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A Study of Optimum Switching Problem for Production Systems Considering Efficiency, Delivery Time and Green Evaluation

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Abstract

This paper aims to derive the optimal switching strategy for production system considering efficiency, delivery time and green evaluation. Nowadays more and more manufacturing and logistics systems not only pursue better work efficiency, but also focus on green energy evaluation issues. Cost reduction and shortening of delivery time are always important management issues in pursuit of efficiency and optimization of the entire production system because of global production competition. In a market situation where customer needs change in various ways, in particular, due to inadequate quality, changes in the local environment, natural disasters and so on. Therefore, prompt planning of management measures such as switching work processes and changing production methods has become an important issue. On the other hand, since the Paris Agreement came into effect, the construction of an environment-friendly production system has been required as an approach to environmental problems such as global warming. In this paper, we propose an optimum switching model of production systems considering efficiency, delivery time and green evaluation using a green evaluation index (GEC: Green Energy Coefficient). We also discuss the optimal switching strategy by numerical observation.

Keywords

Green Evaluation, Sustainable Production, Optimal Switching Problem, Production Networks, Decarbonization Manufacture Management

1. Introduction

The global energy mix is shifting from fossil fuels to renewables. The optimal production strategy considering the usage rate of renewable energy becomes an important issue in sustainable manufacturing management.

After the Paris agreement, many countries committed to a climate neutrality target by 2050, including Japan, the European Union, the UK, South Korea and lately the USA. China has also committed to making its economy climate-neutral by 2060. An interim target of at least 40% renewables in power generation is required in 2030 to transition towards a 100% objective in 2050 [1].

On the other hand, the trade area is expanding significantly recently because of the progress of globalization, and more and more products and services are forced to compete fiercely on a global scale. In such a business environment, it is one of the important issues for a company to keep the delivery date while minimizing the production cost.

Under these circumstances, a trade-off is required between determining the efficiency of power generation and environmental protection, maximizing power generation while minimizing CO_2 emissions in order to protect the environment in the generation mix [2].

Models that optimize inventory and multi-period production can maximize total costs (including energy) while achieving the target GEC (Green Energy Coefficient), and this is becoming a feature for assessing sustainability in manufacturing [3]. In addition, a particle swarm operation time (PSO) algorithm minimizes the total latency and power cost by determining the sequence of jobs and the processing speed. And this algorithm effectively adjusts the computational speed of the machine during execution [4]. As high productivity places a heavy burden on the machine, by reducing useless tasks or finding the optimum batch size not only increases the energy efficiency of the production process, but also avoids the loss of failures due to high loads at the same time [5].

Based on these studies, manufacturing companies are required to build an environment-friendly and sustainable production system with a high ratio of renewable energy while minimizing production cost, idle production, and delays in delivery.

In the multi-period constraint cycle model, there are two or more processes (periods) in one cycle, each process (period) has a limited job processing time, variation, idleness and delivery may occur in the processing time. In this research, in addition to the processing cost, idle/delayed delivery cost evaluated in the previous research, the energy cost generated in the production process is added, and the goal is to minimize the overall cost and achieve the delivery date. Consider the cost related to the amount of power (energy) with regard to the production time as the energy cost in the production line. GEC (Green Energy Coefficient), which is the value obtained by dividing the amount of renewable energy by the total amount of energy used in the production line, is an evaluation index for energy. Then consider the GEC penalty cost incurred if the required GEC level cannot be met by the GEC level in the production line. By adding to the optimal process switching model in the previous research [6], we propose a model that considers production cost, delivery delay/idle cost, and energy cost. An example of the model is shown in **Figure 1**, where a check is

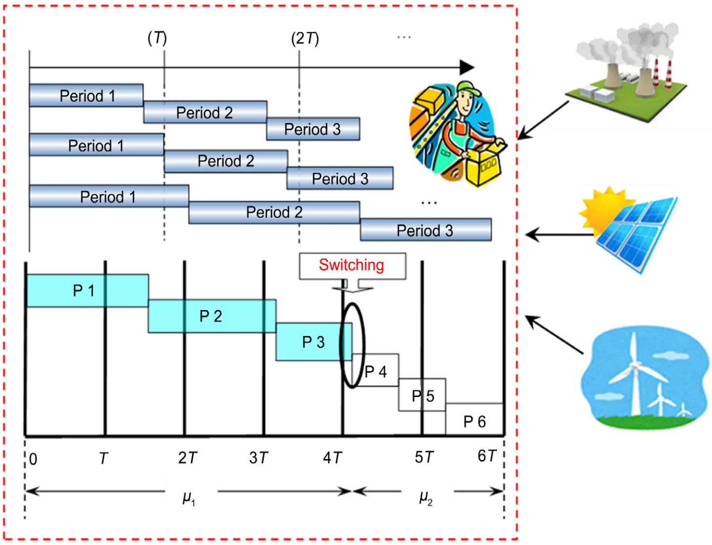

Figure 1. Image of the optimum switching model of production systems considering efficiency, delivery time and green evaluation.

made at the end of period 3 and the processing rate is accelerated at the end of period 3 as 3T has been exceeded. After that, numerical values are actually applied and verified in the proposed model.

The remainder of the study is presented as follows. Section 2 gives an overview of the state-of-the-art pertaining to decarbonization manufacture management in the previous research. In Section 3, we propose an example of formulating the expected cost of energy in consideration of GEC when the processing time follows a general distribution and an exponential distribution. In Section 4, the energy cost is added to the optimal process model of the previous research, and a proposal is made as an optimum switching model considering the production cost, delivery date, and green evaluation. In Section 5, to consider the usefulness of the optimum energy switching model considering GEC and the optimum switching model considering production cost, delivery date, and green evaluation, numerical experiments are performed when the processing speed follows an exponential distribution. Finally, Section 6 concludes this study.

2. The Model

2.1. Problem Formulation

In the production line of multi periods, delay of one period may influence the delivery date of an entire process. We consider controlling the production line by switching the processing speed to a faster one at a given point (time or period). The optimal switching problem is to decide when the processing speed should be switched to minimize the total expectation cost considering efficiency, delivery time and green evaluation.

The optimal switching model for the production line with multiple periods is considered based on the following assumptions:

1) Assuming that T is the target production time per period, the target pro-

duction time of i periods is expressed as iT, and one product is made by a process (line) with n periods.

2) For $i = 1, 2, \cdots, n$, the production time of period i is denoted by T_i which is assumed to be statistically independent, respectively. The usual processing rate is μ_1, and the emergency processing rate is μ_2.

3) K is switching point (the number of switching period). If the reference period k exceeds the target time kT, the processing speed would be switched from the usual processing rate μ_1 (Processing time distribution is $F_1(t)$) to the emergency processing rate μ_2 (Processing time distribution is $F_2(t)$). Therefore, switching may occur in the period $(k + 1)$.

4) The production cost per unit time ($C_s^{(h)}$) occurs when a process is executed before the target production time of the process ($h = 1$ means before switching and $h = 2$ means after switching).

5) The production cost per unit time ($C_p^{(h)}$) occurs when a process is executed after the target production time of the process ($h = 1$ means before switching and $h = 2$ means after switching). However, $C_p^{(1)}$ is the cost incurred before switching, and $C_p^{(2)}$ is the cost incurred after switching ($C_p^{(1)} < C_p^{(2)}$).

6) When $X_n >$ due time of process (nT), the delay cost C_p occurs.

7) When $X_n <$ due time of process (nT), the idle cost C_s occurs.

Some notations are also defined.

X_n: The total production time of i periods ($X_n = \sum_{l=1}^{n} T_l$).

$\Pr(X_n > nT)$: The probability of delay of production line.

$\Pr(X_n < nT)$: The probability of idle of production line.

In order to explain the meaning of switching, we first show in the figure below an example of switching for two tandem production systems with multiple periods. We consider the optimal switching point (optimal switching period k) that minimizes the total expected cost of the production line. Assume that the standard production time for each period is T. When the switching time is $k^* T$, the processing speed is changed in the next period if the period k has not been completed at $k^* T$ (as in **Figure 2**). If the period k is completed at time k^*T, the processing speed does not change (as in **Figure 3**). For example, in **Figure 2**, the switching time (k^*T) is $4T$ and period 4 is not yet completed at $4T$, so the processing rate changes from μ_1 to μ_2 in period 5.

2.2. Mathematical Model

The objective function of this study is to find the optimal switching period k that minimizes the objective function as Equation (1).

$$E[Q_i] = \min_k \left(E\left[C_1(k; T_1, T_2, \cdots, T_n) + C_2(k; T_1, T_2, \cdots, T_n) + C_3(k; T_1, T_2, \cdots, T_n) \right] \right) \quad (1)$$

where,

Q_i: Expected total cost of production line;

$C_1(k; T_1, T_2, \cdots, T_n)$: The production cost;

$C_2(k; T_1, T_2, \cdots, T_n)$: The due date penalty cost;

$C_3(k; T_1, T_2, \cdots, T_n)$: The energy cost.

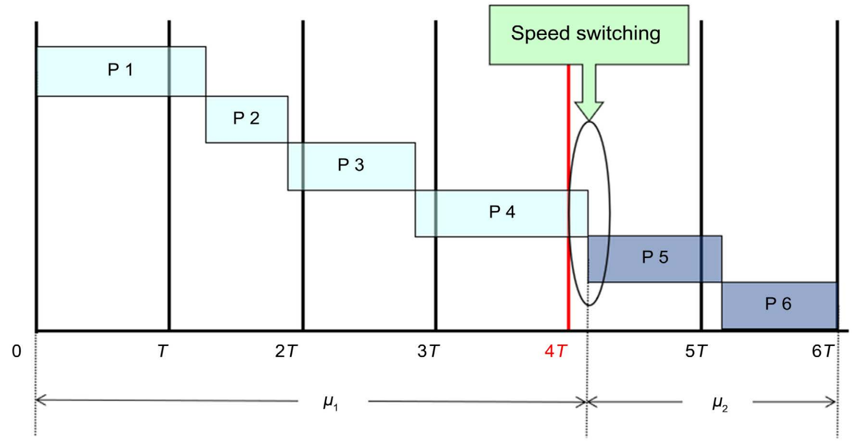

Figure 2. Processing state when switching of processing speed occurs.

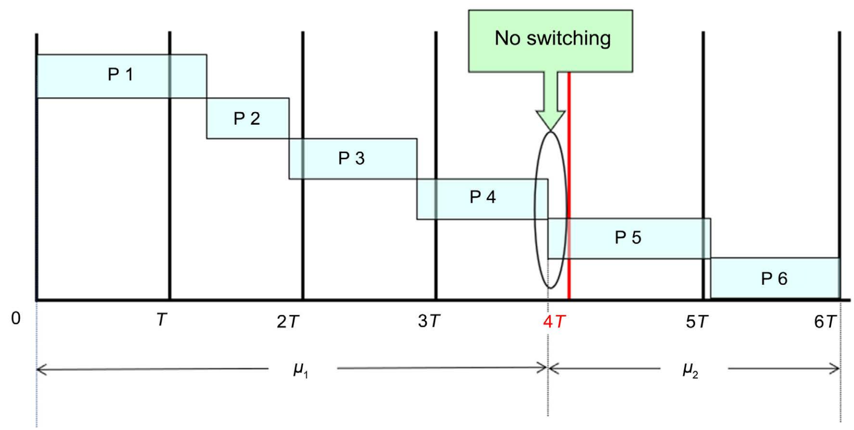

Figure 3. Processing state when no switching of processing speed occurs.

1) Production Cost

From assumptions (1)-(7), we can easily see that

$$E\left[C_1\left(k;T_1,T_2,\cdots,T_n\right)\right]=\sum_{i=1}^{n}E\left[C\left(i\right)\right] \tag{2}$$

where, $E\left[C\left(i\right)\right]$ is the expected cost of period *i*.

In this research, for the calculation, the expected cost is divided in two parts. One part is the expected cost occurred before switching period ($i=1,2,\cdots,k$), the other part is the expected cost occurred after switching period ($i=k+1,k+2,\cdots,n$), where k is the number of switching period, S_i is the production time when $C_p^{(h)}$ occurred.

Therefore, for $i=1,2,\cdots,k$,

$$C\left(i\right)=C_p^{(1)}\cdot S_i+C_s^{(1)}\cdot\left(T_i-S_i\right)=\left(C_p^{(1)}-C_s^{(1)}\right)\cdot S_i+C_s^{(1)}\cdot T_i \tag{3}$$

and for $i=k+1,k+2,\cdots,n$

$$C\left(i\right)=\begin{cases}\left(C_p^{(1)}-C_s^{(1)}\right)\cdot S_i+C_s^{(1)}\cdot T_i & \sum_{i=1}^{k}T_i\le kT\\ \left(C_p^{(2)}-C_s^{(2)}\right)\cdot S_i+C_s^{(2)}\cdot T_i & \sum_{i=1}^{k}T_i>kT\end{cases} \tag{4}$$

2) Due Date Penalty Cost

$$E\left[C_2\left(k;T_1,T_2,\cdots,T_n\right)\right]=C_pP_r\left\{\sum_{l=1}^{n}T_l>U_n\right\}+C_sP_r\left\{\sum_{l=1}^{n}T_l\le U_n\right\} \tag{5}$$

where,

$C_pP_r\left\{\sum_{l=1}^{n}T_l>U_n\right\}$ is the delayed expected cost, $C_sP_r\left\{\sum_{l=1}^{n}T_l\le U_n\right\}$ is the idle expected cost.

2) The energy cost

$$E\left[C_3\left(k;T_1,T_2,\cdots,T_n\right)\right]=Z_0\cdot e_0\cdot X_n+\max\left\{\left(\rho-\rho'\right),0\right\}\cdot C_e\cdot X_n \tag{6}$$

where, $Z_0\cdot e_0\cdot X_n$ is the expected energy cost in the production line, $\max\left\{\left(\rho-\rho'\right),0\right\}\cdot C_e\cdot e_0\cdot X_n$ is the GEC penalty cost.

In this paper, $C_1\left(k;T_1,T_2,\cdots,T_n\right)$ and $C_2\left(k;T_1,T_2,\cdots,T_n\right)$ are calculated using the results of previous studies [6]. The calculation method of green evaluation is proposed as follows.

3. Mathematical Formulation of Green Evaluation

In this study, the energy cost includes the expected energy cost used in the production line, and the penalty cost when the green evaluation index GEC (Green Energy Coefficient) is not satisfied.

$$E\left[C_3\left(k;T_1,T_2,\cdots,T_n\right)\right]=Z_0\cdot e_0\cdot X_n+\max\left\{\left(\rho-\rho'\right),0\right\}\cdot C_e\cdot X_n \tag{7}$$

where, the average unit cost of energy Z_0 is calculated as Equation (8).

$$\begin{aligned}Z_0&=\rho Z_e+\left(1-\rho\right)Z_t\\&=\rho\left(\omega_1Z_1+\omega_2Z_2+\cdots+\omega_mZ_m\right)+\left(1-\rho\right)\left(\omega_{m+1}Z_{m+1}+\omega_{m+2}Z_{m+2}+\cdots+\omega_sZ_s\right)\end{aligned} \tag{8}$$

and ρ is the proportion of renewable energy in total energy.

The weighted average price according to renewable energy Z_e is calculated as Equation (9).

$$Z_e=\omega_1Z_1+\omega_2Z_2+\cdots+\omega_mZ_m \tag{9}$$

and weighted average price of energy by conventional generation methods Z_t is calculated as Equation (10).

$$Z_t=\omega_{m+1}Z_{m+1}+\omega_{m+2}Z_{m+2}+\cdots+\omega_sZ_s \tag{10}$$

Then

$$\begin{cases}\omega_1+\omega_2+\cdots+\omega_m=1\\\omega_{m+1}+\omega_{m+1}+\cdots+\omega_s=1\end{cases} \tag{11}$$

Notation for parameters is as follows.

T_i: Production time of period i (random variables, independent in the period $i=1,2,\cdots,n$)

m: Number of renewable energies used in the production line;

s: Number of energies used in the production line;

Z_0: Average unit price of energy;

Z_j: Unit price of energy j;

ω_j: Weighting in energy j;

e_0: Amount of energy required per unit time;

y_j: Amount of each kind of energy;

ρ: Actual GEC level in the production line;

ρ': GEC level required by government;

C_e: Penalty cost charged when GEC level is not achieved;

X_n: Expected total production time.

The calculation of the expected total production time X_n is explained in following sections.

3.1. Calculation Method of the Total Production Time for Green Evaluation in Switching Model

In this study, the production time T_i before switching and after switching are assumed to be follows $F_1(t)$ and $F_2(t)$, which are statistically independent, respectively. Also, $F_j^{(l)}(t)$ is the times convolution of $F_j(t)$ and $f_j^{(l)}(t)$ is its probability density function.

Let X_n be the expected total production time for a line with n periods.

$$X_n = E\left[\sum_{i=1}^{n} T_i\right] \tag{12}$$

From assumptions (1)-(7) and **Figure 4** and **Figure 5**, we can see that

For $k = 1, 2, \cdots, n$

$$\begin{aligned} E\left[\sum_{i=1}^{n} T_i\right] &= E\left[Y_1 \middle| Y_1 > kT\right] \cdot \Pr\left\{Y_1 > kT\right\} + E\left[Y_2 \middle| Y_1 > kT\right] \cdot \Pr\left\{Y_1 > kT\right\} \\ &\quad + E\left[Y_1 \middle| Y_1 \le kT\right] \cdot \Pr\left\{Y_1 \le kT\right\} + E\left[Y_2 \middle| Y_1 \le kT\right] \cdot \Pr\left\{Y_1 \le kT\right\} \end{aligned} \tag{13}$$

where,

$$Y_1 = \sum_{i=1}^{k} T_i \quad \text{and} \quad Y_2 = \sum_{i=k+1}^{n} T_i \tag{14}$$

Y_1 and Y_2 are random variables, and their cumulative distribution functions are $F_{Y_1}^{(k)}(y_1)$ and $F_{Y_2}^{(n-k)}(y_2)$ and their probability density functions are $f_{Y_1}^{(k)}$ and $f_{Y_1}^{(n-k)}$, respectively.

In addition, the probabilities of $Y_1 > kT$ and $Y_1 \le kT$ are calculated as follows:

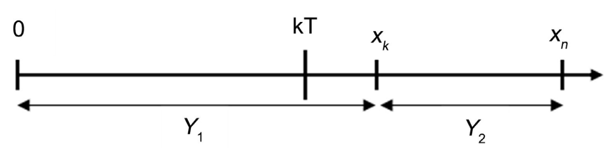

Figure 4. The case of $Y_1 > kT$.

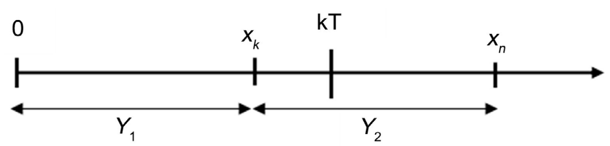

Figure 5. The case of $Y_1 \le kT$.

$$\Pr\{Y_1 > kT\} = \int_{kT}^{\infty} f_{Y_1}^{(k)}(y_1)\,\mathrm{d}y_1 \tag{15}$$

$$\Pr\{Y_1 \le kT\} = 1 - \Pr\{Y_1 > kT\} = 1 - \int_{kT}^{\infty} f_{Y_1}^{(k)}(y_1)\,\mathrm{d}y_1 \tag{16}$$

and the conditional expectations are calculated respectively as follows:

$$E\left[Y_1 \middle| Y_1 > kT\right] = \int_{kT}^{\infty} y_1 f_{Y_1|Y_1>kT}^{(k)}(y_1)\,\mathrm{d}y_1 \tag{17}$$

$$E\left[Y_2 \middle| Y_1 > kT\right] = \int_{kT}^{\infty}\int_{y_1}^{\infty} y_2 f_{Y_2}^{(n-k)}(y_2)\, f_{Y_1|Y_1>kT}^{(k)}(y_1)\,\mathrm{d}y_2\mathrm{d}y_1 \tag{18}$$

$$E\left[Y_1 \middle| Y_1 \le kT\right] = \int_{0}^{kT} y_1 f_{Y_1|Y_1\le kT}^{(k)}(y_1)\,\mathrm{d}y_1 \tag{19}$$

$$E\left[Y_2 \middle| Y_1 \le kT\right] = \int_{0}^{kT}\int_{y_1}^{\infty} y_2 f_{Y_2}^{(n-k)}(y_2)\, f_{Y_1|Y_1\le kT}^{(k)}(y_1)\,\mathrm{d}y_2\mathrm{d}y_1 \tag{20}$$

Substituting Equation (15)-(20) into Equation (13), $E\left[\sum_{i=1}^{n} T_i\right]$ is given by following Equation (21).

$$\begin{aligned} E\left[\sum_{i=1}^{n} T_i\right] &= \int_{kT}^{\infty} y_1 f_{Y_1|Y_1>kT}^{(k)}(y_1)\,\mathrm{d}y_1 \cdot \int_{kT}^{\infty} f_{Y_1}^{(k)}(y_1)\,\mathrm{d}y_1 \\ &+ \int_{kT}^{\infty}\int_{y_1}^{\infty} y_2 f_{Y_2}^{(n-k)}(y_2)\, f_{Y_1|Y_1>kT}^{(k)}(y_1)\,\mathrm{d}y_2\mathrm{d}y_1 \cdot \int_{kT}^{\infty} f_{Y_1}^{(k)}(y_1)\,\mathrm{d}y_1 \\ &+ \int_{0}^{kT} y_1 f_{Y_1|Y_1\le kT}^{(k)}(y_1)\,\mathrm{d}y_1 \cdot \left\{1 - \int_{kT}^{\infty} f_{Y_1}^{(k)}(y_1)\,\mathrm{d}y_1\right\} \\ &+ \int_{0}^{kT}\int_{y_1}^{\infty} y_2 f_{Y_2}^{(n-k)}(y_2)\, f_{Y_1|Y_1\le kT}^{(k)}(y_1)\,\mathrm{d}y_2\mathrm{d}y_1 \cdot \left\{1 - \int_{kT}^{\infty} f_{Y_1}^{(k)}(y_1)\,\mathrm{d}y_1\right\} \end{aligned} \tag{21}$$

3.2. The Total Production Time Follows Exponential Distribution

In this paper, for numeric consideration, the production time T_i is assumed to be exponential distributed and statistically independent, respectively.

Therefore, the probability density functions of random variables Y_1 and Y_2 are shown as follows:

$$f_{Y_1}^{(k)}(y_1) = \frac{\mu_1^k}{(k-1)!} y_1^{k-1} \mathrm{e}^{-\mu_1 y_1}$$

$$f_{Y_2}^{(n-k)}(y_2) = \begin{cases} \dfrac{\mu_1^{n-k}}{(n-k-1)!} y_2^{n-k-1} \mathrm{e}^{-\mu_1 y_2} & Y_1 \le kT \\ \dfrac{\mu_2^{n-k}}{(n-k-1)!} y_2^{n-k-1} \mathrm{e}^{-\mu_2 y_2} & Y_1 > kT \end{cases}$$

and the probabilities of $Y_1 > kT$ and $Y_1 \le kT$ are calculated as follows:

$$\Pr\{Y_1 > kT\} = \int_{kT}^{\infty} f_{Y_1}^{(k)}(y_1)\,\mathrm{d}y_1 = \sum_{l=0}^{k-1} \frac{(\mu_1 kT)^l}{l!} \mathrm{e}^{-\mu_1 kT} \tag{22}$$

$$\Pr\{Y_1 \le kT\} = 1 - \Pr\{Y_1 > kT\} = 1 - \int_{kT}^{\infty} f_{Y_1}^{(k)}(y_1)\,\mathrm{d}y_1 = 1 - \sum_{l=0}^{k-1} \frac{(\mu_1 kT)^l}{l!} \mathrm{e}^{-\mu_1 kT} \tag{23}$$

Based on the characteristic of exponential distribution, the conditional expectations in Equation (13) are given by following four Lemmas (see details in Supplementary material).

From (6), (13), (22), (23) and Lemmas 1-4, $E\left[C_3(k; T_1, T_2, \cdots, T_n)\right]$ is given by following theorem 1.

Theorem 1

For $k = 1, 2, \cdots, n$, the expected energy cost of n periods in switching model can be obtained by Equation (24).

$$
\begin{aligned}
& E\left[C_3\left(k; T_1, T_2, \cdots, T_n\right)\right] \\
& = Z_0 \cdot e_0 \cdot \left\{ \frac{n}{\mu_1} - (n-k)\left(\frac{1}{\mu_1} - \frac{1}{\mu_2}\right) \cdot \sum_{l=0}^{k-1} \frac{\left(\mu_1 kT\right)^l}{l!} \mathrm{e}^{-\mu_1 kT} \right\} \\
& \quad + \max\left\{\left(\rho - \rho'\right), 0\right\} \cdot C_e \cdot e_0 \cdot \left\{ \frac{n}{\mu_1} - (n-k)\left(\frac{1}{\mu_1} - \frac{1}{\mu_2}\right) \cdot \sum_{l=0}^{k-1} \frac{\left(\mu_1 kT\right)^l}{l!} \mathrm{e}^{-\mu_1 kT} \right\}
\end{aligned}
\tag{24}
$$

4. Experimental Consideration

In this chapter, we perform a numerical experiment to demonstrate the application and the performance of the proposed optimal switching model considered production cost, delivery date, and green evaluation in a production line. We consider the optimal switching period to minimize the total expected cost by numerical experiments.

4.1. Consideration on Green Evaluation

In this section, four types of electricity are used: $Z_1 = 2.4$ for industrial photovol taic power generation, $Z_2 = 3.3$ for offshore wind power generation, $Z_3 = 1.3$ for coal-fired power generation, and $Z_4 = 1.0$ for nuclear power generation based on 2014 data from the Ministry of Economy, Trade and Industry of Japan (2015). Figure 7 shows the target year and target ratio of renewable energy for major advanced countries. In this section, the required GEC level by government is set at $\rho' = 0.4$ which most of the major industrialized countries aim to achieve by 2030 based on the 2019 data of Natural Resources and Energy [7] in Figure 6.

Figure 7 shows tendency of energy cost due to changes in actual GEC level (ρ) and penalty coefficient when the optimal switching period k = 1, k = 5 and k = 10, where the parameter is shown in Table 1.

In Figure 7, the vertical axis is expected energy cost, the horizontal axis is actual GEC level in the production line (ρ), the interior axis is the penalty cost charged when GEC level is not achieved (C_e). The groups are allocated in order of k = 1, k = 5, k = 10 from the left.

From Figure 7, it can be noted that the energy cost changes greatly according to actual GEC level in the production line. Also, it can be note that the energy cost increases with rising of the switching period (k).

The results of Figure 7 will help manager set the GEC level in the production line for the energy mix plan.

4.2. Consideration on Total Expected Cost

In this section, an illustrative example is presented to verify the feasibility of the model. An example of a parameter setting is shown in Table 2, where the emergency processing speed is set to $\mu_2 = 0.6$ and the required GEC level is set to $\rho' = 0.4$. As the normal processing speed is varied over a range of $\rho' = 0.2, 0.3, 0.4, 0.5, 0.6, 0.7$ the relationship between the total expected cost and the optimal switching process k when the GEC level (ρ) is set to $\rho = 0.2$ and $\rho = 0.4$ are shown in Table 3 and Table 4 respectively. Table 3 shows the behavior of the optimal switching period by change of the usual processing rate when emergency processing rates of system is 0.6, and actual GEC level in the production line (ρ) is 0.2 (Table 2).

From Table 3, it can be noted that when usual processing rates of line are 0.1, 0.2, 0.3, 0.4 and 0.5, the optimal switching periods (k^*) are 2, 2, 5, 8 and 9, respectively.

Table 4 shows the behavior of the optimal switching period by change of the usual processing rate when emergency processing rates of system is 0.6, and actual GEC level in the production line (ρ) is 0.4.

From Table 4, it can be noted that when usual processing rates of line are 0.1, 0.2, 0.3, 0.4 and 0.5, the optimal switching periods (k^*) are 2, 3, 5, 8 and 9, respectively.

In addition, as the value of GEC level (ρ) increased from 0.2 to 0.4, all costs in Table 4 decreased compared to Table 3. It is considered that because the GEC penalty cost decreased as the GEC level increased and the influence of the energy cost has become smaller compared to the total expected cost.

Main renewable energy ※Excluding hydropower	Wind 16.3%	Wind 14.9%	Wind 18.0%	Solar 8.3%	Wind 4.4%	Wind 6.0%	Wind 4.4%	Wind 4.4%	Solar 5.2%
Taget Year	①2025 ②2035	2030	2020	2020	2030	2035	–	2020	2030
Target ratio of renewable energy	①40~45% ②55~60% Total power ratio	44% Total power ratio	40% Total power ratio	35~38% Total power ratio	40% Total power ratio	80% Clean energy as a percentage of total electricity	– It's not set at the national level.	15% Non-fossil share of primary energy	22~24% Total power ratio

Figure 6. Target year and target ratio of renewable energy for major.

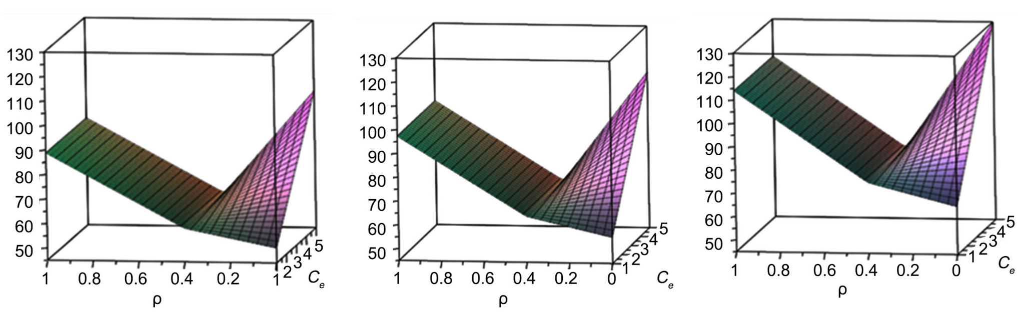

Figure 7. Tendency of energy cost due to changes in actual GEC level (ρ) and penalty coefficient (C_e) (From left to right, are $k = 1$, $k = 5$ and $k = 10$.)

Table 1. Parameter settings.

$\mu_1 = 0.2$	$\omega_1 = 0.5$	$Z_1 = 2.4$	$\rho' = 0.4$
$\mu_2 = 0.6$	$\omega_2 = 0.5$	$Z_2 = 3.3$	$e_0 = 0.8$
$T = 5$	$\omega_3 = 0.8$	$Z_3 = 1.3$	
$n = 10$	$\omega_4 = 0.2$	$Z_4 = 1$	

Table 2. An example of parameter setting.

$C_s^{(1)} = 1$	$C_s = 20$	$\mu_2 = 0.6$	$\omega_1 = 0.5$	$Z_1 = 2.4$
$C_p^{(1)} = 2$	$C_p = 200$	$T = 5$	$\omega_2 = 0.5$	$Z_2 = 3.3$
$C_s^{(2)} = 3$	$C_e = 4$	$n = 10$	$\omega_3 = 0.8$	$Z_3 = 1.3$
$C_p^{(2)} = 6$	$\rho' = 0.4$	$e_0 = 0.8$	$\omega_4 = 0.2$	$Z_4 = 1$

Table 3. Behaviours of the optimal switching period by change of the usual processing rate ($\rho = 0.2$).

	$\mu_1 = 0.1$	$\mu_1 = 0.2$	$\mu_1 = 0.3$	$\mu_1 = 0.4$	$\mu_1 = 0.5$
$k = 1$	308.735	206.966	131.277	100.121	83.247
$k = 2$	300.392	202.464	129.608	97.485	80.355
$k = 3$	323.371	202.592	128.470	95.895	79.101
$k = 4$	360.480	205.949	127.804	94.967	78.557
$k = 5$	402.105	212.310	127.599	94.437	78.320
$k = 6$	442.648	221.431	127.884	94.156	78.218
$k = 7$	479.649	232.803	128.689	94.037	78.177
$k = 8$	512.724	245.604	130.024	94.030	78.162
$k = 9$	542.492	258.619	131.802	94.099	78.159
$k = 10$	569.501	268.572	133.343	94.182	78.160

Table 4. Behaviours of the optimal switching period by change of the usual processing rate ($\rho = 0.4$).

	$\mu_1 = 0.1$	$\mu_1 = 0.2$	$\mu_1 = 0.3$	$\mu_1 = 0.4$	$\mu_1 = 0.5$
$k = 1$	287.890	192.066	119.810	90.949	75.693
$k = 2$	280.909	187.485	117.876	88.158	72.748
$k = 3$	303.174	187.248	116.498	86.474	71.472
$k = 4$	338.628	190.144	115.635	85.488	70.917
$k = 5$	378.065	195.997	115.274	84.924	70.675
$k = 6$	416.085	204.583	115.432	84.622	70.572
$k = 7$	450.345	215.403	116.137	84.491	70.529
$k = 8$	480.531	227.639	117.392	84.476	70.514
$k = 9$	507.310	240.080	119.106	84.541	70.511
$k = 10$	531.261	249.452	120.596	84.622	70.512

From the above analysis, we can know that the policy of optimal switching could be found by the proposed model according to the usage rate of renewable energy, processing rate, and due date of the production process.

5. Summary

In the achievement of smart manufacturing, optimal operation management for management information systems and applications has been paid to attention recently. This paper aims to derive an optimal switch model considered efficiency, delivery time and green evaluation for production system with multiple periods in smart manufacturing.

In this study, we proposed an optimal switching model for production line considering efficiency, delivery time and green evaluation. We also proposed a method for calculating the expected cost related to energy in consideration of GEC. The optimal switching period (k) which minimizes the total expected cost considering the energy cost was confirmed, and the optimal integration policies could be found in the numerical experiment.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Supplementary Material

Lemma 1

For $k=1,2,\cdots,n$,

$$E\left[Y_1\middle|Y_1>kT\right]=\frac{\frac{k}{\mu_1}\left\{\Pr\left\{Y_1>kT\right\}+\frac{\left(\mu_1 kT\right)^k}{k!}\mathrm{e}^{-\mu_1 kT}\right\}}{\Pr\left\{Y_1>kT\right\}}$$

Lemma 2

For $k=1,2,\cdots,n$,

$$E\left[Y_2\middle|Y_1>kT\right]=\frac{n-k}{\mu_1}\cdot\frac{\int_{kT}^{\infty}f_{Y_1}^{(k)}\left(y_1\right)\mathrm{d}y_1}{\Pr\left\{Y_1>kT\right\}}=\frac{n-k}{\mu_2}$$

Lemma 3

For $k=1,2,\cdots,n$,

$$E\left[Y_1\middle|Y_1\le kT\right]=\frac{\frac{k}{\mu_1}-\frac{k}{\mu_1}\left\{\Pr\left\{Y_1>kT\right\}+\frac{\left(\mu_1 kT\right)^k}{k!}\mathrm{e}^{-\mu_1 kT}\right\}}{\Pr\left\{Y_1>kT\right\}}$$

Lemma 4

For $k=1,2,\cdots,n$,

$$E\left[Y_2\middle|Y_1\le kT\right]=\frac{n-k}{\mu_1}$$

Proof

In this research, because the production time $T_i\left(i=1,2,\cdots,k\right)$ is assumed to be exponential distributed and statistically independent, respectively, which the mean value of usual processing rate is $1/\mu_1$, and the emergency processing rate is $1/\mu_2$, so, for $k=1,2,\cdots,n$,

$$\Pr\left\{Y_1>kT\right\}=\int_{kT}^{\infty}f_{Y_1}^{(k)}\left(y_1\right)\mathrm{d}y_1=\sum_{l=0}^{k-1}\frac{\left(\mu_1 kT\right)^l}{l!}\mathrm{e}^{-\mu_1 kT}$$

$$\Pr\left\{Y_1\le kT\right\}=1-\Pr\left\{Y_1>kT\right\}=1-\int_{kT}^{\infty}f_{Y_1}^{(k)}\left(y_1\right)\mathrm{d}y_1=1-\sum_{l=0}^{k-1}\frac{\left(\mu_1 kT\right)^l}{l!}\mathrm{e}^{-\mu_1 kT}$$

and Lemmas 1-4:

$$E\left[Y_1\middle|Y_1>kT\right]=\int_{kT}^{\infty}y_1 f_{Y_1|Y_1>kT}^{(k)}\left(y_1\right)\mathrm{d}y_1=\frac{\frac{k}{\mu_1}\left\{\Pr\left\{Y_1>kT\right\}+\frac{\left(\mu_1 kT\right)^k}{k!}e^{-\mu_1 kT}\right\}}{\Pr\left\{Y_1>kT\right\}}$$

$$\begin{aligned}E\left[Y_2\middle|Y_1>kT\right]&=\int_0^{\infty}\int_{y_1}^{\infty}y_2 f_{Y_2}^{(n-k)}\left(y_2\right)f_{Y_1|Y_1>kT}^{(k)}\left(y_1\right)\mathrm{d}y_2\mathrm{d}y_1\\&=\frac{n-k}{\mu_1}\cdot\frac{\int_{kT}^{\infty}f_{Y_1}^{(k)}\left(y_1\right)\mathrm{d}y_1}{\Pr\left\{Y_1>kT\right\}}=\frac{n-k}{\mu_2}\end{aligned}$$

$$E\left[Y_1\middle|Y_1\le kT\right]=\int_0^{kT}y_1 f_{Y_1|Y_1\le kT}^{(k)}\left(y_1\right)\mathrm{d}y_1=\frac{\frac{k}{\mu_1}-\frac{k}{\mu_1}\left\{\Pr\left\{Y_1>kT\right\}+\frac{\left(\mu_1 kT\right)^k}{k!}\mathrm{e}^{-\mu_1 kT}\right\}}{\Pr\left\{Y_1>kT\right\}}$$

$$E\left[Y_2\left|Y_1 \le kT\right.\right]=\int_0^{\infty}\int_{y_1}^{\infty} y_2\, f_{Y_2}^{(n-k)}\left(y_2\right) f_{Y_1|Y_1\le kT}^{(k)}\left(y_1\right)\mathrm{d}y_2\mathrm{d}y_1=\frac{n-k}{\mu_1}.$$

Substituting above equations into Equation (13), we can get that, for $k=1,2,\cdots,n$

$$\begin{aligned}E\left[\sum\nolimits_{i=1}^{n}T_i\right]&=E\left[Y_1\left|Y_1>kT\right.\right]\cdot\Pr\left\{Y_1>kT\right\}+E\left[Y_2\left|Y_1>kT\right.\right]\cdot\Pr\left\{Y_1>kT\right\}\\&\quad+E\left[Y_1\left|Y_1\le kT\right.\right]\cdot\Pr\left\{Y_1\le kT\right\}+E\left[Y_2\left|Y_1\le kT\right.\right]\cdot\Pr\left\{Y_1\le kT\right\}\\&=\frac{n}{\mu_1}-(n-k)\left(\frac{1}{\mu_1}-\frac{1}{\mu_2}\right)\cdot\sum\nolimits_{l=0}^{k-1}\frac{\left(\mu_1 kT\right)^l}{l!}\mathrm{e}^{-\mu_1 kT}\end{aligned}\quad(25)$$

Therefore, by Equation (6) and Equation (25), Theorem 1 is proven.

When the production time of each period follows the exponential distribution of the parameters μ_1 and μ_2, $E\left[C_1\left(k;T_1,T_2,\cdots,T_n\right)\right]$, $E\left[C_2\left(k;T_1,T_2,\cdots,T_n\right)\right]$ could be calculated as follows, which are Proofed by [6].

$$\begin{aligned}&E\left[C_1\left(k;T_1,T_2,\cdots,T_n\right)\right]\\&=\frac{k}{\mu_1}C_s^{(1)}+\frac{n-k}{\mu_1}C_s^{(1)}\left(1-\sum\nolimits_{l=0}^{k-1}\frac{\left(\mu_1 kT\right)^l}{l!}\mathrm{e}^{-\mu_1 kT}\right)\\&\quad+\frac{n-k}{\mu_2}C_s^{(2)}\sum\nolimits_{l=0}^{k-1}\frac{\left(\mu_1 kT\right)^l}{l!}\mathrm{e}^{-\mu_1 kT}+\frac{C_p^{(1)}-C_s^{(1)}}{\mu_1}\sum\nolimits_{i=1}^{k}\sum\nolimits_{l=0}^{i-1}\frac{\left(\mu_1 kT\right)^l}{l!}\mathrm{e}^{-\mu_1 kT}\\&\quad+\frac{C_p^{(1)}-C_s^{(1)}}{\mu_1}\sum\nolimits_{i=k+1}^{n}\sum\nolimits_{l=0}^{i-1}\mathrm{e}^{-\mu_1 iT}\sum\nolimits_{l_1}^{l}\frac{\left(\mu_1 kT\right)^{l_1}}{l_1!}\frac{\left(\mu_1\left(i-k\right)T\right)^{l-l_1}}{\left(l-l_1\right)!}\\&\quad+\frac{C_p^{(2)}-C_s^{(2)}}{\mu_2}\left(\sum\nolimits_{i=k+1}^{n}\sum\nolimits_{l=0}^{i-1}\int_{kT}^{iT}\frac{\left(\mu_1 x\right)^{k-1}}{(k-1)!}\mathrm{e}^{-\mu_1 x}\frac{\left\{\mu_2\left(iT-x\right)\right\}^{l-k}}{(l-k)!}\mathrm{e}^{-\mu_2\left(iT-x\right)}\mu_1\mathrm{d}x\right.\\&\quad\left.+\sum\nolimits_{i=k+1}^{n}\sum\nolimits_{l=0}^{k-1}\frac{\left(\mu_1 iT\right)^l}{l!}\mathrm{e}^{-\mu_1 iT}\right)\end{aligned}$$

$$\begin{aligned}&E\left[C_2\left(k;T_1,T_2,\cdots,T_n\right)\right]\\&=C_p\left\{\int_{nT}^{\infty}\int_{kT}^{x_n}\frac{\left(\mu_1 x_k\right)^{k-1}}{(k-1)!}\mathrm{e}^{-\mu_1 x_k}\frac{\left\{\mu_2\left(x_n-x_k\right)\right\}^{n-k-1}}{(n-k-1)!}\mathrm{e}^{-\mu_2\left(x_n-x_k\right)}\mu_1\mu_2\mathrm{d}x_k\mathrm{d}x_n\right.\\&\quad\left.+\int_{nT}^{\infty}\int_{0}^{kT}\frac{\left(\mu_1 x_k\right)^{k-1}}{(k-1)!}\mathrm{e}^{-\mu_1 x_k}\frac{\left\{\mu_1\left(x_n-x_k\right)\right\}^{n-k-1}}{(n-k-1)!}\mathrm{e}^{-\mu_1\left(x_n-x_k\right)}\left(\mu_1\right)^2\mathrm{d}x_k\mathrm{d}x_n\right\}\\&\quad+C_s\left\{\int_{nT}^{nT}\int_{kT}^{x_n}\frac{\left(\mu_1 x_k\right)^{k-1}}{(k-1)!}\mathrm{e}^{-\mu_1 x_k}\frac{\left\{\mu_2\left(x_n-x_k\right)\right\}^{n-k-1}}{(n-k-1)!}\mathrm{e}^{-\mu_2\left(x_n-x_k\right)}\mu_1\mu_2\mathrm{d}x_k\mathrm{d}x_n\right.\\&\quad\left.+\int_{x_k}^{nT}\int_{0}^{kT}\frac{\left(\mu_1 x_k\right)^{k-1}}{(k-1)!}\mathrm{e}^{-\mu_1 x_k}\frac{\left\{\mu_1\left(x_n-x_k\right)\right\}^{n-k-1}}{(n-k-1)!}\mathrm{e}^{-\mu_1\left(x_n-x_k\right)}\left(\mu_1\right)^2\mathrm{d}x_k\mathrm{d}x_n\right\}\end{aligned}$$