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Operational reliability and quality loss of diversely configurated manufacturing cells with heterogeneous feedstocks

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Abstract

Machine reliability in cellular manufacturing is a challenging engineering problem in the formation and design of manufacturing cells. The heterogeneity of feedstock quality is also common in manufacturing industry. However, so far, no work has been done to investigate the performance of diversely configurated manufacturing cells under the heterogeneous feedstocks. In this paper, considering the actual engineering condition, the uniformly random arrival and the clustered arrival of low-quality feedstocks are proposed and modeled by the homogeneous Poisson process and Hawkes process, respectively. Also, to study the mixed reliability of a machine under the impact of heterogeneous feedstocks, a mixed failure-rate model is constructed by the mixture of exponential and Weibull distributions, and the processing quality is modeled by a non-homogeneous Poisson process with a dynamic intensity function. Then, we achieve a contrastive analysis for operational reliability and quality loss of manufacturing cells with basic serial and parallel configurations under the impact of heterogeneous feedstocks. At last, the designed simulation illustrates the effectiveness of our proposed models, and some results are concluded to provide some guidelines for the design of manufacturing cells.

Keywords

Manufacturing cell, heterogeneous feedstocks, cell configuration, reliability, quality

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Introduction

Due to the capacity of quick response to fluctuations from the market, the flexible manufacturing cell (FMC) has been popularly implemented in the manufacturing industry. A typical FMC is usually composed of several processing machines, robots, and material handling systems.[1] As a core component, the processing machine plays a crucial role in the operation of FMCs.[2] Also, due to the instability of processing quality of upstream suppliers, feedstocks of manufacturing cells will have heterogeneous quality,[3] which will bring destabilizations to the machine and impact the performance of FMCs. Therefore, an investigation into the performance of manufacturing cells under heterogeneous feedstocks is necessary for improving the design and operation of FMCs.

In current researches, the reliability of machines has been considered in the design of manufacturing cells. Das et al.[4] proposed a multi-objective mixed integer programing model to optimize the design of cellular manufacturing systems, where the machine failure was assumed to obey an exponential distribution. Safaei et al.[5] constructed a cellular manufacturing system with a serial-parallel configuration to improve the redundant reliability of cells, where machine failure was also distributed exponentially. Also, many other researches applied the exponential reliability of machines in their performance analysis of manufacturing cells, for example, the performance evaluation of an FMC under random operational conditions,[6] the multi-state

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performance measure of manufacturing cells,[7] and the analysis for the operational performance of a manufacturing cell considering the effect of degraded operation modes.[8] Besides, Das et al.[9] also proposed a preventive maintenance planning model by assuming the machine had the Weibull distributed failure times in a cellular manufacturing system. In summary, current reliability models of machines in the study of manufacturing cells can be concluded as a static model, which cannot reveal the dynamic reliability of machines under the impact of heterogeneous feedstocks. In real-world industry, however, most populations of manufactured items are heterogeneous,[3] including the feedstocks of manufacturing cells. When these heterogeneous feedstocks are processed by a machine in a manufacturing cell, the low-quality ones of them will bring fluctuations to the machine, leading to the dynamic rise of its deterioration.

The dependence of failures is a common phenomenon in the engineering field.[10–14] It is also testified by many studies that the interdependence between machine reliability and product quality in a manufacturing system popularly exists, for example, the investigation of quality and reliability in a fixture system,[15] the study for the propagation of dimensional variations of products in multistage manufacturing systems,[16] the potential failure propagation caused by products in the complex manufacturing system,[17] and the mission reliability analysis based on machine reliability and work-in-process quality.[18] These years, considering the interdependence between machine reliability and product quality, many literatures also studied the performance of manufacturing systems with different configurations. For example, by modeling the dynamic interactions between reliability and quality, Ye et al.[19,20] evaluated the performance of manufacturing systems with serial configurations and serial-parallel configurations.[21] Based on the survival signature-based process optimization approach, Ge and Zhang[22] evaluated and improved the operational reliability of manufacturing systems with multiple process routes, which could be considered to have a network configuration. By integrating machine reliability and product quality, He et al.[23] proposed a Quality-State-Task-Network model to evaluate the mission reliability of the serial multi-station manufacturing system.

Among these studies, the analysis was implemented for manufacturing systems with a certain structure. However, with the improvement of machine flexibility in modern manufacturing industry, more machines with higher flexibility can be applied in the manufacturing cell, and different configurations can be chosen to form a cell in the design of cellular manufacturing systems. Also, in the design of manufacturing cells, the flow line and job shop are two popularly used configurations,[24] which can be considered as the basic serial and parallel structures, respectively. Therefore, some guideline is necessary for helping us to identify the advantages or disadvantages of cell structures when considering the impact of heterogeneous feedstocks. However, so far, no work has been done to investigate what difference the performance of manufacturing cells with these different configurations will have when they operate under the heterogeneous feedstocks.

Therefore, this paper presents a novel framework to investigate the operational reliability and quality loss of diversely configurated manufacturing cells when the quality of feedstocks is heterogeneous. First, the homogeneous Poisson process and Hawkes process are proposed to model two different arrival modes of low-quality feedstocks: the random and uniform arrival when the processing quality of upstream suppliers is stable and the clustered arrival when it is unstable. Then, combining the advantage of exponential distribution in modeling stable failure rate and the advantage of Weibull distribution in modeling increasing failure rate, a mixed failure-rate model of the machine is constructed to evaluate its dynamic reliability under the impact of heterogeneous feedstocks. Simultaneously, a non-homogeneous Poisson process with a dynamic intensity function is established to model the processing quality of machines under mixed reliability. At last, based on the proposed mixed reliability and processing quality models of machines, the operations of 2 two-machine cells with serial and parallel configurations are simulated, and the measurement of operational reliability and quality loss is analyzed.

The simulation results testified the effectiveness of the proposed mixed reliability model and processing quality model on evaluating the operation of machines under heterogeneous feedstocks. It also shows that both uniformly random arrivals and clustered arrivals of low-quality feedstocks will make the performance of manufacturing cells worse, where their impacts do not show significant differences. In the analysis for different configurations of cells, our result reveals that the serial cell has a greater vulnerability to resist the impact of low-qualified feedstocks.

The rest of this paper is organized as follows: Section “The arrival of low-quality feedstocks in manufacturing cells” proposes the studied manufacturing cells and models the arrival of low-quality feedstocks. Section “Reliability and processing quality of machines under heterogeneous feedstocks” details the mixed reliability model and processing quality of the machine. Section “The operational reliability and quality loss of manufacturing cells” proposes the performance measurements of manufacturing cells with different configurations. Section “Simulation design” provides the simulation parameter and scheme. Section “Results analysis” gives the analysis for the operational reliability and quality loss of manufacturing cells. Section “Conclusions” includes the conclusions arising from this research.

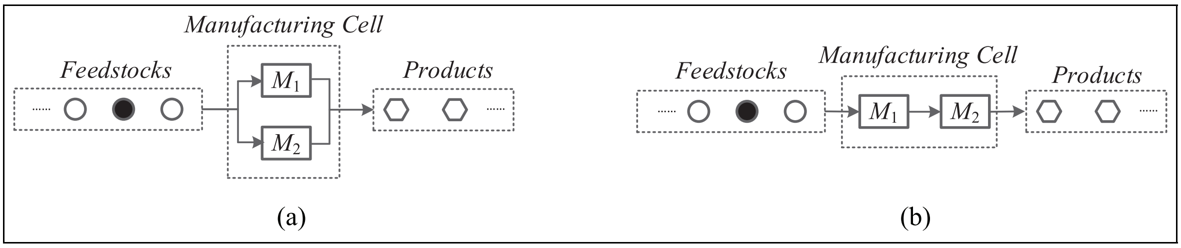

Figure 1. Manufacturing cells: (a) parallel cell and (b) serial cell.

The arrival of low-quality feedstocks in manufacturing cells

In this research, we consider the manufacturing cell with two machines and different configurations: the parallel cell and the serial cell, as shown in Figure 1. To study the difference in the performance of manufacturing cells with different configurations, we assume that both manufacturing cells have the same flexible machines, meaning that each machine has the same parameters and initial values of reliability and processing quality. Also, the two manufacturing cells have the same production rate and the same source of feedstocks.

In actual production, due to the instability of the performance of upstream suppliers, feedstocks with different quality states will be imported into the manufacturing cells. Here, we will discuss the arrival modes of feedstocks that will deteriorate machine reliabilities, namely the arrival of low-quality or unqualified feedstocks. When the upstream supplier operates with steady and regular performance, the arrival of low-quality feedstocks will be random and uniform, but when it operates with a deteriorating performance, low-quality feedstocks may arrive in clusters in some specific batches. In this study, the arrival of low-quality feedstocks is considered as one counting process $\{N(t); t \geqslant 0\}$, and we propose two different stochastic processes to model their different arrival modes.

The homogeneous Poisson process is one point process where the points occur "totally randomly."[3] Here, when the upstream supplier operates with steady and regular performance, we think that low-quality feedstocks will arrive randomly and uniformly, and the counting process $\{N(t); t \geqslant 0\}$ is one homogeneous Poisson process with the following probability distribution function,

$$P\{N(t + \Delta t) - N(t) = n\} = \frac{e^{-\tau t} \cdot (\tau t)^n}{n!}, \tag{1}$$

where the intensity is one constant τ. An example of arrivals of low-quality feedstocks obeying the homogeneous Poisson process is presented in Figure 2(a), which has six low-quality feedstocks during [0, 100].

Also, when the upstream supplier operates with a deteriorating performance, we think that low-quality feedstocks may cluster in some batches. In the statistical field, the Hawkes process is a stochastic process that can effectively depict self-exciting or clustered behaviors[25,26] and has been applied in engineering fields, such as the reliability analysis of systems with self-healing effect[27] and the traffic accident model via the self-exciting process.[28] Therefore, our study proposes a linear Hawkes process to model the counting process $\{N(t); t \geqslant 0\}$ when the arrival shows cluster features, whose intensity function is

$$\lambda(t) = v(t) + \int_{-\infty}^{t} h(t-u)dN(u), \tag{2}$$

where $v(t) > 0$ is the basic intensity when there is no self-exciting behavior and $h(t)$ is the kernel function ($h(t) > 0$ for $t \geqslant 0$, $h(t) = 0$ for $t < 0$),[29] as shown in equation (3).

$$h(t) = \begin{cases} ae^{-bt} & , t \geqslant 0 \\ 0 & , t < 0 \end{cases}, \tag{3}$$

where, $a > 0$, and $b > 0$. When the counting process $\{N(t); t \geqslant 0\}$ obey the Hawkes process with associated history ($H(t)$: $t \geqslant 0$), the conditional probability that one low-quality feedstock will arrive in the next period $[t, t + \Delta t]$ can be calculated by Hawkes[30]

$$P\{N(t + \Delta t) - N(t) = 1|H(t)\} = \lambda(t)\Delta t + o(\Delta t). \tag{4}$$

An example of obeying the Hawkes process is presented in Figure 2(b), which has seven low-quality feedstocks during [0, 100].

The mixed reliability and processing quality of machines under heterogeneous feedstocks

The mixed reliability of machines under heterogeneous feedstocks

The mixed reliability of a machine refers to the probability that the machine could perform its function without failure for a given period when suffering heterogeneous feedstocks. And it is reasonable to assume that the machine will suffer changeable operation risk when processing feedstocks with heterogeneous quality. That is to say, the machine will have a higher probability

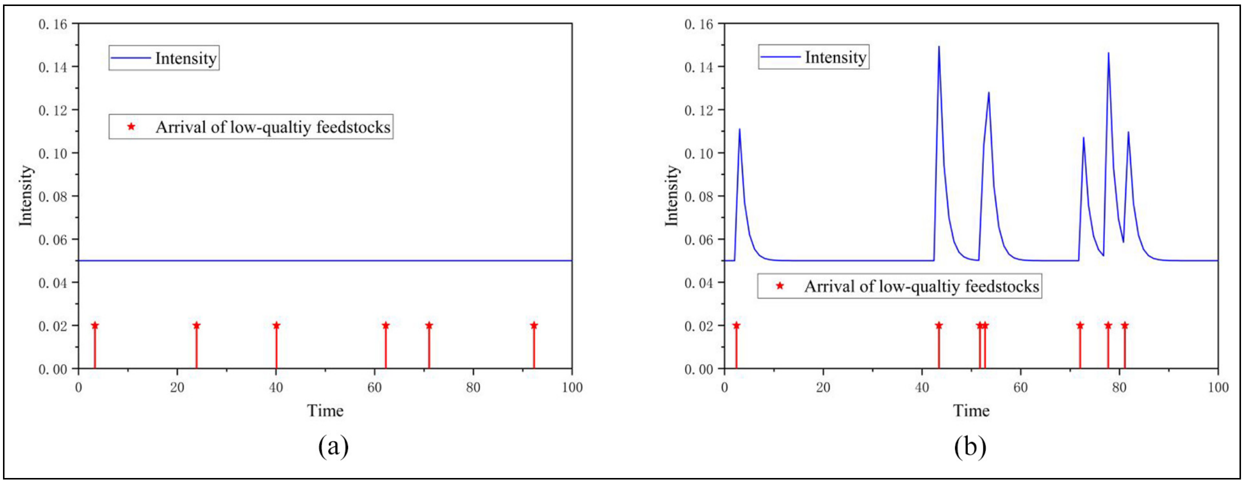

Figure 2. The example of different arrivals of low-quality feedstocks: (a) homogeneous Poisson process ($\tau = 0.05$) and (b) Hawkes process ($v(t) = 0.05$, $a = 0.1$, $b = 0.8$).

to fail when processing low-quality or unqualified feedstocks than the condition when processing high-quality or qualified feedstocks. Given this belief, we study the situation that machines have a stable failure rate when processing high-quality feedstocks but an increasing failure rate when processing low-quality feedstocks. The former condition represents the reliability of machines under the normal degradation when processing expected feedstocks, and the latter one represents the reliability of machines under the severe degradation caused by unexpected low-quality feedstocks.

In reliability engineering, the mixed model has been popularly applied to model the dynamic reliability of engineering systems.[31] For example, the Importance Measure using Gaussian mixture,[32] the Gaussian mixture model in the bearing performance degradation assessment,[33] and the Gaussian mixture model in the reliability analysis of nonlinear systems.[34] Also, this idea of mixture has been applied in the lifetime evaluation of engineering objects.[35,36] Obviously, this idea of mixture also provides us a methodology to model the dynamic reliability of machines under the heterogeneous feedstocks. Therefore, a mixed reliability model of machines is proposed in our study. During processing high-quality feedstocks, the machine has a stable failure rate, whose failure obeys an exponential distribution. However, during processing low-quality feedstocks, the machine will have a deteriorative failure rate. In this study, the deterioration of failure rate caused by low-quality feedstocks is assumed to have a positive correlation with the processing time, which is modeled by the Weibull distribution. Therefore, a mixed failure-rate model is proposed as shown in Figure 3.

We consider the deteriorative failure rate following a Weibull distribution in equation (5),

$$r_d(t_d) = \frac{\beta}{\alpha}\left(\frac{t_d}{\alpha}\right)^{\beta-1}, \tag{5}$$

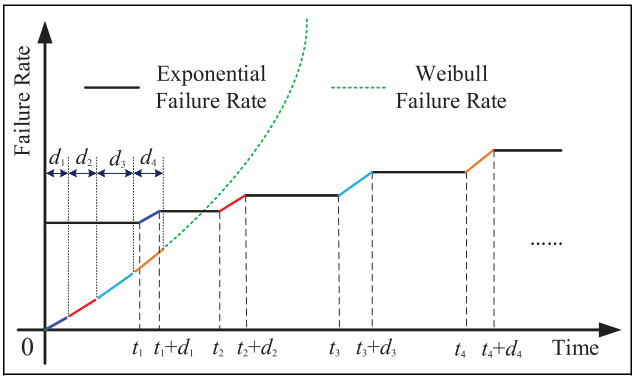

Figure 3. The mixed failure rate of machines under heterogeneous feedstocks.

where t_d is the time processing low-quality feedstocks, and α and β are the scale and shape parameters ($\beta > 1$). Here, $t_d = \sum d_i$, where d_i is the processing time of the ith low-quality feedstock in the machine. We denote r_s as the initial failure rate of the machine under the exponential distribution, then the mixed failure rate can be obtained by

$$r(t) = r_s + r_d(t_d) = r_s + \frac{\beta}{\alpha}\left(\frac{t_d}{\alpha}\right)^{\beta-1}. \tag{6}$$

According to the initial condition at $t = 0$ that $F(0) = 0$ and $r(0) = r_s$, we can obtain the failure probability function of a machine,

$$\begin{aligned} F(t) &= 1 - e^{-\int (r_s + r_d(t))dt} = 1 - e^{-\int_0^t r_s dt} \cdot e^{-\int_0^{\sum d_i} r_d(t)dt} \\ &= 1 - e^{-r_s \cdot t} \cdot e^{-\left(\frac{\sum d_i}{\alpha}\right)^{\beta}}. \end{aligned} \tag{7}$$

Further, the mixed reliability of a machine can be obtained by

$$R(t) = 1 - F(t) = e^{-r_s \cdot t} \cdot e^{-\left(\frac{\sum d_i}{\alpha}\right)^{\beta}}. \tag{8}$$

The processing quality of machines under heterogeneous feedstocks

In last subsection, a mixed reliability model is proposed based on the dynamic degradation caused by heterogeneous feedstocks. Therefore, it is reasonable to state that the processing quality of a machine will depend on its reliability. Also, the Poisson process is one effective mathematical method to model the number of nonconformities or defects in a repetitive process. Therefore, we construct a non-homogeneous Poisson process $\{M(t):\ t \geqslant 0\}$ with the following dynamic intensity function to model the processing quality of a machine when it does not fail and has a failure rate $r(t)$,

$$\varphi(t) = \omega - \varepsilon e^{-\delta \cdot r(t)}, \tag{9}$$

where $\omega > 0$, $\varepsilon > 0$, and $\delta > 0$ are constant parameters, and $M(t)$ is the number of defects produced during $[0, t]$. When a machine suffers a high risk to fail (the failure rate $r(t)$ becomes higher), the intensity of producing defects will increase. Here, $r(t) \in (0,\ \infty)$ and $\varphi(t) \in (\omega - \varepsilon,\ \omega)$, meaning that the intensity of producing defects is bounded. Specifically, we set $\omega = \varepsilon = P_{rm}$, where P_{rm} is the production rate of the machine in a cell, which can ensure the following two truths. When the failure rate of a machine tends to zero, $r(t) \to 0$, its intensity of producing defects will also tend to zero, $\varphi(t) \to 0$, meaning that the machine will operate in an almost ideal condition. When the failure rate tends to infinity, $r(t) \to \infty$, its intensity of producing defects will tend to their production rates, $\varphi(t) \to P_{rm}$, meaning that almost all products produced by it are defects.

Also, according to the mixed failure-rate model in Figure 3, we can conclude that when processing high-quality feedstocks, the machine has a stable failure rate and the intensity of producing defects is constant, so that processing quality obeys a homogeneous Poisson process (HPP). However, when processing low-quality feedstocks, the machine will have a deteriorative failure rate and the intensity of producing defects is an increasing function so that the processing quality obeys a non-homogeneous Poisson process (NHPP).

The operational reliability and quality loss of manufacturing cells

In general, system reliability is defined as the probability that the system performs its intended function under stated conditions without failure for a given period, and the reliability of a manufacturing system greatly depends on the reliability of its machines.[22] Therefore, to a great extent, the number of reliable working machines in a manufacturing cell can represent its operation performance. In this section, we use the probabilities that the manufacturing cell will suffer a different number of failed machines to measure its operational reliability. We denote $R_1(t)$ and $R_2(t)$ as the reliability of machine 1 and machine 2 in Figure 1, respectively, with $F_1(t)$ and $F_2(t)$ as their failure probabilities. Then, we use the probabilities, that there are 0, 1, and 2 machines failing in a two-machine manufacturing cell at time t, to measure the operational reliabilities of the manufacturing cells in Figure 1. And the calculation can be realized by equation (10),

$$\begin{cases} R_{U2}(t) = F_1(t) \cdot F_2(t) \\ R_{U1}(t) = R_1(t) \cdot F_2(t) + F_1(t) \cdot R_2(t) \\ R_{U0}(t) = R_1(t) \cdot R_2(t) \end{cases}, \tag{10}$$

where $R_{U2}(t)$, $R_{U1}(t)$, and $R_{U0}(t)$ represent that the manufacturing cell has 2, 1, and 0 failed machines at time t, respectively. And they satisfy that $R_{U2}(t) + R_{U1}(t) + R_{U0}(t) = 1$. When a cell has a higher $R_{U0}(t)$ and lower $R_{U2}(t)$, it will have higher operational reliability.

According to the processing quality model, the probability that there are m defects produced by a machine during $[t,\ t + \Delta t]$ can be obtained by the non-homogeneous Poisson process, as shown in equation (11),

$$P\{M(t + \Delta t) - M(t) = m\} = e^{-(m(t+\Delta t) - m(t))} \frac{[m(t + \Delta t) - m(t)]^m}{m!}, \tag{11}$$

where $m(t) = \int_0^t \varphi(s)ds$ is the average defect during $[0, t]$. For the parallel cell, low-quality feedstocks have the same probability to be assigned to each machine. Here, during $[0, t]$, the defects flowing out from the parallel cell equals the total number of defects produced by both machines. We define the accumulative percentage of defects flowing out from the parallel cell as the accumulative quality loss (AQL) of the parallel cell, which is calculated by

$$AQL_p(t) = \frac{M_p'(t) - M_p'(0)}{P_r \cdot t} = \frac{\sum_{i=1,2} (M_i(t) - M_i(0))}{P_r \cdot t}, \tag{12}$$

where P_r is the production rate of manufacturing cells, $M_p'(t) - M_p'(0)$ is the defects flowing out from the parallel cell during $[0, t]$.

For the serial cell, all low-quality feedstocks will be processed by machine 1, and all defects of machine 1 will become the feedstock of machine 2. Therefore, during $[0, t]$, the total number of defects flowing out from the serial cell equals the defects produced by machine 2.

Therefore, the AQL of the serial cell can be calculated by

$$AQL_S(t) = \frac{M_S'(t) - M_S'(0)}{P_r \cdot t} = \frac{M_2(t) - M_2(0)}{P_r \cdot t}, \quad (13)$$

where $M'_S(t) - M'_S(0)$ is the defects flowing out from the serial cell during [0, t].

Also, for a given time increment Δt, we define the instantaneous percentage of defects flowing out from a cell at time t as the instantaneous quality loss (IQL),

$$IQL_Z(t) = \frac{N_Z(t + \Delta t) - N_Z(t - \Delta t)}{2\Delta t \cdot P_r}, \quad (14)$$

where $Z = \{P, S\}$ representing the parallel and serial cells.

Simulation design

Simulation parameters

In the simulation, we set the production rate of manufacturing cells as $P_r = 1$, meaning that each manufacturing cell can process one feedstock during the unit time. Also, we set the arrival intensity of low-quality feedstocks in Poisson mode as $\tau = 0.05$, meaning that 5% of imported feedstocks will be low-quality. For the convenience of comparison, we also set the basic arrival intensity of low-quality feedstocks in the Hawkes mode as $v(t) = 0.05$ and parameters of the kernel function as $a = 0.1$, $b = 0.8$. The initial failure rate of the exponential distribution when process high-quality feedstocks is set as $r_s = 0.0002$, and the parameters of the deteriorative failure rate of Weibull distribution when processing low-quality feedstocks are set as $\alpha = 1500$, $\beta = 2.7$. These parameters of failure rate can exactly present the fact that the effect on the deterioration of failure rate will be weak when a machine suffers a small quantity of low-quality feedstocks but will become more and more strong with the accumulation of processed low-quality feedstocks.

Also, according to the production rate of the manufacturing cell, we can get the production rate of machines in parallel and serial cells: $P_{rP} = 0.5$ and $P_{rS} = 1$, and the processing time per product in the machine: $time_p = 1/P_{rP} = 2$ and $time_s = 1/P_{rS} = 1$. Based on these production rates of machines, we set the parameters of the processing quality in parallel and serial cells as follows,

$$\begin{cases} \omega_P = 0.5, \ \varepsilon_P = 0.5, \ \delta_P = 346.75 \\ \omega_S = 1, \quad \varepsilon_S = 1, \quad \delta_S = 346.75 \end{cases}. \quad (15)$$

Here, because parallel and serial cells have the same machines, we set $\delta_P = \delta_S$, representing that failure rates have the same effect scale on processing quality in the machine.

Simulation scheme

In this simulation, we simulate the operation of manufacturing cells for the time $T = 30{,}000$. First, we generate the homogeneous Poisson and Hawkes arrival instants of low-quality feedstocks $T_P = \{t_{p1}, t_{p2}, \ldots, t_{px}\}$ and $T_H = \{t_{h1}, t_{h2}, \ldots, t_{hy}\}$ during [0, 30,000], where x and y are the numbers of low-quality feedstocks in the two arrival modes. For the parallel manufacturing cell and homogeneous Poisson arrival T_P, the simulation scheme is illustrated in Figure 4. When simulating the parallel manufacturing cell and Hawkes arrival T_H, we can use the same simulation scheme in Figure 4 but replace the arrival instants T_P by T_H.

For the serial manufacturing cell and homogeneous Poisson arrival instants T_P of low-quality feedstocks, the simulation scheme has four steps, which are discussed below.

- **Step 1**: At the beginning, set the current instant $t_{cur} = 0$ and $i = 1$, and the numbers of low-quality feedstocks imported to machines 1 and 2 are $J_1 = 0$ and $J_2 = 0$.
- **Step 2**: Generate next instants that machines 1 and 2 produce defects under the stable failure rate by the HPP, denoted as t_1 and t_2.
- **Step 3**: Judge the earliest instant: $min\ (t_{pi}, t_1, t_2)$, which has the following three cases.
- ➢ **Case 1**: The arrival of low-quality feedstocks of machine 1 at t_{pi} is the earliest instant. Judge whether this low-quality feedstock in machine 1 will become a defect by the NHPP.
- **Condition 1**: Yes. Machine 2 will also receive one low-quality feedstock from machine 1. Update the number of low-quality feedstocks imported to machines 1 and 2: $J_1 = J_1 + 1$, $J_2 = J_2 + 1$. Update the failure rate at different instants according to the t_d in Table 1, and the numbers of defects produced by each machine during the intervals are obtained by the modes in Table 2. Then, update the current instant $t_{cur} = t_{pi} + 2 \times time_s$, $i = i + 1$.
- **Condition 2**: No. Only machine 1 receives a low-quality feedstock. Update the number of low-quality feedstocks imported to machine 1: $J_1 = J_1 + 1$. Update the failure rate at different instants according to the t_d of No. 1–3 in Table 1, and the numbers of defects produced by each machine during the intervals are obtained by the modes of No. 1–2 in Table 2. Then, update the current instant $t_{cur} = t_{pi} + time_s$, $i = i + 1$.
- ➢ **Case 2**: The instant t_1 that machine 1 produces a defect is the earliest one. Therefore, machine 2 will receive one low-quality feedstock from machine 1. Update the number of low-quality feedstocks

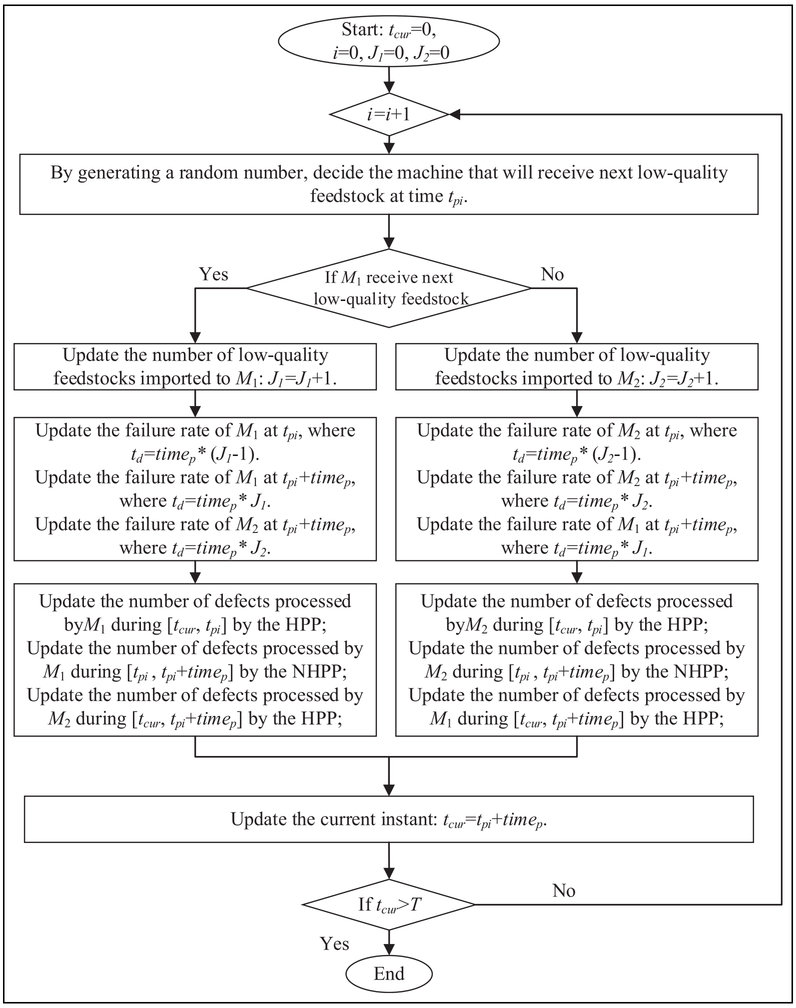

Figure 4. Simulation scheme of the parallel manufacturing cell.
t_{cur}: current instant; $J_1(J_2)$: the number of low-quality feedstocks imported to machine 1(2); M_1: machine 1; M_2: machine 2.

Table 1. The time t_d processing low-quality feedstocks at different instants in one circle (Case 1).

Machines	No.	Instants	t_d
Machine 1	1	t_{cur}	$time_s \times (J_1 - 1)$
	2	t_{si}	$time_s \times (J_1 - 1)$
	3	$t_{pi} + time_s$	$time_s \times J_1$
	4	$t_{pi} + 2 \times time_s$	$time_s \times J_1$
Machine 2	1	t_{cur}	$time_s \times (J_2 - 1)$
	2	t_{pi}	$time_s \times (J_2 - 1)$
	3	$t_{pi} + time_s$	$time_s \times (J_2 - 1)$
	4	$t_{pi} + 2 \times time_s$	$time_s \times J_2$

Table 2. Modes of producing defects at the different interval in one circle (Case 1).

Machines	No.	Intervals	Modes of producing defects
Machine 1	1	$[t_{cur}, t_{pi}]$	HPP
	2	$[t_{pi}, t_{pi} + time_s]$	NHPP
	3	$[t_{pi} + time_s, t_{pi} + 2 \times time_s]$	HPP
Machine 2	1	$[t_{cur}, t_{pi}]$	HPP
	2	$[t_{pi}, t_{pi} + time_s]$	HPP
	3	$[t_{pi} + time_s, t_{pi} + 2 \times time_s]$	NHPP

Table 3. The time t_d processing low-quality feedstocks at different instants in one circle (Case 2).

Machines	No.	Instants	t_d
Machine 1	1	t_{cur}	$time_s \times (J_1 - 1)$
	2	t_1	$time_s \times (J_1 - 1)$
	3	$t_1 + time_s$	$time_s \times (J_1 - 1)$
Machine 2	1	t_{cur}	$time_s \times (J_2 - 1)$
	2	t_1	$time_s \times (J_2 - 1)$
	3	$t_1 + time_s$	$time_s \times J_2$

Table 4. Modes of producing defects at the different interval in one circle (Case 2).

Machines	No.	Intervals	Modes of producing defects
Machine 1	1	$[t_{cur}, t_1]$	HPP
	2	$[t_1, t_1 + time_s]$	HPP
Machine 2	1	$[t_{cur}, t_1]$	HPP
	2	$[t_1, t_1 + time_s]$	NHPP

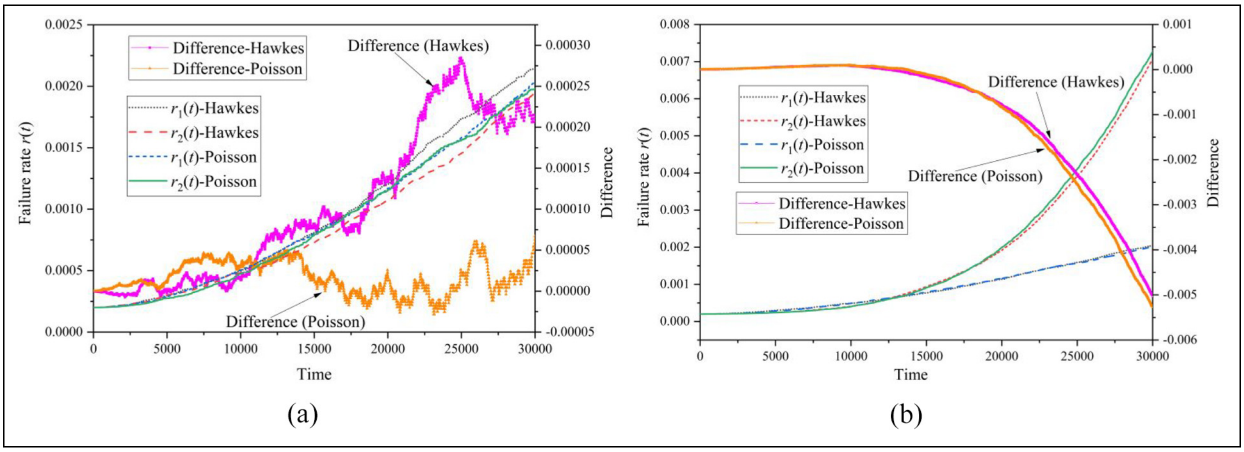

Figure 5. The failure rate of machines in each manufacturing cell: (a) parallel cell and (b) serial cell.

imported to machine 2: $J_2 = J_2 + 1$. Update the failure rate at different instants according to the t_d in Table 3, and the numbers of defects produced by each machine during the intervals are obtained by the modes in Table 4. Then, update the current instant $t_{cur} = t_1 + time_s$.

- **Case 3**: The instant t_2 that machine 2 produces a defect is the earliest one. During $[t_{cur}, t_2]$, the modes and times t_d of both machines do not change. Update the number of defects produced by machine 2 and update the current instant $t_{cur} = t_2$.

- **Step 4**: Whether current time $t_{cur} \geqslant T$? If YES, stop the simulation; If NO, go back to Step 2.

Also, for the serial manufacturing cell and Hawkes arrival instants T_H of low-quality feedstocks, the simulation scheme has the same four steps which need to replace the arrival instants T_P by T_H.

Results analysis

In this section, the operation is simulated according to the designed scheme. Based on the simulation of the homogeneous Poisson and Hawkes arrival modes, the numbers of low-quality feedstocks during [0, 30,000] are $x = 1511$ and $y = 1497$. Then, the operational reliability and quality loss of each manufacturing cell are analyzed based on the obtained sets of arrival instants: $T_P = \{t_{p1}, t_{p2}, \ldots, t_{px}\}$ and $T_H = \{t_{h1}, t_{h2}, \ldots, t_{hy}\}$.

Failure rates of machines in manufacturing cells

According to the simulation, we analyzed the mixed failure rate of each machine in different manufacturing cells and calculated their differences under the same arrival mode of low-quality feedstocks, as shown in Figure 5. Here, the difference is calculated by Difference $= r_1(t) - r_2(t)$, where $r_1(t)$ and $r_2(t)$ are the failure rate of machines 1 and 2 under the same arrival mode, respectively. The accumulation of low-quality feedstocks makes the mixed failure rate of each machine show an increasing pattern. In the parallel manufacturing cell, because of the same source of low-quality feedstocks, machine 1 and machine 2 have very similar patterns of failure rates no matter what arrival modes the low-quality feedstock has. Also, under both arrival modes, the differences in failure rates show a similar feature, that the difference has a narrow

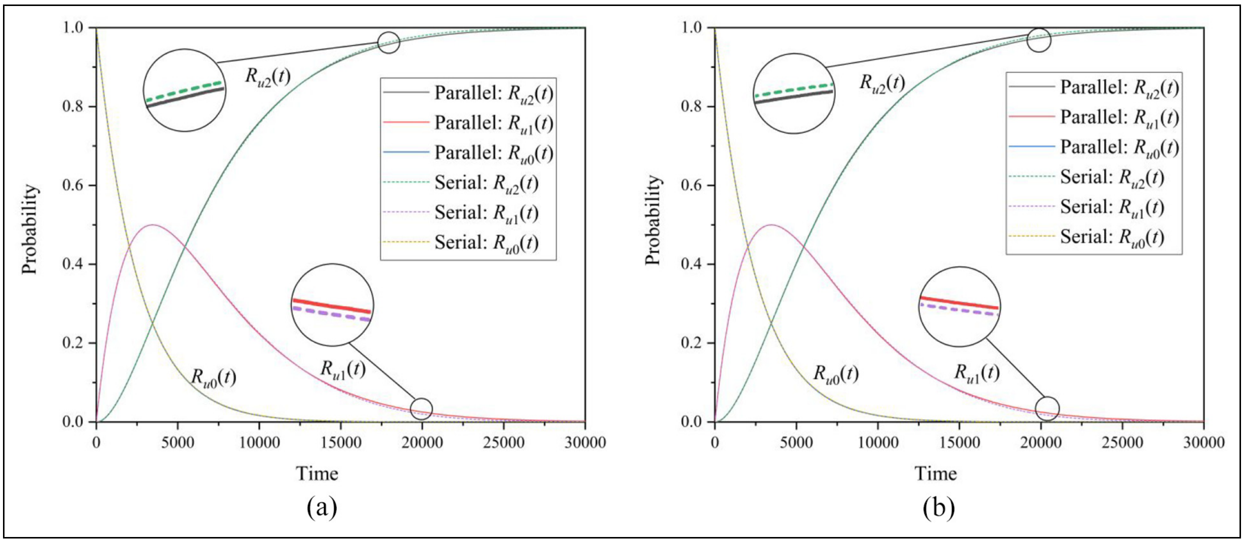

Figure 6. Operational reliabilities of manufacturing cells: (a) Hawkes arrival of low-quality feedstocks and (b) homogeneous Poisson arrival of low-quality feedstocks.

fluctuation at the early stage of machine operation but a wide fluctuation at the late stage. This presents that the machine has stronger survivability to stand up to the impact of low-quality feedstocks at the early stage than the late stage.

In the serial manufacturing cell, when having the same source of low-quality feedstocks, machine 2 has a similar pattern of failure rates with machine 1 at the early stage of their operations but has a faster increasing failure rate than machine 1 at the late stage. This phenomenon can be concluded as two reasons. The first is the dependence of the downstream machine (machine 2) on the upstream machine (machine 1) in the serial manufacturing cell. Specifically, when the failure rate of upstream machine 1 becomes worse because of the shock of low-quality feedstocks, its processing quality will also become worse. Then, more defects are produced and become the low-quality feedstocks of the downstream machine 2, so that its failure rate will increase fast at the late stage. The second reason is the increasingly weaker survivability to stand up to the impact of low-quality feedstocks at the late stage.

In the serial cell, the failure rate of machine 2 at the late stage is much higher than machine 1, where $r_2(t)$ is close to 0.007 at $t = 30{,}000$ but $r_1(t)$ is only 0.002. However, both $r_1(t)$ and $r_2(t)$ are about 0.002 at $t = 30{,}000$ in the parallel cell. This means that, when having the same machines, the downstream machine 2 in a serial cell has a much higher probability to fail at the late stage than the upstream machine in the serial cell and all machines in the parallel cell.

Operational reliability of manufacturing cells

In this section, we give the three measurements of the operational reliability for each manufacturing cell in Function (10), as shown in Figure 6. Under each arrival mode of low-quality feedstocks, the Probability R_{u2} (t) that the manufacturing cell has two failed machines ascends with time, the Probability R_{u0} (t) that the manufacturing cell has zero failed machine descends with time, and the Probability R_{u1} (t) that manufacturing cell has one failed machine ascends first and then descends with time. Although the difference is very small, we also can see that the serial cell has a higher Probability R_{u2} (t) than the parallel cell at the late stage, representing that the serial cell will have lower operational reliability in a long-term operation. This is because the dependence between upstream and downstream machines in the serial cell makes the reliability of the downstream machine worse, which does not happen in the parallel cell. This is coincident with the observation in last subsection that the downstream machine in a serial cell will suffer more risk to fail at ac later stage. Therefore, the serial configuration of manufacturing cells will show more disadvantages in reliability than the parallel configuration at the later stage.

On the other hand, the reliabilities of machines and cells under homogeneous Poisson and Hawkes arrivals of low-quality feedstocks do not show significant differences, meaning that both the uniformly random arrivals and clustered arrivals of low-quality feedstocks will have a similar effect on the operational reliability of manufacturing cells.

Quality loss of manufacturing cells

In this section, the AQL of manufacturing cells is analyzed for different arrival modes of low-quality feedstocks, as shown in Figure 7.

At the early stage (Time < 15,000), the serial cells have a relatively lower AQL than the parallels. However, at the later stage (Time > 15,000), the AQL of the serial cell will have a faster rise than the one of

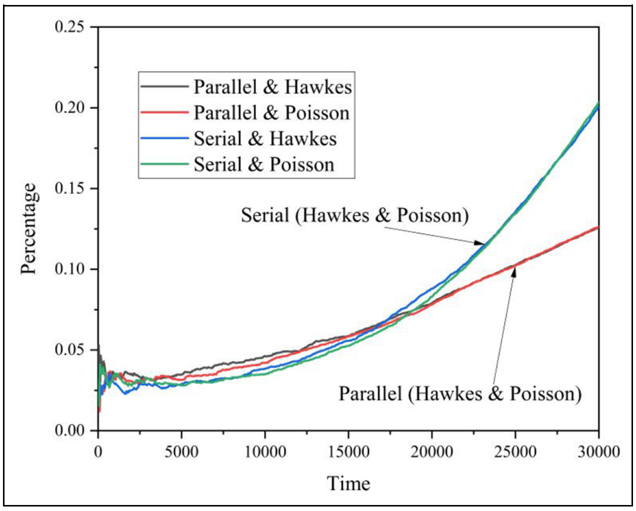

Figure 7. Accumulative quality loss of cells.

parallel cells, which is caused by the fast rise of the failure rate of the downstream machine 2 in the serial cell. This also means that the serial cell is less reliable than the parallel cell at the later stage. Furthermore, when having different arrival modes of low-quality feedstocks, the AQL of both serial and parallel cells does not present a significant difference.

Also, the IQL of the manufacturing cell is analyzed based on the equation (14), as shown in Figure 8. Here, the time increment $\Delta t = 100$. Obviously, due to the deterioration of failure rates, the IQL of cells will show growth and instability with the deterioration of processing quality. That is to say, the high IQL is always accompanied by a wider fluctuant interval, representing the higher instability of processing quality. It might also be noted that the IQL of the serial cell rises much faster than the parallel cell at the late stage, which also attributes to the impact of upstream machines on downstream machines in the serial cell, leading to the

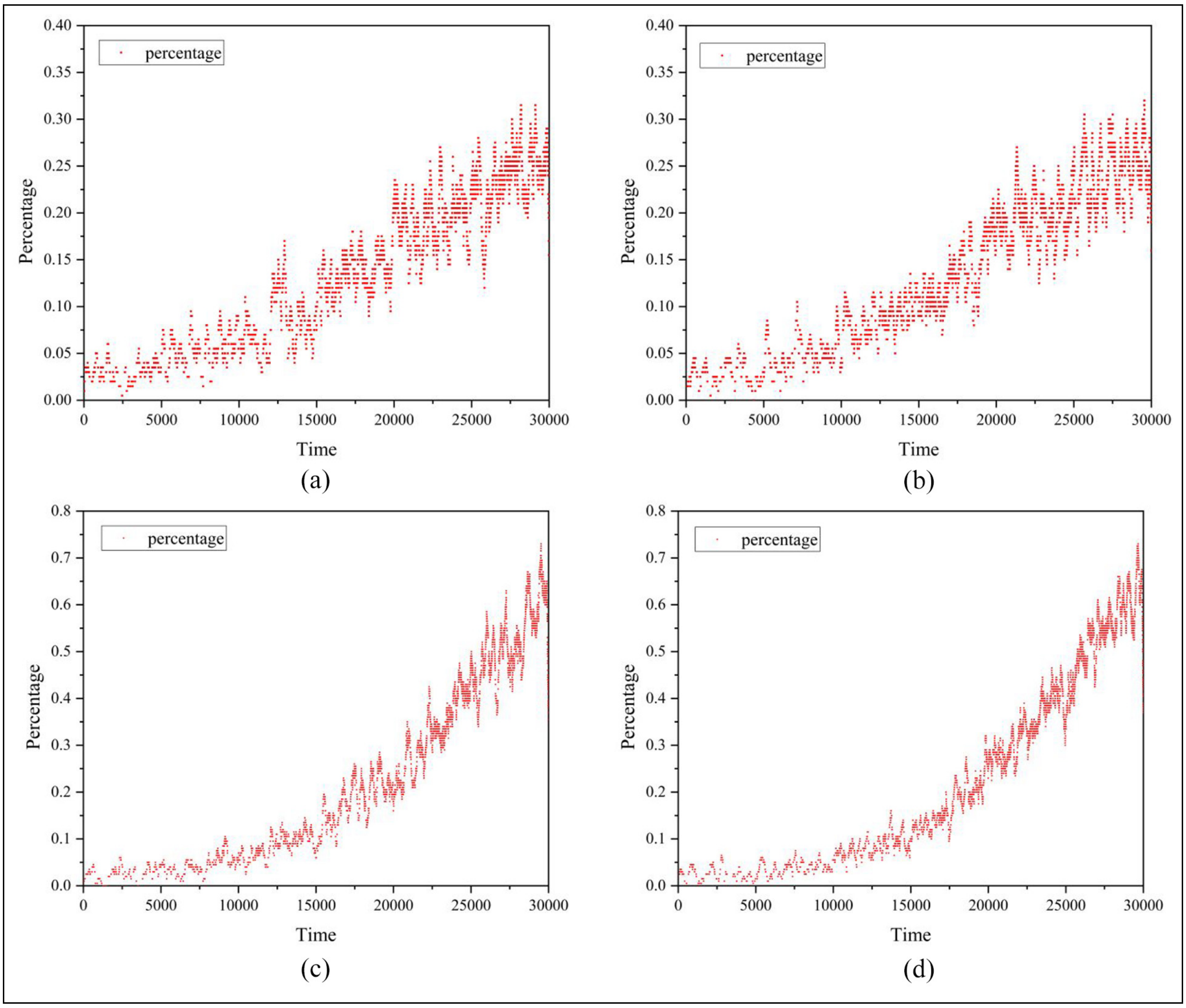

Figure 8. Instantaneous quality loss of cells: (a) parallel cell under Hawkes arrivals, (b) parallel cell under homogeneous Poisson arrivals, (c) serial cell under Hawkes arrivals, and (d) serial cell under homogeneous Poisson arrivals.

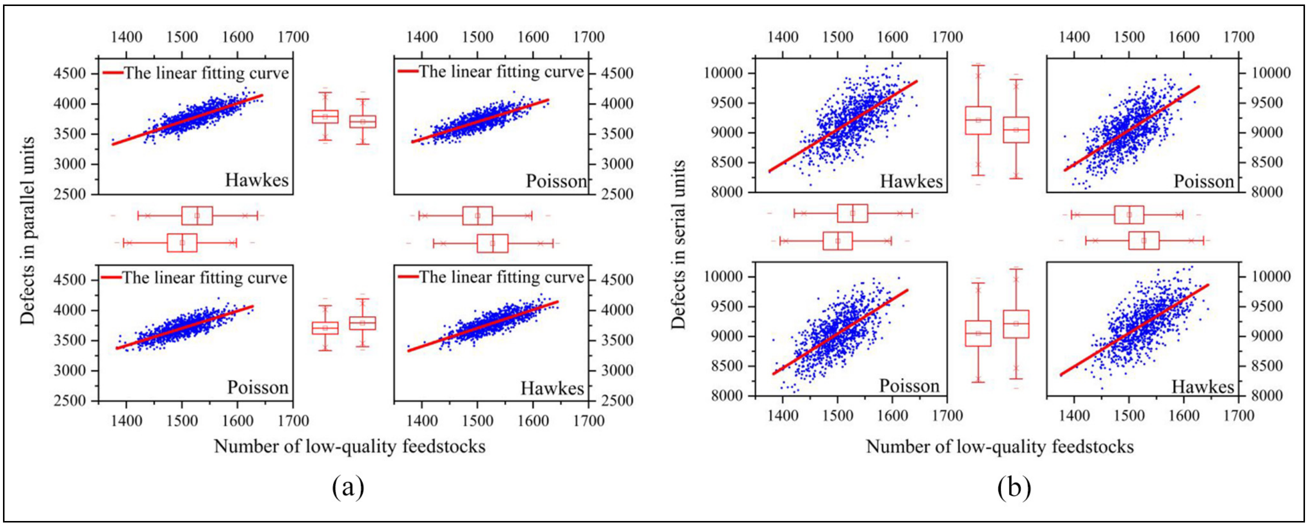

Figure 9. Box plots of defects and low-quality feedstocks in the manufacturing cell: (a) the parallel manufacturing cell and (b) the serial manufacturing cell.

increasingly weaker performance of downstream machines. Therefore, the serial manufacturing cell has a much higher IQL at the late stage.

Correlation analysis between low-quality feedstocks and defects

In this Section, the simulations under 1000 randomly generated arrival time sets T_P and T_H of low-quality feedstocks are implemented to further explore the correlation between the arrival of low-quality feedstocks and defects produced in manufacturing cells. By the simulations, we obtain the box plot of defects and low-quality feedstocks in each manufacturing cell, as shown in Figure 9. The linear fitting curves are provided for the scatter diagrams in each condition. It shows that fitted curves in serial cells have a greater slope than those in the parallel cells. This means that when suffering the same increment of low-qualified feedstocks, the serial cell may produce more defects. It proves the vulnerability of serial cells to the impact of low-qualified feedstocks. Also, it can be observed that the points in serial cells are more scattered, which shows the quality performance of serial cells will have a greater instability than the parallel cells.

Also, based on these data, we analyzed the Pearson Correlation Coefficient between the number of low-quality feedstocks and the number of defects produced by the manufacturing cell, as shown in equation (16),

$$r = \frac{\sum_{i=1}^{Num} (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{Num} (X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{Num} (Y_i - \bar{Y})^2}}, \tag{16}$$

Table 5. The Pearson correlation coefficient between low-quality feedstocks and defects.

	Parallel	Serial
Hawkes	0.8172	0.6696
Poisson	0.8005	0.6835

where X_i and Y_i are denoted as the number of low-quality feedstocks and defects in the ith simulated operation, and $Num = 1000$ is the number of simulations. The obtained Pearson Correlation Coefficient is shown in Table 5. Obviously, under both arrival modes of low-quality feedstocks, low-quality feedstocks and defects in the parallel cell always have a much stronger correlation than the ones in the serial cell. This means that, compared to the quality performance of a serial cell, the quality performance of a parallel cell has a stronger linear relationship with the quality of feedstocks from upstream suppliers.

Conclusions

Aiming at the research gap that no work has been done to evaluate the performance of diversely configurated manufacturing cells under the heterogeneous feedstocks, our study proposes an effective framework to fill up this gap to seek valuable decision information for the design of manufacturing cells. First, considering the actual condition in production engineering, the uniformly random arrival and the clustered arrival of low-quality feedstocks are modeled by the homogeneous Poisson process and Hawkes process, respectively. Then, in view of the different impacts from heterogeneous feedstocks, the reliability of machines when processing high-quality feedstocks is modeled by the exponential distribution, and the reliability when processing low-quality feedstocks is modeled by the Weibull distribution, exactly depicting the dynamic risk of machines under the low-quality feedstocks. Further, a mixed reliability model of machines is constructed by the mixture of exponential and Weibull distributions. Simultaneously, based on the mixed failure rates of machines, the processing quality of machines is modeled by a non-homogeneous Poisson process with a dynamic intensity function. At last, the operational reliability and quality loss of manufacturing cells with the basic serial and parallel configurations are analyzed on the basis of proposed models.

The simulation result proves that both uniform and clustered arrivals of low-quality feedstocks can deteriorate the performance of manufacturing cells, which do not show significant differences. Also, our result reveals the dependence between upstream and downstream machines in the serial cell, whose negative effect on both quality and reliability of serial cells is also testified by our simulation. At last, the analysis for the correlation between low-quality feedstocks and defects also demonstrates the greater vulnerability of serial cells to resist the impact of low-qualified feedstocks. In summary, through the proposed models and performance analysis for the basic serial and parallel manufacturing cells under the heterogeneous feedstocks, we hope some guidelines can be provided for the design of cellular manufacturing systems in the future.

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