Scheduling Problems in the Lot Production Lines of the Toyota Production System

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Abstract: The focus of this paper is the scheduling problems in the lot production lines of the Toyota production system (TPS). As the problems are serious in not only the TPS, but also other production systems, the author introduces some results gained by studying the problems in hope that the problems will be researched more widely. It is well known that lot production lines of the TPS are operated utilizing an order point system. However, a problem exists in that the setup schedule for each lot production line when utilizing this method is not made in advance; thus, setup cannot be implemented based on the schedule. As such, another method is adopted for the TPS. This other method is not well known, so it must be analyzed and scheduling algorithms developed for it. Moreover, the author demonstrates the properties of operating lot production lines controlled by the method. As a result, it is shown that this method can be utilized for not only the TPS, but also other production systems. There is another problem as well. Generally speaking, it is very difficult to reduce the number of employees working on a lot production line in proportion to the decreasing production quantity of the line. For this, the author researches how to improve worker productivity on lot production lines when the production quantities of the lines drop. Though this problem is basically a scheduling issue, it is shown that this problem should be investigated from a wider perspective.

Key words: Toyota production system, Lot production line, Scheduling, Approximation algorithm, Properties of operations, Worker productivity

1 INTRODUCTION

The focus of this paper is the scheduling problems in the lot production lines of the Toyota production system (TPS). As the problems are serious in not only the TPS, but also other production systems, the author introduces some results gained by studying the problems in hope that the problems will be researched more widely.

It is well known that lot production lines in the TPS are operated utilizing an order point system [1]. When the inventory of a part becomes equal to or less than the ordering point, the part is produced in a lot production line at a predetermined lot size. Therefore, the setup schedules for lot production lines cannot be determined in advance and the setup workload in a day is apt to fluctuate according to the number of parts produced in the lot production lines in any one day. As a result, another method is adopted for the TPS [2]. This method is as follows. Lot production lines produce parts according to schedules that are planned in advance using lot sizes predetermined for each part. In practice, the lot size of the part produced in the lot production line is equal to the consumption of the part in the subsequent process during the time interval between the starting time of the previous production run of the part and the starting time of the next production run. This time interval is called the “production time interval.” As lot production line schedules are determined in advance, in order to adapt to the fluctuation in parts consumption in the subsequent process, the lot size of a part generally changes each time it is produced. As the setup schedule for each lot production line in this method is made in advance, setup can be implemented based on the schedule. Let us call this method “FTVL” from now on. Since FTVL is not well known, the author
researches how to do scheduling when using FTVL and analyzes, using numerical examples, the properties of operations in lot production lines controlled by FTVL.

Next, the second scheduling problem of lot production lines is explained. The production speed of a line utilizing the line production method can be changed easily in proportion to the daily production quantity of the line. If the daily production quantity of the line is to drop in the next month, the cycle time of the line is increased to longer than the current month, thereby making it easy to reduce the number of workers on that line. As a result, line productivity and worker productivity in the line will be maintained in the next month. On the other hand, the production speed of a lot production line cannot be changed widely in proportion to the daily production quantity of a line. Let us assume that the daily workload of a lot production line is very low and all of the lot production lines can produce the necessary parts in only 3-4 hr every day. As the number of hours lot production lines are used each day is short, workers need to be operating some of them in order to eliminate the waiting time of the workers, not the waiting time of the lot production lines. Therefore, scheduling must be created that enables all of the lot production lines to be operated using a minimum number of workers and requiring the minimum waiting time for them. However, it is very difficult to obtain the appropriate schedule. Therefore, it is hard to maintain worker productivity in lot production lines.

In the TPS, there is a philosophy called Shojinka in Japanese. Basically, it is equivalent to increasing worker productivity by adjusting and rescheduling human resources. Worker productivity is a very important aspect in the TPS. Accordingly, it is important to research how to increase the worker productivity of lot production lines when the production quantities of the lines decrease. This is, of course, a type of scheduling problem. But the author shows that it should be investigated from a wider point of view.

Scheduling problems on lot production lines have been studied by many researchers [3–6]. The main focus of research has been to determine the production schedule and the lot sizes that minimize the setup cost and parts inventories under some designated conditions. However, methods such as FTVL have not been studied yet [2]. In addition, when the workload of lot production lines is low, a method for improving the worker productivity of lot production lines has not researched yet.

The remainder of this paper is organized as follows. The FTVL scheduling method is described in Section 2. Section 3 demonstrates the properties of lot production lines operations controlled using FTVL. Section 4 discusses research on improving worker productivity in lot production lines, and Section 5 is the conclusion.

2 FTVL SCHEDULING

Firstly, press lines that are lot production lines at Toyota Motor Corporation (hereafter referred to as Toyota) are illustrated as the model lot production line in this paper. Press machines are directly allocated in the parts processing sequence, and are positioned as close to each other as possible in order to eliminate wasteful movement. To lower the production lead time, the lot sizes of parts are made as small as possible by shortening the setup time. A press line produces more than 10 kinds of parts. The quantity of each part used in the subsequent process (i.e., the body line) in a day fluctuates slightly during the month. However, the total quantity of each part used in the subsequent process in a day is mostly constant throughout the month. This is because the number of vehicles produced in an assembly line in a day is nearly constant throughout the month as well. As a result, there is very little fluctuation in the daily workload of each press line during the month.

Next, FTVL is explained more precisely. Using FTVL, the lot size of each part is designated in advance and this lot size is called, “designated lot size.” Though the lot size of each part is given as the designated lot size, let the lot sizes of each part in scheduling be the consumption of each part in the subsequent process during the production time intervals. As part consumption in unit time is mostly constant in the TPS, the consumption of each part in the subsequent process during the production time intervals can be computed by part consumption in unit time multiplied by the production time interval. The schedule in FTVL is developed so that the consumption of each part in the subsequent process during the production time interval is equal to the designated lot size of the part to the furthest possible
extent. When press lines produce parts in practice, the parts lot sizes are also the quantities of the parts consumed in the subsequent process during the production time interval. Therefore, FTVL needs to hold a parts inventory that is equal to the maximum consumption of the part during all of the production time intervals of that part. If the maximum consumption of the part during the production time intervals is larger than the designated part lot size, the maximum consumption minus the designated lot size is considered to be the safety stock of that part. Then, when using FTVL, the part consumption in the production time intervals must be kept smaller than the designated lot size of the part.

As the scheduling problem for FTVL is a combinatorial optimization problem, algorithms such as meta-heuristics, branch and bound methods, and so on are regarded as appropriate scheduling methods. However, as algorithms that can be used easily in a factory are very important, some papers [7], [8] have proposed convenient and useful approximation algorithms.

From a theoretical point of view, algorithms that obtain an optimal solution should be developed. The author therefore proposes an idea which is a basic theory for a branch and bound method. For example, let the partial schedule from the first day to the tenth day of the FTVL be \( S \). The total safety stock of all the parts in partial schedule \( S \) can be computed by summing the safety stock of each part. Moreover, assume that a partial schedule or a whole schedule of one month developed by adding the schedule after the tenth day to the partial schedule \( S \) is \( S_k \). Then, the total safety stock in \( S \) is equal to the total safety stock in \( S_k \). A branch and bound method can be constructed by making use of the above formula. Further discussion is omitted in this paper, but it is hoped that other new algorithms will be proposed.

Recently, the concept on lot sizes in FTVL for the TPS has been slightly modified. The lot size in an order point system is reduced only when the setup time is shortened. However, as the lot size when using FTVL is the parts consumption in the subsequent process during the production time interval, the lot size is always variable. For example, suppose that the designated lot size of the part is the quantity of the part used in the subsequent process in a day. In this case, the part will be produced once a day in the lot production line. If the quantity is reduced by 10% the next month, production of the part in the lot production line will be produced once approximately every 1.1 days. But it is understood by the workers producing the part in the lot production line that the part is produced once a day rather than once every 1.1 days. Then, let the designated lot size for the part in the next month be the quantity of the part used in the subsequent process for a day in the next month. Generally, let the designated lot size of the part for the next month be the quantity of the part used in the subsequent process in \( n \) days in the next month, where \( n \) is an integer. In the case that the quantity of the part used in the subsequent process in a day is large, as the designated lot size should be small, let \( n \) be small. Let the number of parts produced once every two days in the lot production line be an even number. In the same way, let the number of parts produced once in \( n \) days in the lot production line be \( m \times n \) to the furthest possible extent, where \( m \) is an integer. Therefore, it is very easy to let the number of parts produced in the lot production line in a day be nearly constant throughout the month. As a result, the workload of the lot production line in a day becomes nearly constant throughout the month as well. An appropriate FTVL schedule can thus be easily obtained.

3 PROPERTIES OF LOT PRODUCTION LINE OPERATIONS

To prove that the FTVL method is useful in not only the TPS, but also other production systems, the operation properties of lot production lines controlled using FTVL are demonstrated. One paper [8] has analyzed the properties using numerical examples. Let the conditions of the numerical examples correspond to the real conditions of press lines at Toyota to the furthest possible extent. Moreover, assume that the distribution of the quantity of the parts used in the subsequent process in a day is a normal distribution. As a result, the operation properties obtained using the numerical experiments are regarded to be the same as the operation properties of real press lines. The results of the experiments are as follows:
(1) Change in starting time of production runs

Let the difference between the starting time of the real production run and the starting time of the production run planned in the production schedule be $DST$. The mean $|DST|$ of each part is smaller than 10 min when the coefficient of variation of the normal distribution for each part is 0.05 and is small. If the coefficient of variation is 0.25, the mean $|DST|$ of each part is about 20 min and is not large. In cases when the designated lot size is not large, the starting time of the real production run in a lot production line is nearly the same as the starting time of the production run planned by the production schedule. Therefore, lot production lines operated using FTVL can provide the stable production of parts.

(2) Safety stock

As the quantity of the part used in the subsequent process in a day fluctuates, here let “minimum safety stock” of the part be the minimum part inventory which does not run short for the subsequent process minus the designated lot size of that part. The mean of the minimum safety stock of each part in lot production lines controlled using FTVL is approximately the part quantity used in the subsequent process in half of a day when the coefficient of variation is 0.25. Understanding this, the minimum safety stock is not large. If there is a shortage of some parts in the factory, lot production lines operate overtime to produce the parts. Therefore, the level of minimum safety stock held in practice can be reduced significantly.

(3) Comparison with method of producing according to the schedule

Let the production method producing parts with the lot size designated by the production schedule at the time designated by the production schedule be “the planned production method.” This planned production method is analyzed using numerical examples. The conditions of the experiments for the planned production method are the same as those used for FTVL. The mean minimum safety stock of each part in the planned production method is approximately two times the mean minimum safety stock of each part when using FTVL. Let,

$S_f$ : maximum safety stock, which is the largest of all the minimum safety stock of each part using FTVL

$Sp$ : maximum safety stock, which is the largest of all the minimum safety stock of each part using the planned production method.

$Sp$ is three times larger than $S_f$. Compared to the planned production method, it is possible to operate the lot production lines with lower parts inventories by utilizing FTVL for the lot production lines. Moreover, since parts production and setting up lot production lines are carried out based on the production schedule, production is very stable. Therefore, FTVL is recommended as a new method for controlling lot production lines.

4 ISSUE OF LOT PRODUCTION LINES WITH LOW WORKLOADS

4.1 Issue of Lot Production Lines with Low Workloads

In the case of lot production lines with heavy workloads, the problem is trying to produce much more in the same unit of time. In other words, the number of strokes executed per hour by the machines in lot production lines is increased. As a result, the productivity of the lot production lines is increased. However, when the workload of a lot production line is very low, it is very important to improve worker productivity in the line by reducing the number of workers and worker waiting time. How should lot production lines with the low workloads be managed? This is a new kind of scheduling problem, and developing an algorithm for it is one research theme. For example, meta-heuristics such as simulated annealing is regarded as one algorithm for the problem. However, here the problem is dealt with from a practical point of view and is researched using the press lines at Toyota.

4.2 Specific Measures

The means to increase worker productivity of press lines are as follows:

(1) “Yose Dome” (in Japanese)

Assume that the workloads of some press lines will be low next month. Let all of the parts produced in the press line with low workload be able to be produced in another press line. The press line that will not produce any parts the following month will be stopped. In this way, the number of press lines producing parts in the next month is reduced. As a result, the workload of the press lines producing parts will larger in the next month. The press lines will be able to be operated easily in the next month, and press line productivity and worker productivity in the lines will be maintained. This method is called “Yose Dome” in the TPS.

(2) Number of workers in press lines

The number of workers necessary in a press line varies with the kinds of parts produced in the line. For
example, the number of workers in some press line is four to five. In the case that the number of workers in the press line varies with the kind of parts, developing a schedule minimizing the total number of workers necessary in all press lines is very difficult. Therefore, the number of workers necessary in each press line is made constant for all parts produced in the press line, thereby eliminating waste in the press line.

(3) Production hours in proportion to the number of workers in press lines
Here, assume that a press line with six workers produces a part in 1.5 hours, and the same press line with four workers is made to be able to produce the same part in approximately 2.25 (\(= 6 \times 1.5 \div 4\)) hours. If the number of workers is reduced to two, the same press line is made to be able to produce the same part in approximately 4.5 hours with two workers on it. For this purpose, the workers must be multi-skilled. Moreover, even though press line waiting time may occur, worker waiting time must be eliminated. This is because improving worker productivity is more important than improving the productivity of press lines. When the production quantities of press lines are decreased, the number of workers in the press lines is reduced, for example from six to four or two. As a result, the total number of workers in all press lines will be reduced, and worker productivity will be maintained or improved. Of course, the press line production hours will increase.

(4) Efficiency of line balancing
Press line balancing efficiency relates to the immediately preceding discussion (4.2 (3)). If an attempt is made to increase the number of strokes per hour made by the press machines, workers will have waiting times more frequently. Suppose that the press line workload is heavy and the workers are on the line 7.5 hr per day. The press line produces a part using five workers. The working hours for one of the five workers in a day are 70% of 7.5 hr. This shows that the waiting time of the worker is 30% of 7.5 hr. The mean time of the working hours of five workers is 72.2% of 7.5 hr. In other words, the press line balancing efficiency is 0.722. Next, a case in which line balancing is improved is demonstrated. A part is produced in 100 min on a press line with six workers. Reducing the number of workers from six to four, the part was first produced in 167 min. But it could be produced in 98 min by repeating production of the part in the same line. Worker productivity increased by 53%, as shown using the next formula,
\[6 \times 100 \div (4 \times 98) = 1.53\, .\]
The press line balancing efficiency with four workers is 0.93, showing significantly enhanced efficiency. By reducing the number of workers in press lines producing parts and continuously improving line balancing efficiency, worker productivity in the lines will increase.

(5) Wall between workplaces
Press shops are comprised of approximately 10 workplaces called “Kumi” in Japanese. A press line in the press shop belongs to any Kumi. The allocation of workers to press lines is considered for each Kumi. Theoretically, if the number of workers necessary at some Kumi is 8.6, then nine workers are allocated. If the allocation of workers to press lines is considered by press shop rather than Kumi, the total number of workers necessary can be reduced.

4.3 Scheduling Method
The number of press lines in a press shop is not large, and the number of workers necessary for producing parts in each press line is less than six. Then, it is easy to schedule the operations of all the press lines by hand. The specific procedure is as follows:

[Scheduling procedure]
(1) Prepare as follows in advance. Make the number of workers necessary in each press line constant for all parts produced in the press line. Additionally, make it easy to change the number of workers necessary for producing each part.
(2) Develop a schedule that minimizes the total number of workers necessary in the press shop.
(3) Compute the total waiting time of all workers in the schedule.
(4) If the total waiting time is large, obtain a new schedule with a lower total waiting time by means of devising as stated below. Repeat this method until an appropriate schedule is attained.

① Review the part of the schedule with the worker waiting time.
② Increase the hours required for producing some of the parts by reducing the numbers of workers necessary.
③ Divide the operating hours of some press lines into two or three phases.
Table 1 The Workload and Number of Workers for Each Press Line

<table>
<thead>
<tr>
<th>Line</th>
<th>Workload</th>
<th>No. of workers</th>
<th>Line</th>
<th>Workload</th>
<th>No. of workers</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.5</td>
<td>3</td>
<td>H</td>
<td>5.5</td>
<td>3~4</td>
</tr>
<tr>
<td>B</td>
<td>2.5</td>
<td>3</td>
<td>I</td>
<td>5.5</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
<td>1.5</td>
<td>3</td>
<td>J</td>
<td>6.5</td>
<td>7~8</td>
</tr>
<tr>
<td>D</td>
<td>3.5</td>
<td>4</td>
<td>K</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>E</td>
<td>3</td>
<td>5~6</td>
<td>L</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>F</td>
<td>3.5</td>
<td>2</td>
<td>M</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>G</td>
<td>1.5</td>
<td>3~4</td>
<td></td>
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</tr>
</tbody>
</table>

Fig. 1 The First Schedule

[Example]

The daily workload of each press line and the number of workers necessary for each press line in the press shop are given in Table 1. The workload in Table 1 shows the operating hours of press lines in a day. The operating hours of workers in a day are 7.5. Since the workload of each line is very low, overtime for producing parts in the press lines can be avoided. Fig. 1 is a schedule. The x-axis and y-axis in Fig. 1 show the number of workers necessary and operation hours, respectively. The portions colored in a black ink in Fig. 1 show the worker waiting time. Assume that production in the plant starts at 8:00 a.m. Press line E produces parts from 8:00 a.m. to 11:00 a.m. every day except holidays. The operating hours of press line K are divided into two phases. Fig. 1 shows that the total number of workers necessary is 27 and the total waiting time of workers in the press shop is 42.5 hr. First of all, let the necessary number of workers in lines E, G, H and J be five, three, three and seven, respectively. Moreover, divide the operating hours of Line I into three phases. As a result, the schedule shown in Fig. 2 is obtained. The total number of workers necessary is 24 and the total waiting time of workers is 29 hr. Moreover, reduce the number of workers in lines B, E, G, J and K by one. The new schedule shown in Fig. 3 is obtained. None of the press line hours are broken down into phases. The total number of workers necessary is 20, and the total worker waiting time is 3 hr and overtime is 2 hr. An appropriate schedule has been obtained.

Understanding the above example, it is difficult to develop a theoretical algorithm for the problem. Firstly, it is very important to accomplish the contents stated in Section 4.2. If the number of lot production lines is not large, it is not difficult to obtain an appropriate schedule.

5 CONCLUSION

This paper discussed scheduling problems for lot production lines in the TPS. Since the lot production line schedule applied utilizing the FTVL method is determined in advance, the order point system is superior to FTVL from the viewpoint of just-in-time production. However, as the lot sizes of lot production lines are very small, the number of lot production lines in operation when utilizing FTVL gradually increase.
at Toyota. Even if parts quantities used in subsequent processes in a day fluctuate, the operation of lot production lines controlled by FTVL remains stable. Therefore, FTVL should be adopted for not only TPS, but also other production systems. Moreover, it is hoped that an algorithm that will enable obtaining better scheduling using the FTVL method will be developed.

Whenever the workload of lot production lines is low, it is difficult to keep and improve worker productivity in lot production lines. Theoretical problems such as scheduling problems in the study of lot production lines have been researched by many researchers. In this paper, it was shown that it is very important to improve worker productivity in practical lot production lines. Since it is difficult to obtain appropriate scheduling when the number of lot production lines is large, it is hoped that theoretical algorithms will be developed.

ACKNOWLEDGMENTS

This research was partially supported by the Japan Society for the Promotion of Science (JSPS), Grant-in-Aid for Scientific Research (C) No.21510151 from 2009 to 2011 and No.24510193 from 2012 to 2014.

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