Property of Worker Allocation Optimization with Two Professional Workers in Limited-Cycle Multiple Periods

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Abstract – **In this paper, we deal with an assembly line with limited-cycle multiple periods with two kinds of workers. Skills of workers are assumed to be different. We consider an optimization problem for finding an allocation of workers to the line that minimizes total expected cost satisfying the demand. Then we propose a theorem of the property of the optimal worker allocation and discuss the other properties in conditions.**

Keywords - **Worker allocation optimization, limited-cycle problem with multiple periods, processing efficiency**

I. INTRODUCTION

Since the first mathematical formalization of assembly line balancing by Salveson [1], assembly line balancing problem is popularly researched and developed [2]. However, there exists an object with some constraints (e.g., processing time with a target), these constraints produce a risk and the object occurs repeatedly for multiple periods. The problem of minimizing the expected risk in such a situation is called limit-cycle problem with multiple periods (LCPwMP). Yamamoto *et al.* [3] considered how to resolve this kind of problem.

Under uncertain conditions, the result and efficiency of a certain period (of a production cycle) and process are influenced not only by the risks which exist in the current period but also by the risks which exist in the previous periods. Therefore, we discuss the minimum expected risk of the case mentioned above, in which the risk depends on the previous situation and occurs repeatedly for multiple periods. Whether the process satisfies the due time (restriction) usually depends on the state of the past process, as seen in [4] [5]. In particular, when the risk depends on the past processes, which allocation of machines, workers or jobs is most efficient and economical is an important problem in load/risk planning (for example, see [6] [7]).

As limited-cycle scheduling problems, Verzijl [4] analyzed the element and construction of the production system. Enns [8] presented a framework for the analysis of delays within the production system. Benders [5] gave a review for the origin and solution of period batch control system. Xia *et al.* [9] presented an easily implemented hybrid algorithm for the multi-objective flexible job-shop scheduling problem. Recently, Wu *et al.* [10] concerned with the problem in scheduling a set of jobs associated with random due dates on a single machine so as to minimize the expected maximum lateness in stochastic environment. Xie *et al.* [11] proposed a new hierarchical scheduling algorithm to solve the complex product flexible scheduling problem with constraint between jobs.

In previous researches, the LCPwMP is classified into various classes, and it has been proposed as a type of problem with 'a limited-cycle problem with dependent multiple periods', in which the occurrence of an object in a period depends on the occurrences of other objects in the other periods by Yamamoto *et al.* [3] [12]. A recursive formula for the total expected risk and an algorithm for optimal allocations in LCPwMP based on the branch and bound method are proposed [13]. Recently, Yamamoto *et al.* [14] and Kong *et al.* [15] proposed properties of optimal worker allocation with two kinds of workers in which one special worker exists. Then, Kong *et al.* [16] [17] proposed properties of optimal worker allocation with two special workers.

However Kong *et al.* [17] just gave a range of optimal worker allocation with two professional workers, not a certain allocation. It is necessary to find out the certain optimal worker allocation.

In this paper, we analyze the theoretical regularities in order to check out the certain optimal worker allocation with two professional workers. The remainder of the paper is structured as follows: Section II formally describes a simple model (here we call it 'reset model') and defines the optimal worker allocation problem under the reset model. The succeeding section describes the property of optimal worker allocation with two professional workers as theorem. Then numerical experiments will be done trying to find out the properties of optimal worker allocation with two professional workers.

II. MODEL EXPLANATION

In this section, we consider a 'Reset model' which is a simple model of the LCPwMP. Then, we define the optimal allocation problem in reset model.

Reset Model of Limited-Cycle Problem with Multiple Periods

The model is considered based on the following assumptions [17]:

(1) In an assembly line system, n is the number of periods (it may be considered that n is the number of production seats or production processes).

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(2) The production is processed in a rotation of period 1, period 2, ... , and period n. One production will be processed by n periods.
(3) All of the partly-finished productions will be moved to next period and processed by time Z. Specifically Z is the cycle time of all periods.
(4) There are two types of workers, A and B. A represents professional worker whose processing rate is higher than others, B represents common worker. Note that assigning only one worker to each period. The processing time of worker l ($l \in \{A, B\}$), T_l, is self-dependent.
(5) To sum up, Z is the cycle time of all of the stations. Z is also a kind of limited processing time (or target processing time) of each station. We will call Z the target processing time here.

For $l \in \{A, B\}$, when the processing time of worker l is denoted by T_l:

P_l: The probability of worker l becoming idle, which is $\Pr\{T_l \le Z\}$,

Q_l: The probability of the worker l becoming delayed, which is $\Pr\{T_l > Z\}$,

TS_l: The expected idle cost of the worker l, which is $E[(Z - T_l)I(T_l \le Z)]$,

TL_l: The expected delay cost of the worker l, which is $E[(T_l - Z)I(T_l > Z)]$,

where $I(\bullet)$ is an index function and given as follows:

$$I(O) = \begin{cases} 1 & (O \textit{ is true}) \\ 0 & (O \textit{ is not true}). \end{cases}$$

We suppose the following costs as shown in Fig. 1.

In this paper, we consider a fixed target processing time Z. Workers' employment costs and resource will occur whether the processing is done. A processing cost $C_t (\ge 0)$ per unit time will proportional occur to target processing time Z. Otherwise, if the processing time is longer than Z, overtime work or additional resources will be requested in order to meet the target time Z. So the delay cost per unit time, $C_P^{(k)} (\ge 0)$, will occur (that is why we call the model a 'Reset Model'). Meanwhile, if the processing time is shorter than Z, in-process inventory can be considered before moving to the next period. So the idle cost per unit time, $C_S (\ge 0)$, will occur.

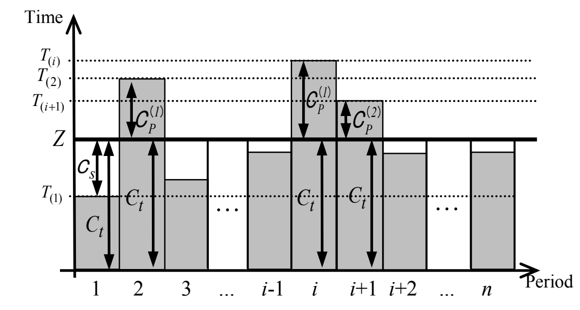

Fig. 1. Costs definition in Reset Model

As a summary of above, we get:

(6) The processing cost per unit time, $C_t (\ge 0)$, for the target processing time limit occurs in each period.
(7) When $T_l \le Z$, the idle cost per unit time, $C_S (\ge 0)$, occurs in each period.
(8) When $T_l > Z$, the delay cost per unit time, $C_P^{(i)} (\ge 0)$, occurs in the period if delay occurs in consecutive k periods before its period, for $i = 1,2,\ldots,n$. In this paper, we suppose that the delayed process time of a period can be recovered by the overtime work or spare workers in this period, and $C_P^{(i)}$ is the cost for all of these. Because the cost rises due to the increase of the delay, in this paper, we suppose the $C_P^{(i)}$ is non-decreasing in i, that is $0 \le C_P^{(1)} \ldots \le C_P^{(n)}$.

The relation between processing time and cost is shown in Fig. 1. In Fig. 1, longitudinal axis represents time, horizontal axis represents period. Letting $T_{(i)}$ be the processing time of period i. For example, in the case that the processing time of period 1 is shorter than target processing time Z ($T_{(1)} < Z$), so the total costs occurred in period 1 are processing cost relative to Z and idle cost relative to the time from $T_{(1)}$ to Z. Meanwhile in the case that processing time of period 2 is longer than target processing time Z ($T_{(2)} > Z$), so the total costs occurred in period 2 are processing cost C_t (per unit time) relative to Z and delay cost $C_P^{(1)}$ (per unit time) relative to the time from Z to $T_{(2)}$. It should be cautious that continuously delayed twice in periods i and i+1. In this case, continuous delay cost $C_P^{(2)}$ ($C_P^{(2)} \ge C_P^{(1)}$) occurs in period i+1.

In the above situation, we consider how to get a most minimized expected total cost by changing the worker allocation.

Optimal allocation Problem under Reset Model

We consider that two workers are allocated to each two periods in the reset model. One of the most important problems is how to allocate workers to periods for minimizing the expected cost in n periods. We call such a problem the optimal allocation problem. For describing the optimal allocation problem, we define the following notations [17]:

For $1 \le i < j \le n$,

$\pi(i, j)$: Two professional workers are allocated in period i and j, $n-2$ common workers are allocated to periods out of period i and period j.

$TC(n; \pi(i, j))$: The total costs of periods 1 to n when workers are allocated by allocation $\pi(i, j)$.

The total cost $TC(n; \pi(i, j))$ of n periods when workers allocated according to allocation $\pi(i, j)$ is expressed as

$$TC(n; \pi(i, j)) = nC_t Z + f(n; \pi(i, j)), \tag{1}$$

where,

$f(n;\pi(i,j))$: The expected cost (the sum of the expected idle cost and the expected delay cost) caused in period n. And it was formulated [12] [13].

By using these notations, the optimal allocation problem with multiple periods becomes the problem of obtaining allocation π^* in the following equation:

$$TC(n;\pi^*) = \min_{1\le i<j\le n} TC(n;\pi(i,j)). \tag{2}$$

In this paper, we call π^* the optimal allocation.

However, it is easily known from (1) that if the target processing time Z is constant, the target production cost, nC_tZ, is also constant, so we can simplify (2) to

$$f(n;\pi^*) = \min_{1\le i<j\le n} f(n;\pi(i,j)). \tag{3}$$

III. PROPERTY OF OPTIMAL WORKER ALLOCATION WITH TWO PROFESSIONAL WORKERS

In this section, we consider the situation in which the processing time of $n-2$ common workers follows the same distribution, that is, two professional workers follow a different distribution from the common workers [15].

Then, expected cost $f(n;\pi(i,j))$ can be expressed as

$$f(n;\pi(i,j)) = \left(C_S(n-2)TS_B + 2TS_A\right) + \sum_{l=1}^{n}\left(\sum_{\alpha=1}^{l} CF(l,\alpha;\pi(i,j))\right), \tag{4}$$

where, for $1\le\alpha\le l\le n$,

$CF(l,\alpha;\pi(i,j))$: The expected cost accrues in the period l in the situation in which period $l-\alpha$ is not delayed, α periods from period $l-\alpha+1$ to period l are delayed consecutively in the allocation $\pi(i,j)$ as shown in Fig. 2.

Before the theorem we declare the following lemmas which are useful for the proof of the theorem.

For $1\le o\le l$,

Lemma 1:

$$f(n;\pi(i,j+1)) - f(n;\pi(i,j))$$
$$= \begin{cases} \left(\begin{array}{l} (Q_A-Q_B)\cdot TL_B\cdot A(i,j) \\ +(Q_A-Q_B)\cdot\begin{pmatrix} C_P^{(j-i+1)} \\ -C_P^{(j-i)}\end{pmatrix}\cdot Q_B^{j-i-1}\cdot\begin{pmatrix}\dfrac{Q_A}{Q_B}\cdot TL_B \\ -TL_A\end{pmatrix} \\ +\left(C_P^{(j+1)}-C_P^{(j)}\right)\cdot Q_A^2\cdot Q_B^{j-1}\cdot\left(\dfrac{TL_A}{Q_A}-\dfrac{TL_B}{Q_B}\right)\end{array}\right) & \\ \qquad\qquad i=i_o,\ j=j_o & \\ (Q_A-Q_B)\cdot TL_B\cdot A(i,j) & \\ \qquad\qquad i_o+1\le i\le i_{o+1}-1,\ j_o+1\le j\le j_{o+1}-1, & \end{cases} \tag{5}$$

holds, where

$$\begin{aligned} A(i,j) \equiv &\sum_{\alpha=1}^{n-j-1}\left(\left(C_P^{(\alpha+1)}-C_P^{(\alpha)}\right)\cdot Q_B^{\alpha-1}\right) \\ &-\sum_{\alpha=1}^{j-i-1}\left(\left(C_P^{(\alpha+1)}-C_P^{(\alpha)}\right)\cdot Q_B^{\alpha-1}\right) \\ &-\sum_{\alpha=j-i}^{j-1}\left(\left(C_P^{(\alpha+1)}-C_P^{(\alpha)}\right)\cdot Q_B^{\alpha-1}\right)\cdot\frac{Q_A}{Q_B}. \end{aligned} \tag{6}$$

Lemma 2:

$$f(n;\pi(i+1,j)) - f(n;\pi(i,j))$$
$$= \begin{cases} \left(\begin{array}{l} (Q_A-Q_B)\cdot TL_B\cdot B(i,j) \\ +(Q_A-Q_B)\cdot\left(C_P^{(j-i)}-C_P^{(j-i-1)}\right)\cdot Q_B^{j-i-2}\cdot TL_A \\ +\left(C_P^{(i+1)}-C_P^{(i)}\right)\cdot Q_B^{i}\cdot Q_A\cdot\left(\dfrac{TL_A}{Q_A}-\dfrac{TL_B}{Q_B}\right)\end{array}\right) & \\ \qquad\qquad i=i_o,\ j=j_o & \\ (Q_A-Q_B)\cdot TL_B\cdot B(i,j) & \\ \qquad\qquad i_o+1\le i\le i_{o+1}-1,\ j_o+1\le j\le j_{o+1}-1, & \end{cases} \tag{7}$$

holds, where

$$\begin{aligned} B(i,j) \equiv &\sum_{\alpha=1}^{j-i-2}\left(\left(C_P^{(\alpha+1)}-C_P^{(\alpha)}\right)\cdot Q_B^{\alpha-1}\right) \\ &+\sum_{\alpha=j-i}^{n-i-1}\left(\left(C_P^{(\alpha+1)}-C_P^{(\alpha)}\right)\cdot Q_B^{\alpha-1}\right)\cdot\frac{Q_A}{Q_B} \\ &-\sum_{\alpha=1}^{i-1}\left(\left(C_P^{(\alpha+1)}-C_P^{(\alpha)}\right)\cdot Q_B^{\alpha-1}\right). \end{aligned} \tag{8}$$

Using the lemmas above, we can obtain the theorem of the optimal allocation with two professional workers as follows:

Theorem.

We suppose $C_P^{(i)}$ is non-decreasing in i, if $Q_A<Q_B$ and $\dfrac{TL_A}{Q_A}<\dfrac{TL_B}{Q_B}$, the optimal allocation $\pi(i,j)$ is in $\left\{\pi(i,j)\,\middle|\, i\ge\dfrac{j-1}{2},\ j\ge\dfrac{n}{2}\right\}$.

Proof of Theorems:

The proof of the Theorem is similar to the proof in Kong *et al.* [17].

As a visualized description, the theorem means that two professional workers should be allocated to periods i and j where period i is in the each last half periods between period 1 and period j-1, period j is in the each last

								l-1	l
Period	$l-\alpha$	$l-\alpha+1$	$\cdots$	$i-1$	i	$i+1$	$\cdots$	j-1	j
Assignment $\pi(i,j)$	B	B	$\cdots$	B	A	B	$\cdots$	B	A
	○	●	$\cdots$	●	●	●	$\cdots$	●	◎

$\underbrace{\qquad\qquad\qquad\qquad}_{\alpha\ \text{Periods}}$

Fig. 2. Image of expected cost $CF(l,\alpha;\pi(i,j))$
(○ : Idle ; ● : Delay ; ◎ : Expected cost of period l)

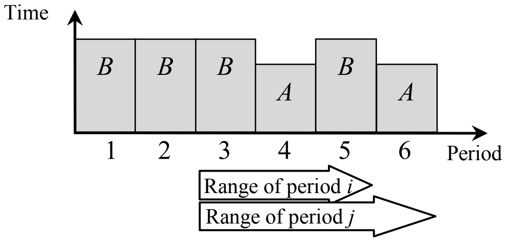

Fig. 3. Image of allocation $\pi(4,6)$

half periods between period 1 and period *n*, as shown in Fig. 3.

Theorem only gives a range of optimal worker allocation with two professional workers. In order to get a certain optimal worker allocation with two professional workers, it is necessary to discuss the factors associated with the certain optimal worker allocation. A valid and feasible way is to do some numerical experiments and analyze the theoretical regularities.

IV. NUMERICAL ANALYSIS

In this section, we study more strict properties of the optimal worker allocation with two professional workers. Especially, worker A is professional worker whose processing rate, μ_A, is higher than others, and the number of worker A is 2. Worker B is common worker, the number of worker B is $n-2$. It means $\mu_A > \mu_B$, where μ_A is the processing rate of worker A, μ_B is the processing rate of worker B.

We set the parameters as follows,

Consecutive Delay Cost $C_P^{(i)}$:

$C_P^{(1)}=40$, $C_P^{(2)}=80$, $C_P^{(3)}=160$, $C_P^{(4)}=320$, $C_P^{(5)}=640$, $C_P^{(6)}=1280$, $C_P^{(7)}=2560$, $C_P^{(8)}=5120$; Period $n=7$;

Target Processing Time $Z=2$; Idle Cost $C_S=20$.

When $\mu_A=0.2$, $\mu_B=0.1$, expected costs of each allocation $\pi(i,j)$, where $1\le i<j\le 8$, can be get as shown in Table I. Also the trend of expected costs is shown in Fig. 4 and Fig. 5.

From Table I, Fig. 4 and Fig. 5, we can get that, in this case, the trend of expected costs of allocation $\pi(i,j)$ weather relating to i or j, where $1\le i<j\le 8$, is monotone decreasing. From the results, we can prophesy that, in this cast the optimal allocation of two professional workers is $\pi(n-1,n)$. And the conditions of this optimal allocation can be derived by Lemma 1 and Lemma 2.

When $\mu_A=0.3$, $\mu_B=0.1$, expected costs of each allocation $\pi(i,j)$, where $1\le i<j\le 8$, can be get as shown in Table II. Also the trend of expected costs is shown in Fig. 6 and Fig. 7.

From Table II, Fig. 6 and Fig. 7, we can get that, in this case, the trend of expected costs under allocation $\pi(i,j)$ relating to j, where $1\le i<j\le 8$, is monotone decreasing except $\pi(7,8)$. From the results, we can prophesy that, in this cast the optimal allocation of two professional workers is $\pi(n-2,n-1)$. And the conditions of this optimal allocation can be derived by Lemma 1 and Lemma 2.

TABLE I

EXPECTED COSTS OF EACH ALLOCATION $\pi(i,j)$

($1\le i<j\le 8$, $\mu_A=0.2$, $\mu_B=0.1$)

j	2	3	4	5	6	7	8
1	π(1, 2) 26787	π(1, 3) 25838.4	π(1, 4) 25206.7	π(1, 5) 24735.2	π(1, 6) 24306.8	π(1, 7) 23815.2	π(1, 8) 23138.5
2		π(2, 3) 24607.6	π(2, 4) 23979.8	π(2, 5) 23514.6	π(2, 6) 23096.6	π(2, 7) 22622.1	π(2, 8) 21973.2
3			π(3, 4) 23196.2	π(3, 5) 22734.8	π(3, 6) 22323.2	π(3, 7) 21859	π(3, 8) 21227.1
4				π(4, 5) 22202.3	π(4, 6) 21794.5	π(4, 7) 21336.6	π(4, 8) 20715.1
5					π(5, 6) 21379.3	π(5, 7) 20925.3	π(5, 8) 20310.2
6						π(6, 7) 20523.1	π(6, 8) 19911.8
7							π(7, 8) 19421.1

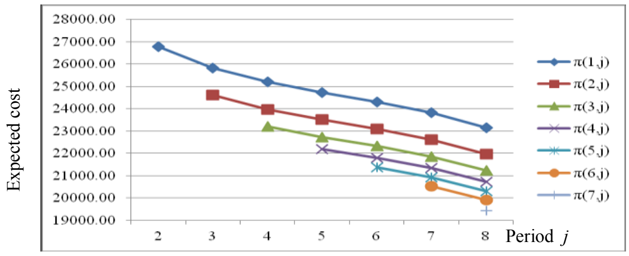

Fig. 4. Trend of expected costs relativing to period j

($\mu_A=0.2$, $\mu_B=0.1$)

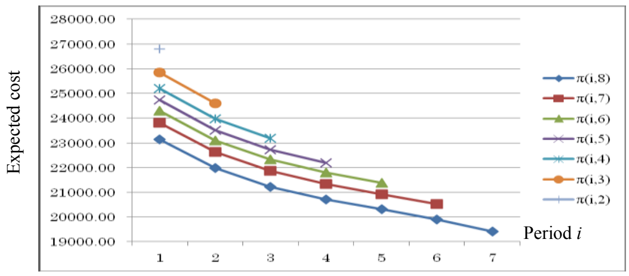

Fig. 5. Trend of expected costs relativing to period i

($\mu_A=0.2$, $\mu_B=0.1$)

TABLE II

EXPECTED COSTS OF EACH ALLOCATION $\pi(i,j)$

($1\le i<j\le 8$, $\mu_A=0.3$, $\mu_B=0.1$)

j	2	3	4	5	6	7	8
1	π(1, 2) 22698.6	π(1, 3) 21093	π(1, 4) 20140.2	π(1, 5) 19603.5	π(1, 6) 19350	π(1, 7) 19316	π(1, 8) 19494
2		π(2, 3) 19313.9	π(2, 4) 18357	π(2, 5) 17813.8	π(2, 6) 17550	π(2, 7) 17498	π(2, 8) 17648
3			π(3, 4) 17287.4	π(3, 5) 16740.3	π(3, 6) 16469	π(3, 7) 16408	π(3, 8) 16540
4				π(4, 5) 16116.3	π(4, 6) 15842	π(4, 7) 15773	π(4, 8) 15895
5					π(5, 6) 15510	π(5, 7) 15438	π(5, 8) 15553
6						π(6, 7) 15318	π(6, 8) 15429
7							π(7, 8) 15493

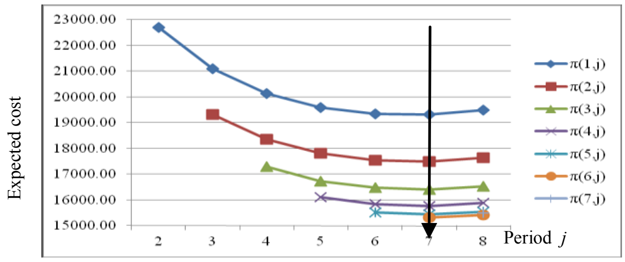

Fig. 6. Trend of expected costs relativing to period j
($\mu_A = 0.3$, $\mu_B = 0.1$)

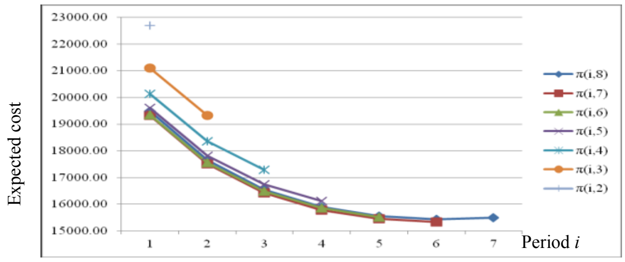

Fig. 7. Trend of expected costs relativing to period i
($\mu_A = 0.3$, $\mu_B = 0.1$)

V. CONCLUSION

In this paper, we considered the properties of optimal allocation with two professional workers in LCPwMP. First, we systematically classified and modeled the multi-period problem and defined the optimal workers allocation problem under the reset model. Secondly, we proposed theorem of optimal worker allocation with two professional workers. Then we discussed the certain optimal worker allocation with two professional workers by analyzing the results of numerical experiments. From the analyzing, we get

1. In certain condition(s), allocation $\pi(n-1,n)$ is the optimal worker allocation.
2. In other certain condition(s), allocation $\pi(n-2,n-1)$ is the optimal worker allocation with two professional workers.

We prophesied two cases of optimal worker allocation, but not limited to the two cases.

As future researches, we will derive conditions of the two cases of optimal allocation analyzed in section IV, and do lots of numerical experiments to find out the other cases of optimal allocation of two professional workers or more. As a final goal, we expect to derive the property of the optimal worker allocation theoretically and get an optimal cycle time Z by using the properties.

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REFERENCES

[1] M. E. Salveson, “The assembly line balancing problem,” *The Journal of Industrial Engineering*, vol. 6, no. 3, pp. 18–25, 1955.

[2] B. Nils, F. Malte, and S. Armin, “A classification of assembly line balancing problems,” *European Journal of Operational Research*, vol. 183, pp. 674-693, 2007.

[3] H. Yamamoto, M. Matsui, and J. Liu, “A basic study on a limited-cycle problem with multi periods and the optimal assignment problem ” (in Japanese), *Journal of Japan Industrial Management Association*, vol. 57, pp. 23-31, 2006.

[4] J. J. Verzijl, *Production planning and information systems*, London: Macmillan, 1976, pp. 16–17.

[5] J. Benders, “The origin of period batch control (PBC),” *International Journal of Production Research*, vol. 40, pp. 1–6, 2002.

[6] D. Bergamashi, R. Cigolin, M. Perona, and A. Portiol, “Order review and release strategies in job shop environment: A review and a classification,” *International Journal of Production Research*, vol. 35, pp. 399–420, 1997.

[7] P. M. Swamidass, *Encyclopedia of production and manufacturing management*, Boston: Kluwer, 2000.

[8] S. T. Enns, “MRP performance effects due to lot size and planned lead time settings,” *International Journal of Production Research*, vol. 39, pp. 461–480, 2001.

[9] W. J. Xia, and Z. M. Wu, “Hybrid particle swarm optimization approach for multi-objective flexible job-shop scheduling problems,” *Control and Decision*, vol. 20, no. 2, pp. 137–141, 2005.

[10] X. Wu, and X. Zhou, “Stochastic scheduling to minimize the expected maximum lateness,” *European Journal of Operational Research*, vol. 190, pp. 103–115, 2008.

[11] Z. Xie, S. Hao, G. Ye, and G. Tan, “A new algorithm for complex product flexible scheduling with constraint between jobs,” *Computers & Industrial Engineering*, vol. 57, pp. 766–772, 2009.

[12] H. Yamamoto, J. Sun, and M. Matsui, “A study on limited-cycle scheduling problem with multiple periods,” Computer & Industrial Engineering, vol. 59, no. 4, pp. 675-681, 2010.

[13] H. Yamamoto, M. Matsui, and X. S. Bai, “A branch and bound method for the optimal assignment during a Limit-cycle problem with multiple periods” (in Japanese), *Journal of Japan Industrial Management Association*, vol. 58, pp. 37-43, 2007.

[14] H. Yamamoto, J. Sun, M. Matsui, and X. D. Kong, “A study of the optimal arrangement in the reset limited-cycle problem with multiple periods: with fewer special workers” (In Japanese), *Journal of Japan Industrial Management Association*, vol. 62, no. 5, pp. 239-246, 2011.

[15] X. Kong, J. Sun, H. Yamamoto, and M. Matsui, “A Study of an optimal arrangement of a processing system with two kinds of workers in a limited-cycle problem with multiple periods,” presented at the *11th Asia Pacific Industrial Engineering & Management Systems Conference (APIEMS2010)*, Melaka, Malaysia, 2010. (on CD-ROM)

[16] X. Kong, J. Sun, H. Yamamoto, and M. Matsui, “Two special Workers’ optimal assignment with two kinds of workers under a limited-cycle problem with multiple periods,” presented at the *21st International Conference of Production Research (ICPR2011)*, Stuttgart, Germany, 2011. (on CD-ROM)

[17] X. Kong, J. Sun, H. Yamamoto, and M. Matsui, “Optimal worker assignment with two special workers in limited-cycle multiple periods,” presented at the *2011 Asian Conference of Management Science & Applications (ACMSA2011)*, Sanya, China, 2011. (on CD-ROM)