be equal to $m_k\times\mathrm{MOW}_1$. The dynamics of the system satisfies:

$$\int_0^T\left(m_i(t)-m_{i-1}(t)\right)dt=N_{i-1}(0)+I_i-I_{i-1}^L \quad i=2,\cdots,k \quad (12)$$

where I_i^L is denoted as the minimum number of parts we should maintain in machine M$_i$ to prevent machine M$_k$ from starvation.

Set $T = \text{MOW}_1$, and add all i 's for both sides of Equation (12),

$$m_k \text{MOW}_1 = \sum_{i=2}^{k}\left(N_{i-1}(0) + I_i - I_{i-1}^L\right)$$
$$\therefore \text{MOW}_1 = \frac{\sum_{i=2}^{k}\left(N_{i-1}(0) + I_i\right) - \sum_{i=1}^{k-1} I_i^L}{m_k} \tag{13}$$

In the continuous-flow model, the value of I_i^L can be calculated as

$$I_i^L = CT_i \cdot m \tag{14}$$

where CT_i is the cycle time of machine M_i and m is the system flow rate determined by the production rate of the bottleneck machine. Therefore,

$$\frac{I_i^L}{I_k^L} = \frac{CT_i \cdot m}{CT_k \cdot m} = \frac{m_k}{m_i}. \tag{15}$$

Since machine M_k has been running during $(0, \text{MOW}_1]$, there is always one part in machine M_k (i.e., $I_k^L = 1$). Then, $I_i^L = \frac{m_k}{m_i} = 1$ due to the same production rates. Substituting it into Equation (13), we have

$$\text{MOW}_1 = \frac{\sum_{i=2}^{k}\left(N_{i-1}(0) + I_i\right) - (k-1)}{m_k} \tag{16}$$

2.2.2 MOW for an Unbalanced Serial Line

Consider an unbalanced serial line whose machine-level production rates m_i (i = 1, 2, ···, k) are different in Figure 5. Assume that machine M_b is the bottleneck machine in the system. The MOW_1 of machine M_1, which is located upstream of machine M_b, can be computed by Equation (17):

$$\begin{aligned} \text{MOW}_1 &= \frac{\sum_{i=2}^{b}\left(N_{i-1}(0) + I_i\right) - \sum_{i=1}^{b-1} I_i^L}{m_b} \\ &= \frac{\sum_{i=2}^{b}\left(N_{i-1}(0) + I_i\right) - \sum_{i=1}^{b-1} \frac{m_b}{m_i}}{m_b} \\ &= \frac{\sum_{i=2}^{b}\left(N_{i-1}(0) + I_i\right)}{m_b} - \sum_{i=1}^{b-1}\left(\frac{1}{m_i}\right) \end{aligned} \tag{17}$$

On the other hand, machine M_k is located downstream of the bottleneck machine M_b. We can use the reversibility property to derive the MOW_k:

$$\begin{aligned} \text{MOW}_k &= \frac{\sum_{i=k-1}^{b}\left(N_i^r(0) + I_i\right)}{m_b} - \sum_{i=k}^{b+1} \frac{1}{m_i} \\ &= \frac{\sum_{i=b}^{k-1}\left(N_i^r(0) + I_i\right)}{m_b} - \sum_{i=b+1}^{k} \frac{1}{m_i} \\ &= \frac{\sum_{i=b}^{k-1}\left(\left(C_i - N_i(0)\right) + I_i\right)}{m_b} - \sum_{i=b+1}^{k} \frac{1}{m_i} \end{aligned} \tag{18}$$

Of course, Equation (18) can be directly derived from Equation (12).

$$\int_0^{\text{MOW}_k}\left(m_i(t) - m_{i+1}(t)\right)dt = \left(C_i - N_i(0)\right) + I_i - I_{i+1}^L \quad i = b, \cdots, k-1$$
$$\begin{aligned} \therefore \text{MOW}_k &= \frac{\sum_{i=b}^{k-1}\left(\left(C_i - N_i(0)\right) + I_i - I_{i+1}^L\right)}{m_b} \\ &= \frac{\sum_{i=b}^{k-1}\left(\left(C_i - N_i(0)\right) + I_i\right) - \sum_{i=b+1}^{k} \frac{m_b}{m_i}}{m_b} \end{aligned} \tag{19}$$

2.3. MOW for Assembly/Disassembly Systems

2.3.1. Assembly Systems

Real manufacturing systems often consist of serial and assembly systems. Therefore, we also investigate MOWs for assembly systems in addition to the MOW in the serial lines. Suppose that machine M_1 produces part p_1 and machine M_2 makes part p_2. Parts p_1 and p_2 are assembled in machine M_3 as shown in Figure 6.

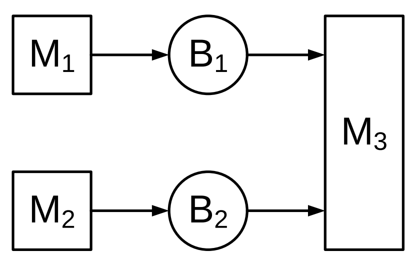


Figure 6: A model for an assembly system

We analyze the MOWs of machine M_1 in two different cases:

Case 1: machine M_3 is the bottleneck machine

Machine M_2 has little influence on machine M_1 so that we can use a 2M1B model with M_1-B_1-M_3 for MOW_1 and with M_2-B_2-M_3 for MOW_2. By Equation (4), the MOW_1 and MOW_2 would be given as

$$\begin{aligned}\mathrm{MOW}_1 &= \frac{N_1(0)+I_1}{m_3} - \frac{I_1^L}{m_1} \\ \mathrm{MOW}_2 &= \frac{N_2(0)+I_2}{m_3} - \frac{I_2^L}{m_2}\end{aligned}. \qquad (20)$$

Case 2: machine M_2 is the bottleneck machine

The dynamics for buffers B_1 and B_2 can be written as Equations (21) and (22), respectively.

$$\int_0^{\mathrm{MOW}_1} m_1(t)dt - \int_0^{\mathrm{MOW}_1} m_3(t)dt = N_1(0) + I_3 - I_1^L, \qquad (21)$$

$$\int_0^{\mathrm{MOW}_1} m_2(t)dt - \int_0^{\mathrm{MOW}_1} m_3(t)dt = C_2 - N_2(0) + I_2 - I_3^L. \qquad (22)$$

Therefore,

$$\begin{aligned}\mathrm{MOW}_1 &= \frac{N_1(0)+I_3-I_1^L+(C_2-N_2(0))+I_2-I_3^L}{m_2} \\ &= \frac{N_1(0)+I_3+(C_2-N_2(0))+I_2}{m_2} - \frac{I_1^L+I_3^L}{m_2}\end{aligned}. \qquad (23)$$

The MOW in an assembly system can be also calculated using the reversibility property which is discussed in Section 2.1. The assembly system in Figure 6 can be redrawn like the one in Figure 7 (a), which can be further transformed equivalently to a serial line in Figure 7 (b).

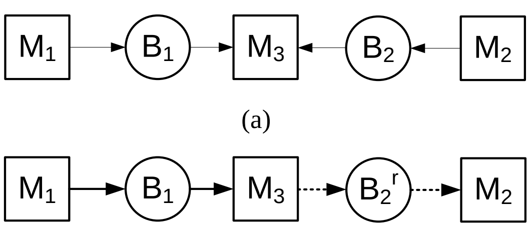


Figure 7: Equivalent serial lines of an assembly system

By using Equation (13) which is developed for MOWs of serial lines, MOWs for machines M_1 and M_3 are calculated as

$$\begin{aligned}\mathrm{MOW}_3 &= \frac{N_2^r(0)+I_2-I_3^L}{m_2} \\ \mathrm{MOW}_1 &= \frac{N_1(0)+I_2+N_2^r(0)+I_3-I_1^L-I_3^L}{m_2} \\ &= \frac{N_1(0)+I_2+\left(C_2-N_2(0)\right)+I_3}{m_2} - \frac{I_1^L+I_3^L}{m_2}\end{aligned} \qquad (24)$$

which is exactly the same with Equation (23).

2.3.2. Disassembly Systems

A basic disassembly system is shown in Figure 8 and its equivalent serial lines are presented in Figure 9 (a) and (b) for the cases that the split machine is the bottleneck and a non-split machine is the bottleneck one, respectively.

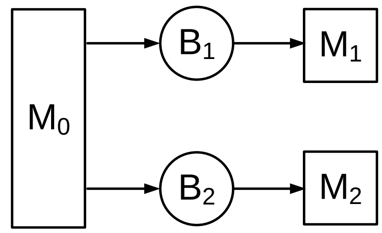
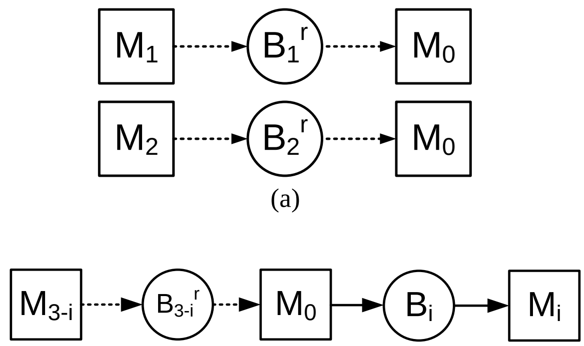


Figure 8: Disassembly system



(b)

Figure 9: Equivalent serial lines for the disassembly system

Their MOWs for the non-bottleneck machines in both cases are given by

$$\begin{cases}\mathrm{MOW}_0 = 0 \\ \mathrm{MOW}_i = \dfrac{C_i - N_i(0) + I_0 - I_i^L}{m_0}\end{cases} \quad \text{if } \mathrm{M_b} = \mathrm{M}_0,\ i = 1,2 \qquad (25)$$

$$\begin{cases}\mathrm{MOW}_0 = \dfrac{N_i(0)+I_i-I_0^L}{m_i} \\ \mathrm{MOW}_i = 0 \\ \mathrm{MOW}_{3-i} = \dfrac{C_{3-i}-N_{3-i}(0)+I_0+N_i(0)+I_i-(I_{3-i}^L+I_0^L)}{m_i}\end{cases} \qquad (26)$$

$$\text{if } \mathrm{M}_b = \mathrm{M}_i,\ i = 1,2$$

2.4. MOW for General Manufacturing Systems

Using all the results shown above, we are able to compute the MOW for machines in a general manufacturing system shown in Figure 10, including assembly/disassembly and serial/parallel lines.

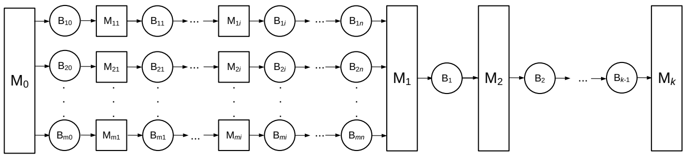


Figure 10: MOW in a combined system

We define l^{ij} as a line (or path) from machine M_i to machine M_j that satisfies the following:

- The structure of the line is M-B-M-B-…-B-M.
- All the connecting pairs in l^{ij} can be found in the original system either with the forward or backward order.

Let $L^{ib} = \{l_1^{ib}, l_2^{ib}, \cdots\}$ be the set of all the possible lines (or paths) from machine M_i to the bottleneck machine M_b. Then MOW_i of machine M_i in a general system is given by

$$\text{MOW}_i = \min \text{MOW}_i\left(L^{ib}\right) = \min_{\text{all } n}\left(\text{MOW}_i\left(l_n^{ib}\right)\right), \qquad (27)$$

where $\text{MOW}_i\left(l_n^{ib}\right)$ means the MOW of machine M_i in line l_n^{ib}.

3. CASE STUDY IN SIMULATION

3.1. Simulation-based MOW calculation

For transient behavior of a system with many uncertainties such as random machine failures, it is difficult to analyze them even if the behavior of machines obeys some probability models. Hence, it might not be feasible to obtain analytical MOWs of such systems. Uncertainties (random machine failure and its consequences) and disturbance (maintenance and raw material readiness, etc.) will affect production line smoothness. In order to have a model as close to a real production line as possible, a simulation is often used. Chang *et al*. [15] proposed an algorithm to estimate the MOW via a simulation and is given by

$$\text{MOW}_i = T_i^{\text{empty}} - T_i^{\text{resume}}, \qquad (28)$$

where T_i^{empty} is the time until the buffers and all machines between machine M_i and machine M_b (excluding machine M_i but including the bottleneck machine M_b) are empty, and T_i^{resume} is the time duration from the time when the job enters machine M_i to the time when that job is ready to enter machine M_b.

If the simulation model for a production line is built, it is easy to obtain values of T_i^{empty} and T_i^{resume} from the simulation model for the MOW calculation. Moreover, we can show that this simulation-based MOW algorithm in Equation (28) agrees with the analytical results in Equation (17). By definition, T_i^{empty} and T_i^{resume} are given by

$$T_1^{\text{empty}} = \frac{\sum_{i=2}^{b}\left(N_{i-1}(0) + I_i\right)}{m_b}, \qquad T_1^{\text{resume}} = \sum_{i=1}^{b-1}\frac{1}{m_i}.$$

Hence, MOW_1 for machine M_1 can be calculated as

$$\text{MOW}_1 = T_1^{\text{empty}} - T_1^{\text{resume}} = \frac{\sum_{i=2}^{b}\left(N_{i-1}(0) + I_i\right)}{m_b} - \sum_{i=1}^{b-1}\left(\frac{1}{m_i}\right) \qquad (29)$$

which is identical with Equation (17).

3.2. MOW Validation via Simulation

MOW can be validated through a simulation using the MOW definition. Since MOW is defined as the maximum time interval that will not influence the bottleneck machine despite shutting down a specific machine M_i, stopping machine M_i for shorter than its MOW_i will not induce any work loss on the bottleneck machine. On the other hand, if machine M_i is shut down for longer than its MOW_i, it will cause the bottleneck machine M_b to be either starved or blocked, resulting in a system production loss. Using this idea, the validation steps via a simulation can be summarized:

1) Calculate MOW_i for machine M_i
2) Force machine M_i to be idle for a given time duration T
3) Collect completion times for each completed job on the bottleneck machine M_b via a simulation
4) Repeat Steps 2 and 3 with different Ts
5) Compare the results in Step 4 under different Ts to see if the completion time difference between consecutive jobs is larger than the cycle time of machine M_b

3.3. Numerical Case Studies

We perform the simulation-based MOW calculations and validate them with the following two manufacturing systems. This simulation work is done using the discrete event simulation of SIMUL8.

3.3.1. Case Study 1: Serial Line

Consider a system whose layout, characteristics, and initial levels are shown in Figure 11 and Table 1.

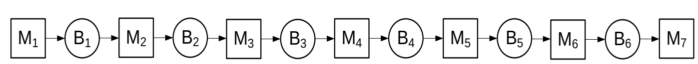


Figure 11: The layout of a serial line for case study 1

Table 1: System characteristics for a system in Figure 11

Machine	M_1	M_2	M_3	M_4	M_5	M_6	M_7
Avg. Cycle Time	60	60	60	66	60	60	60
Initial Content, I_i	1	1	1	1	1	1	1

Buffer	B_1	B_2	B_3	B_4	B_5	B_6
Capacity, C_i	5	5	5	5	5	5
Initial Contents, $N(0)$	3	3	4	1	2	2

With the one hour warm-up period, the percentages of each machine's working, starvation, and blockage time are recorded via a simulation and shown in Table 2. It reveals that machine M_4 operates all the time and can be regarded as the short-term bottleneck machine of this serial production line. MOWs can be calculated such that their stoppages will not influence the working time of machine M_4. MOW for each machine is shown in Table 3 and plotted in Figure 12 after running the simulation model 200 times.

Table 2: Percentage of working/starvation/blockage time

Machine	Working Time (%)	Starvation Time (%)	Blockage Time (%)
M_1	99.29(±0.63)	0	0.71(±0.63)
M_2	96.84(±1.47)	2.02(±1.36)	1.14(±0.82)
M_3	93.44(±2.05)	1.19(±1.02)	5.37(±2.15)
M_4	100	0	0
M_5	91.74(±1.57)	8.26(±1.57)	0
M_6	91.85(±1.97)	8.15(±1.97)	0
M_7	91.89(±1.71)	8.11(±1.71)	0

Table 3: MOWs for system in Figure 11

Machine	M_1	M_2	M_3	M_4	M_5	M_6	M_7
Analytical MOW_i	11.3	7.9	4.5	0	4.5	7.9	11.3
Simulation-based MOW_i (95% C.I.)	11.14 (±0.37)	7.76 (±0.36)	4.39 (±0.21)	0	4.46 (±0.32)	7.70 (±0.36)	11.15 (±0.41)

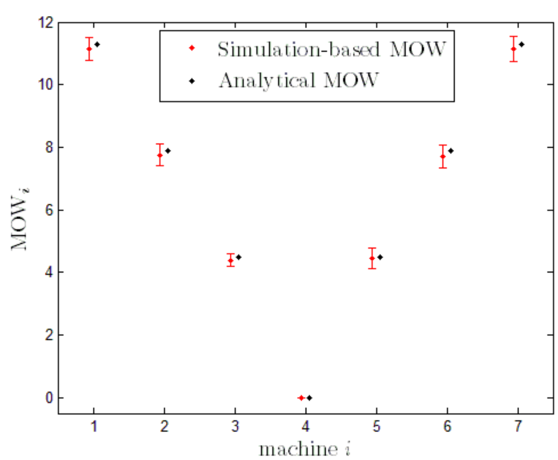


Figure 12: MOWs for system in Figure 11

We set up the initial buffer levels $N_i(0)$ in a way that the reversed line of M_4-B_4-M_5-B_5-M_6-B_6-M_7 (equal to M_7-B^r_6-M_6-B^r_5-M_5-B^r_4-M_4) is exactly identical with the forward line of M_1-B_1-M_2-B_2-M_3-B_3-M_4. As results, we can observe symmetric MOWs values about machine M_4 as shown in Figure 12.

The validation is performed for machines M_2 and M_6 which are symmetric around M_4. For machine M_2, we set T as the time for which we stop machine M_2, and record the completion time of consecutive parts that go through the bottleneck machine M_4 under different Ts. The simulation is run 200 repetitions and the average completion time is plotted in Figure 13.

If we stop machine M_2 first, there are still 9 parts remaining to be processed by machine M_4 (3 parts in buffer B_2, 4 parts in buffer B_3, 2 parts in both machines M_3 and M_4). Therefore, no matter what T value is, there is no difference in completion time for the first 9 parts. However, starting from the 10th part, the discontinuity appears. As shown in Figure 13, if T = 6 or 7 minutes, there are almost no differences comparing with the case of T = 0 (i.e., no machine downs). On the other hand, if we shut down machine M_2 for 8 minutes, the discontinuity will occur in several repetitions. It indicates that MOW_2 (7.76±0.36) lies between 7 and 8 minutes.

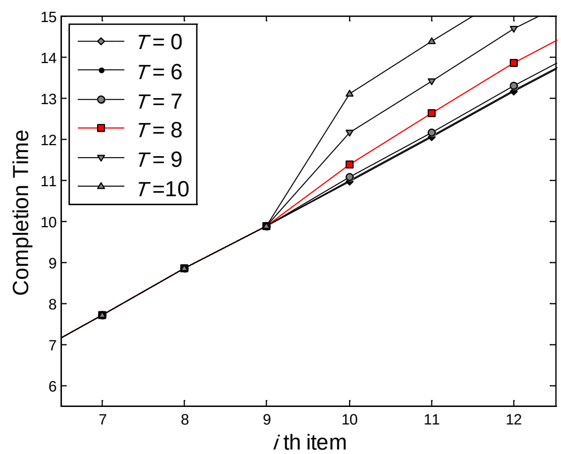


Figure 13: MOW validation for machine M2

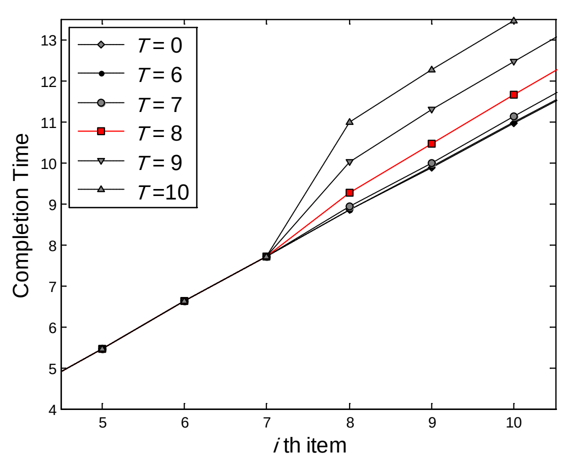


Figure 14: MOW validation for machine M_6

Similarly, if we shut machine M_6 down, there will be 7 spaces left until machine M_4 gets blocked (3 spaces in buffer B_5 and 4 spaces in buffer B_4) and the discontinuity may occur starting from the 8th parts. Figure 14 shows the completion times under different *T*s for which we shut down machine M_6, and the fact that the behavior is similar with that in Figure 13. Again, Figure 14 provides an evident that the actual MOW_6 (7.70 ±0.36) lies between 7 and 8 minutes.

3.3.2. Case Study 2: Combined System

Next, we consider a system combined with serial lines and assembly/disassembly system. The machine cycle times and buffer capacities are shown in Table 4.

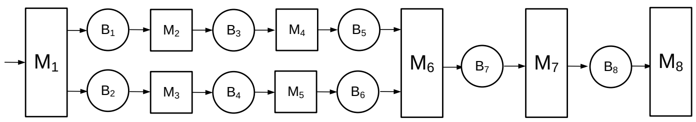


Figure 15: The layout of the system in case study 2

Table 4: Characteristics of the system

Machine	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8
Cycle Time	60	60	60	60	60	62	60	65

Buffer	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8
Capacity, *C*	3	3	3	3	3	3	3	3

Table 5: Percentage of working/starvation/blockage time

Machine	Working Time (%)	Starvation Time (%)	Blockage Time (%)
M_1	97.31(±1.39)	0	2.69(±1.39)
M_2	94.63(±1.60)	1.64(±1.23)	3.73(±1.57)
M_3	96.73(±1.10)	0.57(±0.54)	2.70(±1.06)
M_4	93.94(±1.99)	0.69(±0.74)	5.37(±2.02)
M_5	95.30(±1.96)	1.07(±0.87)	3.63(±1.92)
M_6	96.41(±1.56)	1.61(±1.18)	1.98(±1.59)
M_7	93.13(±1.52)	2.84(±1.49)	4.04(±1.80)
M_8	98.86(±1.16)	1.14(±1.16)	0

The starvation and blockage time for all machines during the collection period (1 hour) are provided in Table 5, showing that machine M_8 is the short-term bottleneck machine of the system. For machines M_6 and M_7, there is only one path to machine M_8. On the other hand, for machines M_1, M_2, M_3, M_4, and M_5, there are two paths to reach machine M_8. For example, machine M_2 can reach machine M_8 via either a forward path of M_2-B_3-M_4-B_5-M_6-B_7-M_7-B_8-M_8 or a backward of M_2-B^r_1-M_1-B_2-M_3-B_4-M_5-B_6-M_6-B_7-M_7-B_8-M_8.

Table 6: Initial buffer levels for system

Machine	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8
Initial Contents, I_i	1	1	1	1	1	0	1	1

Buffer	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8
Initial Contents, $N(0)$	3	1	2	1	2	1	2	2

Here we consider the case that the initial values of the buffers are chosen as shown in Table 6, and MOWs are calculated and displayed in Table 7 and Figure 16. MOW_2 is calculated from the reversed line M_2-B^r_1-M_1-B_2-M_3-B_4-M_5-B_6-M_6-B_7-M_7-B_8-M_8 which is a disassembly system.

Table 7: MOWs with the initial buffer level in Table 6

Machine	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8
Analytical MOW_i	6.90	6.99	5.75	5.67	4.58	4.5	2.25	0
Simulated MOW_i (95% C.I.)	6.79 (±0.68)	6.89 (±0.94)	5.59 (±1.19)	5.53 (±0.88)	4.45 (±1.11)	4.47 (±0.88)	2.18 (±0.42)	0

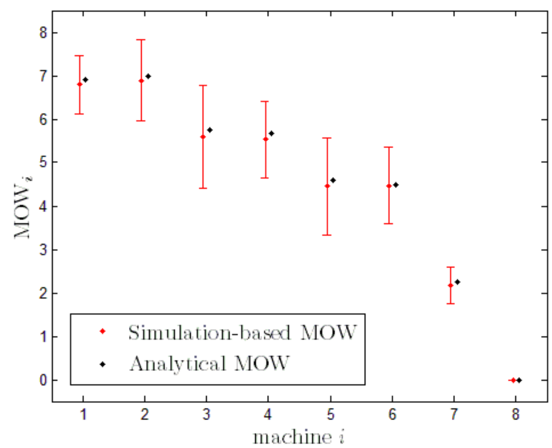


Figure 16: MOWs calculation

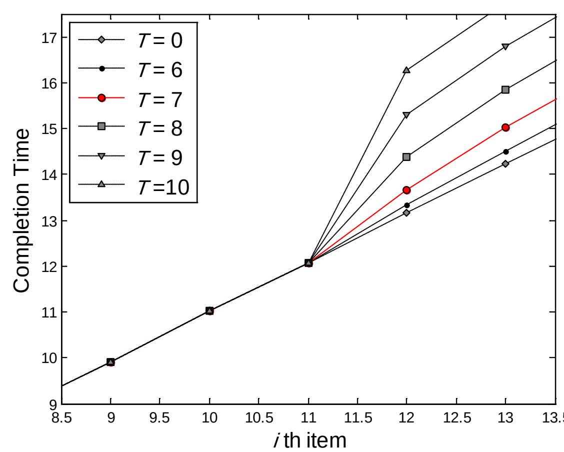


Figure 17: MOW validation for machine M_2

Buffer B_1 is initially full, indicating that machine M_1 will be blocked until machine M_2 resumes working. Hence MOW_1 and

MOW_2 are similar with each other. Additionally, MOW_3 and MOW_4 are similar since $N_4(0) + N_6(0) = N_5(0)$. Moreover, when we calculate MOW_5, the case of $N_6(0) = 1$ and $I_6 = 0$ is the same with the case of $N_6(0) = 0$ and $I_6 = 1$. Therefore, MOW_5 and MOW_6 are similar as shown in Figure 16. Its validation of MOW_2 is performed in Figure 17, which shows that discontinuity on machine M_8 begins when machine M_2 is down for 7 minutes, evidenced the analytical and simulated MOW_2 (6.89 ±0.94).

4. CONCLUSIONS AND FUTURE WORK

In this paper, we have analyzed the MOW for serial and assembly/disassembly systems, and extended its results to a more general manufacturing system. A simulation-based MOW algorithm is studied to calculate the MOW via a simulation. Numerical case studies are conducted to demonstrate how to compute MOWs with different configurations of manufacturing systems. This MOW will provide the maximum maintenance time window before starting to lose production throughputs. Future work regarding the theoretical MOW and its application includes: 1) effective way to detect a short-term bottleneck machine of complex systems, 2) analytical models for the stochastic lines, and 3) decision-making policies for maintenance opportunities based on the real-time data and its MOW.

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