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A production evaluation method for energy consumption rate considering rush orders

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Abstract
In a real production line, rush orders arise frequently, and they must be produced more quickly than standard production runs. Rush orders may require setup changes to process the order and to resume normal production once the order is completed. Increased setup times are qualitatively understood to decrease production efficiency and to increase the energy required to produce each manufactured unit., Previous studies have not investigated the effects of rush orders on plant productivity and energy consumption. A better understanding of these effects is needed to develop production evaluation methods that can achieve continued reduction in production energy use. In this paper, we proposed a production evaluation method that theoretically formulated the relation between lot size and energy consumption rate while considering rush orders in a production line. A formulation was developed to define this relationship. The formulation was verified using simulation results. We carried out the case studies for the validity of the proposed formulation.

Keywords : Rush orders, Manufacturing system simulation, Productivity, Energy efficiency, Lot size, Formulation, Energy consumption rate

1. Introduction

The national Act on the Rational Use of Energy, as amended April 2014, requires that the energy consumed by the manufacturing sector be reduced, on average, by at least 1% annually (Agency for Natural Resources and Energy, 2018). In addition, the 2015 Paris Agreement obligates all signatory countries to adopt measures to achieve specified reductions in greenhouse gas emissions (United Nations Framework Convention on Climate Change). To meet these emission reduction targets, one area of particular domestic focus has been to reduce industrial energy consumption. This effort includes initiatives to analyze energy use in the manufacturing sector, and to greatly increase manufacturing energy efficiency using improved energy management technologies (Ministry of Economy). Thus, a more complete understanding of how and where energy in used in the manufacturing sector is needed to help reduce greenhouse gas emissions.

Several simulation methods to evaluate manufacturing energy use and productivity can be found in the literature (Kim et al., 2003; Kim et al., 2005; McLean et al., 2005; Mitsuyuki et al., 2004; Williams et al., 1998; Hibino, 2014; Hibino et al., 2015; Kim et al., 2015). In general, industries must maintain sufficiently high productivity while limiting energy consumption. To balance these competing demands, plant managers must evaluate both manufacturing

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productivity and overall energy use throughout the design and implementation of manufacturing operations (Göschel et al., 2012). Several production evaluation tools to perform such evaluations have been proposed. Some of these methods determine the energy consumption per unit of production at the level of individual machines (Heilala et al., 2008; Ghandimi et al., 2014; Weinnert et al., 2014; Langer et al., 2014; Frigerio et al., 2014; Frigerio et al., 2015), while other methods have been applied at the production line level (Murayama et al., 2005; Sakuma et al., 2013; Hibino et al., 2014; Schultz et al., 2015; Li et al., 2012; Beier et al., 2017; Herrmann et al., 2011; Yamaguchi et al., 2016; Kobayashi et al., 2016). The latter methods evaluate energy consumption by considering aspects of production line design, such as machine processing time, the ability to hold work-in-progress between machines (i.e., the buffering capacity), and the overall number of production machines in the line. Alternatively, these methods may focus on ways to evaluate varying production lot sizes regarding energy consumption per unit of production throughput. Finally, some studies have considered the effect of the production lot size on manufacturing energy efficiency in order to propose approaches and simulation models (Sheehan et al., 2016; Marchi et al., 2019) These latter studies assumed baseline production lots and did not take the occurrence of rush orders into account.

In a real production line, rush orders arise frequently, and they must be produced more quickly than standard production runs. Rush orders may require setup changes to process the order and to resume normal production once the order is completed. Increased setup times are qualitatively understood to decrease production efficiency and to increase the energy required to produce each manufactured unit., Previous studies have not investigated the effects of rush orders on plant productivity and energy consumption. A better understanding of these effects is needed to develop production evaluation methods that can achieve continued reduction in production energy use.

In this paper, we propose a production evaluation method that theoretically formulates the relation between lot size and energy consumption rate while considering rush orders in a production line. A formulation is developed to define this relationship. The formulation is verified using simulation results. We carry out the case studies for the validity of the proposed formulation.

2. Proposed formulation

2.1. Assumptions

In this work, the following assumptions are made.

- The individual machines may be in only one operational state, either running, idle, or in setup state. Exception: The first machine does not enter an idle state.
- The production lot size is fixed.
- The production lot size of the rush order is fixed.
- Machine processing is serial (i.e., performed by a series of unit operations).
- There is no parts assembly process.
- The total operating time is sufficiently long to reach steady state conditions
- The buffer after each machine has enough buffer capacity.

2.2 Nomenclature

The notations used in this paper are listed as follows:

B^k: ratio of $MTBF^k$ to $MTTR^k$
E: total energy consumption in a line during operation time
E^k: energy consumption by machine k
e: energy consumption per time in a line
e_b^k: energy consumption per time during setup by machine k
e_i^k: energy consumption per time during idle by machine k
e_r^k: energy consumption per time during running by machine k
e_s^k: energy consumption per time during setup by machine k
$GIRO$: generation interval of rush orders
k: k'th machine in a line
LS: lot size

LS_{RO}: lot size of a rush order
$MTBF^k$: mean time between machine failures of machine k
$MTTR^k$: mean time to repair of machine k
n: number of machines in a line
P: total production volume of a line during operation time
P^k: total production volume by machine k
p: throughput of a line
p^k: throughput of machine k
p_0^k: throughput when machine k operates solo
p_r^k: production volume per unit time of machine k
q^k: works-in-process coefficient in machine k
$SetUp^k$: setup time per unit of a lot for machine k
T: total operating time in a line
T_b^k: total breakdown time of machine k
T_i^k: total idle time of machine k
T_r^k: total running time of machine k
T_s^k: total setup time of machine k
$T_{s\_1}^k$: total rush order setup time of machine k
$T_{s\_2}^k$: total setup time for routine production following a rush order of machine k
$T_{s\_3}^k$: total additional setup time required for normal orders of machine k
U: energy consumption rate of a line during operation time
U^k: energy consumption rate of machine k during operation time
γ^k: time required to setup a normal order after a rush order
λ^k: time required for a setup
μ^k: time required for a rush order setup

2.3. Energy consumption index

In the manufacturing industry, the "energy consumption per unit" index is used to evaluate how energy use and productivity are related (Agency for Natural Resources and Energy, (2017); Ministry of Economy, Trade and Industry, Energy innovation strategy, (2016). The energy consumption rate in a line during operation time *U,* is defined as

$$U = E/P \quad (1)$$

where E is the total energy consumption of the line during operation time, and *P* is the total production volume of the line during operation time.
The units of *U* are Joule/unit. If in Eq. 1 we divide the numerator and denominator by the total operation time *T*, the expression for *U* becomes

$$U = (E/T)/(P/T) = e/p \quad (2)$$

where *e* is the energy consumption per time (in units of Joule/second, or watt) and *p* is the throughput of the line, expressed as units produced/second. Figure 1 summarizes the relationships between the variables *U, E, P, T, e*, and *p*.

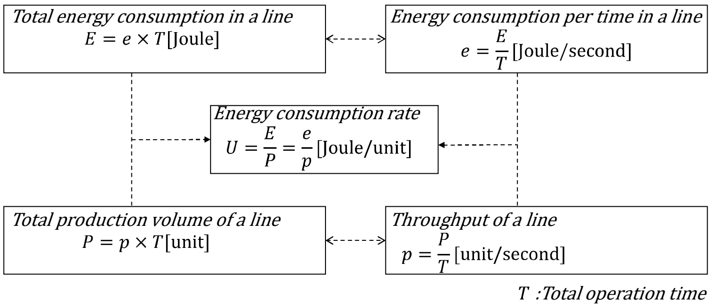

Fig.1 Relationship between variables.

2.4. Rush order definition

When rush orders arise at a production site, they must be processed more quickly than normal production operations. Rush orders that alternate with standard production runs add longer setup times, which result in production disruptions and increasing energy consumption per unit. For this study, we assume that rush orders occur at a frequency defined by the generation interval of the rush orders (GIRO), as shown in Fig. 2. Furthermore, for purposes of this study the rush order must meet the following two criteria.

- According to the GIRO, the production of regular orders must be interrupted.
- In each machine, rush orders must be prioritized over regular orders. Therefore, the GIRO must be the same for all the machines.

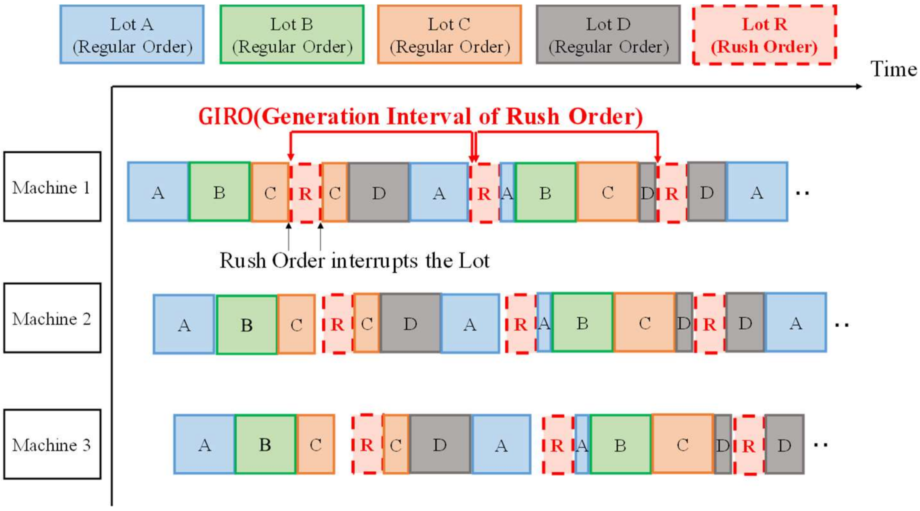

Fig.2 Temporal relationship of rush order and regular order.

2.5 Works-in-process coefficient q^k

A buffer is assumed to be present between each pair of machines. When the production capabilities of a machine exceed that of the next machine in the series, the buffer must hold works-in-process until they can be taken up by the next machine.

Let P^k represent the total production volume for machine k. Dividing P^k by P yields a works-in-process coefficient for each machine:

$$q^k = \frac{P^k}{P} \tag{3}$$

where q^k is the works-in-process coefficient for machine k. By inspection, P^k is seen to be the q^k multiplied by P.

2.6. Time occupied by machine k in each state

2.6.1. Total running time T_r^k

Since P^k is the product of the production volume per unit time of machine k p_r^k and the total running time of machine k T_r^k, T_r^k may be represented using P^k and p_r^k as

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$$T_r^k = \frac{P^k}{p_r^k} = \frac{q^k}{p_r^k} P \tag{4}$$

2.6.2. Total setup time T_s^k

T_s^k is the total setup time for machine k. T_s^k is obtained by multiplying $SetUp^k$, and P^k. $SetUp^k$ is setup time per unit of a lot in machine k.

$$T_s^k = P^k \times SetUp^k$$

$$= q^k P \times SetUp^k \tag{5}$$

T_s^k can be resolved into (i) $T_{s\_1}^k$ which is the total rush order setup time of machine k, (ii) $T_{s\_2}^k$ which is the total setup time for a routine order following a rush order of machine k, and (iii) $T_{s\_3}^k$ which is the total additional setup time required for normal orders of machine k. These components are detailed below.

(i) Total rush order setup time of machine k $T_{s\_1}^k$

In this study, we assume that T is much longer than the $GIRO$. Hence, the number of rush order setups at each machine k is given by T divided by the $GIRO$. If the time required to set up each rush order is μ^k, $T_{s\_1}^k$ can be expressed as

$$\begin{aligned} T_{s_1}^k &= \frac{T}{GIRO} \times \mu^k = q^k P \left(\frac{T\mu^k}{GIRO \times q^k P} \right) \\ &= q^k P \left(\frac{T/T \times \mu^k}{GIRO \times q^k \times P/T} \right) \\ &= q^k P \left(\frac{\mu^k}{GIRO \times q^k p} \right) \end{aligned} \tag{6}$$

(ii) Total setup time for routine production following a rush order of machine k $T_{s\_2}^k$

The number of setups at machine k under these circumstances is obtained by dividing T by the $GIRO$, which is similar to calculating the number of rush order setups as has been presented above. If the time required to set up a normal order immediately after a rush order is ν^k, then $T_{s\_2}^k$ is expressed as

$$\begin{aligned} T_{s_2}^k &= \frac{T}{GIRO} \times \nu^k = q^k P \left(\frac{T\nu^k}{GIRO \times q^k P} \right) \\ &= q^k P \left(\frac{T/T \times \nu^k}{GIRO \times q^k \times P/T} \right) \\ &= q^k P \left(\frac{\nu^k}{GIRO \times q^k p} \right) \end{aligned} \tag{7}$$

(iii) Total additional setup time required for normal orders of machine k $T_{s\_3}^k$

The number of setups for a routine production run at machine k is obtained by subtracting the rush order production from P^k and dividing the result by the lot size. If the time required to set up machine k for routine production is λ^k, the lot size is LS, and the lot size of a rush order is LS_{RO}, then $T_{s\_3}^k$ is expressed as

$$
\begin{aligned}
T_{s\_3}^{k} &= \frac{P^{k} - \frac{T}{GIRO} \times LS_{RO}}{LS} \times \lambda^{k} \\
&= q^{k}P\left(\frac{\lambda^{k}}{LS} - \frac{T\lambda^{k} \times LS_{RO}}{GIRO \times LS \times q^{k}P}\right) \\
&= q^{k}P\left(\frac{\lambda^{k}}{LS} - \frac{T/T \times \lambda^{k} \times LS_{RO}}{GIRO \times LS \times q^{k} \times P/T}\right) \\
&= q^{k}P\left(\frac{\lambda^{k}}{LS} - \frac{\lambda^{k} \times LS_{RO}}{GIRO \times LS \times q^{k}p}\right)
\end{aligned} \tag{8}
$$

where λ^k is the time required to set up machine k for a normal order, LS is the lot size for a normal order, and LS_{RO} is the lot size for a rush order.

Therefore, T_s^k can be expressed using Eqs.6-8:

$$
\begin{aligned}
T_s^k &= T_{s\_1}^k + T_{s\_2}^k + T_{s\_3}^k \\
&= q^kP\left(\frac{\mu^k}{GIRO \times q^kp} + \frac{\nu^k}{GIRO \times q^kp} + \frac{\lambda^k}{LS} - \frac{\lambda^k \times LS_{RO}}{GIRO \times LS \times q^kp}\right)
\end{aligned} \tag{9}
$$

$SetUp^k$ can be expressed using Eq. 5:

$$
\begin{aligned}
SetUp^k &= \frac{T_s^k}{q^kP} \\
&= \frac{\mu^k}{GIRO \times q^kp} + \frac{\nu^k}{GIRO \times q^kp} + \frac{\lambda^k}{LS} - \frac{\lambda^k \times LS_{RO}}{GIRO \times LS \times q^kp}
\end{aligned} \tag{10}
$$

2.6.3. Total breakdown time (T_b^k)

The present model also must account for machine down time. If the mean time between machine failures at machine k $MTBF^k$ and the mean time to repair at machine k $MTTR^k$ are used, then T_r^k divided by $MTBF^k$ gives the number of breakdowns. The breakdown time at machine k T_b^k, is the product of the number of breakdowns and $MTTR^k$, and it is expressed as

$$
\begin{aligned}
T_b^k &= \frac{T_r^k}{MTBF^k} \times MTTR^k = \frac{MTTR^k}{MTBF^k} \times \frac{P^k}{p_r^k} \\
&= B^k\frac{P^k}{p_r^k} = \frac{q^kB^k}{p_r^k}P
\end{aligned} \tag{11}
$$

Here, we define B^k as the ratio of $MTBF^k$ to $MTTR^k$ as follows:

$$
B^k = \frac{MTTR^k}{MTBF^k} \tag{12}
$$

B^k includes all the variables associated with machine breakdown that are considered in this study. The closer to zero that B^k is, the weaker is the impact of the breakdown.

2.6.4. Total idle time T_i^k

To obtain the idle time, we subtract the time spent by machine k in the run, setup, and breakdown states from the total operation time. The idle time T_i^k is thus

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$$T_i^k = T - T_r^k - T_s^k - T_b^k$$

$$= q^k P \times \left(\frac{T}{q^k P} - \left(\frac{1}{p_r^k} + SetUp^k + \frac{B^k}{p_r^k} \right) \right)$$

$$= P \times \left(\frac{1}{p} - q^k \left(\frac{1}{p_r^k} + SetUp^k + \frac{B^k}{p_r^k} \right) \right) \tag{13}$$

2.6.5. Energy consumption at machine k

If the energy consumed (energy used per unit time) for each state of machine k is expressed as e_r^k, e_s^k, e_b^k, and e_i^k, then total energy consumption at machine k E^k is

$$E^k = e_r^k T_r^k + e_s^k T_s^k + e_b^k T_b^k + e_i^k T_i^k \tag{14}$$

where e_r^k is the energy consumed by machine k in its run state, e_s^k is the energy consumed during machine k's setup, e_b^k is the energy consumed when in machine k is in breakdown, e_i^k is the energy consumed while machine k is idle, and n is the total number of machines in a production line.

2.7 Energy consumption per unit at machine k

The energy consumption per unit at machine k U^k is defined as

$$U^k = \frac{E^k}{P} \tag{15}$$

In terms of Eq. 1, this can be written as

$$U^k = \frac{1}{P} \left(e_r^k T_r^k + e_s^k T_s^k + e_b^k T_b^k + e_i^k T_i^k \right)$$

$$= q^k \left(\frac{e_r^k}{p_r^k} + e_s^k SetUp^k + \frac{e_b^k B^k}{p_r^k} \right) + e_i^k \left(\frac{1}{p} - q^k \left(\frac{1}{p_r^k} + SetUp^k + \frac{B^k}{p_r^k} \right) \right) \tag{16}$$

Equation 16 is the theoretical formulation that relates the lot size and energy consumption per unit, including terms for rush orders that may be processed by machine k.

U is the sum of all the individual machine contributions to energy consumptions over the total production line operation time. U is defined as

$$U = \sum_{k=1}^{n} U^k$$

$$= \sum_{k=1}^{n} q^k \left(\frac{e_r^k}{p_r^k} + e_s^k SetUp^k + \frac{e_b^k B^k}{p_r^k} \right) + e_i^k \left(\frac{1}{p} - q^k \left(\frac{1}{p_r^k} + SetUp^k + \frac{B^k}{p_r^k} \right) \right) \tag{17}$$

Thus, from Eqs.16 and 17, we obtain a formula that relates production lot size and energy consumption per unit, which takes into account the effects of adding rush orders to the production schedule.

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2.8. Calculating the works-in-process coefficient q^k and throughput p assuming infinite buffer capacity

Here, we define a method for calculating the works-in-process coefficient q^k and the throughput p assuming an infinite buffer capacity, using the results of a previous study (Hibino et al., 2019).

We redefine q^k from Eq. 4 using p^k and p as

$$q^k = \frac{P^k}{P} = \frac{P^k/T}{P/T} = \frac{p^k}{p} \tag{18}$$

Equation 18 relates q^k and p, such that if either variable is known, the other may be computed as long as the value of p^k is known.

For convenience, the term appearing in Eq. 16, $\left(\frac{1}{p_r^k} + SetUp^k + \frac{B^k}{p_r^k}\right)^{-1}$, may be defined as p_0^k, the throughput when machine k is operating alone. Thus

$$p_0^k = \left(\frac{1}{p_r^k} + SetUp^k + \frac{B^k}{p_r^k}\right)^{-1} \tag{19}$$

If we assume an infinite buffer capacity, each machine should be able to process continuously; at no time is production interrupted due to lack of capacity for works in process (i.e., blocking does not occur before or after machine k). Under these conditions, work is assumed to be continuously supplied to machine 1 (k=1), and machine 1's throughput p^1 is

$$p^1 = p_0^1 \tag{20}$$

If the throughput capability of a machine k'positioned prior to machine k ($k' < k$) is less than that of machine k (i.e., $p_0^{k'} < p_0^k$), then for some of the line operating time no work can be supplied to machine k; processing stops (starving), and p^k is then determined by $p_0^{k'}$ and not p_0^k . Conversely, when machine k' ($k' < k$) has higher throughput than machine k ($p_0^{k'} > p_0^k$), then p^k will be set by p_0^k. These considerations lead to the following relationships between the throughputs of machines k and $k-1$.

$$p_0^k > p^{k-1} \;\rightarrow\; p^k = p^{k-1} \tag{21}$$

$$p_0^k < p^{k-1} \;\rightarrow\; p^k = p_0^k \tag{22}$$

From Eqs.20–22, we can determine p^k for all k. It is clear that p^k is rate-limited by the machine with lowest throughput positioned before machine k, which can be expressed as

$$p^k = \min\{p_0^1, p_0^2,,, p_0^k\} \tag{23}$$

Similarly, overall production throughput p is rate-limited by the machine with the lowest productivity in the entire line. If the line consists of n machines, then p is given as

$$p = \min\{p_0^1, p_0^2,,, p_0^k,,, p_0^n\} \tag{24}$$

From Eq. 24, when the buffer capacity is assumed to be infinite, p may be determined using individual machine throughput information. Similarly, q^k may also be obtained from Eq. 18:

$$q^k = \frac{p^k}{p} = \frac{min\{p_0^1, p_0^2,,, p_0^k\}}{min\{p_0^1, p_0^2,,, p_0^k,,, p_0^n\}} \tag{25}$$

Thus, for the idealized case of infinite buffer capacity, we may derive p^k, p, and q^k solely from individual machine variables

3. Verification of the proposed formulation

3.1. Conditions of case studies

To investigate the validity of the proposed formulation, we employed numerical simulations of an electronics production line. Virtual data on electrical energy consumption are obtained from simulated production processes as variables data which are possible to be compared to the theoretical formulations presented in Section 2.

Figure 3 shows the design of modeled production line producing printed circuit boards. This simulated processing environment consists of three machines in series that correspond to different unit operations in the factory, specifically, a solder printing station ($k = 1$), a chip mounter ($k = 2$), and a solder reflow station ($k = 3$). A buffer to hold work-in-process is present prior to each machine input stage. The total simulated operating time was 144000 s (8 h × 5 d). Four types of regular orders and one rush order were considered in the simulation, with six lot sizes (30, 60, 90, 120, 240, and 360 pieces) for the regular orders, LS , and one lot size (1) for the rush order, LS_{RO}. Breakdowns occurred only at the chip mounter machine. Setup was required whenever a lot was changed.

In our case studies, there were three rush order patterns used to execute the simulation: (i) a pattern with $GIRO$ = 1500 s, a pattern with $GIRO$ = 3000 s, and a pattern in which no rush order arises, i.e., $GIRO$ = ∞[s]. The simulation was carried out 1000 times for each pattern. The values of p_r^k, λ^k, μ^k, and ν^k used in the simulation were generated using random numbers in based on a normal distribution. Values for $MTBF^k$ and $MTTR^k$were randomly generated based on an exponential distribution. Variables used in the simulations are listed in Table 1.

As shown in prior work (Hibino et al., 2014), this simulation method can evaluate both the productivity and the energy consumption of the modelled production line. The status of each production machine, and the transitions between machines, were simulated using Unified Modeling Language (UML). To derive the energy consumption rate and total production, the status and transitions of each modelled production machine were input to the WITNESS simulation package (Itochu Techno-Solutions Corporation), a discrete event-based simulation tool. To evaluate the model efficacy, the energy consumption per unit of production throughput was plotted per unit evaluation time.

Using the formulation proposed in Section 2 and the initial conditions given in Table 1, we performed simulations of the case studies described above. A key objective of these simulations was to investigate how rush orders affected the energy consumption per unit of production throughput.

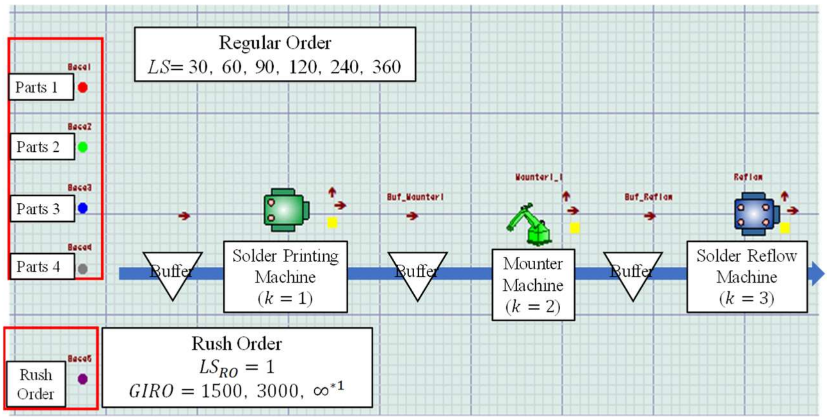

Fig.3 Simulation model of a printed circuit board line

Table 1 Input data in simulation

Input data	Machine		
	Solder Printing (k = 1)	Mounter (k = 2)	Solder Reflow (k = 3)
$1/p_r^k$	10±0.1	10±0.1	10±0.1
e_r^k	1.25	3.75	3.00
e_s^k	3.00	1.50	-
e_b^k	-	0.50	-
e_i^k	0.20	0.20	3.00
λ^k	120±10	120±10	-
μ^k	240±20	240±30	-
ν^k	240±20	240±30	-
$MTBF^k$	-	600(average)	-
$MTTR^k$	-	300(average)	-

3.2. Results of case studies

To obtain p^k and p, we calculate p_0^k. When each machine operates alone, p_0^k is calculated as

$$p_0^1 = \left(10 + \frac{120}{LS}\right)^{-1} \tag{26}$$

$$p_0^2 = \left(10 + \frac{120}{LS}\right)^{-1} \tag{27}$$

$$p_0^3 = \left(10 + \frac{0}{LS}\right)^{-1} \tag{28}$$

Accordingly, p^k and p are expressed as

$$p^1 = \min\{p_0^1\} = \left(10 + \frac{120}{LS}\right)^{-1} \tag{29}$$

$$p^2 = \min\{p_0^1, p_0^2\} = \left(10 + \frac{120}{LS}\right)^{-1} \tag{30}$$

$$p^3 = \min\{p_0^1, p_0^2, p_0^3\} = \left(10 + \frac{120}{LS}\right)^{-1} \tag{31}$$

$$p = \min\{p_0^1, p_0^2, p_0^3\} = \left(10 + \frac{120}{LS}\right)^{-1} \tag{32}$$

U^k was derived for each of the three patterns described above. For the first, second, and third patterns, the results of U^k and U are listed in Tables 2, 3, and 4, respectively.

Finally, we examined the effect of lot size on the predicted energy consumption by each machine k. Table 5 presents the results of U^1 for six lot sizes and three rush order patterns. These values of U^1 are plotted in Fig. 4 against the inverse of lot size for the three case studies, and are represented by the symbols (red: GIRO = 1500 s, green: GIRO = 3000 s, black: no rush order occurs and GIRO = ∞). The figure also gives the calculated U^1 values using the proposed formulations for the three patterns in the case of the solder printing machine; these data are represented by the dashed lines in the figures. The standard deviations of simulation data are represented by error bars.

Tables 6, 7, and 8 present the results of U^2, U^3 and U respectively. The data for these cases are plotted in Figures 5, 6, and 7 respectively, using symbols for the simulation results and dashed lines for the calculated values.

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Table 2 U when $GIRO = 1500$

	U
Solder printing machine U^1	$\left(\frac{12.5+\frac{360}{LS}}{10.0+\frac{120}{LS}}+\frac{1440LS-360}{2520LS+120}\right)\times\left(15.0+\frac{120}{LS}\right)$
Mounter machine U^2	$40.0+\frac{180}{LS}+\frac{720LS-180}{2520LS+120}\left(15.0+\frac{120}{LS}\right)$
Solder reflow machine U^3	$\frac{9000LS}{25200LS+120}\left(15.0+\frac{120}{LS}\right)$
The entire production line U	$40.0+\frac{180}{LS}+\left(\frac{12.5+\frac{360}{LS}}{10.0+\frac{120}{LS}}+\frac{11160LS-540}{2520LS+120}\right)\times\left(15.0+\frac{120}{LS}\right)$

Table 3 U when $GIRO = 3000$

	U
Solder printing machine U^1	$\left(\frac{12.5+\frac{360}{LS}}{10.0+\frac{120}{LS}}+\frac{1440LS-360}{1020LS+120}\right)\times\left(15.0+\frac{120}{LS}\right)$
Mounter machine U^2	$40.0+\frac{180}{LS}+\frac{720LS-180}{1020LS+120}\left(15.0+\frac{120}{LS}\right)$
Solder reflow machine U^3	$\frac{4500LS}{1020LS+120}\left(15.0+\frac{120}{LS}\right)$
The entire production line U	$40.0+\frac{180}{LS}+\left(\frac{12.5+\frac{360}{LS}}{10.0+\frac{120}{LS}}+\frac{6660LS-540}{1020LS+120}\right)\times\left(15.0+\frac{120}{LS}\right)$

Table 4 U when $GIRO \to \infty$

	U
Solder printing machine U^1	$12.5+\frac{360}{LS}$
Mounter machine U^2	$37.5+\frac{180}{LS}$
Solder reflow machine U^3	$30.0+\frac{360}{LS}$
The entire production line U	$80.0+\frac{900}{LS}$

Table 5 Results of U^1 for six lot sizes and three rush order patterns.

GIRO	*LS*	U^1 [kWs/product] theoretical data calculated by proposed formulation	U^1 [kWs/product] virtual real data obtained from simulation	
			average	standard deviation
1500	30	59.746	59.283	2.992
1500	60	50.062	49.646	2.634
1500	90	46.744	46.212	2.655
1500	120	45.065	44.514	2.426
1500	240	42.516	42.216	2.316
1500	360	41.657	41.409	2.268
3000	30	44.000	43.586	2.019
3000	60	35.874	35.535	1.715
3000	90	33.082	32.709	1.659
3000	120	31.666	31.344	1.598
3000	240	29.513	29.219	1.495
3000	360	28.787	28.476	1.464
–	30	33.250	33.256	1.404
–	60	26.208	26.178	1.145
–	90	23.779	23.743	1.074
–	120	22.545	22.515	1.039
–	240	20.667	20.638	0.962
–	360	20.032	20.003	0.946

Note :- rush order does not occur

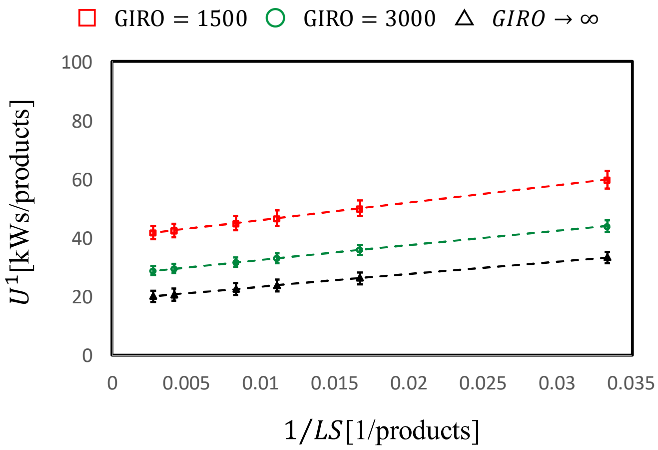

Fig.4 Simulation results and our proposed formula for $1/LS$ dependence of U^1

Table 6 Results of U^2 for six lot sizes and three rush order patterns

GIRO	*LS*	U^2 [kWs/ product] theoretical data calculated by proposed formulation	U^2 [kWs/product] virtual real data obtained from simulation	
			average	standard deviation
1500	30	59.248	58.981	1.153
1500	60	54.927	54.700	1.097
1500	90	53.482	53.207	1.104
1500	120	52.760	52.471	1.040
1500	240	51.674	51.500	1.026
1500	360	51.312	51.156	0.986
3000	30	51.375	51.186	0.683
3000	60	47.833	47.683	0.644
3000	90	46.651	46.485	0.639
3000	120	46.060	45.916	0.638
3000	240	45.173	45.072	0.630
3000	360	44.877	44.752	0.607
–	30	46.000	46.010	0.401
–	60	43.000	43.002	0.372
–	90	42.000	42.006	0.369
–	120	41.500	41.504	0.370
–	240	40.750	40.753	0.361
–	360	40.500	40.502	0.362

Note :- rush order does not occur

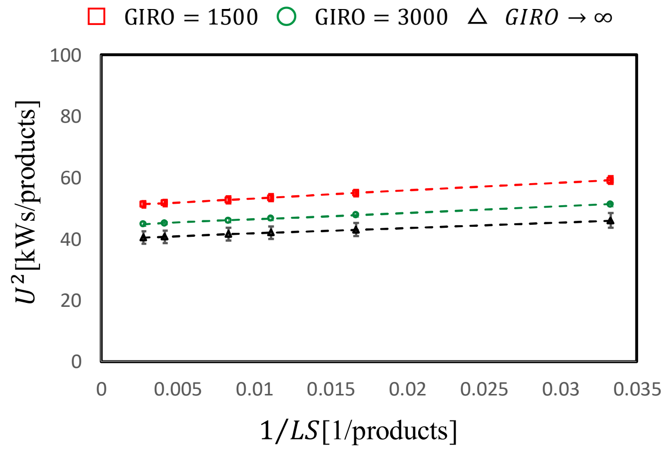

Fig. 5 Simulation results and our proposed formula for $1/LS$ dependence of U^2

Table 7 Results of U^3 for six lot sizes and three rush order patterns

GIRO	*LS*	U^3 [kWs/ product] theoretical data calculated by	U^3 [kWs/product] virtual real data obtained from simulation: average	standard deviation
1500	30	83.496	83.033	4.201
1500	60	74.853	74.450	3.965
1500	90	71.965	71.376	4.092
1500	120	70.519	69.857	3.811
1500	240	68.349	68.006	3.738
1500	360	67.625	67.389	3.683
3000	30	67.750	67.340	3.114
3000	60	60.666	60.341	2.911
3000	90	58.302	57.913	2.935
3000	120	57.120	56.800	2.897
3000	240	55.346	55.118	2.823
3000	360	54.755	54.398	2.795
-	30	57.000	57.046	2.411
-	60	51.000	50.966	2.229
-	90	49.000	48.984	2.218
-	120	48.000	47.970	2.216
-	240	46.500	46.459	2.170
-	360	46.000	45.954	2.175

Note :- rush order does not occur

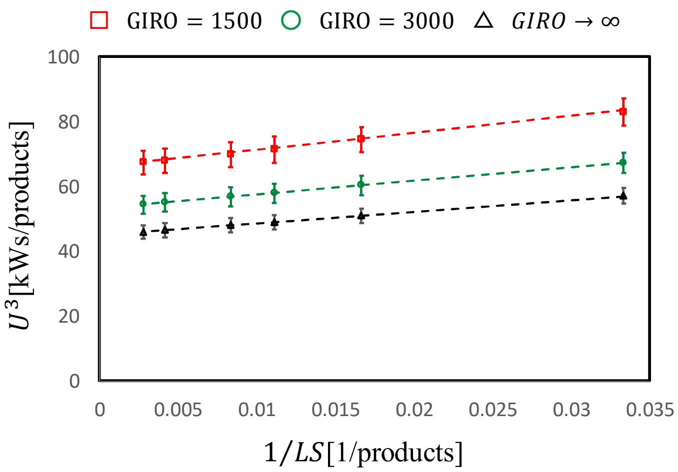

Fig.6 Simulation results and our proposed formula for $1/LS$ dependence of U^3.

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Table 8 Results of U for six lot sizes and three rush order patterns

GIRO	*LS*	U [kWs/product] theoretical data calculated by	U [kWs/product] virtual real data obtained from simulation	
			average	standard deviation
1500	30	202.490	201.297	8.336
1500	60	176.524	178.796	7.689
1500	90	170.512	170.795	7.844
1500	120	168.343	166.842	7.269
1500	240	162.539	161.722	7.073
1500	360	160.595	159.954	6.931
3000	30	163.124	162.112	5.812
3000	60	144.374	143.559	5.267
3000	90	138.036	137.107	5.229
3000	120	134.846	134.060	5.130
3000	240	130.032	129.408	4.946
3000	360	128.419	127.626	4.863
-	30	136.250	136.312	4.215
-	60	120.208	120.146	3.744
-	90	114.779	114.734	3.660
-	120	112.045	111.989	3.624
-	240	107.917	107.850	3.492
-	360	106.532	106.459	3.482

Note :- rush order does not occur

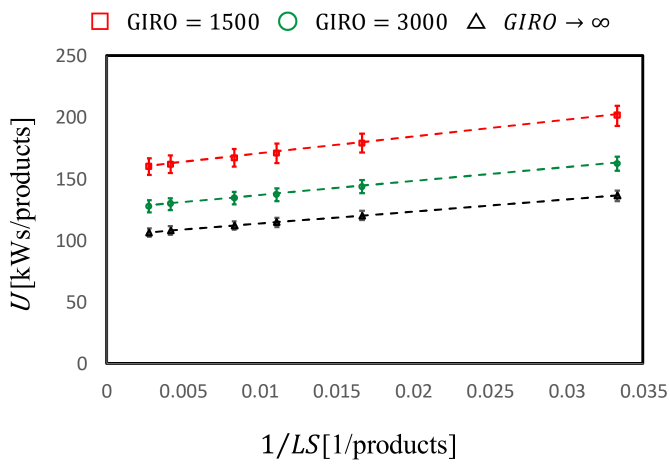

Fig. 7 Simulation results and our proposed formula for $1/LS$ dependence of U.

Figures 4–7 show that the data obtained using our proposed formulation are within the uncertainty range of the simulation data. Our proposed formulation (Eqs.16 and 17) was validated by these results. Furthermore, Figs. 4–7 show that when rush orders occurred frequently, the energy consumption per unit of production throughput increased. This is because demands to perform rush orders increase setup time and cause production stagnation, resulting in decreases in total production volume.

4. Conclusion

In this paper, we proposed a production evaluation method that theoretically formulates the relation between lot size and energy consumption rate while considering rush orders in a production line. A formulation was developed to define this relationship. The formulation was verified using simulation results. We carried out the case studies for the validity of the proposed formulation by using simulations of a printed circuit boards production line. We used virtual data obtained from a developed simulation. We confirmed that there was a match between the virtual data obtained from simulation and the data calculated by using the proposed formulation. Future work will include applying this formulation to lot-size optimization. In the future, this formulation will be applied to lot-size optimization.

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