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Formalising Specific-Energy Consumption under a Production-Management Form where Rush Orders Are Added in Time Slots

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Abstract. Factory-production activity is conducted based on production plans, which will unavoidably have to be revised due to changes in the production context. These changes should be considered when drafting production plans because of the frequent occurrence of rush orders with short deadlines. Since rush orders interrupt regular orders, we may consider that increased setup times, lower production quantities, and increased specific-energy consumption will accompany their addition.

We have previously supposed a management form that immediately adds rush orders to the production line, and proposed expressions for calculating the specific-energy consumption. Actual companies, looking to restrict increases in setup times, may implement management where rush orders are accumulated and added in time slots. However, in studies on formulae for calculating specific-energy consumption that consider rush orders, we see no consideration of management where the rush orders are added in time slots. Accordingly, this study presents a pre-emptive evaluation method using specific-energy consumption by formalising it for management where rush orders are added in time slots.

Keywords: Rush order, specific energy consumption, production management

1 Introduction

Efficient energy use is becoming a vital issue in all fields. One concern in industry is the reduction of energy consumed in production activities. Revisions to Japan's Energy Conservation Act stipulate the annual reduction of specific-energy consumption by at least 1% [1]. In addition, following COP21 (United Nations Climate Change Conference) in December 2015, greenhouse-gas reduction targets have been released, and it is now obligatory to establish measures for attaining these targets [2]. Accordingly, to achieve a more energy-efficient industry, energy-management techniques are needed to understand and analyse in detail how energy is consumed in production processes, and to use energy efficiently [3,4]. Thus, going forward, the industrial world is

simultaneously considering productivity and energy-consumption amounts, and is seeking both production planning using specific-energy consumption and pre-emptive evaluation methods [5–13].

Factory-production activity is based on production plans. These plans will be unavoidably revised because of the changes in production context that accompany uneven operation times, the arrival of rush orders, etc. When drafting production plans, changes in the production context should be considered. Rush orders with short deadlines should especially be considered because of their frequent occurrence [14,15].

In particular, rush orders interrupt regular orders. When a rush order is added to the production line, setup preparations are needed to set aside the regular order to attend to the rush-order production, and again to return to the regular order. This leads to increased setup times and delayed deliveries.

Trzyna et al. analysed production times for regular orders accompanied by added rush orders [16]. Zhu et al. proposed a mixed-integer linear programming method for minimising the total running time [17]. Other studies have proposed methods for restricting delayed-delivery and setup time increases using production-scheduling methods [18–22]. However, these studies focus on productivity when rush orders are added, and do not assess the energy-consumption amounts.

Meanwhile, the present authors have proposed pre-emptive evaluation methods that consider the energy-consumption amounts in addition to productivity [10–13]. In these pre-emptive evaluation studies, expressions for calculating the specific-energy consumption have been proposed. In particular, in one of our studies on calculating specific-energy consumption while considering rush orders, we supposed and formalised a management form that immediately adds rush orders to the production line [13].

We see that actual companies, looking to restrict increases in setup times, may implement management forms where rush orders are added in certain time slots; namely, rather than adding rush orders to the production line immediately, this management form will enter rush-order production after a certain period of time, once the lot size is larger [23]. However, studies on formulae for calculating specific-energy consumption that consider rush orders do not consider management where rush orders are added in time slots.

Accordingly, this study presents a pre-emptive evaluation method that formalises specific-energy consumption for management where rush orders are added in time slots. Specifically, we suppose a management form where rush orders are not added immediately to the production line; instead, time slots are set aside for building larger lot sizes. Under this supposition, we derive the total time for each production facility state, derive the total energy-consumption amount, and propose a formula for calculating the specific-energy consumption.

2 Formalising the Specific-Energy Consumption

2.1 Specific-energy consumption

In industry, ‘specific-energy consumption’ has become an indicator for assessing the production quantity versus the energy consumed during production [24]. In this study, we define specific-energy consumption SEC as follows.

$$SEC = \frac{E}{P}, \quad (1)$$

where:

SEC is the specific energy consumption [kWs/product],
 P is the total production quantity in the production line, and
 E is the total energy consumption [kWs].

2.2 Preconditions

This study presumes the following conditions.

- The state of a production facility (herein, ‘facility’) will either be running, setup, or idle.
- The facilities are linked in series.
- Rush orders appear according to a ‘generation interval’ $GIRO$ [seconds/unit]; the generation interval is fixed, irrespective of time.
- The total operation time T [seconds] is sufficient in duration.
- There are buffers prior to each facility, and the buffer capacity is unlimited.

2.3 Production form in this study

In this study, we suppose a management form where rush orders are added in time slots [23]. Specifically, this is where rush orders are added into rush-order-addition time slots, and their production interrupts the regular orders. Meanwhile, time slots not allocated to rush-order additions (‘no-addition slots’) are slots during which rush orders will be buffered (i.e. and not acted upon). Any rush orders that arrive during the no-addition slots will be collectively entered into production at the start of the next rush-order-addition time slot.

2.4 In-process inventory coefficient q^k

We define the in-process inventory coefficient as the value of facility k ’s production quantity P^k over the total production quantity P . Here, we can express the production quantity for each facility, using the total production quantity.

$$q^k = \frac{P^k}{P}, \quad (2)$$

where:

Superscript k is the ordinal number of the k -th facility in the production line, q^k is the coefficient of facility k 's in-process inventory, and P^k is the production quantity of facility k .

2.5 Total run-time T_r^k for facility k

Facility k 's production quantity P^k is the product of the facility's throughput p_r^k and running time T_r^k ; it can therefore be expressed as follows.

$$T_r^k = \frac{P^k}{p_r^k} = \frac{q^k P}{p_r^k}, \quad (3)$$

where:

Subscript r indicates that the facility is in its running state, T_r^k is the total running-state time of facility k [seconds], and p_r^k is the throughput in facility k [products/second].

2.6 Total setup time T_s^k for facility k

The setup time T_s^k is the product of facility k 's per-work setup time $SetUp^k$ and its production quantity P^k ; it can therefore be expressed as follows. $SetUp^k$ is detailed later in Section 2.8.

$$T_s^k = P^k \times SetUp^k = q^k P \times SetUp^k, \quad (4)$$

where:

Subscript s indicates that the facility is in its setup state, T_s^k is the total setup-state time of facility k [seconds], and $SetUp^k$ is the per-work setup time of facility k [seconds/product].

2.7 Total idle time T_i^k for facility k

The idle time is the total operating time T minus the running time and setup time; accordingly, it may be expressed as follows.

$$T_i^k = T - T_r^k - T_s^k, \quad (5)$$

where:

Subscript i indicates that the facility is in its idle state, and T_i^k is the total idle-state time of facility k [seconds].

2.8 Specific-energy consumption SEC^k for facility k

If we take the electricity consumption for each of the states of facility k to be e_r^k , e_s^k , and e_i^k , respectively, the energy consumption E^k in facility k is as follows.

$$E^k = e_r^k T_r^k + e_s^k T_s^k + e_i^k T_i^k, \quad (6)$$

where:

e_r^k is the electricity consumption per unit time in the running state of facility k ,
 e_s^k is the electricity consumption per unit time in the setup state of facility k , and
 e_i^k is the electricity consumption per unit time in the idle state of facility k .

The specific-energy consumption for facility k , SEC^k , is as follows.

$$\begin{aligned} SEC^k &= E^k / P \\ &= \left((e_r^k T_r^k + e_s^k T_s^k + e_i^k T_i^k) \right) / P \\ &= q^k \left(\frac{e_r^k}{p_r^k} + e_s^k SetUp^k \right) \\ &\quad + e_i^k \left(\frac{1}{p} - q^k \left(\frac{1}{p_r^k} + SetUp^k \right) \right), \end{aligned} \quad (7)$$

where:

p is the throughput for the entire production line [products/second].

Since throughput p is the minimum throughput value if facility k were to operate independently, i.e. for p_0^k , it may be expressed as follows.

$$p = \min\{p_0^1, p_0^2, \dots, p_0^k, \dots, p_0^n\} \quad (8)$$

Here, p_0^k , the throughput from facility k , if it were to operate independently, is the reciprocal value of the sum of the per-work setup time and the cycle time in facility k , as shown in Formula (9).

$$p_0^k = \left(\frac{1}{p_r^k} + SetUp^k \right)^{-1} \quad (9)$$

The total setup time for facility k , T_s^k , is the sum total of the setup time for the sections producing only rush orders, the setup time for sections producing both rush orders and regular orders, and the setup time for sections producing only regular orders. Accordingly, the per-work setup time $SetUp^k$ can be expressed as below in Formula (10).

$$\begin{aligned}
Setup^k &= \frac{T_s^k}{q^k p} \\
&= \frac{\lambda^k}{LS} + \frac{Rt \times (\mu^k + v^k)}{q^k p \times t_{no-addition}} \\
&\quad + \frac{1-Rt}{q^k p \times GIRO} \times \left(\mu^k + v^k - \frac{LS_{RO}}{LS} \lambda^k \right) \\
&\quad - \frac{Rt}{q^k p \times GIRO} \times \left(\frac{\mu^k + v^k}{t_{no-addition}} + \frac{LS_{RO} \times A^k}{p_r^k \times GIRO} \right) \times \left(\mu^k + v^k - \frac{LS_{RO}}{LS} \lambda^k \right) \\
&\quad - \frac{Rt \times LS_{RO}}{q^k p \times GIRO} \times A^k \times \frac{\lambda^k}{LS}
\end{aligned} \tag{10}$$

where:

λ^k is the setup time between regular orders [seconds],

μ^k is the setup time from a regular order to a rush order [seconds],

v^k is the setup time from a rush order to a regular order [seconds],

LS is the lot size of the regular order,

LS_{RO} is the lot size of the rush order,

d is the number of times that rush orders are collated (i.e. number of time slots), and

$t_{no-addition}$ is the length of time during which rush orders are not added [seconds/day].

In this study, we assume d is same value as the number of days in the schedule.

$$R_t = \frac{dt_{no-addition}}{T} \tag{11}$$

Here, when there are only rush-order-addition slots, i.e. when $dt_{no-addition} = 0$, then $R_t = 0$. This indicates that the company's management form is to add rush orders to the production line immediately.

We also define common term A^k as follows.

$$A^k = 1 + \frac{\mu^k}{t_{no-addition}} + \frac{LS_{RO}}{p_r^k \times GIRO} \tag{12}$$

Above, we proposed Formula (7) for calculating the specific-energy consumption, as well as Formulae (10), (11), and (12) for calculating Formula (7)'s setup time per-work $Setup^k$. We have therefore proposed a formula for calculating the specific-energy consumption under a management form where rush orders are added in time slots.

3 Conclusion

In this study, we presented a pre-emptive evaluation method for simultaneously assessing both the energy-consumption amount and productivity of a production facility by proposing a formula for specific-energy consumption that considers rush orders. In particular, we proposed a formula for calculating the specific-energy consumption that supposes a management form where rush orders are added in time slots.

In the future, we will verify the validity of our proposed formula by undertaking case studies.

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