Optimal Worker Assignment Considering Worker’s Skill on Different Task in Limited-Cycle Multiple Periods

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Abstract: In uncertain cases, the result and efficiency of a current period (or production cycle) are influenced not only by the risks which exist in current period but also by the risks which exist in the previous ones. What is more, the risk itself is also affected greatly by the risks which exist in the earlier periods. This kind of problem is called a limited-cycle problem with multiple periods. Normally, workers’ efficiency is different on different tasks. How can we get an optimal assignment to minimize the total expected costs? In this paper, we consider the optimal worker assignment considering two kinds of efficiency, clever or poor efficiency on tasks. The regularity will be described that n-1 workers have two clever tasks of all, 1 worker has no clever task by contrast. Also, some numerical experiments will be done to check out the regularity of the optimal assignment that each worker has two or three clever tasks.

Key Words: Optimal worker assignment, worker’s skill on different task, limited-cycled problem, multiple periods.

1. Introduction

The classical assignment problem can be given as that suppose we have n resources to which we want to assign to n tasks on a one-to-one basis. Suppose also that we know the cost of assigning a given resource to a given task. We wish to find an optimal assignment-one which minimizes total cost [1]. In this paper, we do not consider the resource-to-task; we consider the problem that how to assign n workers to n tasks (periods) on a one-to-one basis to get minimum expected cost. Suppose also that we know the cost of assigning a given worker to a given task. The costs include expected idle cost or delay cost according to not only the balance between processing time and target processing time, but also the continuous delay cost. We wish to find an optimal assignment-one which minimized total expected cost under reset model (herein called the reset model, “reset” means that the processing time of each station starts from 0) of limited-cycle problem with multiple periods. Under uncertain conditions, the result and efficiency of a certain production cycle period and a certain process are influenced not only by the risks that exist in the current period but also by the risks that existed in the foregoing periods. Therefore, we discuss the minimum expected risk of the case mentioned above, in which the risk depends on the foregoing situation and occurs repeatedly for multiple periods. Whether the process (period or site) satisfies the time limit (restriction) usually depends on the state of the foregoing process, as seen in [2]-[4]. The problem that which assignment of machines, workers, or jobs is the most efficient and economical (optimal assignment) is important in load or risk planning [5], particularly in the case of risk that depends on the circumstances of a foregoing process (e.g., the case of a manufacturing line during a multi-period).

In previous research, the limited-cycle model with multiple periods has been separated into various classes, and it has been proposed by Yamamoto et al.[6],[7] in the form of “a limited-cycle model with dependent multiple periods” in which the occurrence of an event within a period depends on the occurrences of other events in other periods. A recursive formula for the total expected risk and an algorithm for optimal assignments were proposed for limited-cycle models with multiple periods based on the branch-and-bound method [7],[8]. Recently, Yamamoto et al.[9] and Kong et al.[10] proposed some regularity for an optimal assignment of two kinds of workers, among which one special worker exists. In addition, Kong et al.[11] proposed some regularity of optimal assignment with two kinds of workers with two special workers who process slowly.

The previous researches were done with an assumption that the processing rate of worker on each period is the same. Although, in real life, the processing rate of worker variable when doing different tasks. The aim of this paper is to formulate a new problem called here worker assignment problem applying reset model with limited-cycle multiple periods. Additionally, Theorem of opti-
nal worker assignment is proposed. The next section describes a model with some notation and assumptions before it defines the optimal worker assignment problem. The succeeding sections describe the regularity of optimal worker assignment with no overlap clever efficiency period. Then the regularity of optimal worker assignment with two clever efficiency periods in which one competitive clever efficiency period exists is researched by some numerical experiments. The results of this paper are similar to the bowl phenomenon of a series manufacturing line [12]-[15] with simple assumptions. The results obtained in this paper are useful for the design of a production system.

2. Literature Review

Manufacturing facilities are complex, dynamic, stochastic systems. From the beginning of organized manufacturing, the workers, supervisors, engineers, and managers have developed many clever and practical methods for controlling production activities.

Assembly line balancing (ALB) problem is well known because of their availability for improving the system efficiency.

The ALB problem was described by Bryton [16] and published in mathematical form by Salveson [17]. Ever since, the ALB problem has been widely studied by Pinto et al.,[18], Hoffmann et al.,[19], Erel and Sarin,[20], Becker and Scholl,[21]. ALB problems can be classified as single models or multi-models (mixed models) according to the number of products being produced on a single line. They can also be classified as deterministic or stochastic models based on whether the processing time is constant or variable. The single deterministic model (SDM) of ALB problems introduces the concept of a single model assembly line where the processing time is fixed, while the single stochastic model (SSM) introduces the concept of variable processing time.

Much research has been conducted on the SDM as a general ALB problem (Baybars [16], Erel and Sarin [20], Jin and Wu [22], Simaria and Vilarinho [23]). Meanwhile research on the stochastic model has been remarkably limited. Because constraints are very specific to situations, the SSM problem is difficult to formulate. Several authors have made efforts toward recognizing and stating the stochastic processing time (Moodie and Young [24], Silverman and Carter [25]). Most of them, however, assumed that processing time is normally or asymmetrically distributed. This is not realistic, because the performance of workers is directly influenced by their skill level and experience of carrying out a similar process when learning and forgetting of processes can be considered. Most of the previous line-balancing approaches have attempted to solve the same problem, which is defined as how to assign tasks to an ordered sequence of stations so that the precedence relations are satisfied and some measure of effectiveness is optimized (Ghosh and Gagnon [26], Tiwari et al.,[27]). These approaches started with the objective of either minimization of total idle time for a target processing time or minimization of the target processing time for a fixed number of stations (Mills and McClain [28], Ghosh and Gagnon [26], Erel and Sarin [20], Lee et al.,[29],[30]. However, the worker factors were seldom considered in solving the ALB problem. It is widely ignored that in labor-intensive industries like apparel manufacturing, even with an optimal task sequence and minimized idle time (or target processing time), the production line still cannot be balanced in most cases because of the efficiency variance among workers. The efficiency of workers is apparently much influenced by such factors as the emotions, motivation, health, skill level, and experience of the workers (Kamman and Jensen [31]).

Based on the fact that the variance in worker efficiency leads to production line imbalance in those industries that still rely heavily on labor skills, the problem of balancing assembly production line optimally while considering worker efficiency variance thus arises.

3. Model Explanation

In this section, we consider a reset model, which is a simple form of limited-cycle model with multiple periods and some assumptions. Then, we consider the optimal assignment problem under the reset model, with some notations defined.

3.1 Reset Model (a Limited-Cycle Model with Multiple Periods)

The model is considered on the basis of the following assumptions:

1. For an assembly line system, n is the number of periods (which may be regarded as the number of production seats or production processes).
2. The production is processed by each periods in order of period 1, period 2, ..., period n.
3. All of the partly finished products will be moved to next period and processed within time Z. Especially Z is the cycle time of all periods (or all stations). Z is also a kind of limited processing time (or target processing time) for each period. Z is called target processing time.
4. There are n workers. One worker is assigned to each period. The processing time T(l) of worker l (1 ≤ i ≤ n) is statistically independent and follows exponential distribution, the processing time probability density function of worker l is f(l)(t) = μ(l)e−μ(l)Z.

For l (1 ≤ i ≤ n), the processing time of worker l is denoted by T(l). And other symbols are as shown below.

P(l): The probability of worker l becoming idle, which is Pr(T(l) ≤ Z).
Q(l): The probability of worker l becoming delayed, which is Pr(T(l) > Z).
TS(l): The expected idle time of worker l, which is E[(Z - T(l))I(T(l) ≤ Z)]).
TL(l): The expected delay time of worker l, which is E[(T(l) - Z)I(T(l) > Z)]).

The indicator function I(·) is given as follows:
In this paper, we consider a fixed target processing time \( Z \). The basic costs like Personnel expenses, fuel and light expenses will be incurred whether or not the processing is done. A processing cost \( C_l(\geq 0) \) per unit time will accrue in proportion to the target processing time \( Z \). If the processing time is longer than \( Z \), overtime work or additional resources will be requested in order to meet the target time \( Z \). Hence, a delay cost \( CP(\geq 0) \) per unit time will accrue (which is why we call the model a reset model). If the processing time is shorter than \( Z \), in-process inventory can be considered before moving to the next period. Hence, an idle cost \( CS(\geq 0) \) per unit time will accrue. In summary, we have the following:

(5) The processing cost \( C_l(\geq 0) \) per unit time for the target processing time limit accrues in each period.

(6) When \( T_l(i) \leq Z \), an idle cost \( CS(\geq 0) \) per unit time accrues in each period.

(7) When \( T_l(i) > Z \), a delay cost \( CP(k)(\geq 0) \) per unit time accrues in a period if delay (i.e. \( T_l(i) > Z \)) accrued in \( k \) consecutive periods before the period, for \( 1 \leq k \leq n \). In this paper, we suppose that the process delay time of a period can be recovered by overtime work or extra workers in the period, and \( CP(k) \) is the cost for all of these. Because the cost rises due to the increase in the delay, we suppose that in this paper \( CP(k) \) is monotonically increasing on \( k \), that is \( 1 < CP(1) < CP(2) < \cdots < CP(n) \).

The relation between processing time and cost is shown in Figure 1. The vertical axis represents time, and the horizontal axis represents period. Let \( T_l(i) \) be the processing time of period \( i \). For example, in the case that the processing time of period \( i \) is shorter than the target processing time \( Z(T_l(1)) < Z \), the total costs incurred in period 1 are the processing cost relative to \( Z \) and the idle cost relative to the time from \( T_l(1) \) to \( Z \). Moreover, in the case that the processing time of period 2 is longer than the target processing time \( Z(T_l(2)) > Z \), the total costs incurred in period 2 are the processing cost \( C_l \) (per unit time) relative to \( Z \) and the delay cost \( CP(1) \) (per unit time) relative to the time from \( Z \) to \( T_l(2) \). It should be noted that processing is delayed twice, in periods \( i \) and \( i+1 \). In this case, a continual delay cost \( CP(1)CP(2) > CP(3) \) is incurred in period \( i+1 \).

Given the above situation, we consider how to minimize the expected total cost by considering the worker assignment.

### 3.2 Optimal assignment problem under reset model

Consider the case of assigning \( n \) workers to \( n \) periods on a one-to-one basis in reset model, one of the most important problems is how to assign workers to periods for minimizing the expected cost in \( n \) periods. We call such a problem the optimal assignment problem. For stating the optimal assignment problem, we define the following notations:

\[ \begin{align*}
W: & \text{ The set of } M_n, \\
M_n: & \begin{pmatrix}
\mu_{1,1} & \cdots & \mu_{1,n} \\
\vdots & \ddots & \vdots \\
\mu_{n,1} & \cdots & \mu_{n,n}
\end{pmatrix}
\end{align*} \]

where \( \mu_{i,j} \) represents the mean processing rate of worker \( l_i \) to do the task assigned to period \( i \), where \( 1 \leq i \leq n \).

\[ \pi(l_i): \text{ The assignment when worker } l_i \text{ is assigned to period } i. \]

In previous researches, same processing rates of the worker to each task are intended in reset model (seen Eq. (1)), so the assignment can be changed easily (Figure 2).

In this paper, the case of different processing rates (efficiency) of the worker to each task is considered.

From Eq. (2), lots of varieties of the workers’ efficiency vs. task can be considered. For example, as a basis case, there are two kinds of efficiency, clever or poor efficiency on tasks exists. That is, the processing rate of clever efficiency is better than poor efficiency (seen Eq. (3), Figure 3).

\[ \mu_l(i, 1) = \mu_l(i, 2) = \mu_l(i, 3) = \cdots = \mu_l(i, n) \]  \hspace{1cm} (1)

\[ \mu_l(i, 1) \neq \mu_l(i, 2) \neq \mu_l(i, 3) \neq \cdots \neq \mu_l(i, n) \]  \hspace{1cm} (2)

\[ \mu_l(i, 1) \neq \mu_l(i, 2) = \mu_l(i, 3) = \cdots = \mu_l(i, n) \]  \hspace{1cm} (3)

Furthermore, the fewer number efficiency is called special efficiency. The period with special efficiency is called special efficiency period. The simple case will be considered firstly (i.e. the number of worker with special efficiency is one or two).

By using these notations, the optimal assignment problem with multiple periods becomes the problem of obtaining assignment \( \pi^* \) in the following equation:

\[ TC(n; \pi^*, W) = \min TC(n; \pi(l_i), W) \]  \hspace{1cm} (4)

where

\[ TC(n; \pi(l_i), W) = nC_CZ + f(n; \pi(l_i), W) \]  \hspace{1cm} (5)

where \( f(n; \pi(l_i), W) \) represents the total expected cost including expected idle cost and expected delay cost. Kong et al. [32] gave the detail.

In this paper, we call \( \pi^* \) the optimal assignment.

However, it is easily known from Eq. (4) that if the target processing time \( Z \) is fixed, the target processing cost \( nC_CZ \) is also constant, so Eq. (4) can be simplified to

\[ f(n; \pi^*, W) = \min f(n; \pi(l_i), W) \]  \hspace{1cm} (6)

\[ I(O) = \begin{cases}
1 & \text{if } O \text{ is true} \\
0 & \text{otherwise}
\end{cases} \]
4. Optimal Worker Assignment in Reset Model

In this paper, Theorem of optimal worker assignment in reset model considered the clever efficiency to the task is described. Theorem of the case that each worker hands two clever efficiency periods in which only one overlap exists is given as follow.

**Theorem:**

Suppose $C_{P}^{(i)}$ is monotone non-decreasing in $i$, and

\[
\begin{align*}
\mu_{1,1} &> \mu_{1,2} = \mu_{1,3} = \mu_{1,4} = \cdots = \mu_{1,n} \\
\mu_{2,2} &> \mu_{2,3} > \mu_{2,1} = \mu_{2,2} = \cdots = \mu_{2,n} \\
\cdots \\
\mu_{n-1,(n-1)} &> \mu_{n-1,n} > \mu_{n-1,1} = \mu_{n-1,2} = \cdots = \mu_{n-1,n-2} \\
\mu_{n,1} &> \mu_{n,2} = \mu_{n,3} = \cdots = \mu_{n,n}
\end{align*}
\]

(1) if

\[
\mu_{n,i} \leq \mu_{n-1,i} = \mu_{n-2,i} = \cdots = \mu_{1,i},
\]

then

\[
\pi^{*} = \pi(l_{n}, l_{1}, l_{2}, \cdots, l_{n-1})
\]

(2) if

\[
\mu_{n,i} > \mu_{n-1,i} = \mu_{n-2,i} = \cdots = \mu_{1,i},
\]

then

\[
\pi^{*} = \pi(l_{1}, l_{2}, \cdots, l_{n})
\]

where $\mu_{n,i}$ means that period $i$ is the special efficiency period of worker $l_{i}$.

**Proof.**

The theorem can be proved by two steps.

Step 1. Focus the workers who hold clever tasks. First, focus worker $l_{1}$.

For given conditions,

\[
W = \begin{pmatrix}
\mu_{1,1} & \mu_{1,2} & \mu_{1,3} & \cdots & \mu_{1,n} \\
\mu_{2,2} & \mu_{2,3} & \mu_{2,1} & \cdots & \mu_{2,n} \\
\cdots \\
\mu_{n-1,(n-1)} & \mu_{n-1,n} & \mu_{n-1,1} & \cdots & \mu_{n-1,n-2} \\
\mu_{n,1} & \mu_{n,2} & \mu_{n,3} & \cdots & \mu_{n,n}
\end{pmatrix}
\]
Fig. 3 Image of worker assignment problem (worker efficiency vs. task)

\[ f(n; \pi(l_1, l_1, l_1, \ldots), W) = f(n; \pi(l, l_1, l_1, \ldots), W) \]
\[ < f(n; \pi(l, l_1, l_1, \ldots), W) \]
holds, where \( \pi(l_1, l_1, l_1, \ldots) \) represents worker \( l_1 \) is assigned to period 1. Then, by the same way, we can get a similar equipment about worker \( l_2 \)

\[ f(n; \pi(l, l_2, l_1, \ldots), W) = f(n; \pi(l, l, l_2, \ldots), W) \]
\[ < f(n; \pi(l, l_2, l_1, \ldots), W) \]

Finally, the optimal assignment of workers \( l_3, l_4, \ldots, l_{n-1} \) can also be written by the similar equipment. Then, the following can be get

\[ f(n; \pi^*, W) = f(n; \pi(l_1, l_2, l_3, \ldots, l_{n-1}, l_n), W) \]
or

\[ f(n; \pi^*, W) = f(n; \pi(l_1, l_1, l_2, \ldots, l_{n-1}, l_n), W) \]

Step 2. Focus the worker who hold no clever task. According to the workers’ efficiency with no clever task, applying the theorem proposed by Kong et al.,[32],

if

\[ \mu_{n,i} = \mu_{n-1,i} = \cdots = \mu_{1,i}, \]

then

\[ \pi^* = \pi(l_1, l_1, l_2, \ldots, l_{n-1}) \]

if

\[ \mu_{n,i} > \mu_{n-1,i} = \cdots = \mu_{1,i}, \]

then

\[ \pi^* = \pi(l_1, l_2, \ldots, l_n). \]

Therefore, the theorem is proved.

The theorem means, when \( n-1 \) workers hand two clever efficiency periods with only one overlap among workers, one worker hands no clever efficiency periods,

(1) If the processing rate of the worker who hands no clever periods is smaller than the other workers who hand an overlap clever periods, then the optimal assignment is represented by \( \pi(l_1, l_2, \ldots, l_{n-1}) \). It means that the worker who hands no clever periods should be assigned to the first period.

(2) If the processing rate of the worker who hands no clever periods is bigger than the other workers who hand an overlap clever periods, then the optimal assignment is represented by \( \pi(l_1, l_2, \ldots, l_n) \). It means that the worker who hands no clever periods should be assigned to the last period. Much other regularity can be considered similarly.

5. Numerical Experiments

In this section, the case that \( n - 1 \) workers have two clever efficiency periods with one overlap exist, and one worker without clever efficiency period exist (as shown in Tables 1-2) is studied by numerical experiment. The overlap clever efficiency period is called competitive clever efficiency period. The parameters are set as follow: Processing rate of each worker is as shown in Tables 1-2;

Period \( n = 6 \);
Target processing time \( Z = 2 \);
Idle cost \( C_S = 20 \);
Consecutive delay cost \( C_P^{(i)} \) where \( C_P^{(i)} \) is monotone non-decreasing in \( i \), \( C_P^{(1)} = 40, C_P^{(2)} = 50, C_P^{(3)} = 60, C_P^{(4)} = 70, C_P^{(5)} = 80, C_P^{(6)} = 90 \).
As the results of the 4 cases, the optimal worker assignment is also \( \pi^* = \pi(l_1, l_2, l_3, l_4, l_5) \). This result fitted the theorem proposed by Yamamoto et al. (2011).

The mechanism of the results can be considered like that, when just consider the assignment of workers \( l_1, l_2, l_3, l_4, l_5 \) who have clever efficiency period to periods 1-6, two assignments can be get. That is \( \pi(\phi, l_1, l_2, l_3, l_4, l_5) \) or \( \pi(l_1, l_2, l_3, l_4, l_5, \phi) \), where \( \phi \) means the period is empty (there is no worker can be assigned to this period). Then, worker \( l_4 \) should be assigned to period 1 or period 6 to get optimal assignment. Because the processing rate of
worker $l_6$ on each period is the same (that is smaller than the other workers’ clever efficiency periods), conditions of the theorem are satisfied by Yamamoto et al. (2011).

6. Conclusions
In this paper, a new problem called optimal worker assignment problem is formulated as a development of classical assignment problem applying reset model with multiple periods. And theorem of optimal worker assignment is proposed. Additionally, some numerical experiments are done to research the other theorem of optimal worker assignment. The results of the numerical experiments fitted the optimal worker assignment theorem proposed by Yamamoto et al. (2011).

As further work, the regularity of optimal worker assignment with the variety of the workers’ efficiency can be considered.

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### Table 1 Value set of worker’s processing rates (case 1)

| Worker | Period | 1   | 2   | 3   | 4   | 5   |
|--------|--------|-----|-----|-----|-----|-----|
| $l_1$  |       | 1.0 | 1.0 | 0.2 | 0.2 | 0.2 |
| $l_2$  |       | 0.2 | 1.0 | 1.0 | 0.2 | 0.2 |
| $l_3$  |       | 0.2 | 0.2 | 1.0 | 1.0 | 0.2 |
| $l_4$  |       | 0.2 | 0.2 | 0.2 | 1.0 | 1.0 |
| $l_5$  |       | 0.2 | 0.2 | 0.2 | 0.2 | 1.0 |
| $l_6$  |       | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |

### Table 2 Value set of worker’s processing rates (case 2)

| Worker | Period | 1   | 2   | 3   | 4   | 5   |
|--------|--------|-----|-----|-----|-----|-----|
| $l_1$  |       | 1.0 | 1.0 | 0.5 | 0.5 | 0.5 |
| $l_2$  |       | 0.5 | 1.0 | 1.0 | 0.5 | 0.5 |
| $l_3$  |       | 0.5 | 0.5 | 1.0 | 1.0 | 0.5 |
| $l_4$  |       | 0.5 | 0.5 | 0.5 | 1.0 | 1.0 |
| $l_5$  |       | 0.5 | 0.5 | 0.5 | 0.5 | 1.0 |
| $l_6$  |       | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |

### Table 3 Value set of worker’s processing rates (case 3)

| Worker | Period | 1   | 2   | 3   | 4   | 5   |
|--------|--------|-----|-----|-----|-----|-----|
| $l_1$  |       | 1.0 | 1.0 | 0.9 | 0.9 | 0.9 |
| $l_2$  |       | 0.9 | 1.0 | 1.0 | 0.9 | 0.9 |
| $l_3$  |       | 0.9 | 0.9 | 1.0 | 1.0 | 0.9 |
| $l_4$  |       | 0.9 | 0.9 | 0.9 | 1.0 | 1.0 |
| $l_5$  |       | 0.9 | 0.9 | 0.9 | 0.9 | 1.0 |
| $l_6$  |       | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 |

### Table 4 Value set of worker’s processing rates (case 4)

| Worker | Period | 1   | 2   | 3   | 4   | 5   |
|--------|--------|-----|-----|-----|-----|-----|
| $l_1$  |       | 1.0 | 1.0 | 0.9 | 0.9 | 0.9 |
| $l_2$  |       | 0.9 | 1.0 | 1.0 | 0.9 | 0.9 |
| $l_3$  |       | 0.9 | 0.9 | 1.0 | 1.0 | 0.9 |
| $l_4$  |       | 0.9 | 0.9 | 0.9 | 1.0 | 1.0 |
| $l_5$  |       | 0.9 | 0.9 | 0.9 | 0.9 | 1.0 |
| $l_6$  |       | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |

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