Method for operating energy-saving idle facilities on production lines considering breakdowns

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Abstract
In recent years, reducing standby electric power consumption by individual production facilities has been studied to reduce their energy consumption, particularly regarding machine tools, industrial robots, etc., which are principal types of facilities in production systems. Energy-saving idle state capable production facilities (energy-saving idle facilities) have been developed and have begun to be commercialized. They can be in the normal idle state, permitting the quick startup of production from their idle state to reduce energy. Specifically, auxiliary machines unused during idling are shut down, thus minimizing electric power consumption. Such an idle state is defined as the energy-saving idle state (eco-idle state). The research and development of energy-saving idle facilities is advancing, but a lack of effective methods to operate production lines after energy-saving idle facilities have been introduced on these lines is hindering their introduction. Past research has proposed methods for operating energy-saving idle facilities on production lines. However, breakdowns occurring in production facilities have not been considered. This paper proposes a method for operating energy-saving idle facilities on production lines considering breakdowns. The method consists of an idle-time prediction algorithm and an idle-state selection algorithm. Case studies are presented to confirm the effectiveness of the proposed method.

Keywords: Production facility operation of energy-saving idle state, Production line, Simulation, Productivity, Energy consumption, Breakdown

1. Introduction

On November 4, 2016, the Paris Agreement was implemented, and the first session of the conference of the parties who participated in the Paris Agreement was held, obligating the parties to reduce the emissions of greenhouse effect gases worldwide (Ministry of Foreign Affairs, 2016). In Japan, the Energy Saving Law was revised in April 2014 to reduce the annual average of the specific energy consumption by manufacturing by 1%; thus, it important to reduce the energy consumed by production activities (Ministry of Economy, 2017). Approximately 43% of all energy consumed in Japan is consumed by manufacturing activities (Ministry of Economy, 2016). The largest share of energy consumed in manufacturing is electric power, which is consumed by production facilities and ordinary facilities, with approximately 83% consumed by the former and 17% by the latter (Ministry of Economy, 2011; Ministry of Economy, 2017). Therefore, an effective method to reduce the consumption of energy in manufacturing is to reduce the energy consumed by production processes. Past studies regarding production processes have primarily focused on improving their productivity by improving the flow efficiency of objects and minimizing the time that the objects are stopped between processes—particularly, research on the improved efficiency of processes through simulations (McLean et al., 2005; Kim et al., 2005; Mitsuyuki et al., 2004; Hibino and Fukuda,2006; Hibino and Fukuda, 2008). In recent years, studies that evaluate the productivity and energy consumption of production processes and energy consumption
reduction simultaneously have been performed (Beier et al., 2017; Hibino et al., 2014a; Kobayashi et al., 2016; Yamaguchi et al., 2016).

Other research has been conducted recently to reduce the standby electric power consumption of individual production facilities to reduce the energy usage of such facilities, particularly in the areas of machine tools and industrial robots, which are principal facilities in production systems (Kawai et al., 2016). Energy-saving idle state capable production facilities (energy-saving idle facilities) have been developed and their commercialization has begun. Energy-saving idle facilities have, in addition to normal idle states that permit the quick start-up of production, other idle states to save energy (DENSO WAVE Incorporated, 2016; FUJI CORPORATION, 2016). Specifically, auxiliary machines unused during idling are shut down, thus minimizing electric power consumption. Such an idle state is defined as an energy-saving idle state (eco-idle state). The research and development of energy-saving idle facilities is advancing; however, effective methods for operating production lines after energy-saving idle facilities have been introduced on such production lines have not been developed, thereby hindering their introduction.

The first proposed method for operating an energy-saving idle facility on a production line was introduced by Hibino et al. (2018). However, it did not consider breakdowns of production facilities.

This paper proposes a method for operating energy-saving idle facilities on production lines considering breakdowns. The method consists of an idle-time prediction algorithm and an idle-state selection algorithm. Case studies are presented to confirm the effectiveness of our proposed method.

2. Energy-saving idle facilities

Restrictions on the operation of a production line consisting of energy-saving idle facilities are analyzed in this section. In energy-saving idle facilities, auxiliary machines not used during idling are turned off (below, “shutdown”) to reduce wasteful consumption of electric power. To restart production by an energy-saving idle facility from its eco-idle state, it is necessary to start the auxiliary machines that have been shut down (below, “startup”). Therefore, to introduce energy-saving idle facilities on a production line and use them in the eco-idle state, the following two conditions must be satisfied.

Condition 1. It must be possible to lower energy consumption using the eco-idle state (see Fig. 1).

When an energy-saving idle facility is used in the eco-idle state, in addition to energy consumed in the eco-idle state, energy is consumed during production facility shutdown and start-up. When the total energy consumed by shutdown $E_{sleeping}$, energy consumed by startup $E_{standing}$, and energy consumed during the eco-idle state $E_{eco-idle}$ is greater than the energy consumed during the normal idle state $E_{idle}$, the energy consumed is increased by using the eco-idle state. Therefore, the restrictive condition that satisfies Condition 1 is represented by the following equation.

$$E_{idle} > E_{sleeping} + E_{eco-idle} + E_{standing}$$

(1)

Condition 2. The eco-idle state must not affect productivity (see Fig. 2).

When using the eco-idle state of an energy-saving idle facility, in addition to the eco-idle state time, the production facility shutdown and startup constitute the operating time. If the total of shutdown time $t_{sleeping}$, startup time $t_{standing}$, and eco-idle state time $t_{eco-idle}$ is longer than the production facility idle time $t_{idle}$, then using the eco-idle state affects productivity. Therefore, the restrictive condition that satisfies Condition 2 is given by the following equation.

$$t_{idle} > t_{sleeping} + t_{eco-idle} + t_{standing}$$

(2)
3. Previous research

The first report to propose an idle-state transition model, idle-state selection algorithm, and idle-time prediction algorithm to operate energy-saving idle facilities on a production line was published by the authors (Hibino and Yanaga, 2018). We extend that work in this paper to consider equipment breakdown.

3.1 Idle-state transition model

This section analyzes and organizes the facility state and state transitions that consider the eco-idle state of energy-saving idle facilities, focusing on machine tools and industrial robots that are representative facilities of production systems. The proposed idle state transition model is shown in Figure 3. Two idle states—normal idle state and eco-idle state—are modeled separately. This is performed by hierarchically modeling the eco-idle state as multiple sub-eco-idle states (Eco-idle2(n)). The eco-idle state is accompanied by the shutdown and startup states; therefore, before and after the sub-eco-idle state, the shutdown state and startup state are modeled.

A state-transition can be defined by applying regularity. Using the idle-state, waiting arrival of work (Idle1), as an example, after work arrives, a transition to the running state occurs. Once the running state is completed, the machine will wait for the next work and a transition to the normal idle state occurs. After all work has been processed, a transition to the eco-idle state occurs.
3.2 Idle state selection algorithm

This study assumes that on a production line consisting of \( m \) production facilities, the idle state that permits the highest reduction in energy consumption by the \( m \)th production facility is selected.

3.2.1 Formulation of idle state energy consumption

To select the idle state that can reduce energy consumption, the quantities of energy consumed by either normal idle-state 2 or eco-idle state 2 are formulated based on the following items.

3.2.1.1 Formulation of quantity of energy consumed by the normal idle state

Assuming that production facility \( m \) has an idle time \( t_{idle}^{(m)} \), the quantity of energy consumed when production facility \( m \) has selected normal idle-state 2 is formulated.

If the quantity of electric power consumed in normal idle-state 2 is represented by \( P_{idle}^{(m)} \), the quantity of energy consumed by normal idle-state 2 \( E_{idle}^{(m)} \) is defined by the following equation (see Fig. 4).

\[
E_{idle}^{(m)} = P_{idle}^{(m)} \times t_{idle}^{(m)}
\]  

(3)

Fig. 3 Idle-state transition model.

Fig. 4 Relationship between energy consumption and idle time in normal idle-state 2.
3.2.1.2 Formulation of energy consumption by eco-idle state

Hypothesizing that production facility \( m \) has an idle time \( t_{\text{idle}}^{(m)} \), the energy consumed when production facility \( m \) selects the use of eco-idle state \( 2(n) \) is formulated as follows.

Shutting down the energy-saving idle facility from normal idle-state 2 to eco-idle state \( 2(n) \) requires a shutdown time \( t_{\text{sleeping2}(n)}^{(m)} \) and consumes a start-up energy \( E_{\text{sleeping2}(n)}^{(m)} \). Eco-idle state \( 2(n) \) consumes the energy \( E_{\text{eco-idle2}(n)}^{(m)} \). In an energy-saving facility, starting idle-state 2 up from eco-idle state \( 2(n) \) requires a startup time \( t_{\text{standing2}(n)}^{(m)} \) and consumes a startup energy \( E_{\text{standing2}(n)}^{(m)} \) (see Fig. 5).

The total time for shutdown and startup is considered as the time required to transition from the eco-idle state and the total startup energy consumption and shutdown energy consumption is considered as the quantity of energy consumption necessary to transition from or return to the eco-idle state. If the required time is represented by \( t_{2}(n) \) and the required energy consumption is represented by \( E_{2}(n) \), then they are represented by the following equations (see Fig. 6).

\[
\begin{align*}
    t_{2}(n) &= t_{\text{sleeping2}(n)}^{(m)} + t_{\text{standing2}(n)}^{(m)} \quad (4) \\
    E_{2}(n) &= E_{\text{sleeping2}(n)}^{(m)} + E_{\text{standing2}(n)}^{(m)} \quad (5)
\end{align*}
\]

![Fig. 5 Relationship between energy consumption and idle time on the eco-idle 2 state including sleeping state and standing state (No.1).](image1)

![Fig. 6 Relationship between energy consumption and idle time on the eco-idle 2 state including sleeping state and standing state (No.2).](image2)

From the above, if the quantity of electric power consumed by eco-idle state \( 2(n) \) is \( P_{\text{eco-idle2}(n)}^{(m)} \), the total energy consumed to use eco-idle state \( 2(n) \), \( E_{\text{total eco-idle2}(n)}^{(m)} \) is represented by the following equation.

\[
E_{\text{total eco-idle2}(n)}^{(m)} = P_{\text{eco-idle2}(n)}^{(m)} \times (t_{\text{idle}}^{(m)} - t_{2}(n)) + E_{2}(n) \quad (6)
\]

This is limited to the case: \( t_{2}(n) \leq t_{\text{idle}}^{(m)} \).

3.2.2 Formulation of reference time when energy consumption can be reduced using eco-idle state

To select the idle state that can reduce energy consumption, the formulae for energy consumed by normal idle state 2 and by eco-idle state \( 2(n) \) are used to determine the reference time when it is possible to reduce energy consumption by transitioning to the eco-idle state.

The reference time \( t_{21}^{(m)} \), which indicates when it is possible to reduce energy consumption using eco-idle state \( 2(1) \),
is the time value from the intersection of the graph of energy consumption of normal idle state 2 $E_{idle}^{(m)}$ (Eq. (3)) and the graph of energy consumption of eco-idle state 2(1) $E_{total \, eco−idle2(1)}^{(m)}$ (Eq. (6)). Therefore, the following equation can be introduced.

$$\text{Pow}_{idle}^{(m)} \times t_{idle}^{(m)} = \text{Pow}_{eco−idle2(1)}^{(m)} \times \left( t_{idle}^{(m)} - t_{2(1)}^{(m)} \right) + E_{2(1)}^{(m)}$$  \hspace{1cm} (7)

If it is hypothesized that the idle time $t_{idle}^{(m)}$ of production facility $m$ is the time value $t_{c1}^{(m)}$ of the intersection, Eq. 7 can be rewritten as follows.

$$\text{Pow}_{idle}^{(m)} \times t_{c1}^{(m)} = \text{Pow}_{eco−idle2(1)}^{(m)} \times \left( t_{c1}^{(m)} - t_{2(1)}^{(m)} \right) + E_{2(1)}^{(m)}$$  \hspace{1cm} (8)

By rearranging Eq. (8), the reference time $t_{c1}^{(m)}$, which indicates when energy consumption can be reduced using eco-idle state 2(1), can be represented by the following equation.

$$t_{c1}^{(m)} = \frac{E_{2(1)}^{(m)} - \text{Pow}_{eco−idle2(1)}^{(m)} \times t_{2(1)}^{(m)}}{\text{Pow}_{idle}^{(m)} - \text{Pow}_{eco−idle2(1)}^{(m)} \times t_{2(1)}^{(m)}}$$  \hspace{1cm} (9)

Figure 7 specifically shows a case where the energy-saving idle facility that is the object uses both eco-idle state 2 and normal idle-state 2. Furthermore, it is hypothesized that it exhibits sub-eco-idle states 2(1), 2(2), and 2(3).

4. **Proposed method for operating energy-saving idle facilities on production lines considering breakdown**

4.1 **Factors contributing to the idle time of production facilities**

If the proposed idle-state selection algorithm can predict the idle time resulting from the production facilities on a production line, it will be possible to select an idle state that can reduce energy consumption without impacting productivity. The primary reasons why facilities on production lines have idle times are attributed to the setup time needed to change product type, sudden breakdowns, shutting down of workflow by variations in working hours, and shutdowns required by production plans. To transition production facilities to an idle state that permits a reduction in energy consumption, it is necessary to accurately predict the idle time by considering these factors.
This study proposes a prediction algorithm for the idle time of production facilities when considering a sudden breakdown from among the major causes of idle time mentioned above.

Production facilities break down frequently because of the deterioration of production facility components, unavailability of parts, or short-circuiting of electronic circuits, halting the processing of partially completed products (Japanese Standards Association, 2001; Makabe, 2013). In this study, it was assumed that each production facility broke down during each mean time between failures (MTBF) and that it began operating again after the mean time to repair (MTTR). This study assumed that breakdowns occurred accidentally and did not occur during setting up or during idle time. It was also assumed that the processing of partially completed products that were being processed immediately before a breakdown resumed after a breakdown repair. In this study, the number of production facilities that break down during a certain period is assumed to be one facility.

4.2 Hypothesized production line

It is hypothesized that on a production line consisting of $m$ production facilities, the production facilities are linked by transport equipment and buffers, and partially completed products flow from production facility 1 toward production facility $m$. On the production line, assuming that partially completed products are supplied without interruption, it is hypothesized that the buffer size between production facilities is infinite.

With these assumptions in mind, $t_{worked\_in\_cycle}^{(m)}$ is defined as the mid-process time, which is an elapsed period from the start time to the current time in a processing period. $PrO{T}^{(m)}$ is defined as the total quantity produced in production facility $m$.

4.3 Method for operating energy-saving idle facilities on production lines considering breakdown

The proposed operation method is used when a breakdown occurs in a facility on the production line. The method consists of an idle-time prediction algorithm and an idle-state selection algorithm. The method is applied to facilities in which a later production process breakdown occurs.

The idle-time prediction algorithm predicts an idle-time for each related facility by considering the restriction on the impact on productivity, which is Condition 2 in Section 2.

The idle-state selection algorithm selects a suitable idle-state for each related facility by considering the restriction on energy consumption, which is Condition 1 in Section 2.

In the case when a breakdown occurs on the production line, the idle-time prediction algorithm is run first and calculates the prediction idle-time. The idle-state selection algorithm is then run and selects a suitable idle-state using the prediction idle-time. Figure 8 provides an overview of the method when a breakdown occurs.
4.3.1 Idle-time prediction algorithm

The idle-time prediction algorithm predicts an idle-time for each related facility by considering the restriction on the impact on productivity, which is Condition 2 in Section 2.

A production line consisting of $m$ production facilities is hypothesized to predict the idle time of production facility $m$ arising from the breakdown of production facility 1 (see Fig. 9). Representing the moment in time when production facility 1 breaks down as $t^{\text{Breakdown}(0)}$, the time when partially completed goods being processed by production facility $m$ and partially completed products halted between buffer 1 and buffer $m$ have completed manufacture as $t^{\text{Breakdown}(1)}$, and then the time when the first partially completed products reach production facility $m$ is represented as $t^{\text{Breakdown}(2)}$. The idle time of production facility $m$ is represented by $t_{\text{idle}}$, then $t^{\text{Breakdown}(1)}$, $t^{\text{Breakdown}(2)}$, and $t_{\text{idle}}$ are represented by the equations discussed in the

Fig. 8 Outline of method for operating energy-saving idle facilities on production lines considering breakdown

| Case 1 | Case 2 | Case 3 |
|--------|--------|--------|
| $t^{\text{EcoIdle2(1)}}$ | $t^{\text{EcoIdle2(2)}}$ | $t^{\text{EcoIdle2(3)}}$ |

| Decision items | $t^{\text{EcoIdle2(1)}}$ | $t^{\text{EcoIdle2(2)}}$ | $t^{\text{EcoIdle2(3)}}$ |
|----------------|---------------------|---------------------|---------------------|
| Time for sleeping and standing operation | $t^{\text{EcoIdle2(1)}}$ | $t^{\text{EcoIdle2(2)}}$ | $t^{\text{EcoIdle2(3)}}$ |

| Energy consumption $[J]$ | $t^{\text{EcoIdle2(1)}}$ | $t^{\text{EcoIdle2(2)}}$ | $t^{\text{EcoIdle2(3)}}$ |
|--------------------------|---------------------|---------------------|---------------------|
| $t_{\text{EcoIdle2(1)}}$ | $t_{\text{EcoIdle2(2)}}$ | $t_{\text{EcoIdle2(3)}}$ |
following sections.

4.3.1.1 Calculation of \( t_{\text{Breakdown}(1)}^{(m)} \)

The time when processing all completed products in production facility \( m \), and when completed products stopped between buffer 1 and buffer \( m \) has transpired \( t_{\text{Breakdown}(1)}^{(m)} \) is given below.

\[
t_{\text{Breakdown}(1)}^{(m)} = (ProT^{(1)} - ProT^{(m)})t_{\text{cycle}}^{(m)} + t_{\text{working in cycle}}^{(m)}
\]  

(10)

4.3.1.2 Calculation of \( t_{\text{Breakdown}(2)}^{(m)} \)

After production facility \( m \) has passed through mean time to repair(1), the time \( t_{\text{Breakdown}(2)}^{(m)} \) when the first partially completed product reaches production facility \( m \) is calculated as below.

\[
t_{\text{Breakdown}(2)}^{(m)} = \text{MTTR}^{(1)} - t_{\text{cycle}}^{(1)} + \sum_{i=1}^{m-1} (t_{\text{cycle}}^{(i)} + t_{\text{transportation}}^{(i)})
\]  

(11)

4.3.1.3 Calculation of \( t_{\text{idle}}^{(m)} \)

The idle time \( t_{\text{idle}}^{(m)} \) of production facility \( m \) caused by the breakdown of production facility 1 is calculated. Production facility \( m \) is in the idle state when the time that it has completed processing all partially completed products and when partially completed products have stopped between buffer 1 and buffer \( m \) reaches \( t_{\text{Breakdown}(1)}^{(m)} \).

Subsequently, the time when production facility 1 has passed through mean time to repair ((MTTR)\(^{(1)}\)) in Eq. (11) and the first partially completed products reaching production facility \( m \) has become \( t_{\text{Breakdown}(2)}^{(m)} \), the processing of partially completed products restarts.

From the above, the idle time \( t_{\text{idle}}^{(m)} \) of production facility \( m \) arising from the breakdown of production facility 1 is
calculated by the following equation.

\[ t_{idle}^{(m)} = t_{breakdown(2)}^{(1)} - t_{breakdown(1)}^{(1)} \]

\[ = MTTR^{(1)} - t_{worked_in_cycle}^{(1)} + \sum_{i=1}^{m-1} (t_{cycle}^{(i)} + t_{transportation}^{(i)}) \]

\[ - (PrT^{(1)} - PrT^{(m)}) t_{cycle}^{(m)} + t_{worked_in_cycle}^{(m)} \]  \[ (12) \]

### 4.3.2 Idle-state selection algorithm

The idle-state selection algorithm selects a suitable idle-state for each related facility by considering the restriction on energy consumption, which is Condition 1 in Section 2, when a breakdown occurs in the production line.

The reference time specified in Section 3.2.2 is used to select the idle state that can reduce energy consumption.

When it is hypothesized that production facility \( m \) has an idle time \( t_{idle}^{(m)} \), comparing idle time \( t_{idle}^{(m)} \) with a reference time can divide the selection of the idle state into the following cases (see Fig. 8).

#### [Case1]
When idle time \( t_{idle}^{(m)} \) is shorter than reference time \( t_{c1}^{(m)} \) if eco-idle state 2(1) were to be used, continuing with normal idle state 2 can reduce energy consumption.

#### [Case2]
When idle time \( t_{idle}^{(m)} \) is longer than reference time \( t_{c1}^{(m)} \) if eco-idle state 2(1) were to be used and is shorter than reference time \( t_{c2}^{(m)} \) if eco-idle state 2(2) were to be used, then using eco-idle state 2(1) can reduce energy consumption.

#### [Case3]
When idle time \( t_{idle}^{(m)} \) is longer than reference time \( t_{c2}^{(m)} \) if eco-idle time 2(2) were to be used and is shorter than reference time \( t_{c3}^{(m)} \) if eco-idle time 2(3) were to be used, using eco-idle time 2(2) can reduce energy consumption.

### 5. Case study

In this section, the effectiveness of the proposed method for operating energy-saving idle facilities on production lines considering breakdown is verified. Case studies are conducted to verify the proposed idle-time prediction algorithm and the proposed idle-state selection algorithm. The proposed algorithms are implemented in a discrete event simulation using WITNESS, which is a discrete simulation software.

#### 5.1 Production line considered

The case study evaluated and verified the electric power consumed by a production line consisting of three industrial robots as the energy consumed. The production facilities are linked by transport facilities and buffers, and it is hypothesized that partially completed products flow from production facility 1 to production facility 3. The cycle times of the three production facilities are considered as equal. It is assumed that breakdown occurs in production facility 1. The MTBF and MTTR conform to a Weibull distribution and normal distribution, respectively. Figure 10 shows the installed production line and the input data to each production facility.
5.2 Verification of the proposed idle time prediction algorithm

This section verifies the effectiveness of the proposed idle time prediction algorithm. The data of the predicted idle time $t_{idle}$ calculated by Eq. (12) were compared with the virtual actual data for the idle time obtained by simulation to evaluate the algorithm’s productivity and to verify its effectiveness. It is assumed that breakdown occurs in production facility 1. The MTBF of production facility 1 conformed to a Weibull distribution (shape parameter: 0.2, scale parameter: 90). Regarding the MTTR, two normal distributions were evaluated. In one case study, the MTTR conformed to a normal distribution (average value: 150, variance: 2). In the second case study, the MTTR conformed to a normal distribution (average value: 150, variance: 0). The execution time is 5,000 s. For MTTR (1), an average normal distribution value of 150 is used to calculate $t_{idle}^{(m)}$.

One case study is first carried out using a normal distribution (average value: 150, variance: 0) as the MTTR. The data of the predicted idle time $t_{idle}^{(m)}$ calculated by Eq. (12), and the virtual actual data for idle time obtained by the simulation, are listed in Table 1. The predicted idle times $t_{idle}^{(m)}$ for production facility 2 and production facility 3 were calculated without error when comparing the predicted idle times to the virtual actual data for idle times obtained by the simulation.
Table 1 Verification of the proposed idle time prediction algorithm using a normal distribution MTTR
(average value: 150, variance: 0)

| The number of breakdown | Facility 2 |   |   | Facility 3 |   |   |
|-------------------------|------------|---|---|------------|---|---|
|                         | \( t_{idle} \) [s] | Idle time by simulation [s] | Error rate [%] | \( t_{idle} \) [s] | Idle time by simulation [s] | Error rate [%] |
| 1                       | 150.00     | 150.00 | 0.00% | 150.00     | 150.00 | 0.00% |
| 2                       | 149.19     | 149.19 | 0.00% | 130.00     | 130.00 | 0.00% |
| 3                       | 147.59     | 147.59 | 0.00% | 147.59     | 147.59 | 0.00% |
| 4                       | 157.68     | 157.68 | 0.00% | 137.68     | 137.68 | 0.00% |
| 5                       | 138.54     | 138.54 | 0.00% | 128.54     | 128.54 | 0.00% |
| 6                       | 149.54     | 149.54 | 0.00% | 129.54     | 129.54 | 0.00% |
| 7                       | 149.80     | 149.80 | 0.00% | 129.80     | 129.80 | 0.00% |
| 8                       | 143.09     | 143.09 | 0.00% | 133.09     | 133.09 | 0.00% |
| 9                       | 154.76     | 154.76 | 0.00% | 144.76     | 144.76 | 0.00% |
| 10                      | 149.93     | 149.93 | 0.00% | 139.93     | 139.93 | 0.00% |
| 11                      | 131.49     | 131.49 | 0.00% | 131.49     | 131.49 | 0.00% |
| 12                      | 149.22     | 149.22 | 0.00% | 129.22     | 129.22 | 0.00% |
| 13                      | 149.59     | 149.59 | 0.00% | 149.59     | 149.59 | 0.00% |
| 14                      | 130.70     | 130.70 | 0.00% | 130.70     | 130.70 | 0.00% |
| 15                      | 139.36     | 139.36 | 0.00% | 150.00     | 150.00 | 0.00% |
| 16                      | 159.98     | 159.98 | 0.00% | 130.00     | 130.00 | 0.00% |
| 17                      | 27.69      | 27.69  | 0.00% | 170.00     | 170.00 | 0.00% |
| 18                      | 139.33     | 139.33 | 0.00% | 118.33     | 118.33 | 0.00% |
| 19                      | 149.40     | 149.40 | 0.00% | 142.40     | 142.40 | 0.00% |
| 20                      | 149.65     | 149.65 | 0.00% | 130.00     | 130.00 | 0.00% |
| 21                      | 149.87     | 149.87 | 0.00% | 129.87     | 129.87 | 0.00% |
| 22                      | 150.00     | 150.00 | 0.00% | 130.00     | 130.00 | 0.00% |

Average of absolute value \(0.00\%\) Average of absolute value \(0.00\%\)

The second case study is carried out using a normal distribution (average value: 150, variance: 2) as the MTTR. The data of the predicted idle times \(t_{idle}^{(m)}\) calculated by Eq. (12), and the virtual actual data for idle times obtained by the simulation, are listed in Table 2. The predicted idle times \(t_{idle}^{(m)}\) for production facility 2 and production facility 3 were calculated with good agreement when comparing the predicted idle times to the idle times predicted by the virtual actual data.

Through the two case studies, we confirmed the effectiveness of the proposed idle time prediction algorithm.
Table 2 Verification of the proposed idle time prediction algorithm using a normal distribution
(average value: 150, variance: 2) MTTR

| The number of breakdown | Facility 2 | Facility 3 |
|-------------------------|-----------|-----------|
|                         | $t_{idle}^{(2)}$ [s] | Idle time by simulation [s] | Error rate [%] | $t_{idle}^{(3)}$ [s] | Idle time by simulation [s] | Error rate [%] |
| 1                       | 150.00    | 150.81    | 0.54%    | 150.00    | 150.81    | 0.54%    |
| 2                       | 149.19    | 147.32    | -1.26%   | 129.19    | 127.32    | -1.46%   |
| 3                       | 141.05    | 140.96    | -0.06%   | 131.05    | 130.96    | -0.07%   |
| 4                       | 152.14    | 151.28    | -0.56%   | 142.14    | 141.28    | -0.60%   |
| 5                       | 132.99    | 131.03    | -1.50%   | 130.00    | 128.04    | -1.53%   |
| 6                       | 149.96    | 150.69    | 0.49%    | 129.96    | 130.69    | 0.56%    |
| 7                       | 149.22    | 149.07    | -1.01%   | 130.00    | 129.85    | -0.12%   |
| 8                       | 159.37    | 159.48    | 0.07%    | 149.37    | 149.48    | 0.07%    |
| 9                       | 139.26    | 142.26    | 2.11%    | 129.26    | 132.26    | 2.27%    |
| 10                      | 149.27    | 149.63    | 0.24%    | 129.27    | 129.63    | 0.28%    |
| 11                      | 158.90    | 162.65    | 2.30%    | 148.90    | 152.65    | 2.46%    |
| 12                      | 135.16    | 136.08    | 0.68%    | 130.00    | 130.92    | 0.70%    |
| 13                      | 149.23    | 150.01    | 0.52%    | 144.23    | 145.01    | 0.53%    |
| 14                      | 149.46    | 150.35    | 0.59%    | 150.00    | 150.89    | 0.59%    |
| 15                      | 148.57    | 149.91    | 0.90%    | 140.00    | 141.34    | 0.95%    |
| 16                      | 149.23    | 149.67    | 0.36%    | 129.23    | 129.67    | 0.34%    |
| 17                      | 150.20    | 150.20    | 0.00%    | 170.00    | 171.11    | 0.65%    |
| 18                      | 149.68    | 150.72    | 0.69%    | 117.68    | 118.72    | 0.88%    |
| 19                      | 149.63    | 148.98    | -0.44%   | 130.00    | 139.34    | -0.47%   |
| 20                      | 130.29    | 129.94    | -0.27%   | 129.00    | 139.65    | -0.25%   |
| 21                      | 149.64    | 152.29    | 1.74%    | 129.64    | 129.65    | 2.00%    |
| 22                      | 150.00    | 150.60    | 0.40%    | 130.00    | 130.60    | 0.46%    |

Average of absolute value 0.72% Average of absolute value 0.81%

5.3 Verification of the proposed idle-state selection algorithm

This section verifies the effectiveness of the proposed idle-state selection algorithm. The reference time $t_{c1}^{(m)}$, which is the time when it is possible to reduce energy consumption using the eco-idle state, is calculated. The reference time $t_{c1}^{(2)}$, when it is possible to reduce energy consumption using eco-idle state 2(1) in production facility 2, and the reference time $t_{c2}^{(2)}$ when it is possible to reduce energy consumption using eco-idle state 2(2), can be calculated by Eq. (9) using the given input data to production facility 2 as the following equation.

$$t_{c1}^{(2)} = t_{idle}^{(2)} - \frac{PowC_{ecoIdle2(1)}^{(2)} \times t_{idle}^{(2)} - PowC_{idle}^{(2)}}{PowC_{idle}^{(2)} - PowC_{ecoIdle2(1)}^{(2)}} = 0.48 - 0.06 \times 2.6 = 0.11 - 0.06 = 6.48$$

(13)

$$t_{c2}^{(2)} = t_{idle}^{(2)} - \frac{PowC_{ecoIdle2(1)}^{(2)} \times t_{idle}^{(2)} + PowC_{ecoIdle2(1)}^{(2)} \times t_{idle}^{(2)}}{PowC_{ecoIdle2(1)}^{(2)} - PowC_{ecoIdle2(2)}^{(2)}}$$

$$= \frac{8.2 - 0.48 - 0 \times 25.5 + 0.06 \times 2.6}{0.06 - 0} = 131.27$$

(14)

The reference time $t_{c1}^{(3)}$, when it is possible to reduce energy consumption using eco-idle state 2(1) in production facility 3, and the reference time $t_{c2}^{(3)}$, when it is possible to reduce energy consumption using eco-idle state 2(2), can be calculated by Eq. (9) using the given input data to production facility 3 as follows.
When breakdown occurs in production facility 1 and production facility 2 has an idle time $t_{idle}^{(2)}$, by comparing idle time $t_{idle}^{(2)}$ with reference times $t_{c1}^{(2)}$ and $t_{c2}^{(2)}$, a suitable idle state was selected by our proposed idle-state selection algorithm. Similarly, when breakdown occurs in production facility 1 and production facility 3 has idle time $t_{idle}^{(3)}$, by comparing idle time $t_{idle}^{(3)}$ with reference times $t_{c1}^{(3)}$ and $t_{c2}^{(3)}$, a suitable idle state was selected by our proposed idle-state selection algorithm.

By using the first case study conditions discussed in Section 5.2, a case study was carried out. The results of the case study are shown in Table 3 and Table 4. Every time a breakdown occurred, the idle-state selection algorithm was performed. It was confirmed that the idle-state selection algorithm selected the most suitable idle state in response to the predicted idle time and the reference time. It was also confirmed that it is possible to reduce the energy consumption by applying the idle-state selection algorithm.

| The number of breakdown | $t_{c1}^{(2)}$ [s] | $t_{c2}^{(2)}$ [s] | $t_{idle}^{(2)}$ [s] | Select idle state | Energy consumption by Nomal idle [kWs] | Energy consumption by Ecoidle [kWs] | Reduced Energy consumption [kWs] |
|-------------------------|---------------------|---------------------|----------------------|-------------------|----------------------------------------|----------------------------------|-------------------------------|
| 1                       | 150.00              | Ecode2(2)           | 16.50                | 8.20              | 8.30                                   |
| 2                       | 149.19              | Ecode2(2)           | 16.41                | 8.20              | 8.21                                   |
| 3                       | 147.59              | Ecode2(2)           | 16.23                | 8.20              | 8.03                                   |
| 4                       | 157.68              | Ecode2(2)           | 17.34                | 8.20              | 9.14                                   |
| 5                       | 138.54              | Ecode2(2)           | 15.24                | 8.20              | 7.04                                   |
| 6                       | 149.54              | Ecode2(2)           | 16.45                | 8.20              | 8.25                                   |
| 7                       | 149.80              | Ecode2(2)           | 16.48                | 8.20              | 8.28                                   |
| 8                       | 143.09              | Ecode2(2)           | 15.74                | 8.20              | 7.54                                   |
| 9                       | 154.76              | Ecode2(2)           | 17.02                | 8.20              | 8.82                                   |
| 10                      | 149.93              | Ecode2(2)           | 16.49                | 8.20              | 8.29                                   |
| 11                      | 131.49              | Ecode2(2)           | 14.46                | 8.20              | 6.26                                   |
| 12                      | 149.22              | Ecode2(2)           | 16.41                | 8.20              | 8.21                                   |
| 13                      | 149.59              | Ecode2(2)           | 16.45                | 8.20              | 8.25                                   |
| 14                      | 130.70              | Ecode2(1)           | 14.38                | 8.17              | 6.21                                   |
| 15                      | 139.36              | Ecode2(2)           | 15.33                | 8.20              | 7.13                                   |
| 16                      | 159.98              | Ecode2(2)           | 17.60                | 8.20              | 9.40                                   |
| 17                      | 27.69               | Ecode2(1)           | 3.05                 | 1.99              | 1.06                                   |
| 18                      | 139.33              | Ecode2(2)           | 15.33                | 8.20              | 7.13                                   |
| 19                      | 149.40              | Ecode2(2)           | 16.43                | 8.20              | 8.23                                   |
| 20                      | 149.65              | Ecode2(2)           | 16.46                | 8.20              | 8.26                                   |
| 21                      | 149.87              | Ecode2(2)           | 16.49                | 8.20              | 8.29                                   |
| 22                      | 150.00              | Ecode2(2)           | 16.50                | 8.20              | 8.30                                   |

Table 3 Verification of the proposed idle-state selection algorithm in production facility 2

Table 4 Verification of the proposed idle-state selection algorithm in production facility 3
5.4 Verification of effectiveness of proposed operating method

The verification reported in this section was performed by focusing on and evaluating the productivity and energy consumption in two cases of breakdown in production facility 1: the case where production facility 2 and production facility 3 continued in the normal idle state, and the case in which they used the eco-idle state 2. MTBF(1) exhibited a Weibull distribution and MTTR(1) exhibited a normal distribution. The execution time was 10,000 s. Table 5 shows the execution results when MTTR(1) was varied. The results indicate that eco-idle state 2 can be used, and that using the eco-idle state can reduce energy consumption without impacting productivity. Therefore, the effectiveness of the energy-saving idle facility operating method was confirmed.

| The number of breakdown |  $t_{c1}^{(3)}$ [s] |  $t_{c2}^{(3)}$ [s] | Select idle state | Energy consumption by Normal idle [kWs] | Energy consumption by Ecoidle [kWs] | Reduced Energy consumption [kWs] |
|------------------------|---------------------|---------------------|------------------|----------------------------------------|----------------------------------|---------------------------------|
| 1                      | 150.00              | Ecoide2(2)          | 25.50            | 8.20                                   | 17.30                            |
| 2                      | 150.00              | Ecoide2(1)          | 22.10            | 8.12                                   | 13.98                            |
| 3                      | 147.59              | Ecoide2(2)          | 25.09            | 8.20                                   | 16.89                            |
| 4                      | 137.68              | Ecoide2(2)          | 23.41            | 8.20                                   | 15.21                            |
| 5                      | 128.54              | Ecoide2(1)          | 21.85            | 8.04                                   | 13.81                            |
| 6                      | 129.54              | Ecoide2(1)          | 22.02            | 8.10                                   | 13.93                            |
| 7                      | 129.80              | Ecoide2(1)          | 22.07            | 8.11                                   | 13.95                            |
| 8                      | 133.09              | Ecoide2(2)          | 22.63            | 8.20                                   | 14.43                            |
| 9                      | 144.76              | Ecoide2(2)          | 24.61            | 8.20                                   | 16.41                            |
| 10                     | 129.93              | Ecoide2(1)          | 22.09            | 8.12                                   | 13.97                            |
| 11                     | 131.49              | Ecoide2(2)          | 22.35            | 8.20                                   | 14.15                            |
| 12                     | 129.22              | Ecoide2(1)          | 21.97            | 8.08                                   | 13.89                            |
| 13                     | 149.59              | Ecoide2(2)          | 25.43            | 8.20                                   | 17.23                            |
| 14                     | 130.00              | Ecoide2(1)          | 22.10            | 8.12                                   | 13.98                            |
| 15                     | 150.00              | Ecoide2(2)          | 25.50            | 8.20                                   | 17.30                            |
| 16                     | 130.00              | Ecoide2(1)          | 22.10            | 8.12                                   | 13.98                            |
| 17                     | 170.00              | Ecoide2(2)          | 28.90            | 8.20                                   | 20.70                            |
| 18                     | 118.33              | Ecoide2(1)          | 20.12            | 7.42                                   | 12.69                            |
| 19                     | 142.40              | Ecoide2(2)          | 24.21            | 8.20                                   | 16.01                            |
| 20                     | 130.00              | Ecoide2(1)          | 22.10            | 8.12                                   | 13.98                            |
| 21                     | 129.87              | Ecoide2(1)          | 22.08            | 8.12                                   | 13.96                            |
| 22                     | 130.00              | Ecoide2(1)          | 22.10            | 8.12                                   | 13.98                            |

6. Conclusion
This paper proposes a method for operating energy-saving idle facilities on production lines considering breakdown. The method consists of an idle-time prediction algorithm and an idle-state selection algorithm. The method is applied to facilities in the later production process when a breakdown occurred. The idle-time prediction algorithm predicts an idle-time for each related facility by considering the restriction on the impact on productivity, which was presented as Condition 2 when a breakdown occurs in the production line. The idle-state selection algorithm selects a suitable idle-state for each related facility by considering the restriction on energy consumption, which was presented as Condition 1. When a breakdown occurs in the production line, the idle-time prediction algorithm is first run to calculate the prediction idle-time. The idle-state selection algorithm is then run to select a suitable idle-state using the prediction idle-time.

Case studies were carried out to confirm the effectiveness of our proposed method for a production line consisting of three industrial robots. We also simulated the case studies for comparison purposes. We confirmed that our proposed method can reduce energy consumption in an energy-saving idle production facility when a breakdown occurs in the production line.

As future research, we plan to propose an algorithm to predict idle time that considers work time variations.

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