

Formulation of Relationship Between Productivity and Energy Consumption in Manufacturing System

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Abstract. In the industrial world, since the amount of energy to consume is very large, it is required to manage and reduce energy consumption while maintaining a high productivity. In order to approach the theoretical realization the production conditions that affect a productivity or energy consumption, we investigate the formulation of the relationship between energy consumption and production throughput, and verify it by using numerical simulation.

Keywords: Sustainable manufacturing system · Simulation · Productivity · Energy consumption · Mathematical formulation

1 Introduction

Recently, in various fields, reduction of energy consumption has been an important issue. [1–3] In particular, in the world of industrial, since the amount of energy to consume is very large, management of energy consumed is greatly required. It is necessary to reduce energy consumption while maintaining a high productivity. [3]

In the previous study, a simulation environment for sustainable manufacturing systems considering the productivity and energy consumption have been established, and an implementation for the simulation environment has been proposed [5, 6]. The state transition model for facility has been proposed and expressed by using a Unified Modelling Language (UML) model. A case study for a middle-scale semiconductor manufacturing line was carried out by using constructed simulation system. It has been found that the energy consumption per production throughput increase with decreasing lot size and, become a constant value with increasing lot size. This result has indicated that the number of times of setting-up increase with decreasing lot size. Since the energy is required for setting-up, energy consumption per production throughput becomes large.

However, in the manufacturing system, the theoretical realization the production conditions, such as lot size, failure rate, and so on that affect a productivity and energy consumption is not understood clearly. In this paper, therefore, we propose the formulation of the relationship between energy consumption and production throughput, and verify it by using numerical simulation system constructed in our previous report.

2 Formalizing the Energy Consumption and Throughput

2.1 Energy Consumption Per Throughput, U

One of the most important indicators in the evaluation of productivity and energy consumption of manufacturing systems is energy consumption per production throughput (U). U is defined as

$$U = \frac{E}{P}. \quad (1)$$

Here, U is energy consumption per production throughput and the unit is [J/product], E is energy consumption and the unit is [J], P is production throughput and the unit is [product]. An electric energy consumption per second is also defined electric power consumption e [W].

A line with n equipment which have m kinds of facility state is assumed in this study. An facility in line always belongs to some status during operating time (T), so the operating time of k -th facility (T^k) equal to T . The relation between T and the total of operating time of x state in k -th facility (T_x^k) is given by

$$T = T^k = \sum_x^m T_x^k. \quad (2)$$

The total electric energy consumption is given by

$$E = \sum_k^n E^k = \sum_k^n \sum_x^m e_x^k T_x^k, \quad (3)$$

where E^k is the total electric energy consumption of k -th facility, and e_x^k is electric power consumption of x state in k -th facility. Therefore, the energy consumption per production throughput can be written as

$$U = \sum_k^n U^k = \sum_k^n \frac{E^k}{P} = \sum_k^n \sum_x^m \frac{e_x^k T_x^k}{P}. \quad (4)$$

Here U^k is the energy consumption per production throughput in k -th facility. By using Eq. (4), U can be calculated by e_x^k , T_x^k and P . Figure 1 shows the summary of the relationship between E , P , T , U , e , and p .

2.2 Coefficient of Work in Process, q^k

In a line, a buffer is generally set up between facility. When some work exist in a buffer, production throughput in line and production throughput of each facility (P^k) is not same, that is,

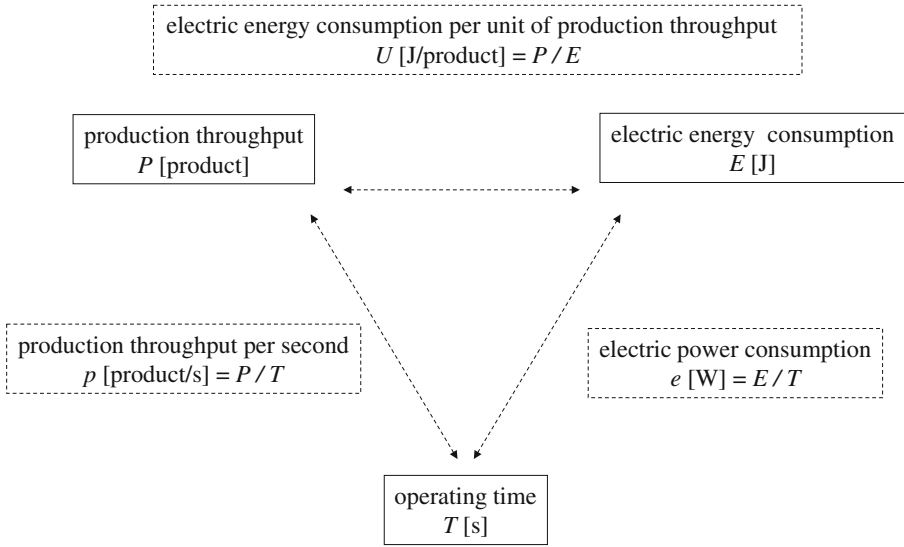


Fig. 1. Relationship between E, P, T, U, e , and p .

$$P^k > P. \tag{5}$$

Here, coefficient of work in process (q^k) can be defined as

$$q^k \equiv \frac{P^k}{P}. \tag{6}$$

In the case of $P^k = P$, q^k equal 1. Usually, q^k increases as previous process, i.e.,

$$q^1 \geq \dots \geq q^{k-1} \geq q^k \geq q^{k+1} \geq \dots \geq q^n = 1. \tag{7}$$

2.3 Operating Time of State of x in K -th Facility, T_x^k

In this study, a state of running, setting-up, and idling will be discussed. The state of running, setting-up, and idling are described by $x = r, s$, and i , respectively.

In a running state in k -th facility, the production throughput per second (p_r^k) is the reciprocal of the cycle time (c_r^k). Production throughput in k -th facility (P_r^k) is calculated by multiplying T_r^k by $c_r^k = 1/p_r^k$. When the q_r^k is taken into account, T_r^k is obtained as

$$T_r^k = q_r^k \frac{P}{p_r^k}. \tag{8}$$

P divided by lot size (LS) is frequency of setting-up in k -th facility. The q_r^k and λ^k which is defined by the time required for a once setting-up are taken into consideration, T_s^k obtained as

$$T_s^k = q^k \frac{P}{LS} \lambda^k. \quad (9)$$

It seems to be reasonable that T_s^k decrease with increasing LS.

Since a facility in line always belongs to some status during operation, so the operating time of k -th facility (T^k) equal to the sum of T_r^k , T_s^k and the operating time of idling state in k -th facility (T_i^k);

$$T^k = T_r^k + T_s^k + T_i^k. \quad (10)$$

As $T^k = T$,

$$\begin{aligned} T_i^k &= T - T_r^k - T_s^k \\ &= T - \frac{q^k}{p_r^k} P - \frac{q^k \lambda^k}{LS} P \\ &= P \left(\frac{T}{P} - \frac{q^k}{p_r^k} - \frac{q^k \lambda^k}{LS} \right) \\ &= P \left(\frac{1}{p} - \frac{q^k}{p_r^k} - \frac{q^k \lambda^k}{LS} \right). \end{aligned} \quad (11)$$

Equations (9) (10) and (11) are substituted into Eq. (4), U^k is calculated as

$$\begin{aligned} U^k &= \frac{1}{P} (e_r^k T_r^k + e_s^k T_s^k + e_i^k T_i^k) \\ &= \frac{1}{P} \left(e_r^k \frac{q^k P}{p_r^k} + e_s^k \frac{q^k P}{p_r^k} + e_i^k P \left(\frac{1}{p} - \frac{q^k}{p_r^k} - \frac{q^k \lambda^k}{LS} \right) \right) \\ &= q^k \left(\frac{e_r^k}{p_r^k} + \frac{e_s^k \lambda^k}{LS} \right) + e_i^k \left(\frac{1}{p} - q^k \left(\frac{1}{p_r^k} + \frac{\lambda^k}{LS} \right) \right). \end{aligned} \quad (12)$$

3 Simulation

The simulation system of manufacturing has already been developed using the Witness software which is a commercial discrete event simulator (Lanner). In this paper, a middle-scale semiconductor manufacturing line which consists of three facilities, the solder printing facility, the IC mounting facility (mounter facility), and the solder reflow facility is simulated. The three facilities were modelled in Witness using our proposed state transition model. The printing facility, the mounter facility, and the reflow facility

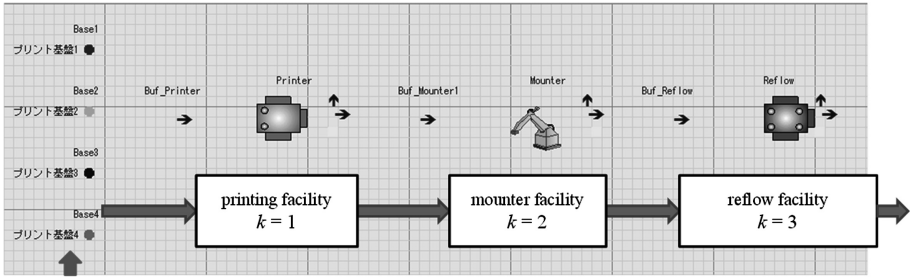


Fig. 2. Simulation model of the middle-scale semiconductor manufacturing line.

Table 1. Input data in simulation.

input data	Facility				
	printing $k=1$	mounter $k=2$	reflow $k=3$		
$1/p_r^k$	[s]	10	10	10	
e_r^k	[kW]	1.25	3.75	0.8*	*0.4 (rising), 1.2 (falling)
λ^k	[s]	120	120	-	
e_s^k	[kW]	3	1.5	-	
e_t^k	[kW]	0.2	0.2	0.8*	*0.4 (rising), 1.2 (falling)

are numbered to $k = 1$ to 3 , respectively. Figure 2 show a simulation model of the middle-scale semiconductor manufacturing line. Table 1 shows the simulation input data. In contrast to simulation, input electric power consumption of running state and idle state in reflow facility (e_r^k and e_t^k) different between rising and falling of temperature in furnace, the average value is used in formulation as below. There are four types of lot sizes as 15, 30, 90, 360. The size of buffer between each facilities is big enough. The simulation period in this simulation is 40 h (5 day \times 8 h).

4 Results and Discussion

Figure 3 show the relationship between electric energy consumption per production throughput and inverse of lot size. The opened circle in Fig. 3 indicate the simulation results of the electric energy consumption per production throughput of printing facility (U^1). Note that the linear correlation exists between the U^1 and inverse of lot size. In this

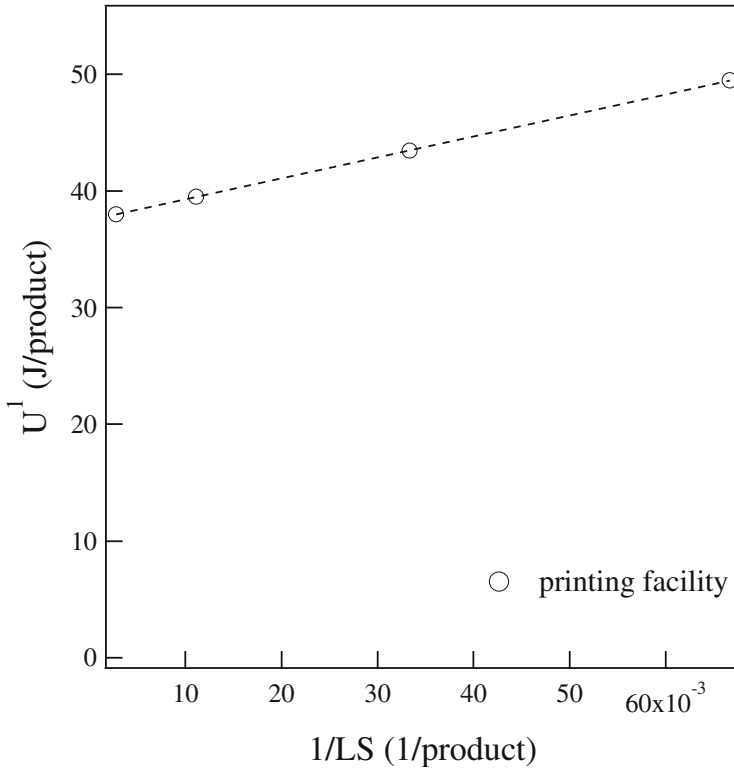


Fig. 3. *LS* dependence of U^1 . Simulation results (open circle) and formulation results (dashed line)

simulation, since the cycle time of facilities is almost same, and the failure of facilities is not considered, the q^k can be considered as 1. Furthermore, the operating time of idling state in the printing facility is zero, because the size of buffer between each facilities is big enough. Taking these assumption into account, U^1 and p are given by

$$U^1 = \left(\frac{e_r^1}{p_r^1} + \frac{e_s^1 \lambda^1}{LS} \right), \tag{13}$$

$$\frac{1}{p} = \left(\frac{1}{p_r^1} + \frac{\lambda^1}{LS} \right), \tag{14}$$

respectively. The dashed line in Fig. 3 denotes calculated Eq. (13). The simulation results and formulation results are in reasonably good agreement. The opened circle and dashed line in Fig. 4 indicate the simulation results of production throughput and formulation results (Eq. (14)), respectively. Note that the results agrees well. We can obtain a relation between U^1 and p as

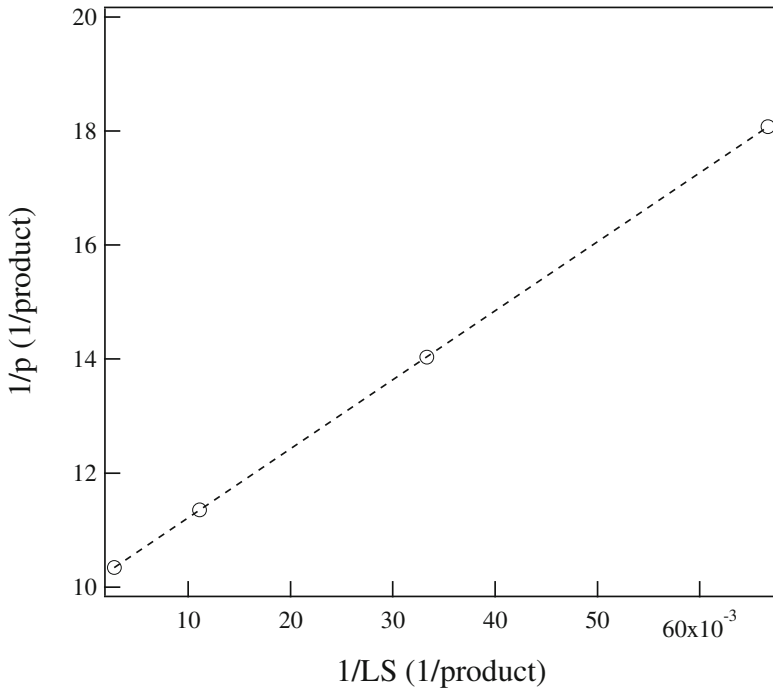


Fig. 4. *LS* dependence of $1/p$. Simulation results (open circle) and formulation results (dashed line)

$$U^1 = \frac{e_s^1}{p} + \frac{e_r^1}{p_r^1} - \frac{e_s^1}{p_r^1} \tag{15}$$

from Eqs. (13) and (14). We can understand that energy consumption per production throughput decreases with an increase productivity.

5 Conclusion

In order to approach the theoretical realization the production conditions that affect a productivity or energy consumption, we investigated the formulation of the relationship between energy consumption and production throughput, and verified it by using numerical simulation. The simulation results and formulation results are in reasonably good agreement. The relation between lot size and energy consumption per production throughput, production throughput were understood. It is clearly shown that energy consumption per production throughput decreases with an increase productivity.

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