

# A Method for Evaluating Energy Consumption Rates in Production with Rush Orders

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## Abstract

Quicker turnaround times than usual are required for rush orders in a genuine manufacturing line. It may be necessary to make adjustments to the setup in order to execute rush orders and then return to regular production after they are finished. It is generally believed that longer setup periods lead to less efficient manufacturing and higher energy consumption for each created unit. There has been a lack of research on how rush orders affect energy usage and industrial productivity. For the purpose of creating production assessment techniques that may accomplish the ongoing decrease of production energy usage, a deeper comprehension of these consequences is required. This study presents a technique for evaluating output that takes into account rush orders in a manufacturing line and conceptually formulates the link between lot size and energy consumption rate. This connection was defined by the development of a formulation. We used the results of the simulations to confirm the formulation. To ensure the suggested formulation was viable, we conducted the case studies.

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

## 1. Introduction

Reducing energy consumption by the manufacturing sector by at least 1% yearly is mandated by the national Act on the Rational Use of Energy, as modified in April 2014 (Agency for Natural Resources and Energy, 2018). Furthermore, all nations that have signed the Paris Agreement of 2015 are obliged to take action in order to reduce their emissions of greenhouse gases to certain levels (UN Framework Convention on Climate Change). Reducing industrial energy use has been an area of significant domestic attention in order to accomplish these emission reduction objectives. As part of this endeavor, the Ministry of Economy is launching programs to study industrial energy use and implement new energy management technologies to significantly boost manufacturing energy efficiency. To that end, a better knowledge of the industrial sector's energy consumption patterns is necessary for the purpose of lowering emissions of greenhouse gases. For the purpose of assessing energy consumption and productivity in manufacturing, several simulation

approaches have been published in the literature (e.g., Kim et al., 2003; McLean et al., 2005; Mitsuyuki et al., 2004; Williams et al., 1998; Hibino, 2014; Hibino et al., 2015; Kim et al., 2015). In general, it is essential that companies decrease their energy usage while maintaining a sufficiently high production. Plant managers need to consider manufacturing productivity and total energy usage when designing and implementing manufacturing activities in order to balance these opposing needs (Göschel et al., 2012). A number of techniques for evaluating production have been suggested for this purpose. Heilala et al. (2008), Ghandimi et al. (2014), Weinnert et al. (2014), Langer et al. (2014), Frigerio et al. (2014), Schultz et al. (2015), Li et al. (2012), Beier et al. (2017), Herrmann et al. (2011), Yamaguchi et al. (2016), and Kobayashi et al. (2016) are some of the methods that have been applied at the level of the production line. The second set of criteria assesses power use by looking at the architecture of the production line as a whole, taking into account factors

like processing time, buffering capacity, and the total number of equipment. On the other hand, these techniques could center on approaches to measure energy usage per unit of production throughput in relation to different production lot sizes. Lastly, Sheehan et al. (2016) and Marchi et al. (2019) are two research that have suggested methods and simulation models to improve manufacturing energy efficiency by taking production lot size into account. The subsequent studies failed to account for the possibility of rush orders since they relied on baseline manufacturing quantities.

Quicker turnaround times than usual are required for rush orders in a genuine manufacturing line. It may be necessary to make adjustments to the setup in order to execute rush orders and then return to regular production

after they are finished. It is generally believed that longer setup periods lead to less efficient manufacturing and higher energy consumption for each created unit. There has been a lack of research on how rush orders affect energy usage and industrial productivity. For the purpose of creating production assessment techniques that may accomplish the ongoing decrease of production energy usage, a deeper comprehension of these consequences is required.

This study presents a technique for evaluating output that takes into account rush orders in a manufacturing line and conceptually formulates the link between lot size and energy consumption rate. To clarify this connection, a formula is constructed. The results of the simulation are used to validate the formulation. To ensure the suggested formulation is valid, we conduct the case studies.

## 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

$e_s^k$ : 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

$LS_{R0}$ : 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  
 $\gamma^k$ : time required to setup a normal order after a rush order  
 $\lambda^k$ : time required for a setup  
 $\mu^k$ : 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

$$U = E/P \tag{1}$$

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

$$U = (E/T)/(P/T) = e/p \tag{2}$$

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  $p$ .

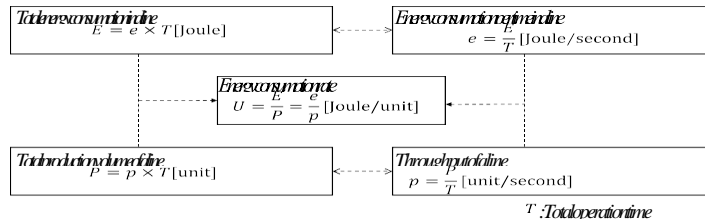


Fig.1 Relationship between variables.

### 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.

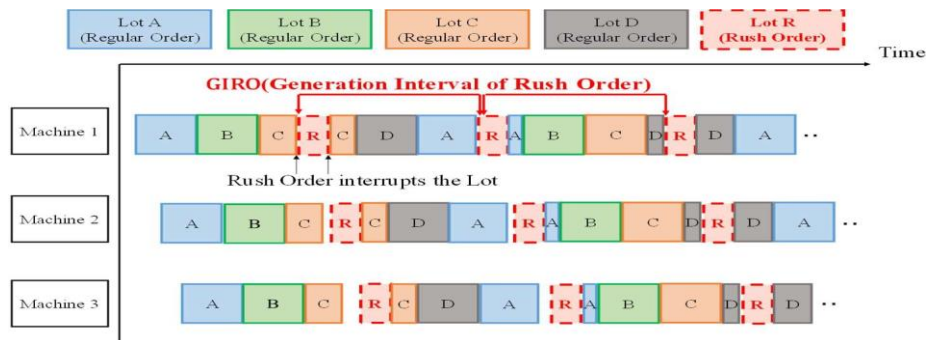


Fig.2 Temporal relationship of rush order and regular order.

### 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

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

**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  $k$ .

$$\begin{aligned} T_s^k &= P^k \times SetUp^k \\ &= q^k P \times SetUp^k \end{aligned} \tag{5}$$

$T_s^k$  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  $\mu^k$ ,  $T_{s_1}^k$  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  $\nu^k$ , 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  $\lambda^k$ , the lot size is  $LS$ , and the lot size of a rush order is  $LS_{R0}$ , then  $T_{s_3}^k$  is expressed as

$$\begin{aligned}
 T_{s,3}^k &= \frac{P^k - \frac{T}{GIRO} \times LS}{LS} \times \lambda^k \\
 &= q^k P \left( \frac{\lambda^k}{LS} - \frac{T \lambda^k \times LS_{R0}}{GIRO \times LS \times q^k P} \right) \\
 &= q^k P \left( \frac{\lambda^k}{LS} - \frac{T/T \times \lambda^k \times LS_{R0}}{GIRO \times LS \times q^k \times P/T} \right) \\
 &= q^k P \left( \frac{\lambda^k}{LS} - \frac{\lambda^k \times LS_{R0}}{GIRO \times LS \times q^k P} \right)
 \end{aligned} \tag{8}$$

where  $\lambda^k$  is the time required to set up machine  $k$  for a normal order,  $LS$  is the lot size for a normal order, and  $LS_{R0}$  is the lot size for a rush order.

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

$$\begin{aligned}
 T_s^k &= T_{s,1}^k + T_{s,2}^k + T_{s,3}^k \\
 &= q^k P \left( \frac{\mu^k}{GIRO \times q^k p^k} + \frac{\nu^k}{GIRO \times q^k p^k} + \frac{\lambda^k}{LS} - \frac{\lambda^k \times LS_{R0}}{GIRO \times LS \times q^k p^k} \right)
 \end{aligned} \tag{9}$$

Setup  $p^k$  can be expressed using Eq. 5:

$$\begin{aligned}
 Setup^k &= \frac{T_s^k}{q^k P} \\
 &= \frac{\mu^k}{GIRO \times q^k p^k} + \frac{\nu^k}{GIRO \times q^k p^k} + \frac{\lambda^k}{LS} - \frac{\lambda^k \times LS_{R0}}{GIRO \times LS \times q^k p^k}
 \end{aligned} \tag{10}$$

### 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  $T^k$  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

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

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

$$\begin{aligned}
 T_i^k &= T - T_r^k - T_s^k - T_b^k \\
 &= q^k P \times \left( \frac{T}{q^k P} - \left( \frac{1}{p_r^k} + SetUp^k + \frac{B^k}{p_r^k} \right) \right) \\
 &= P \times \left( \frac{1}{p} - q^k \left( \frac{1}{p_r^k} + SetUp^k + \frac{B^k}{p_r^k} \right) \right)
 \end{aligned} \tag{13}$$

### 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

$$\begin{aligned}
 U^k &= \frac{1}{P} (e_r^k T_r^k + e_s^k T_s^k + e_b^k T_b^k + e_i^k T_i^k) \\
 &= q^k \left( \frac{e_r^k}{p_r^k} + e_s^k SetUp^k + \frac{e_b^k B^k}{p_r^k} \right) + e_i^k \left( \frac{1}{p} - q^k \left( \frac{1}{p_r^k} + SetUp^k + \frac{B^k}{p_r^k} \right) \right)
 \end{aligned} \tag{16}$$

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

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

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.

### 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

$$q^k = \frac{p^k}{p} = \frac{p^k \cancel{p}}{\cancel{p} p} = \frac{p^k}{p} \quad (18)$$

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,  $(\frac{1}{p_r^k} + SetUp^k + \frac{B^k}{p_r^k})^{-1}$ , may be defined as  $p_0^k$ , the throughput when machine  $k$  is operating alone. Thus

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

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

$$p^1 = p_0^1 \quad (20)$$

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  $k-1$ .

$$p_0^k > p_0^{k-1} \rightarrow p^k = p_0^{k-1} \quad (21)$$

$$p_0^k < p_0^{k-1} \rightarrow p^k = p_0^k \quad (22)$$

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

$$p^k = \min\{p_0^1, p_0^2, \dots, p_0^k\} \quad (23)$$

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

$$p = \min\{p_0^1, p_0^2, \dots, p_0^k, \dots, p_0^n\} \quad (24)$$

From Eq. 24, when the buffer capacity is assumed to be infinite,  $p$  may be determined using individual machine

### 3. Verification of the proposed formulation

#### 3.1. Conditions of case studies

In order to test the suggested formulation, we used computer models of a manufacturing line for electronic components. In order to compare the theoretical formulations given in Section 2 with virtual data on electrical energy usage, this section uses variables collected from simulated industrial processes.

The schematic for the modelled assembly line that makes PCBs is shown in Figure 3. One solder printing station ( $k = 1$ ), one chip mounter ( $k = 2$ ), and one solder reflow station ( $k = 3$ ) make up this virtual processing environment, which represents various unit processes in the factory. There is a buffer to store WIP before each machine input step. With 8 hours divided by 5 days, the total amount of time the system was simulated to operate was 144000 seconds. The simulation took into account four kinds of regular orders and one kind of rush order, with six different lot sizes for the regular orders (OS) and one lot size for the rush order (LSRO): 30, 60, 90, 120, 240, and 360 pieces, respectively. It was only the chip mounter machine that broke down. Each time there was a significant change, setup was necessary. Three different rush order patterns were used to run the simulations in our case studies: i) a design where  $GJRO =$

There are three possible patterns: one with  $GJRO = 3000$  s, another in which no rush order occurs, and finally,  $GJRO = \infty$ [s]. Each pattern was simulated a thousand times. The simulation employed random integers based on a normal distribution to produce the values of  $k_k$ ,  $\mu_k$ ,  $\sigma_k$ , and  $\nu_k$ . Random values were created for  $MTBF_k$  and  $MTTR_k$ .

founded on the principle of exponential growth. See Table 1 for a complete list of the variables used in the simulations.

This simulation approach can assess the energy consumption and productivity of the modeled manufacturing line, as shown in previous research (Hibino et al., 2014). Use of Unified Modeling

Language (UML) allowed for the simulation of machine status and machine transitions. A discrete event-based simulation program called WITNESS (Itochu Techno-Solutions Corporation) was used to calculate the overall production and energy consumption rate. This tool took as input the state and transitions of each simulated manufacturing machine. The model's effectiveness was assessed by plotting the energy consumption per unit of manufacturing throughput per unit of assessment time.

We simulated the aforementioned case studies using the formulation suggested in Section 2 and the starting circumstances provided in Table 1. Examining the impact of rush orders on energy usage per unit of manufacturing throughput was a primary goal of these simulations.

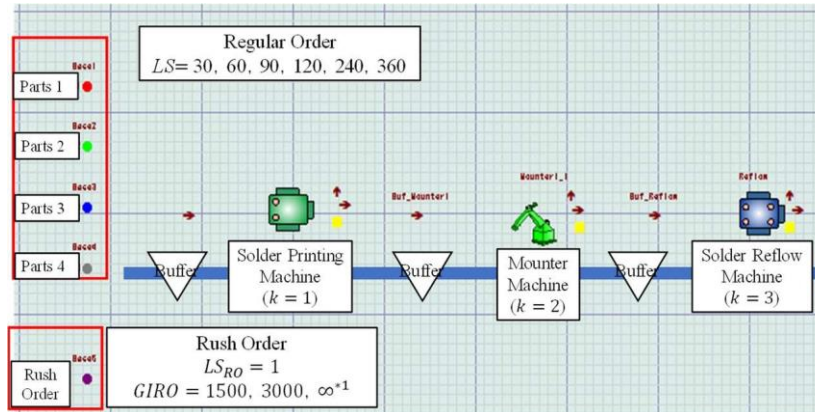


Fig.3 Simulation model of a printed circuit board line

Table 1 Input data in simulation

Input data	Machine		
	Solder Printing (k = 1)	Mounter (k = 2)	Solder Reflow (k = 3)
$\lambda^k$	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
$\lambda^k$	120±10	120±10	-
$\mu^k$	240±20	240±30	-
$\nu^k$	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  $e_{p_0}^k$ . When each machine operates alone,  $p_0^k$  is calculated as

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

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

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

Accordingly,  $p^k$  and  $p$  are expressed as

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

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

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

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

$U^k$  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  $U^l$  for six lot sizes and three rush order patterns. These values of  $U^l$  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 =  $\infty$ ). The figure also gives the calculated  $U^l$  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.

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  $GIRO \rightarrow \infty$

$U$	
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

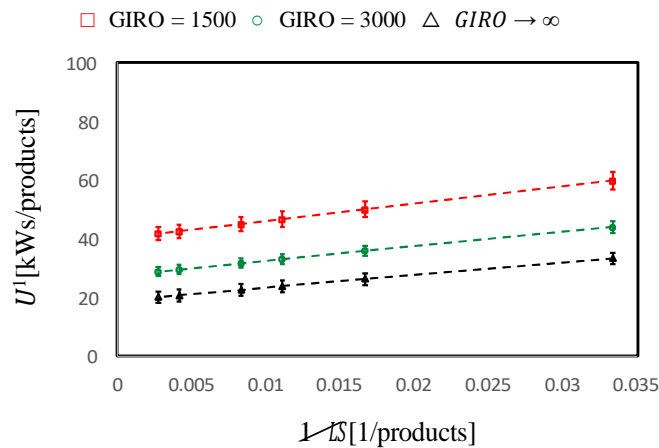


Fig.4 Simulation results and our proposed formula for  $1/LS$  dependence of  $U^1$   
Table 6 Results of  $U^2$  for six lot sizes and three rush order patterns

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

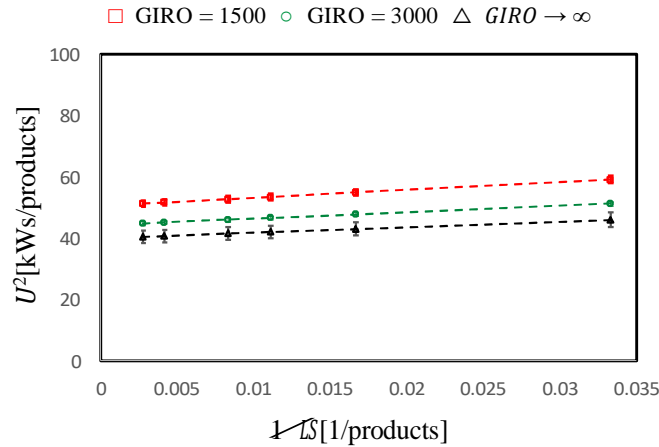


Fig. 5 Simulation results and our proposed formula for  $1/LS$  dependence of  $U^2$

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

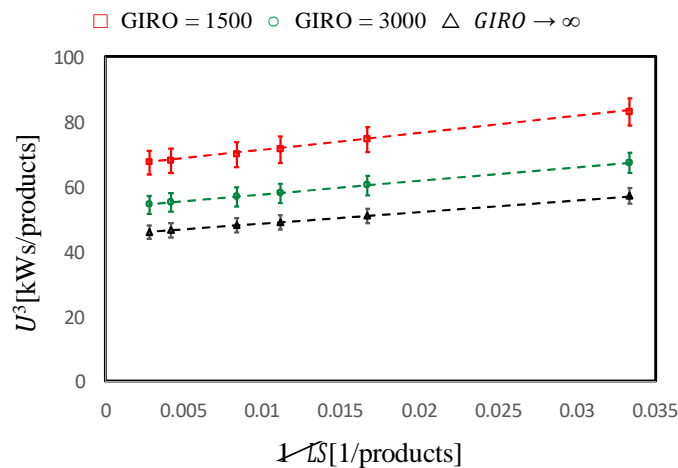


Fig.6 Simulation results and our proposed formula for  $1/LS$  dependence of  $U^3$ .

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

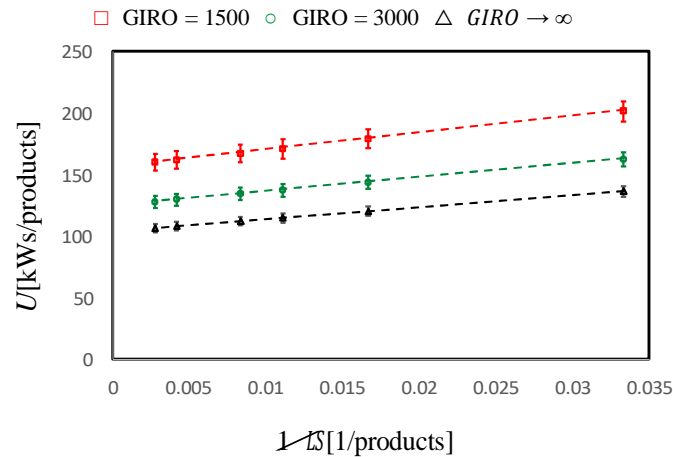


Fig. 7 Simulation results and our proposed formula for  $1/LS$  dependence of  $U$ .

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



This study presents a technique for evaluating output that takes into account rush orders in a manufacturing line and conceptually formulates the link between lot size and energy consumption rate. This connection was defined by the development of a formulation. We used the results of the simulations to confirm the formulation. Through the use of simulations of a printed circuit boards manufacturing line, we conducted the case studies to validate the suggested formulation. We relied on data generated by a computer simulation. We verified that the virtual data acquired via simulation matched the data computed using the suggested formulation. Using this formulation for lot-size optimization is something we want to tackle in the future. This formula will be used for optimizing lot sizes in the future.

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