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Bottleneck identification and alleviation in a blocked serial production line with discrete event simulation: A case study

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ABSTRACT

Aiming at the gap between theoretical research and practical application in the production bottleneck field, we apply five bottleneck identification methods in a serial production line in aerospace industry based on discrete event simulation and Plant Simulation software, meanwhile discuss the influence of the bottleneck machine quantity on the system performance. This paper evaluated the practicability, accuracy and limitation of various bottleneck identification methods at the practical level. The results of the bottleneck alleviation manifest that increasing the number of bottleneck machines can effectively improve the system performance, but the more machine quantity, the smaller performance improvement. More importantly, the paper studies the influence mechanism and function relationship of the bottleneck machine quantity on the maximum completion time from an interesting actual phenomenon for the first time. The function obtains the condition that the maximum completion time achieve the minimum. The research and conclusion of this paper have essential reference significance for production guidance and theoretical research, and can also contribute to narrow the gap between theory and application of the production bottleneck field.

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1. Introduction

The bottleneck is the machine or resource that affects the production capacity of the system in a period, which directly restricts the throughput of the whole system [1-6]. Therefore, bottleneck identification and alleviation are a vitally important production problem and the first step of production management, and it is of considerable significance to improve production efficiency, economic benefit and reduce energy consumption. The definition of the bottleneck is distinct for different production systems, and the bottleneck identification methods proposed in most researches are often not universal [7, 8]. The bottleneck is also a dynamic process that may move from one machine to another [9, 10]. Therefore, it is very complicated and challenging to apply the bottleneck identification theory to actual production.

To the best of our knowledge, bottleneck identification methods in most studies are proposed by two approaches: computer simulation [11-14] or mathematical analysis [15-18]. The conventional identification methods include as follows:

- The subsequent machine of the buffer with the highest average work-in-progress quantity is the bottleneck [11],
- The most utilized or least idle machine is the bottleneck [19],
- The next machine to the station with the highest blocking rate is the bottleneck [20],
- The machine with the longest average activity time is the bottleneck [21],
- The machine that processes the least variance or means absolute deviation of the inter-departure time is the bottleneck [14, 22], and
- The most sensitive machine to the system throughput is the bottleneck [23].

The purpose of bottleneck identification is to alleviate the bottleneck and improve system productivity. However, how to alleviate the bottleneck is a problem involving specific scenarios, and the methods to alleviate the bottleneck are also different for specific systems. The general alleviation methods include as follows:

- Increase the number of bottleneck machines [11, 21],
- Increase the buffer capacity before the bottleneck station [14], and
- Improve the production efficiency or reduce the processing time of the bottleneck machine [11, 24].

Although many researchers have established different bottleneck identification methods for various production systems, the practical application of these theories is rare. The reason is reflected in the complexity and uncertainty of the actual production system, such as limited buffer capacity, blocked, random interference, unique scenes. Moreover, these characteristics are difficult to be truly reflected by the theoretical model. Actual case studies on bottleneck alleviation are also rare, the effectiveness of alleviation methods has not been fully verified, and the general conclusions are still lacking. Therefore, there is a gap between the bottleneck theory and the practical application, which may be due to the fact that most papers focus on one or more practical problems at a time, and it is a challenge to apply the theory to various practical environments.

This paper aims to provide a case study that fully considers various bottleneck identification and alleviation methods, hoping to draw general conclusions for practice and theory, and also to narrow the gap between theory and application. The rest of the article is organized as follows. Section 2 proposes the materials and methods of the case study. Section 3 describes the system and establishes a virtual model based on Plant Simulation software. Section 4 shows the simulation results. Section 5 discusses the results of section 4. The summary and general conclusions will be presented in section 6.

2. Materials and methods

The serial production line, as the basic form of other types of production lines, is a typical discrete event dynamic system. The ideal serial production line model is shown in Fig. 1.

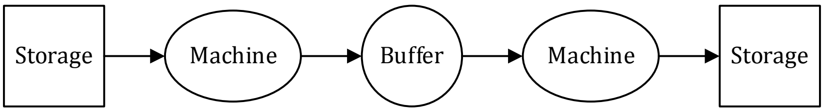

Fig. 1 The ideal model of the serial production line

The production activity in the serial production line is a dynamic process so that the bottleneck will change with this dynamic process. That means there is more than one bottleneck in the production process. Nevertheless, the primary bottleneck in a period is always significant and prominent, which is widely recognized by bottleneck theory and practical. Therefore, it is feasible to determine the most significant bottleneck based on the actual situation.

With the advent of Industry 4.0, computer simulation has become an important tool for production optimization [25]. Compared with mathematical modelling and algorithms, computer simulation can accurately reflect the system characteristics when faced with complex and dynamic production problems [26-29]. Simulation as a powerful tool to guide decision-making in an uncertain environment can simulate the whole production cycle by processing a series of discrete event points on the time axis successively. Recent literature also points out that discrete event simulation is an effective means to solve discrete event systems [30, 31]. Therefore, we adopt the method of discrete event simulation to carry out the case study.

The research method of this paper can be described as follows, and the Plant Simulation software was used for creation of virtual model.

- Analysis layout and material flow of the system, and collect the time information of each process.
- Determines the feasible bottleneck identification method according to the actual system information.
- Establishes and verifies the simulation model of the system.
- Analysis system bottleneck based on the simulation model and identification method.
- Determines the appropriate bottleneck alleviation methods according to the actual system and the identified bottleneck machine, then discusses the performance of the alleviation method.
- Summarizes and concludes.

3. System analysis and modelling

3.1 Problem description

The case study involved a product processing and testing system in the aerospace field. The production layout is shown in Fig. 2. The system is mainly composed of the warehouse, four frame manipulators, two sets of transmission devices, some composite processing platforms (CP) and a series of auxiliary process platforms.

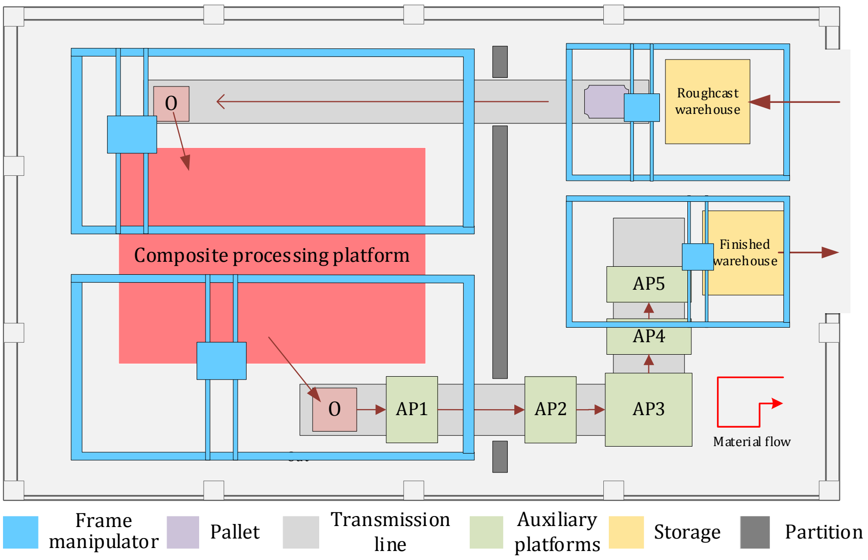

Fig. 2 The layout of the system

The material flow process can be described as follows:

- The frame manipulator carries the parts from the roughcast warehouse (RW) to the pallet until the pallet is filled, then the transport line begins to move with the pallet to the leftmost side of the track. The pallet capacity is 2. 15 s is needed for each part to be transported from the warehouse to pallet. The length of the transport line is 12 m, and the speed is 0.3 m/s.
- The second frame manipulator (FM, feeding manipulator) carries the parts from the pallet to the composite processing platform for processing, which requires 85 s for each frame manipulator to carry, and the processing time of the compound platform is 568 s.

- After the completion of the composite processing platform, the parts are carried by the third frame manipulator (BM, blanking manipulator) to the starting point of another transmission line, and each frame manipulator in this stage needs 57 s.
- The transmission line carries the parts through 5 auxiliary platforms (AP1, AP2, AP3, AP4, AP5) in turn, and the fourth frame manipulator (OM, offline manipulator) carries it to the finished product warehouse (FW). The processing time of the five stations is 10 s, 10 s, 10 s, 30 s, 30 s. The time of the frame manipulator off the line is 40 s.

Besides, if there are multiple compound processing platform, the feeding and blanking manipulator may face the problem of multiple targets, then the feeding to take the principle of proximity, the blanking to take the "first finished parts first blanking" strategy.

3.2 Problem assumption

According to the problem description, the system is a blocked serial production line system, which has no buffers. To facilitate the case study and the establishment of the simulation model, we suggest the following hypotheses in the case study:

1) The system is completely reliable and will not break down;
2) Due to the high degree of automation and the stable machining efficiency, the processing time is regarded as an absolute constant;
3) The finished product warehouse has enough capacity;
4) The number of parts stored in the roughcast warehouse is 40 and evaluates the production performance by the production indicators when 40 parts were all processed.

Six bottleneck identification methods are mentioned in the introduction, but the system has no buffer, so it is not feasible by the average work-in-progress of the buffer. The other five methods are all available, which will be applied to our practical case.

3.3 Model construction

Plant Simulation is used in this paper, and it is an object-oriented discrete event simulation software that can significantly reduce the difficulty of modelling and analysis with the characteristics of inheritance, encapsulation and visualization.

Establish machine objects, control strategies and data collection strategies for each process according to the system layout and material flow process. After repeated adjustments and modifications, the final simulation model is shown in Fig. 3. The object of “BF1”, “BF2” and “BF3” was created for ease of modelling and had no impact on the simulation logic.

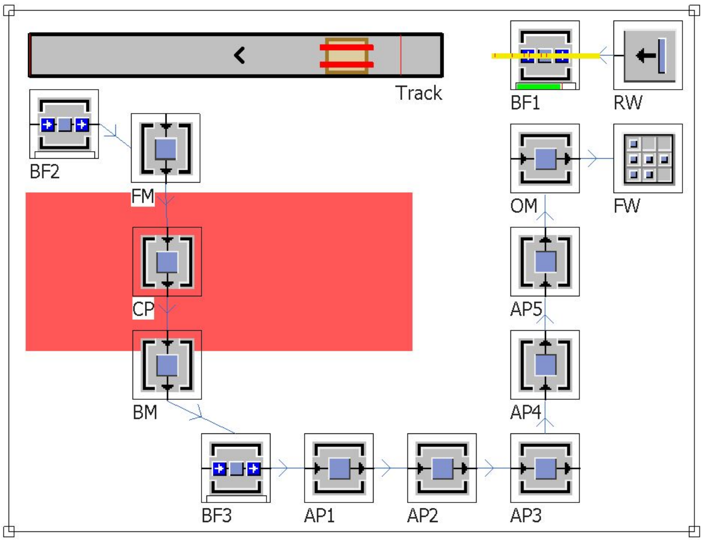

Fig. 3 The simulation model in plant simulation software

3.4 Model validation

The validity of the model is the premise of drawing correct results and conclusions. We allege that the established model is valid based on the following facts:

- The model runs correctly until all 40 parts are offline.
- The time of each production process is discussed and determined repeatedly by the planners after taking full account of the actual situation.
- The planners consider that the simulation logic is consistent with the actual production logic described in 3.1 by observing the simulation animation. (https://www.bilibili.com/video/av82436626/)

4. Results of the simulation

For the case study, the five available bottleneck identification methods are the most utilized or least idle machine (BT_1); The next machine to the station with the highest blocking rate (BT_2); The machine with the longest average activity time (BT_3); The machine that processes the least variance or mean absolute deviation of the inter-departure time (BT_4); The most sensitive machine to the system throughput (BT_5).

The evaluation indexes of BT_1, BT_2, BT_3 and BT_4 are machine utilization rate (MUR) or machine idle rate (MIR), machine blocking rate (MBR), average activity time (ACT), average absolute deviation (ITA) or variance (ITV) of inter-departure time.

BT_5 is the natural explanation of the bottleneck, but this concept is relatively vague, and the evaluation index is difficult to establish. Literature [21] solved the problem of job shop bottleneck identification through complex mathematical models and algorithms, but the authenticity and accuracy of mathematical modelling in diverse and complex environments could not be guaranteed. Therefore, we propose an intuitive mean that observe the Gantt chart to judge the most sensitive machine for throughput.

Collecting time information in the whole production cycle through model simulation, obtaining the indexes and shown in Table 1.

Table 1 shows that the bottlenecks identified by BT_1 and BT_3 are CP. However, the evaluation indexes of BT_2 and BT_4 do not show the difference on the machine, and the bottleneck is not distinguished. The result of BT_5 is also CP, its Gantt chart and specific discussion will be put in Section 5.

Then consider the measure to alleviate the bottleneck after CP is determined as the bottleneck. There is no buffer in the case study, so it is not feasible to increase the buffer capacity in front of the bottleneck. Besides, all the work is done by automatic equipment, so the production efficiency can hardly be accelerated. Therefore, the measure to alleviate the bottleneck is to increase the number of composite processing platforms.

Table 1 Evaluation indexes of the BT_1, BT_2, BT_3, BT_4

Machine	BT_1		BT_2	BT_3	BT_4	
	MUR, %	MIR, %	MBR, %	ACT, s	ITA	ITV
FM	12.9	87.1	0	85	0	0
CP	**86.3**	**13.7**	0	**568**	0	0
BM	8.7	91.3	0	57	0	0
AP1	1.5	98.5	0	10	0	0
AP2	1.5	98.5	0	10	0	0
AP3	1.5	98.5	0	10	0	0
AP4	4.6	95.4	0	30	0	0
AP5	4.6	95.4	0	30	0	0
OM	6.1	93.9	0	40	0	0

To determine the impact of the bottleneck machine quantity on the system performance, we consider a total of five scenarios, corresponding to the number of composite machining platforms of 1, 2, 3, 4, 5, then established the simulation model and control strategy for each scenario. The evaluation indexes in each scenario are completion time of the first part (FAT, first arrival time), completion time of the last part (FCT, final completion time), mean time interval between the part entering the finished warehouse (MCT, mean cycle time), utilization of the composite processing platform (CPU), utilization of feeding manipulator (FMU), utilization of blanking manipulator (BMU), maximum machine utilization (MMU), average machine utilization (AMU). The simulation results of those indexes are shown in Table 2.

Table 2 System performance evaluation in each scenario

Scenario No.	FAT, s	FCT, s	MCT, s	CPU, %	FMU, %	BMU, %	MMU, %	AMU, %
1	865	26332	653.1	86.3	12.9	8.7	86.3	15.9
2	865	13357	320.3	85	25.5	17.1	85	27.9
3	865	9354	217.7	80.9	36.3	24.4	80.9	35.9
4	865	6997	157.2	81.1	48.6	32.6	81.1	43.7
5	865	5776	125.9	78.6	58.8	39.5	78.6	48.9

5. Discussion

5.1 Evaluation of each bottleneck identification method

There are four machine states: working, waiting, blocked and failed. From the results in Table 1, it can be seen that the three states other than the working do not necessarily exist, such as the blocked state of the machine in our case study.

Machine utilization represents the working state, is the natural characteristic of the machine. Using machine utilization as an indicator to identify the bottleneck can determine the use degree of the machine. High usage means that parts are stacked in front of it, forming bottlenecks.

Average activity time is correlated with the machine utilization. With the total completion time is equal, the higher the machine utilization, the longer time the part stays on each machine, which is also the average activity time.

The inter-departure time of each part arrive at each machine in the case is shown in Fig. 4. The abscissa represents the sequence of parts arriving at each machine, and the ordinate represents the corresponding arrival time. It can be seen that the part arrival time of each machine is proportional to the part arrival sequence, which means that the processing interval time of all the part begins in each machine is equal.

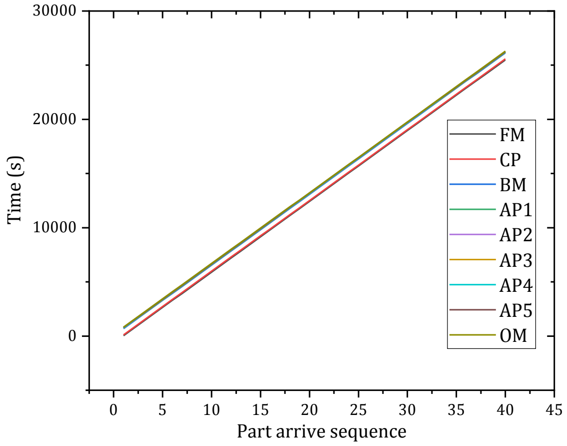

Fig. 4 The inter-departure time of each part arrive at each machine

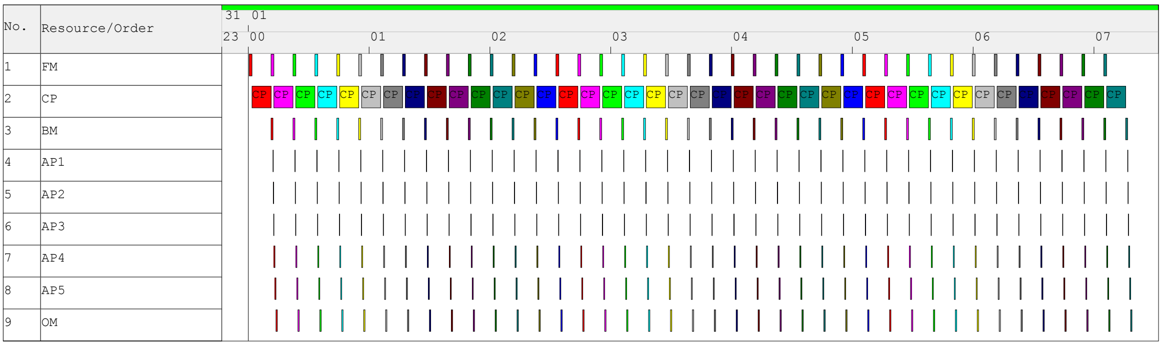

Fig. 5 The Gantt chart of the system

The Gantt chart is shown in Fig. 5. The abscissa is time (unit: h), and the ordinate is machine sequence. Each block in the Gantt chart represents the starting processing time and processing duration of the corresponding part on the corresponding machine. It can be seen that the processing duration of the parts in the CP is the longest, which has a more significant impact on the final completion time and throughput than other machines. Therefore, the composite processing platform is the most sensitive machine to the throughput, means it is the bottleneck machine.

It should be noted that the practicability, accuracy and limitation of these bottleneck identification methods are specific to this case study, which does not mean that these methods are wrong in principle, but indicates that there is a gap between theory and application.

5.2 The impact of the bottleneck machine quantity on system performance

The FAT represents the speed of the system laying, the FCT and the MCT represent production efficiency, and the machine utilization represents the degree of efficient output. Besides, the factory is very concerned about the utilization of the CP, FM and the BM. Therefore, we selected a total of eight indicators in Table 2 to evaluate the system performance.

The completion time curves and mean cycle time under five scenarios are shown in Fig. 6. According to Fig. 6(a), it can be known that the first completion time of the five scenarios is the same, while the maximum completion time presents a downward trend, which means increase the bottleneck machine quantity cannot improve the system laying speed, but can effectively improve the production efficiency. It can be seen from Fig. 6(b) that the relationship between the mean cycle time and the number of bottleneck machines presents a decreasing trend with decreasing acceleration. It can be inferred from this trend that as the number of bottlenecks continues to increase, the final completion time and the mean cycle time will hardly decrease once the threshold is reached.

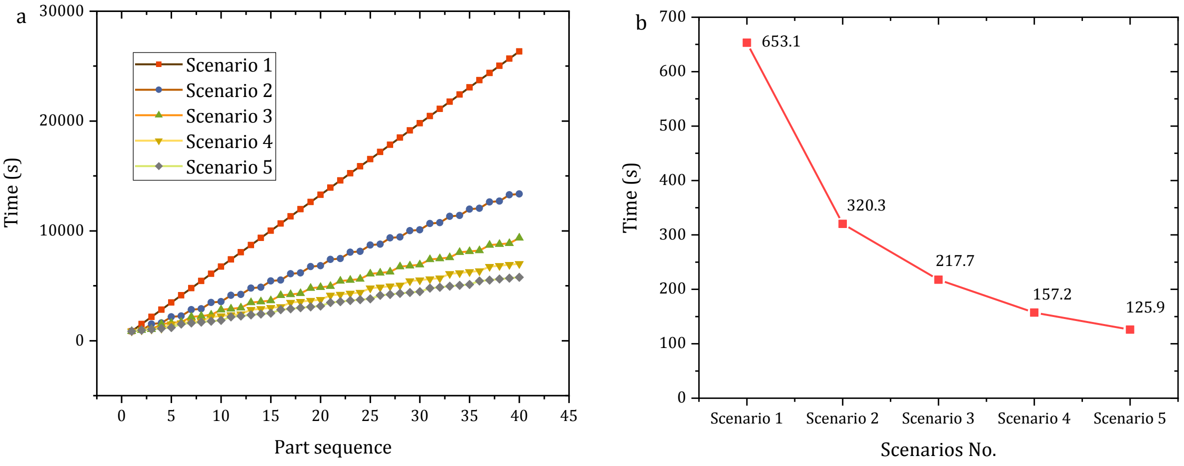

Fig. 6 (a) The completion time of each part in each scenario; (b) The mean cycle time of each scenario

The utilization rate of each machine under five scenarios is shown in Fig. 7. It can be seen in Fig. 7(a) that with the increase of the bottleneck machine quantity, the mean utilization rate of the composite processing platform (MCP) decreases with a small range, while the utilization rate of the non-bottleneck station increases significantly. It can be seen in Fig. 7(b) that with the increase of the bottleneck machine quantity, the maximum machine utilization rate decreases slightly, while the average machine utilization rate increases significantly, which indicates that increasing the bottleneck machine quantity can improve the balance of the whole serial production line system.

From the above analysis, it can be drawn that increasing the number of bottleneck machines can effectively alleviate the bottleneck. However, the alleviate ability decreases with the machine quantity increases. The more bottleneck machines, the smaller the performance improvement to the production system. At the same time, increasing the machine quantity will bring more resource consumption and economic investment, which means that the bottleneck machine quantity should meet the requirements of both system performance and economy, and there must be a balance between the two. For the case study, the number of bottleneck machines was ultimately determined to be 3.

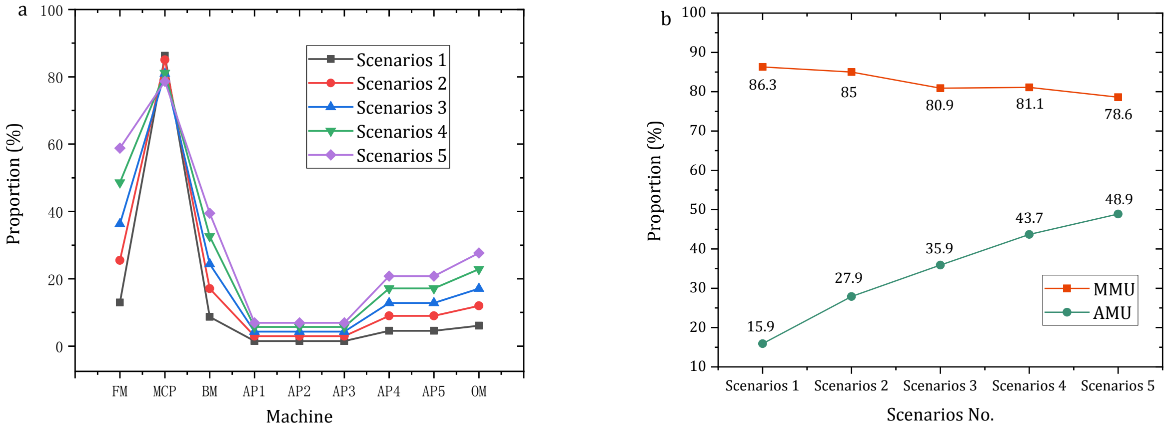

Fig. 7 (a) Machine utilization in each scenario; (b) The maximum and average machine utilization in each scenario

5.3 The function between final completion time and bottleneck machine quantity

According to Fig. 6(a), when the bottleneck machine quantity is greater than 1, the interval of part completion time is not equal. This phenomenon can be explained as the group warehousing under different quantity of bottleneck machine, which means the parts are completed in groups, and the number of parts per group is equal to the bottleneck machine quantity. The completion time curve in scenarios 5 is shown in Fig. 8, which intuitively shows the phenomenon that five parts are put into storage as a group, with short completion interval time within the group and long completion interval time between the groups.

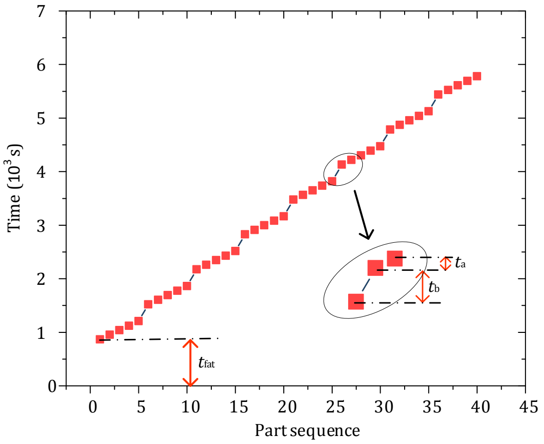

Fig. 8 The completion time of each part in scenarios 5

According to Fig. 8, the final completion time is related to five factors: completion time of the first part denoted by t_{fat}, the completion interval time within the group denoted by t_a, the completion interval time between the groups denoted by t_b, the number of times t_a appears denoted by n_a, the number of times t_b appears denoted by n_b. Besides, there is only t_b when the number of bottleneck machines is 1. The objective function can be preliminarily expressed as follows.

$$C_{\max} = \begin{cases} t_{\text{fat}} + n_{\text{bi}} \times t_{\text{bi}} + n_{ai} \times t_{ai} & i > 1 \\ t_{\text{fat}} + n_{\text{bi}} \times t_{\text{bi}} & i = 1 \end{cases} \tag{1}$$

where

$$t_{\text{fat}} = \sum_{k=1}^{m} t_k \tag{2}$$

$$n_{\text{bi}} = \begin{cases} floor\left(\frac{y}{i}\right) - 1 & mod\left(\frac{y}{i}\right) = 0 \\ floor\left(\frac{y}{i}\right) & mod\left(\frac{y}{i}\right) \neq 0 \end{cases} \tag{3}$$

$$n_{\text{ai}} = \begin{cases} y - floor\left(\frac{y}{i}\right) & mod\left(\frac{y}{i}\right) = 0 \\ y - floor\left(\frac{y}{i}\right) - 1 & mod\left(\frac{y}{i}\right) \neq 0 \end{cases} \tag{4}$$

Where $C_{\max}$ is the final completion time, i is the number of bottleneck machines (i is a positive integer), t_k is the processing time of the machine k, m is the total process quantity, y is the number of parts needs to be processed; "*floor*" means rounding down, "*mod*" means remainder.

The Gantt chart of the first two groups in the feeding manipulator (M1, machine no.1) and composite processing platform (M2, machine No.2) is shown in Fig. 9. All scenarios can be described in Fig. 9, t_a can be regarded as the completion interval of the part in the second group, while t_b can be regarded as the time between the last part in the first group and the first part in the second group.

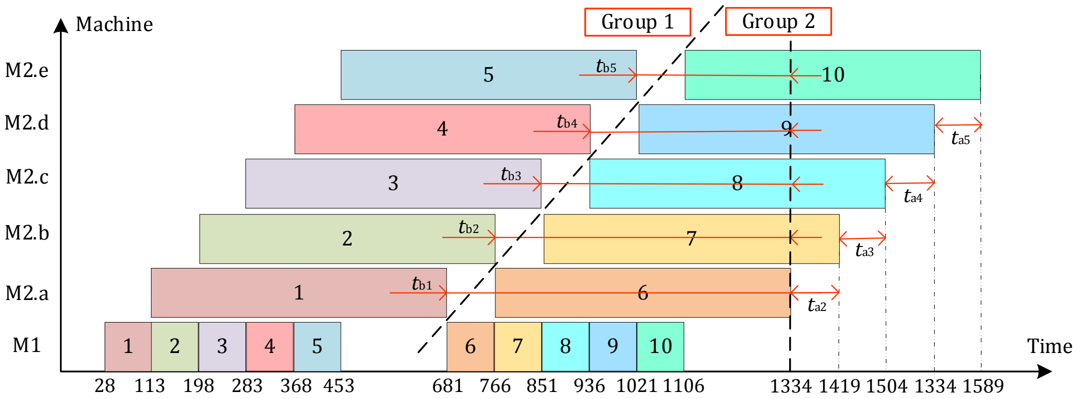

Fig. 9 The Gantt chart of the first two groups

For instance, parts 1 and 6 describe scenarios 1. Since the feeding frame manipulator needs to wait for the completion of the composite processing platform to continue feeding, the process (6, 1) (representing the processing of part No. 6 on machine No. 1) shall not begin until the process (1, 2) is completed. It means that the period from the end of the process (1, 2) to the end of the process (6, 2) is the interval time between the groups in scenario 1, which denoted by t_{b1}.

Parts 1, 2, and 6, 7 represent scenarios 2. Since there are two CP at scenarios 2, process (2, 1) can be started immediately after the process (1, 1) completes, while (6, 1) can only start after the processes (1, 2) and (2, 2) all complete. Then the period from the end of the process (2, 2) to the end of the process (6, 2) is the interval time between the groups in scenario 2, which denoted by $t_{b2.}$ The interval time within the group can represent the time from the end of the process

(6, 2) to the end of the process (7, 2) and denoted by t_{a2}. Similarly, the corresponding t_{a2}, t_{a3}, t_{a4}, t_{a5} and t_{b1}, t_{b2}, t_{b3}, t_{b4}, t_{b5} can be obtained and has been shown in Fig. 9.

For analysis and representation comprehensible, we introduce the concept of the secondary bottleneck to distinguish the most significant bottleneck. A fundamental principle of the secondary bottleneck is that as the number of bottleneck machines increases, the bottleneck will move from the current bottleneck to the secondary bottleneck. The identification method of the secondary bottleneck is similar to the primary bottleneck. Sort the indexes in table 1, and the second one is the secondary bottleneck. According to Table 2, FM is the secondary bottleneck machine in the case study.

According to the above analysis and Fig. 9, with the increase of the bottleneck machine quantity, t_a remains unchanged and is equal to the processing time of the FM. However, every time the number of bottleneck machines increases by one, t_b reduces the processing time of a secondary bottleneck. t_a and t_b can be expressed as follows.

$$t_{ai} = t_{\mathrm{sb}} \quad i > 1 \tag{5}$$

$$\begin{aligned} t_{bi} &= t_{\mathrm{pb}} + t_{\mathrm{sb}} - (i-1) \times t_{\mathrm{sb}} \\ &= t_{\mathrm{pb}} - (i-2) \times t_{\mathrm{sb}} \end{aligned} \tag{6}$$

Where t_{sb} is the processing time of secondary bottleneck, t_{pb} is the processing time of primary bottleneck. Although we can only know from Fig. 9 that t_{ai} is equal to the processing time of FM, and t_{bi} is equal to the processing time of CP. Nevertheless, through further analysis by changing the time of each station, we found that t_{sb} is always equal to the processing time of secondary bottleneck, and t_{pb} is always equal to the processing time of primary bottleneck. Then the $C_{\max}$ can be expressed as follows.

$$C_{i\max} = \begin{cases} \sum_{k=1}^{m} t_k + \left[y - floor\left(\frac{y}{i}\right)\right] \times t_{\mathrm{sb}} + \left[floor\left(\frac{y}{i}\right) - 1\right] \times \left(t_{\mathrm{pb}} - (i-2) \times t_{\mathrm{sb}}\right) & i > 1, mod\left(\frac{y}{x}\right) = 0 \\ \sum_{k=1}^{m} t_k + \left[y - floor\left(\frac{y}{i}\right) - 1\right] \times t_{\mathrm{sb}} + floor\left(\frac{y}{i}\right) \times (t_{\mathrm{pb}} - (i-2) \times t_{\mathrm{sb}}) & i > 1, mod\left(\frac{y}{x}\right) \neq 0 \\ \sum_{k=1}^{m} t_k + \left[floor\left(\frac{y}{i}\right) - 1\right] \times \left(t_{\mathrm{pb}} - (i-2) \times t_{\mathrm{sb}}\right) & i = 1 \end{cases} \tag{7}$$

After arrangement

$$C_{i\max} = \begin{cases} \sum_{k=1}^{m} t_k + floor\left(\frac{y}{i}\right) \times \left(t_{\mathrm{pb}} - (i-1) \times t_{\mathrm{sb}}\right) + (y + i - 2) \times t_{\mathrm{sb}} - t_{\mathrm{pb}} & i > 1, mod\left(\frac{y}{x}\right) = 0 \\ \sum_{k=1}^{m} t_k + floor\left(\frac{y}{i}\right) \times \left(t_{\mathrm{pb}} - (i-1) \times t_{\mathrm{sb}}\right) + (y-1) \times t_{\mathrm{sb}} & i > 1, mod\left(\frac{y}{x}\right) \neq 0 \\ \sum_{k=1}^{m} t_k + [y-1] \times \left(t_{\mathrm{pb}} + t_{\mathrm{sb}}\right) & i = 1 \end{cases} \tag{8}$$

According to Eq. 8, when $t_{\mathrm{pb}} - (i-1) \times t_{\mathrm{sb}}=0$, the $C_{i\max}$ gets the minimum value. Then according to Eq. 8, the condition can be expressed as the Eq. 9 and Eq. 10 after the arrangement.

$$i = mod(\frac{t_{\mathrm{pb}}}{t_{\mathrm{sb}}} + 1) \tag{9}$$

$$\frac{t_{\mathrm{pb}}}{i-1} = t_{\mathrm{sb}} \tag{10}$$

From Eq. 8, we can draw that when making the production plan, the number of the part batch should be an integer multiple of the bottleneck machine quantity. From Eq. 9, we can get the optimal configuration number of the bottleneck machine. The final completion time achieves the minimum value when Eq. 10 is valid.

6. Conclusion

This paper applied the bottleneck theory to studied a blocked serial production line system in the aerospace field based on discrete event simulation, meanwhile discussed the performance of five bottleneck identification methods, the effect of the bottleneck machine quantity on system performance, obtained the function between final completion time and bottleneck machine quantity. Through the case study in this paper, we have reached the following conclusions:

- The bottleneck identification method based on machine utilization or average activity time is universal and practical. The method which is based solely on the machine idle rate, blockage rate, and the average absolute deviation or variance of the inter-departure time of the machine has some limitations. The method based on the sensitivity of throughput is the most natural interpretation of the bottleneck, which is most accurate but difficult to apply.
- Increasing the bottleneck machine quantity can accelerate the production efficiency and improve the utilization rate of non-bottleneck machine and system balance. However, the alleviation capacity decreases as the number of machines increases.
- The general function between the final completion time and bottleneck machine quantity in the blocked serial production line is obtained, which shows that the production efficiency is determined by the primary bottleneck and the secondary bottleneck. It also manifests that the condition of the final completion time gets the minimum value.

The main contribution of this paper is it evaluates the performance of various bottleneck identification and alleviation methods with a practical case, and discusses the relationship between the final completion time and the bottleneck machine quantity in the blocked serial production line for the first time, which has important significance to actual production guidance. Also, the case study indicates that some bottleneck identification methods may not be available to solve some practical problems, which also proves that there is a gap between theoretical research and practical application. Therefore, another contribution of this paper is it provides a practical case for theoretical researchers to reflect and use for reference.

The limitation of this paper is that it only provides some general conclusions in the blocked serial production line. Our next work is to introduce the buffer based on this paper, and research the effect between the system performance, the bottleneck machine quantity and the buffer capacity.

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