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On the design of a flow line with intermediate buffers and mixed corrective maintenance

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Abstract

We considered a mixed corrective maintenance policy for machines in a two-machine one-buffer flow line. The machines had stochastic processing times and suffered from unexpected failures. In the case of a failure, the machines were either minimally repaired or their failing components were replaced by spare parts. While the replacement strategy is rapid and the system can be considered new thereafter, spare parts provisioning and storage costs are very high. Thus, we additionally considered minimal repairs, which are less expensive and restore the system to a working condition at a minimum. We modeled the system as a continuous-time Markov chain. This approach was used to measure the performance of the flow line and the mixed corrective maintenance policy employed. To facilitate design decisions for the flow line, we considered both the cost of an interstage buffer and the maintenance costs for machines in line. We formulated an optimization problem based on a profit function that enables the simultaneous optimization of the buffer size and maintenance strategy. Our numerical analyses reveal useful insights into the performance and optimal design of the flow line depending on the utilized maintenance strategy.

Keywords: flow line, buffer, spare parts, mixed corrective maintenance

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1. Introduction

In the present study, we considered a flow line with intermediate buffers and machines that have stochastic processing times and suffer from failures. The machines and production process were assumed to have already been chosen. Thus, we sought to determine the optimal size of the buffer and the best maintenance strategy.

The rapid repair of machines in flow lines is highly important because a failure of one machine affects the entire line and thus reduces the throughput. Furthermore, the dependencies of buffer size, maintenance actions, and machine parameters (e.g., production rates and failure rates) are very complex. As such, the isolated optimization of maintenance for single machines is not useful in this case. Notably, the number of studies that have integrated flow lines with intermediate buffers and machine maintenance is growing. However, while research largely remains focused on preventive and condition-based maintenance strategies, existing maintenance strategies that are applied in the case of unexpected failures are not considered.

We considered a mixed corrective maintenance policy (MCMP) for machines in a flow line with an intermediate buffer. Essentially, in the case of a failure, a machine or critical component that induces a machine failure can be kept and repaired or replaced. The first case, which is known as a minimal repair in the literature, means that the failing part is repaired. This restores the intended function such that the machine can continue producing. However, the repaired machine is not as perfect as it was when new. In the second case, a spare part replaces the failed part. Thereafter, the machine is as good as new. The minimal repair is associated with low costs in terms of the equipment required but requires a long period. Moreover, the exact repair duration is not usually known in advance. Notably, replacement with a spare part ensures a rapid repair. However, spare parts provisioning is very expensive and parts must be kept in stock to avoid machine downtime. An MCMP makes use of both alternatives. In this paper, we considered Policy IV of the standard replacement policies with minimal repair discussed in Mamabolo & Beichelt (2004). This MCMP works as follows: At the first $n-1$ failure, minimal repairs are performed and the system is replaced at the n^{th} failure.

The contribution of this paper is the development of a model for the evaluation and optimization of the MCMP for a flow line with an intermediate buffer. Furthermore, we studied the behavior of such a system and demonstrate how to design the MCMP and the buffer.

The remainder of this paper is organized as follows. In Section 2, we present the existing literature regarding the maintenance of flow lines. A detailed description of the problem considered in this paper, with all assumptions, can be found in Section 3. Section 4 presents the respective Markov chain. In Section 5, the numerical results are presented for different parameter settings of the flow line to analyze the system behavior as well as optimal system designs. Finally, Section 6 concludes the paper.

2. Literature review

The analysis and optimization of unreliable production lines with intermediate buffers is an extensively studied field of research (see reviews by Dallery & Gershwin, 1992 and Weiß et al., 2018). After a brief introduction to maintenance optimization, we focus on the literature related to models with maintenance decisions for flow lines with intermediate buffers.

Maintenance strategies depend on the nature of machine failures and can be divided into preventive, condition-based, and corrective. While the first two strategies attempt to avoid unexpected failures by interrupting the production for short maintenance activities, the latter applies in the case of an unexpected failure. The aim is to rapidly restore the machine to the point that production can be continued. Reviews of existing literature regarding maintenance optimization can be found in Wang (2002) and De Jonge & Scarf (2020).

Considering maintenance for machines in production systems is challenging due to the interdependences of the machines and the interstage buffers commonly used to improve production system performance. To analyze these dependencies, two-machine one-buffer systems are often studied as a base case. These systems represent the studied problem with its trade off and the modeling effort is adequate. Furthermore, the two-machine one-buffer system can serve as a basis for decomposition and aggregation approaches to study longer flow lines.

Meller & Kim (1996) considered the two-machine one-buffer system and presented a model in which preventive maintenance on the first machine is triggered by a certain buffer inventory level. A few articles have dealt with the optimal condition-based preventive maintenance strategy, whereas the maintenance decision depends on the state of the deteriorating machine. For example, Karamatsoukis & Kyriakidis (2010) assumed that a preventive maintenance action repairs a machine such that it is as new. Fithouhi et al. (2017) additionally optimized the threshold state to which a machine is restored. Furthermore, Kang & Ju (2019) generated preventive maintenance strategies in which the policies are flexible so that machines can be restored to a better state depending on the inventory level of the buffer. Moreover, Bouslah et al. (2018) modeled preventive maintenance for both operation- and quality-dependent failures. Additionally, longer production lines that considered preventive maintenance were studied in Savsar (2008), Fithouhi et al. (2017), Nahas (2017), Nahas & Nourelfath (2018), Kang & Ju (2019), Gu et al. (2020), and Zhou et al. (2021). Although the considered models assumed that a machine is repaired in the case of a failure, they did not consider corrective maintenance actions as part of the optimization problem.

Some articles considered spare parts provisioning for preventive maintenance in production lines with intermediate buffers (Gan et al., 2013; Gan & Shi, 2014; Gan et al., 2015; Cheng et al., 2017; Gan et al., 2021). Only two papers considered spare part decisions related to corrective maintenance for a two-machine one-buffer system (Kiesmüller & Zimmmermann, 2018; Kiesmüller & Sachs, 2020). For machines with both stochastic and fixed processing times, they showed that spare parts inventory and buffer size decisions interact and that simultaneous optimization leads to large cost savings.

However, many concepts for maintenance policies that can ensure rapid repairs at low cost have not yet been considered for machines in flow lines with a buffer. Notably, a failing system can be kept and repaired or replaced. The optimal choice involving the minimal repair or replacement of a system is one central subject of research. Makabe & Morimura (1963) introduced a policy for determining the optimal number of minimal repairs before replacement. For an overview of maintenance strategies, including replacements and minimal repair, see Mamabolo & Reichelt (2004) or Larbi Rebaiaia & Ait Kadi (2020). In the present paper, we adopt the basic concept of Makabe & Morimura (1963) and investigate the effect of an MCMP on a flow line design with intermediate buffers and spare parts planning.

3. Problem description

In this work, we considered a flow line with two machines, denoted by M^i, $i = 1,2$, with random processing times and one intermediate buffer of size N. During production, a workpiece must be processed at each machine. Notably, the machines suffer from occasional downtimes caused by the failure of critical components. In each machine, we assumed that one unit of the same component is installed—a reasonable assumption if the machines are constructed on a modular basis. Although the benefits of modules in products such as personal computers and automobiles have been recognized for many years (Baldwin & Clark, 2000) or (Chatras & Giard, 2016), their use in manufacturing systems is a later development (Gwiazda et al., 2015) or (Becker et al., 2019). Thus, the same component is installed in different modules and can be found in different machines. This production system is depicted in Figure 1.

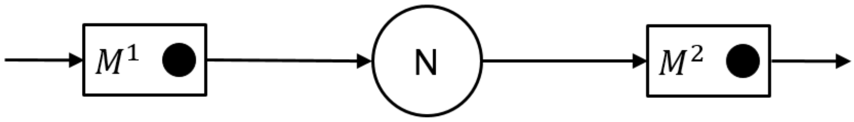

Figure 1 Two-machine one-buffer flow line with mixed corrective maintenance at failure

When a component fails, the machine in which it is installed stops working and production halts until the faulty component is repaired or replaced. A repair-by-replacement strategy is often used in practice since it promotes rapid repairs and thus reduces downtime costs. To successfully apply this strategy, stocks of replacement parts are stored close to the manufacturing system. Since there is one spare part type for the installed base, a single stock point serves all machines in the system.

Only applying the repair-by-replacement policy as a corrective maintenance (CM) strategy can be expensive due to the high cost of spare parts. Due to the uncertainty of failures and long lead times, the storage of spare parts is necessary, which results in high inventory costs being incurred. Therefore, we considered minimal repairs at failure as a second CM action. A minimal repair is more sustainable and reduces waste when compared to the repair-by-replacement strategy (Ait Kadi & Cléroux, 1991). However, a component cannot be frequently repaired because the condition of the component becomes worse with each minimal repair. This can result in a lower production rate of the corresponding machine or a higher failure rate of the component (Fithouhi et al., 2017). We assumed that a minimal repair influences the failure rate of the component while the production rate of the machine remains constant. This is reasonable because we did not consider components with wear-out effects. Consequently, a reduction in the production rate induced by degradation is not reasonable in our case. Furthermore, we assumed that the component is recovered once by a minimal repair and that it must be replaced with the next failure ($R = 1$). This procedure is equivalent to Policy IV of the standard replacement policies with minimal repair discussed in Mamabolo & Beichelt (2004), where the first $n - 1$ failures are removed by minimal repair and the n^{th} failure is restored by replacement. Hereafter, we will refer to this policy as the MCMP.

More specifically, we assume that the lifetime of each component is exponentially distributed with a mean lifetime $1/p$ and failure rate p. The failure rate of the component after minimal repair is p', whereas we assume that the failure rate after minimal repair increases ($p < p'$). After replacement, the component is considered "as good as new."

The minimal repair is performed by a repair crew. The repair rate of the component in M_i is given by r_i, $i = 1{,}2$ and assumed to be exponentially distributed. If a component fails, a minimal repair has already been performed, and a spare part is available (in stock), then the resulting downtime is very short and may be considered negligible (Ait Kadi & Cléroux, 1991). A significant machine downtime only occurs when there is no spare in stock for the failed component. In this case, the machine remains out of service until the next spare parts delivery. In the rare case where more than one machine is down and awaiting a spare part, one must prioritize the replacement part service. In this study, we gave priority to the replacement of the component in the second machine. Naturally, this rule can easily be changed. However, the simultaneous failure of two machines is unlikely in systems that are designed for high throughput. Hence, prioritization has a small effect on performance.

The spare parts inventory is controlled by a one-for-one replenishment policy with a base stock level S. That means that a spare part is ordered as soon as a spare part is taken from the stock. This base stock policy is optimal for expensive spare parts with long lead times and low demand (Feeney & Sherbrooke, 1966). The lead time for one spare part is exponentially distributed with a mean lead time of $1/\gamma$ and delivery rate γ.

The production process heavily depends on the CM strategy for the machines, while machine failures depend on the production process (i.e., buffer size) since component failures are operation dependent. This implies that a component can only fail during production. This mutual interaction between the CM strategy and intermediate buffer can be expanded upon as follows: In the case of one machine experiencing downtime, the other machines in line are not forced to stop and can continue producing if material and workpieces from the buffer are available. In the other case, the flow of material is interrupted and machines will be starved or blocked. Due to the random processing times of the machines, starving and blocking can also appear if an upstream machine is producing and no workpiece is available for production (starving), or if a downstream machine is producing and a workpiece cannot be passed by after production (blocking). The buffer storage decouples the machines such that the effects of random processing times and failures can be mitigated or at least reduced. This yields higher throughput at the cost of higher work in the process. However, the CM strategy must be designed to ensure the high availability of machines at low costs because the intermediate buffer can only decouple the machines and reduce the impact of downtime on other machines. The amount of time that a machine is out of service due to failures, which consequently leads to less throughput, must be reduced by a CM strategy.

Our assumptions regarding the production process are in line with existing literature. We assume that all workpiece transportation times between machines and through the buffer can be neglected or are included in the processing time. The processing times of the machines are exponentially distributed with production rate $\mu_i, (i = 1,2)$. The production line is assumed to be saturated, meaning that workpieces are always available for production at the first machine. Furthermore, finished workpieces can always leave the system after production at the final machine in the line.

The production system can be optimized by defining the optimal buffer size N and the optimal MCMP. For the MCMP, the number of minimal repairs R before replacement and the spare parts base stock level S can be determined. Since the decision variables are related to different categories and should be optimized simultaneously, we use the overall aim of production system profit maximization, which is commonly used in this case (Weiss et al., 2019). The profit can be formulated as

$$Z(N,S,R) = \Pi_{(\mathrm{N,S,R})} \cdot p_{\Pi} - N \cdot c_N - S \cdot c_S - TMC_R \tag{1}$$

with

$$TMC_R = NC_{mR} \cdot c_{mR} + NC_{SP} \cdot c_{SP} \tag{2}$$

Equation (1) is composed of the revenue generated by the throughput $\Pi_{(\mathrm{N,S,R})}$ with the profit coefficient p_{Π}, the costs for spare parts and the buffer, and the costs for the MCMP (TMC_R). Thereby, p_{Π} represents the revenue coefficient while c_N and c_S are the cost coefficients associated with the buffer and spare parts, respectively. The costs of the MCMP (presented in Equation (2)) comprise the cost suffered for each minimal repair NC_{mR} with the cost coefficient c_{mR} and the cost suffered from the number of failure replacements NC_{SP} with the cost coefficient c_{SP}.

Notably, we will also refer to the MCMP for the case where $R = 0$ and no minimal repair is performed before replacement. We considered this a special case of the MCMP. In summary, the decision variables that define the design of the production system and its repair strategy are given by (N, S, R).

4. Evaluation of a two-machine flow line with mixed corrective maintenance strategies

We modeled the flow line with two machines, one intermediate buffer, and MCMP as a continuous-time Markov chain with discrete state space. The state of the system was denoted by $z = (\alpha_1, n, \alpha_2, s, m_1, m_2)$, where α_i is related to the condition of M^i, n is related to the workpieces in the buffer, s is related to the spare parts inventory, and m_i is related to the repair status of the component in M^i. More specifically, $\alpha_i = 0$ implies that M^i is down because a component inside has failed and no spare part is available, or a minimal repair is performed. For $\alpha_i = 1$, M^i is defined as operational. Thus, it either produces or is starving, depending on whether a workpiece is available for production or not (remember that M^1 cannot be starving because we assume a saturated flow line). According to the blocking policy described in Section 2, M^1 can be blocked, which is represented by $\alpha_1 = 2$.

Parameter n serves as the number of workpieces that are released from production at M^1 but did not exit M^2. Dimension s represents the number of spare parts in stock ($s = 0,1,..,S$). If s equals 0, no spare part is in stock. The maximum number of spare parts in resupply is $S + 2$.

For the MCMP, we introduced $m_i \in \{0,1\}$ $\forall i = 1,2$ which represents the state of the component in M^i. Thus, $m_i = 0$ if the component in M^i is new (i.e., the last CM action was a replacement). The case where a minimal repair has been performed is represented by $m_i = 1$. Consequently, based on the variable m_i, we know which CM action must be performed at the next failure. The balance equations in this section were derived for one minimal repair before replacement ($R = 1$). However, with the definition of the states, it is easy to extend the number of minimal repairs before a replacement must recover the machine, or to adapt the maintenance policy for further studies. The flow line without a minimal repair is represented by $R = 0$ (i.e., variable $m_i = 0$ can be neglected in this case). The Markov chain for $R = 0$ can be found in Kiesmüller & Zimmermann (2018).

In what follows, we provide expressions for the balance equations that were derived to determine the steady-state probabilities denoted by $P(\alpha_1, n, \alpha_2, s, m_1, m_2)$ together with the normalization equation. With the steady-state probabilities, we could evaluate the performance of the flow line. The total number of states depends on the buffer size N and the base stock level S and is equal to $16N + 21S + 9NS + 32$. Thus, the numerical determination of the steady-state probability is possible by solving the corresponding equation system.

Since the state space and transitions are rather complex, we structured the balance equations based on the up and down states of the machines. We started with a case in which all machines are down, followed by a case in which one out of two machines is down. Last, we discuss all states in which the machines are up. By applying this pattern, we obtained four types of equations. Within these groups, we considered the internal and boundary states regarding the buffer. For the sake of clarity, we distinguished the states where machines are down whether or not a spare part is in stock. Thus, we obtained a total of 13 types of balance equations. In accordance with the balance equations, we divided the complete state space SS of our system into 13 subsets $\overline{SS_j}$, $\forall\, j = 1,2, \dots ,13$:

$$SS = \bigcup_{j=1}^{13} \overline{SS_j} \tag{3}$$

To include certain peculiarities of the boundary states and MCMP into the balance equations, we used an indicator function χ_T for a logical proposition T, which is defined as

$$\chi_T = \begin{cases} 1, & if\ T\ is\ true \\ 0, & if\ T\ is\ false. \end{cases} \tag{4}$$

For the balance equations, had to distinguish whether the components in the machines have been repaired with a minimal repair $(m_i = 1)$ or not $(m_i = 0)$. On the one hand, this determines the delivery rate of the spare part and, on the other hand, whether the component is fixed by a minimal repair or by replacement. Therefore, we developed Equation (5) to calculate the number of spare parts in resupply. The maximum number of spare parts in resupply was restricted to the base stock level S and the components in the machines. If a component fails and a minimal repair has already been performed $(m_i = 1)$, then a spare part is ordered, which increases the number of spare parts in resupply:

$$R^S_{(\alpha_1,\alpha_2,m_1,m_2)} = S + (1 - \alpha_1) \cdot m_1 + (1 - \alpha_2) \cdot m_2. \tag{5}$$

Here, we present the 13 subsets of the state space with their corresponding balance equations. We start with the subsets $\overline{SS_1}$, $\overline{SS_2}$, and $\overline{SS_3}$, where at least one machine is down and no spare parts are in stock:

$$\overline{SS_1} = \{(0, n, 0,0, m_1, m_2) | n \in \{1,2, \dots, N + 1\},\ m_1, m_2 \in \{0,1\}\} \tag{6}$$

$$\begin{aligned} \left(R^S_{(0,0,m_1,m_2)}\gamma + \chi_{\{m_1=0\}}r_1 + \chi_{\{m_2=0\}}r_2\right)P(0, n, 0,0, m_1, m_2) \\ = \chi_{\{m_1=0\}}pP(1, n, 0,0,0, m_2) + \chi_{\{m_1=1\}}p'P(1, n, 0,0,1, m_2) \\ + \chi_{\{m_2=0\}}pP(0, n, 1,0, m_1, 0) + \chi_{\{m_2=1\}}p'P(0, n, 1,0, m_1, 1) \end{aligned} \tag{7}$$

$$\overline{SS_2} = \{(0, n, 1,0, m_1, m_2) | n \in \{1,2, \dots, N + 1\},\ m_1, m_2 \in \{0,1\}\} \tag{8}$$

$$\begin{aligned} \left(\mu_2 + R^S_{(0,1,m_1,m_2)}\gamma + \chi_{\{m_2=0\}}p + \chi_{\{m_2=1\}}p' + \chi_{\{m_1=0\}}r_1\right)P(0, n, 1,0, m_1, m_2) \\ = \chi_{\{n<N+1\}}\mu_2 P(0, n + 1,1,0, m_1, m_2) \\ + \left(R^S_{(0,1,m_1,m_2)} + 1\right)\chi_{\{m_2=0\}}\gamma P(0, n, 0,0, m_1, 1) \\ + \chi_{\{m_2=1\}}r_2 P(0, n, 0,0, m_1, 0) + \chi_{\{m_1=0\}}pP(1, n, 1,0,0, m_2) \\ + \chi_{\{m_1=1\}}p'P(1, n, 1,0,1, m_2) \end{aligned} \tag{9}$$

$$\overline{SS_3} = \{(1, n, 0,0, m_1, m_2) | n \in \{1,2, \dots, N + 1\},\ m_1, m_2 \in \{0,1\}\} \tag{10}$$

$$\begin{aligned}\left(\mu_1 + R^S_{(1,0,m_1,m_2)}\gamma + \chi_{\{m_1=0\}}p + \chi_{\{m_1=1\}}p' + \chi_{\{m_2=0\}}r_1\right)&P(1,n,0,0,m_1,m_2)\\ &= \chi_{\{n>1\}}\mu_1 P(1,n-1,0,0,m_1,m_2)\\ &+ \left(R^S_{(1,0,m_1,m_2)}+1\right)\chi_{\{m_1=0\}}\gamma P(0,n,0,0,1,m_2)\\ &+ \chi_{\{m_1=1\}}r_1 P(0,n,0,0,0,m_2) + \chi_{\{m_2=0\}}pP(1,n,1,0,m_1,0)\\ &+ \chi_{\{m_2=1\}}p'P(1,n,1,0,m_1,1)\end{aligned} \tag{11}$$

For the considered MCMP, the machines may be forced down; however, a spare part is available. This is represented by $\overline{SS_4}$, $\overline{SS_5}$, and $\overline{SS_6}$:

$$\overline{SS_4} = \{(0,n,0,s,0,0) | n \in \{1,2,\dots,N+1\}, s \in \{1,2,\dots,S\}\} \tag{12}$$

$$\begin{aligned}\left((S-s)\gamma + r_1 + r_2\right)&P(0,n,0,s,0,0)\\ &= (S-s+1)\gamma P(0,n,0,s-1,0,0) + pP(1,n,0,s,0,0)\\ &+ pP(0,n,1,s,0,0)\end{aligned} \tag{13}$$

$$\overline{SS_5} = \{0,n,1,s,0,m_2 | n \in \{1,2,\dots,N+1\}, s \in \{1,2,\dots,S\}, m_2 \in \{0,1\}\} \tag{14}$$

$$\begin{aligned}\left(\mu_2 + (S-s)\gamma + \chi_{\{m_2=0\}}p + \chi_{\{m_2=1\}}p' + r_1\right)&P(0,n,1,s,0,m_2)\\ &= \chi_{\{n<N+1\}}\mu_2 P(0,n+1,1,s,0,m_2)\\ &+ (S-s+1)\gamma P(0,n,1,s-1,0,m_2) + \chi_{\{m_2=1\}}r_2 P(0,n,0,s,0,0)\\ &+ pP(1,n,1,s,0,m_2) + \chi_{\{s<S\}}\chi_{\{m_2=0\}}p'P(0,n,1,s+1,0,1)\end{aligned} \tag{15}$$

$$\overline{SS_6} = \{1,n,0,s,m_1,0 | n \in \{1,2,\dots,N+1\}, s \in \{1,2,\dots,S\}, m_1 \in \{0,1\}\} \tag{16}$$

$$\begin{aligned}\left(\mu_1 + (S-s)\gamma + \chi_{\{m_1=0\}}p + \chi_{\{m_1=1\}}p' + r_2\right)&P(1,n,0,s,m_1,0)\\ &= \chi_{\{n>1\}}\mu_1 P(1,n-1,0,s,m_1,0)\\ &+ (S-s+1)\gamma P(1,n,0,s-1,m_1,0) + \chi_{\{m_1=1\}}r_1 P(0,n,0,s,0,0)\\ &+ pP(1,n,1,s,m_1,0) + \chi_{\{s<S\}}\chi_{\{m_1=0\}}p'P(1,n,0,s+1,1,0)\end{aligned} \tag{17}$$

The lower and upper boundary states of the buffer are divided into the case with no spare parts in stock (represented by $\overline{SS_7}$ and $\overline{SS_8}$) and the case with spare parts in stock ($\overline{SS_9}$ and $\overline{SS_{10}}$):

$$\overline{SS_7} = \{0,0,1,0,m_1,m_2 | \, m_1,m_2 \in \{0,1\}\} \tag{18}$$

$$\begin{aligned}\left(R^S_{(0,1,m_1,m_2)}\gamma + \chi_{\{m_1=0\}}r_1\right)&P(0,0,1,0,m_1,m_2)\\ &= \mu_2 P(0,1,1,0,m_1,m_2) + \chi_{\{m_1=0\}}pP(1,0,1,0,0,m_2)\\ &+ \chi_{\{m_1=1\}}p'P(1,0,1,0,1,m_2)\end{aligned} \tag{19}$$

$$\overline{SS_8} = \{2,N+1,0,0,m_1,m_2 | \, m_1,m_2 \in \{0,1\}\} \tag{20}$$

$$\begin{aligned}\left(R^S_{(1,0,m_1,m_2)}\gamma + \chi_{\{m_2=0\}}r_2\right)&P(2,N+1,0,0,m_1,m_2)\\ &= \mu_1 P(1,N+1,0,0,m_1,m_2) + \chi_{\{m_2=0\}}pP(2,N+1,1,0,m_1,0)\\ &+ \chi_{\{m_2=1\}}p'P(2,N+1,1,0,m_1,1).\end{aligned} \tag{21}$$

$$\overline{SS_9} = \{0,0,1,s,0,m_2 | s \in \{1,2,\dots S\}, m_2 \in \{0,1\}\} \tag{22}$$

$$\begin{aligned}&\big((S-s)\gamma + r_1\big)P(0,0,1,s,0,m_2)\\&\quad = \mu_2 P(0,1,1,0,m_1,m_2) + (S-s+1)\gamma P(0,0,1,s-1,0,m_2)\\&\quad + pP(1,0,1,0,0,m_2)\end{aligned} \tag{23}$$

$$\overline{SS_{10}} = \big\{2, N+1, 0, s, m_1, 0 | s \in \{1,2,\dots S\}, m_1 \in \{0,1\}\big\} \tag{24}$$

$$\begin{aligned}&\big((S-s)\gamma + r_2\big)P(2,N+1,0,s,m_1,0)\\&\quad = \mu_1 P(1,N+1,0,s,m_1,0) + (S-s+1)\gamma P(2,N+1,0,s-1,m_1,0)\\&\quad + pP(2,N+1,1,s,m_1,0).\end{aligned} \tag{25}$$

Now, we consider all states where both machines are up. The internal states related to the buffer are represented by $\overline{SS_{11}}$, while the case in which M^2 is starving is represented by $\overline{SS_{12}}$, and the case in which M^1 is blocked is expressed by $\overline{SS_{13}}$:

$$\overline{SS_{11}} = \big\{(1,n,1,s,m_1,m_2) | n \in \{1,2,\dots,N+1\}, s \in \{0,1,\dots,S\}, m_{1,}, m_2 \in \{0,1\}\big\} \tag{26}$$

$$\begin{aligned}&\big(\mu_1 + \mu_2 + (S-s)\gamma + \chi_{\{m_1=0\}}p + \chi_{\{m_1=1\}}p' + \chi_{\{m_2=0\}}p\\&\quad + \chi_{\{m_2=1\}}p'\big)P(1,n,1,s,m_1,m_2)\\&\quad = \mu_1 P(1,n-1,1,s,m_1,m_2) + \chi_{\{n<N+1\}}\mu_2 P(1,n+1,1,s,m_1,m_2)\\&\quad + \chi_{\{s>0\}}(S-s+1)\gamma P(1,n,1,s-1,m_1,m_2)\\&\quad + \chi_{\{s=0\}}\Big(\chi_{\{m_1=0\}}(S+1)\gamma P(0,n,1,0,1,m_2)\\&\quad + \chi_{\{m_2=0\}}(S+1)\gamma P(1,n,0,0,m_1,1)\Big) + \chi_{\{m_1=1\}}r_1 P(0,n,1,s,0,m_2)\\&\quad + \chi_{\{m_2=1\}}r_2 P(1,n,0,s,m_1,0)\\&\quad + \chi_{\{s<S\}}p'\Big(\chi_{\{m_1=0\}}P(1,n,1,s+1,1,m_2)\\&\quad + \chi_{\{m_2=0\}}P(1,n,1,s+1,m_1,1)\Big)\end{aligned} \tag{27}$$

$$\overline{SS_{12}} = \big\{(1,0,1,s,m_1,m_2) |\ s \in \{0,1,\dots,S\}, m_{1,}, m_2 \in \{0,1\}\big\} \tag{28}$$

$$\begin{aligned}&\big(\mu_1 + (S-s)\gamma + \chi_{\{m_1=0\}}p + \chi_{\{m_1=1\}}p'\big)P(1,0,1,s,m_1,m_2)\\&\quad = \mu_2 P(1,1,1,s,m_1,m_2) + \chi_{\{s>0\}}(S-s+1)\gamma P(1,0,1,s-1,m_1,m_2)\\&\quad + \chi_{\{s=0\}}\chi_{\{m_1=0\}}(S+1)\gamma P(0,0,1,0,1,m_2) + \chi_{\{m_1=1\}}r_1 P(0,0,1,s,0,m_2)\\&\quad + \chi_{\{s<S\}}\chi_{\{m_1=0\}}p' P(1,n,1,s+1,1,m_2)\end{aligned} \tag{29}$$

$$\overline{SS_{13}} = \big\{(2,N+1,1,s,m_1,m_2) |\ s \in \{0,1,\dots,S\}, m_{1,}, m_2 \in \{0,1\}\big\} \tag{30}$$

$$\begin{aligned}&\big(\mu_2 + (S-s)\gamma + \chi_{\{m_2=0\}}p + \chi_{\{m_2=1\}}p'\big)P(2,N+1,1,s,m_1,m_2)\\&\quad = \mu_1 P(1,N+1,1,s,m_1,m_2)\\&\quad + \chi_{\{s>0\}}(S-s+1)\gamma P(2,N+1,1,s-1,m_1,m_2)\\&\quad + \chi_{\{s=0\}}\chi_{\{m_2=0\}}(S+1)\gamma P(2,N+1,0,0,m_1,1)\\&\quad + \chi_{\{m_2=1\}}r_2 P(2,N+1,0,s,m_1,0)\\&\quad + \chi_{\{s<S\}}\chi_{\{m_2=0\}}p' P(2,N+1,1,s+1,m_1,1)\end{aligned} \tag{31}$$

Together with the normalization equation (32), the equation system (3) and (6)–(31) can be solved.

$$\sum_{z \in SS} P(z) = 1 \tag{32}$$

Once the steady-state probability distribution of $z = (\alpha_1, n, \alpha_2, s, m_1, m_2)$ is determined, we can compute all performance measures of the system. For our numerical investigations, we were interested in the throughput of the flow line Π, the number of minimal repairs NR_{mR}, and the number of replacements NR_{SP}. The throughput of the system (see Equation (34)) is the number of produced workpieces per unit of time. For the computation of the throughput, all states are considered where M^2 is processing (33).

$$SS_{\Pi} = \overline{SS_2} \cup \overline{SS_5} \cup \overline{SS_{11}} \cup \overline{SS_{13}} \tag{33}$$

The sum of the probabilities of these states SS_{Π} yields the fraction of time M^2 is producing. Within this effective production time of M^2, workpieces finish production at the rate μ_2, such that the expected throughput is given by:

$$\Pi_{(\mathrm{N,S,1})} = \sum_{z \in SS_{\Pi}} P(z) \cdot \mu_2 \tag{34}$$

To provide an expression for the expected number of minimal repairs NR_{mR} and the expected number of replacements with spare parts NR_{SP}, we required the effective processing time of both machines in the states where the components fail with rate p or p'. Since we assumed operation-dependent failures, the effective processing time depends on the blocking, starving, and downtimes of the machines.

The specific effective processing times of both machines are multiplied by the failure rates p or p':

$$NR_{mR} = \Bigg[\sum_{n=1}^{N+1}\Bigg(\Big(\Big(\sum_{s=0}^{S} 2 \cdot P(1,n,1,s,0,0) + P(1,n,1,s,1,0) + P(1,n,1,s,0,1)\Big)\Big) + \sum_{m_1=0}^{1} P(0,n,1,0,m_1,0) + \sum_{m_2=0}^{1} P(1,n,0,0,0,m_2) + \sum_{s=1}^{S}\big(P(0,n,1,s,0,0) + P(1,n,0,s,0,0)\big)\Bigg) + \sum_{s=0}^{S}\Big(\sum_{m_2=0}^{1} P(1,0,1,s,0,m_2) + \sum_{m_1=0}^{1} P(2,N+1,1,s,m_1,0)\Big)\Bigg] \cdot p \tag{35}$$

$$NR_{SP} = \Bigg[\sum_{n=1}^{N+1}\Bigg(\Big(\Big(\sum_{s=0}^{S} 2 \cdot P(1,n,1,s,1,1) + P(1,n,1,s,1,0) + P(1,n,1,s,0,1)\Big)\Big) + \sum_{m_1=0}^{1} P(0,n,1,0,m_1,1) + \sum_{m_2=0}^{1} P(1,n,0,0,1,m_2) + \sum_{s=1}^{S}\big(P(0,n,1,s,0,1) + P(1,n,0,s,1,0)\big)\Bigg) + \sum_{s=0}^{S}\Big(\sum_{m_2=0}^{1} P(1,0,1,s,1,m_2) + \sum_{m_1=0}^{1} P(2,N+1,1,s,m_1,1)\Big)\Bigg] \cdot p' \tag{36}$$

Other performance measures (e.g., expected spares parts availability, expected spare parts inventory, or work in process) can be computed similarly to the above formulas. However, these are not required for our numerical analysis.

5. Numerical results

In this section, we analyze numerical examples to explain how a production system with MCMP behaves and how it influences the optimal system design of a flow line when applied. Thus, the analyses are divided into two parts. The first part is devoted to the analysis of the influence of MCMP and certain maintenance parameters on the performance of the flow line. Also, the interdependencies between MCMP and buffer size are discussed. Then, the economic perspective is considered in the second part, in which the influence of cost parameters and optimization results are presented.

For the analyses, we chose parameter set 1 as a starting point (see Table 1). Parameter set 1 represents high failure rates, a fast lead time, and a fast repair rate. Parameter set 2 has lower failure rates, a long lead time, and a longer repair time compared to parameter set 1 and was used for the analysis of optimization results. The rates were chosen to be per day (i.e., a repair rate $r_i = 0.5$ equates to an expected repair time of 2 days). We started with parameter set 1 and varied the respective parameters for each investigation. Within our numerical analysis, we also compared the MCMP with minimal repair ($R = 1$) to the special case of the MCMP where the components are directly replaced and no minimal repairs are performed ($R = 0$). For simplicity, we will refer to the case where only replacements are used to recover the machine (R=0) as the replacement strategy (RS) in the discussion.

Parameter set #	μ_1	μ_2	p	p'	γ	r_1	r_2
1	100	100	0.03	0.06	0.1	2	2
2	100	100	0.003	0.006	0.03	0.5	0.5

Table 1 Parameter setting transition rates

First, we analyzed the performance of the flow line depending on the repair parameters and the chosen maintenance strategy. Therefore, we could show the influence of the repair rate on the throughput for different spare parts base stock levels. Furthermore, we compared the throughput for the MCMP with the RS where no minimal repairs are performed. The buffer size N equals 10 for all examples and the repair rates were chosen as $r_i = \{0.5,1,4\}$. The results are depicted in Figure 2.

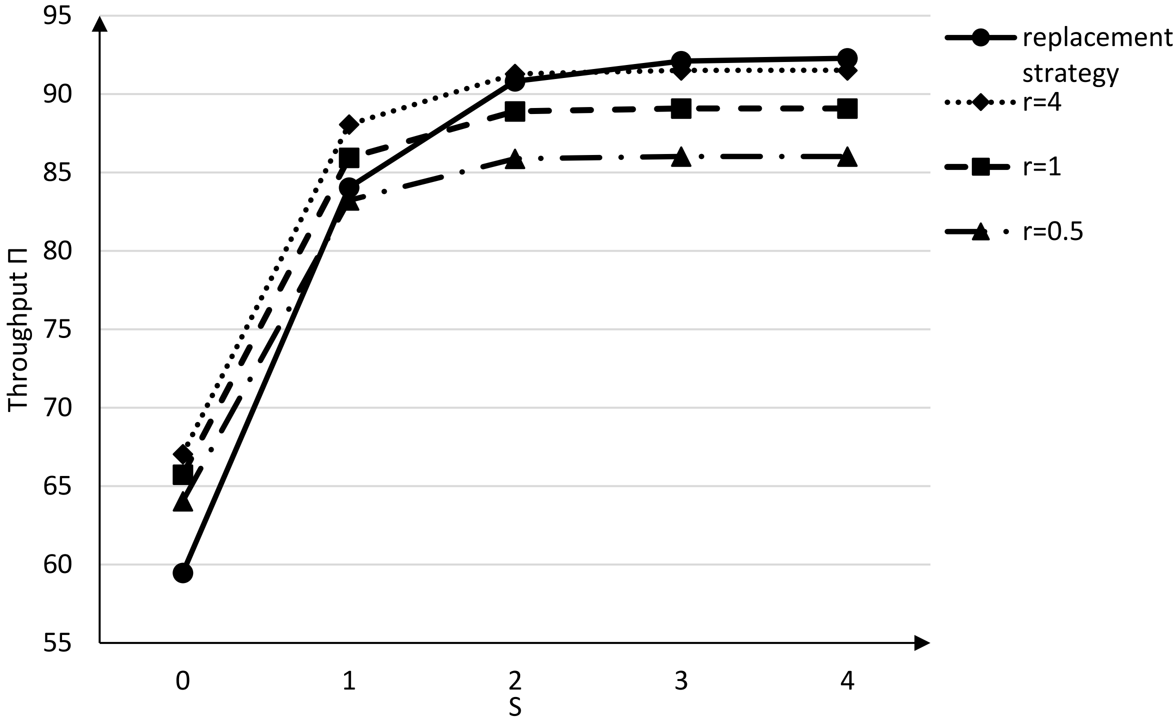

Figure 2 Impact of repair rate on throughput

Depending on the spare parts level S, the behavior of the MCMP and the RS with the respective throughput is different. If no spare parts are kept in stock, the MCMP outperforms the RS because the minimal repair restores the machine once. This reduces the influence of downtime due to spare part shortage in the case of failure. Within the MCMP, the function with the highest repair rate yields the highest throughput. All functions were increasing in S, which had already been shown for the RS in Kiesmüller & Zimmermann (2018). The higher the spare parts base stock level S, the better the RS performs. The gain in throughput for additional spare parts was higher when compared to the MCMP, whereas the level of the spare parts at which the RS outperformed the MCMP depended on the repair rate. For a sufficiently large S, the RS can entirely prevent machine downtime. However, the costs incurred by purchasing spare parts might be so immense that the range with a few spare parts in stock is far more important for practical considerations.

The throughput increases similarly for the MCMP with an increasing S since the out-of-stock probability becomes smaller, thereby reducing the probability of machine downtime. The different repair rates of the MCMP influence the throughput via the idle time of the repaired machine. Adding spare parts to the MCMP does not greatly increase the throughput because spare parts cannot influence downtime during repair. Thus, the curves converge faster than the RS and can yield higher throughput with few spare parts in stock.

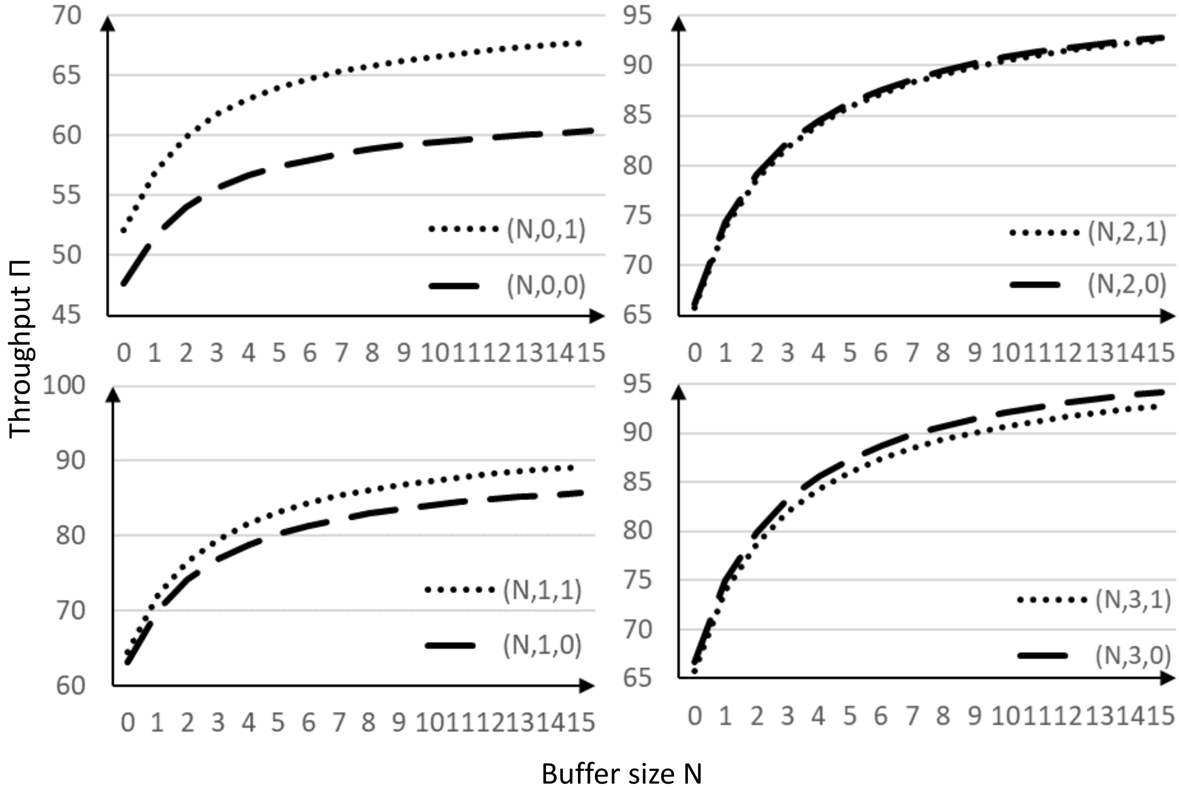

Figure 3 Influence of buffer size on throughput for different MCMP parameters

Figure 3 compares the influence of buffer size on throughput for different spare parts levels for both the MCMP and the RS. Therefore, we present the performance of both maintenance strategies for four different spare parts levels depending on buffer size. To define a certain system design, we introduced the following notation: (N,S,R). Since RS is a special case of MCMP, it can be represented by $R = 0$, meaning that no minimal repairs are performed before replacement. The parameter chosen for Figure 3 is parameter set 1.

For all scenarios, the throughput increased as a function of buffer size N, which is well known from the literature (Gershwin, 1993). However, depending on the spare parts base stock level and whether the MCMP was applied or not, the influence of the buffer was different. For no spare parts and one spare part in stock, the difference between the repair strategies was the largest. The effective production times were higher with the MCMP such that the buffer was more effective in this case. As a result, the relative throughput improvement became larger with more buffer space when compared to the RS. For a spare parts base stock level of 2, the performance of both maintenance strategies was equal in terms of throughput. According to the findings in Figure 2, the RS outperformed the MCMP for the high spare parts level. However, large differences in throughput and the high impact of the buffer—which intensifies the throughput improvement of the MCMP—were only observed for the small spare parts base stock level.

After discussing the general behavior of the flow line with MCMP, we will now consider economic aspects.

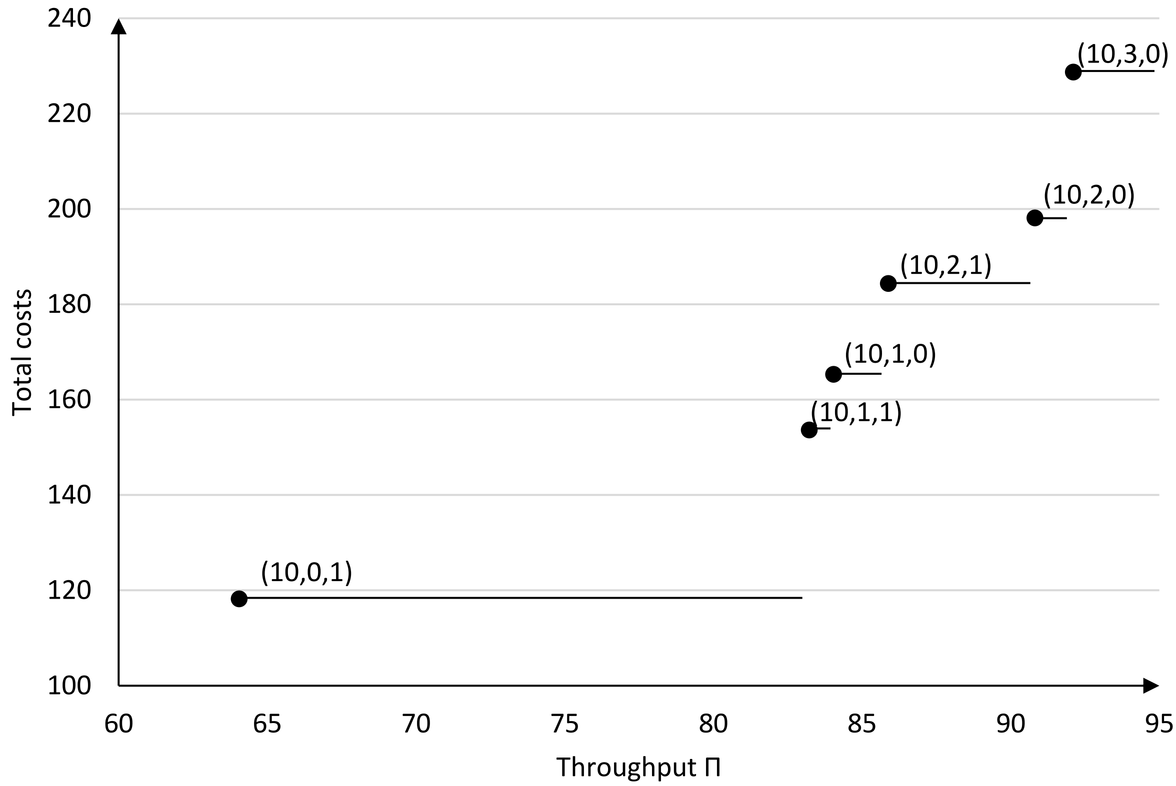

Figure 4 Total costs for best maintenance strategy with a fixed buffer size

Figure 4 presents the total costs associated with the best maintenance strategy for a given buffer size ($N = 10$). The combination of S and R defines the best maintenance strategy that ensures a certain throughput at the lowest cost. The total costs (TC) can be computed by summing up all costs from the profit function (1):

$$\mathrm{TC}(N, S, R) = N \cdot c_N + S \cdot c_S + TMC_R.$$

The production system parameter set 1 was chosen and the cost coefficients were $c_N = 10, c_S = 30, c_{mR} = 10, and\ c_{SP} = 700$. This example represents the case in which the costs for one spare part in stock are higher compared to having one installed buffer space. The costs for replacing a spare part are much higher when compared to performing one minimal repair. Notably, performing minimal repairs incurs throughput losses due to the repair time, which is also indirectly considered by the throughput.

From Figure 4, we gain further insights into the structure of the best maintenance strategy and the corresponding spare parts base stock level depending on different throughput levels. For a small throughput, the best decision is to have no spare parts and apply the MCMP. In this case, the mixed strategy with minimal repairs enables the dispensing of spare parts and reaching the throughput by the combination of buffer space and minimal repairs. For larger throughput levels, the MCMP always yields a lower throughput at a lower cost. The reduction of replacements causes this at the expense of repair time, which reduces the throughput. While MCMP reduces costs, it also restricts the reachable throughput such that a throughput above 90% can only be achieved by the RS (see Figure 4).

To find the optimal solution (N^*, S^*, R^*) that yields maximal profit Z^* (1), we introduced the optimization problem (P). Notably, the objective function (37) was represented by the profit function (1). We formulated two constraints that reduced the solution space and thus enabled us to solve (P) via complete enumeration. The constraints were the limitation of the maximal buffer size $\overline{N}$ and the maximal spare parts base stock level $\bar{S}$. (P) can be formulated as:

$$\max \quad \mathrm{Z}(N, S, R) = \Pi_{(\mathrm{N,S,R})} \cdot p_{\Pi} - N \cdot c_N - S \cdot c_S - TMC_R \tag{37}$$

$$s.t. \quad N \leq \overline{N} \tag{38}$$

$$S \leq \bar{S} \tag{39}$$

$$R \in \{0,1\} \tag{40}$$

$$N, S \in \mathbb{N}_0 \tag{41}$$

The improvement of the throughput via spare parts is naturally limited because spare parts influence machine availability. Thus, a reasonable upper bound for the spare parts level $\bar{S}$ can be determined by calculating a non-stock out probability of 99.99%:

$$P(D(L) \leq \bar{S}) \geq 0.9999 \tag{42}$$

To calculate the demand during the lead time (D(L)), we used an approximation in which we overestimated the real demand for spare parts. Consequently, the upper bound $\overline{S}$ was even more likely to not restrict the optimal solution of the unconstrained problem. The approximation was based on two simplifications. First, we considered an infinite size of the buffer and neglected the passivation effect, such that we assumed that both machines are always producing. Second, we neglected the minimal repairs. Thus, the demand during the lead time was approximated by a Poisson process with parameter $2p$. Space limitations usually restrict the buffer space in a production facility. For the numerical study, the maximal buffer size was 40. The number of minimal repairs before replacements R was restricted to one according to our problem description.

Table 2 presents the optimal system designs, including an optimal MCMP that comprises the optimal buffer size N^*, optimal spare parts base stock level S^*, and the optimal number of minimal repairs before replacement R^*. For each optimal solution (N^*, S^*, R^*), the corresponding profit $Z(\cdot)$ and throughput $\Pi_{(\cdot)}$ was given. We varied all parameters related to the profit function for two different parameter sets of the transition rates. In addition to parameter set 1 (chosen for the previous analysis), we chose a scenario in which the machines have longer lifetimes, the spare parts have longer lead times, and the mean minimal repair time is longer (i.e., parameter set 2).

					Parameter set 1: $\mu_1, \mu_2 = 100, p = 0.03, p' = 0.06,$ $\lambda = 0.1,\ r_1, r_2 = 2$			Parameter set 2: $\mu_1, \mu_2 = 100, p = 0.003, p' = 0.006,$ $\lambda = 0.03,\ r_1, r_2 = 0.5$		
p_Π	c_N	c_S	c_{mR}	c_{SP}	(N^*, S^*, R^*)	$Z(\cdot)$	$\Pi_{(\cdot)}$	(N^*, S^*, R^*)	$Z(\cdot)$	$\Pi_{(\cdot)}$
10	10	10	100	1000	(7,2,1)	753,80	88,26	(7,1,1)	806,07	89,00
	10	50			(6,1,1)	696,53	84,36	(7,1,1)	766,07	89,00
	50	10			(1,2,1)	635,68	73,82	(1,1,1)	680,18	74,35
	50	50			(1,1,1)	588,73	72,04	(1,1,1)	640,18	74,35
30	10	10			(14,3,0)	2590,45	93,89	(14,2,0)	2655,29	94,03
	10	50			(14,2,1)	2486,45	92,23	(14,1,1)	2596,16	93,01
	50	10			(5,3,0)	2287,70	87,34	(5,2,0)	2347,79	87,43
	50	50			(5,2,1)	2188,03	85,86	(5,1,1)	2293,06	86,56
50	10	10			(19,4,0)	4484,11	95,43	(19,2,0)	4552,45	95,36
	10	50			(19,3,0)	4363,67	95,22	(19,2,0)	4472,45	95,36
	50	10			(7,3,0)	4056,86	89,82	(7,2,0)	4120,96	89,93
	50	50			(7,3,0)	3936,86	89,82	(7,1,1)	4046,02	89,00
10	10	10	10		(7,2,1)	756,98	88,26	(7,1,1)	806,39	89,00
			100		(7,2,1)	753,80	88,26	(7,1,1)	806,07	89,00
			500		(7,3,0)	744,26	89,82	(7,1,1)	804,65	89,00
			1000		(7,3,0)	744,26	89,82	(7,2,0)	803,87	89,93
			100	1000	(7,2,1)	753,80	88,26	(7,1,1)	806,07	89,00
				10000	(5,2,1)	441,73	85,86	(7,1,1)	774,03	89,00
				15000	(3,1,1)	274,74	79,48	(7,1,1)	756,23	89,00

Table 2 The optimal (N^*, S^*, R^*) for different cost parameters

The optimization results reveal some important insights into the design of the flow line and the choice of maintenance actions. In the case of a small profit coefficient ($p_\Pi = 10$) and for low costs for minimal repairs ($c_{mR} < 500$ for parameter set 1 and $c_{mR} < 1000$ for set 2), the MCMP should be applied. For higher profit coefficients, the choice of maintenance strategy mainly depends on the cost parameter for spare parts c_S. Usually, the number of spare parts kept in stock is reduced by one if the MCMP is applied. The optimal buffer size depends on the costs for the buffer c_N. In two cases involving parameter set 1, the buffer size was also reduced as a result of an increase in spare parts costs. In both instances, the MCMP was optimal, and higher costs for spare parts c_S and spare parts replacements c_{SP} led to a reduction in spare parts and buffer size. This effect, which also applies to the simple RS (Kiesmüller & Zimmermann, 2018), aims to reduce the operational time and avoid failures. On the contrary, in all instances in which the repair strategy changed due to different costs for spare parts c_S, the buffer size was not affected. However, there is no identifiable causality when the buffer and maintenance decision can be optimized in a sequential manner.

6. Conclusion

During the design phase of flow lines, CM optimization has widely been neglected. Alternatively, maintenance strategies have been developed without considering the complex interactions of machines with intermediate buffers in production lines. In this context, we propose an MCMP for a flow line consisting of two machines and one buffer. The machines are either minimally repaired, or the failing components of the machines are replaced by spare parts. Moreover, the performance of a system can be computed using a continuous-time Markov chain. This model enables the simultaneous optimization of the buffer size and maintenance strategy to maximize the expected profit of the production system. Therefore, the revenue generated by throughput, the costs for buffer size, spare parts provisioning, and the costs for conducting minimal repairs and component replacements are included in the profit function. Moreover, optimal solutions are derived via complete enumeration. The numerical analyses revealed that for different throughput levels, the decision of whether MCMP is beneficial or not changes. Due to the complex dependencies of the buffer size, repair strategy, and spare parts level, as well as their influence on throughput, simultaneous optimization is highly recommended.

Further research can extend our work by considering longer flow lines and generalizing the transition rates. Additionally, the MCMP could be adopted in a manner that facilitates flexible decisions being made for each machine based on whether a component is repaired or replaced, which depends on the state of the machine, the buffer level, or spare parts inventory.

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