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Abstract. Managing energy consumption of manufacturing systems has become immediately necessary because electricity consumption has become severely restricted in Japan after the Tohoku earthquake on March 11, 2011. Moreover the energy conservation law has been revised in Japan in April, 2010. This law requires management of the energy consumption and reinforces the regulation to reduce more than one percentage of the previous year's energy consumption per unit of production throughput. Manufacturing system simulations to evaluate productivity have often been used when designing and improving sustainable manufacturing systems. However, manufacturing system simulations to evaluate energy consumption per unit of production throughput and the amount of energy consumption have not been proposed. The purpose of our research is to establish a simulation environment for sustainable manufacturing systems considering the productivity and energy consumption. We also propose an implementation for the simulation environment. A case study for a middle-scale semiconductor manufacturing line is carried out to confirm the efficiency of our proposed simulation environment.

Keywords: Sustainable Manufacturing System, Simulation, Productivity, Energy Consumption, Facility State Transition.

1 Introduction

Social interest in environmental evaluation, which originates the awareness of global warming and the finite nature of natural resources, has been rising. In industries, finding and evaluating environmental monitoring items in manufacturing systems has become equally important. For example, after the Tohoku earthquake on March 11, 2011, managing energy consumption of the manufacturing systems has become immediately necessary because electricity consumption has become severely restricted in Japan [1]. Moreover the energy conservation law has been revised in Japan in April, 2010. This law requires management of energy consumption and reinforces the regulation to reduce more than one percentage of the previous year's energy consumption per unit of production throughput [2].

On the other hand, industries have also paid attention to increase their productivity[3]. Recent manufacturing systems consist of various sub-systems to increase productivity, and each sub-system is complexly related to other sub-systems [3].

To cope with these demands, there are great expectations for designing and improving sustainable manufacturing systems with considering both the environmental and productivity aspects [4]. There are six main requirements to design and improve the environmental aspect of the sustainable manufacturing systems [4]:

1) Establish the prior evaluation of the environmental aspect in a sustainable manufacturing system design and implementation stage.
2) Define the environmental evaluation items.
3) Establish the measuring scale of prior environmental evaluation.
4) Define the data items that information systems must deal with.
5) Establish management methods that take the environmental aspect into account.
6) Enact an international standard.

In this paper, we focuses on requirement 1) of the above list. Especially we deal with the energy consumption as the environmental aspect. Manufacturing system simulation is often used to evaluate productivity when designing and improving manufacturing systems [3]. Methods have been proposed to evaluate energy consumption using simulation concerning a single machining [5] and a single automated guided vehicle [6]. However, concerning sustainable manufacturing systems including a factory and a line, the necessary items and requirements to concurrently evaluate productivity and energy consumption are not clear. It is difficult to evaluate energy consumption using simulation when the sustainable manufacturing systems are designed and improved.

The purpose of our research is to establish a simulation environment for sustainable manufacturing systems considering the productivity and energy consumption. We propose an implementation for the simulation environment. A case study for a middle-scale semiconductor manufacturing line is carried out to confirm the efficiency of our proposed simulation environment.

2 Proposed Simulation Environment for Productivity and Energy Consumption

We define a formula for the energy consumption per unit of production throughput is as follows:

$$A = B / C \quad (1)$$

where:

A is energy consumption per unit of production throughput,
B is the amount of energy consumption and
C is the production throughput.

To evaluate the throughput using a suitable minimum time unit during the design stage, manufacturing system simulation is often used [3]. Manufacturing system simulations support creation of suitable manufacturing system conditions by means of simulation models. One of the main purposes of the manufacturing system simulation is to evaluate productivity while analyzing material flow and information flow. A simulation is executed paying attention to particular events of interest which are considered to occur instantaneously. The stagnation phenomena for the material flow in manufacturing systems are often evaluated by simulation.

On the other hand, the total energy consumption in a manufacturing system is calculated by summing the amount of energy consumption for each facility. The energy consumption for each facility is calculated by adding the amount of energy consumption in each facility state (e.g. producing state, idle state, stopping state, etc.). For example, in a machining facility that is one of the most fundamental facilities in a manufacturing system, the method of measuring the amount of electricity consumption is defined by the standards organization in Japan [7]. The amount of electricity consumption for the machining facility is measured by a procedure that follows a starting state, idle state, producing state, and stopping state sequence. Therefore, with the machining facility, if the facility states and their state transitions and allotted times are clear, the electricity consumption is estimated by the sum of the electricity consumption in response to the periods for each facility state.

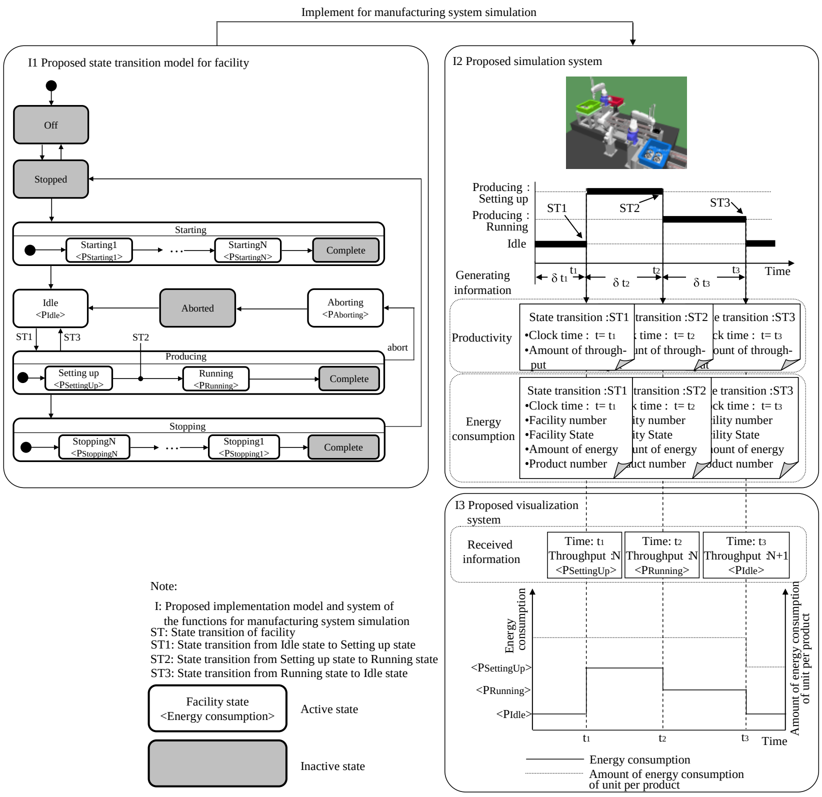


Fig. 1 Our proposed simulation environment for productivity and energy

To evaluate the energy consumption per unit of production throughput and the amount of energy consumption when designing and improving the manufacturing systems, we propose the following requirements:

Requirement 1(R1): Clarifying facility states, their facility state transitions and relationships between each facility state and total energy consumption.

Requirement 2(R2): Simulating the state transitions along a time progression and generating information of the state transitions with a timestamp.

Requirement 3(R3): Generating information of productivity and energy consumption along a time progression.

Requirement 4(R4): Numerically evaluating and visualizing the amount of the energy consumption per unit of production throughput in the minimum time unit.

We propose a simulation environment for productivity and energy consumption. The simulation environment consists of a state transition model for a facility (I1), a simulation system (I2) and a visualization system (I3).

Figure 1 shows an outline of the proposed state transition model for facility (I1), the proposed simulation system (I2) and the proposed visualization system (I3) using the simulation environment for productivity and energy consumption.

2.1 Proposed State Transition Model for Facility

The state transition model for facility (I1) has a necessary function 1 (F1) to realize R1. F1 consists of two sub-functions that define the facility states and their state transition (F1.1), and define relationships between the facility state and energy consumption (F1.2).

First, the definition of the facility states and their state transition (F1.1) is explained. On the basis of our analysis of typical facilities in manufacturing systems, facility states and their state transition are analysed and summarized. Typical facilities are machining facilities, industrial robot facilities and solder reflow facilities. Solder reflow facilities are important facilities in semiconductor manufacturing systems. Using the results of our analysis, we propose the definition of the facility states and their state transition (F1.1). Sub-function F1.1 consists of three characteristics. First, the facility states in our proposed model are divided into five categories: the starting state, the idle state, the producing state, the stopping state and the aborting state. Second, with the starting state, the producing state and the stopping state, there are usually sub-states in each facility state. Each facility state in the proposed model can be divided into sub-states. Third, with the state transition in our proposed model, a facility state usually changes to the next facility state when an activity in the facility state is completed. However, the idle state cannot change to the producing state until an event occurs, such as when production parts arrive. The stopping state and the aborting state also change from the producing state only when a facility stoppage occurs. The proposed state transition model for facility (I1) is expressed using a Unified Modelling Language (UML) model.

Furthermore, the definition of relationships between the facility state and energy consumption (F1.2) is explained. A calculation formula for the energy consumption E_{sn} of the facility state S_n is as follows:

$$E_{Sn} = \int_{t_{n-1}}^{t_n} P_{Sn}(t)dt \qquad (2)$$

where

t_n is the finishing time of facility state S_n

t_{n-1} is a stated time for facility state S_n

$P_{sn}(t)$ is the energy consumption in facility state Sn at time t.

Using $P_{sn}(t)$, it is possible to calculate the energy consumption of the facility state. However, it is difficult to define $P_{sn}(t)$ for all facilities in a manufacturing system. Therefore, in this study, we use an average P_{sn} from t_{n-1} to t_n.

2.2 Proposed Simulation System

The proposed simulation system (I2) has a necessary function 2 (F2) to realize R2 and R3. F2 consists of three sub-functions that simulate the state transition along a time progression (F2.1), generate productivity information including the throughput with a timestamp in the minimum time unit (F2.2) and generate information of the energy consumption with a timestamp in the minimum time unit (F2.3).

First, the simulation of the state transition along a time progression (F2.1) is explained. The simulation supports suitable manufacturing system conditions by means of simulation models. The simulation model consists of facility simulation models that include the proposed state transition model for the facility. The simulation is executed paying attention to particular events of interest which are considered to occur instantaneously. Each event marks a change of the facility state in the simulation. Between consecutive events, the simulation directly jumps in time from one event to the next. Then facility state information with a timestamp and event information for each state transition that occurs are generated by the simulation.

Second, the generation of productivity information including the throughput with a timestamp in the minimum time unit (F2.2) is explained. The production throughput information with a timestamp along a time progression is generated. Then the production throughput information at the place we define, such as a facility level and/or line level, is obtained.

Third, the generation of information of the energy consumption with a timestamp in the minimum time unit (F2.3) is explained. The energy consumption with a timestamp along a time progression is generated. Then, the energy consumption at the place we define, such as a facility level, is obtained.

2.3 Proposed Visualization System

The proposed visualization system (I3) has a necessary function 3 (F3) to realize R4. F3 consists of two sub-functions that are used to receive information for the productivity and the energy consumption, to calculate the energy consumption per unit of the production throughput in the minimum time unit (F3.1) and to visualize the energy consumption per unit of production throughput (F3.2).

First, the receipt of information for the productivity and the energy consumption and the calculation of the energy consumption per unit of the production throughput in the minimum time unit (F3.1) are explained. The generated information is a simulation clock, facility numbers, the amount of production throughput, the amount of energy consumption and so on. The generated information with a time stamp is sorted and stored in ascending order. The energy consumption per unit of production throughput for each facility is calculated using the generated information and the formula while considering the minimum time unit.

Second, the created energy consumption per unit of production throughput for each facility is visualized using the spraying figures feature.

3. Implementation of Proposed Simulation Environment for Productivity and Energy Consumption

In this chapter, the implementation for the proposed simulation system (I2) and the proposed visualization system (I3) is proposed.

First, implementation for the proposed simulation system (I2) is described. The proposed simulation system has three sub-functions used to satisfy requirement 2 (R2). The function to simulate the state transition along a time progression (F2.1) is implemented in Witness that is a commercial discrete event simulator. Witness provides a simulation engine function and a simulation programming support function. The simulation engine function controls the simulation along a time progression while paying attention to particular events of interest that occur instantaneously. The simulation programming support function helps engineers to develop extension functions using the Visual Basic (VB) programming language. The facility simulation models that include the proposed state transition model for facility (I1) are implemented in Visual Basic.

Second, implementation for the proposed visualization system (I3) is described. The receipt of information for production throughput and energy consumption and the calculation of the energy consumption per unit of the production throughput in the minimum time unit (F3.1) are implemented in Excel that is a commercial spread sheet. We developed a macro program in Excel. The generated information with a time stamp from the simulation is saved in a text file using the CSV format. The macro program in Excel makes it possible to read the CSV file. The generated information with a time stamp is sorted and stored in ascending order in Excel. The energy consumption per unit of production throughput for each facility is calculated using the generated information.

4. Case study

The purpose of this case is to evaluate the application of the simulation environment to a middle-scale semiconductor manufacturing line consisting of three facilities, the solder printing facility, the IC mounting facility (mounter facility), and the solder reflow facility. The three facilities were modelled in Witness using our proposed state transition model. Figure 2 shows a simulation model of the middle-scale semiconductor manufacturing line and simulation input data. There are four types of products. There are three types of lot sizes as 60, 120, 240. The simulation period in this case study is 40 hours over five days.

Using the above conditions, the simulation was performed. The simulation generated facility state information with a timestamp as well as event information for the state transitions with a timestamp including clock time, facility number, amount of electricity consumption, type of product and product number. The simulation also generated the production throughput with a time stamp.

Using the generated information from the simulation, the dynamic changes in the energy consumption per unit of production throughput along the time axis were visualized in the visualization system. The energy consumption per unit of production throughput was numerically expressed along the time line.

Figure 3 shows transitions of the energy consumption per unit of production throughput in the solder reflow facility. The energy consumption per unit of production throughput was getting smaller when the lot size was getting larger in Figure 3.

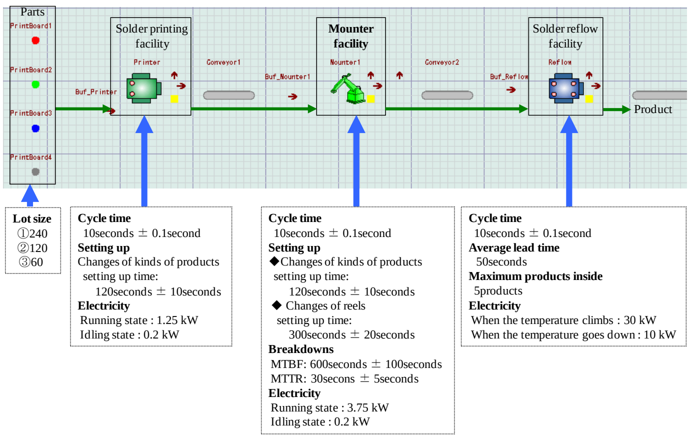


Fig.2 Simulation model of case study

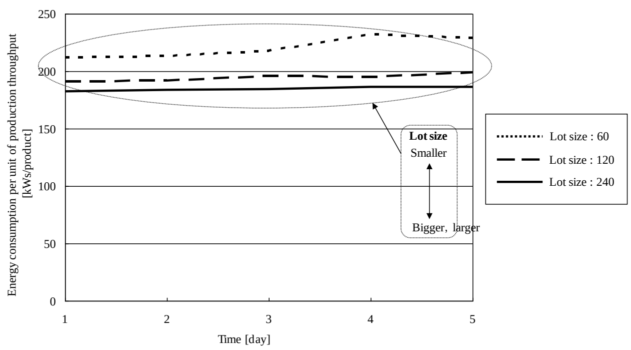
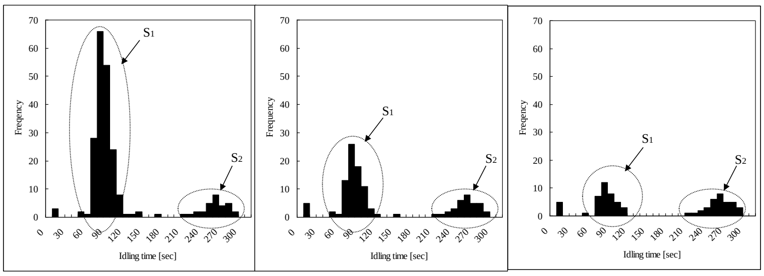


Fig.3 Energy consumption per unit of production throughput in solder reflow facility

To analyze their factors, we focused on the amount of no-load running periods in the solder reflow facility. Figure 4 shows histograms of the no-load running periods in the solder reflow facility. S1 in Figure 4 means influence of setting up changes of kinds of products in the mounter facility. S2 in Figure 4 means influence of setting up changes of the reels in the mounter facility. The frequency of S1 was becoming increasing by decreasing the lot size. The more frequency of S1 increased, the longer no-load running periods became because the stagnation phenomena of the material flow occurred. The stagnation phenomena decreased the throughput. Thus the amount of waste energy in the solder reflow facility increased.

It was confirmed the efficiency of the proposed simulation environment through the case study.



a. Lot size : 60 b. Lot size : 120 c. Lot size : 240

Note :
S_1 : Influence of setting up changes of kinds of products in the mounter facility
S_2 : Influence of setting up changes of the reels in the mounter facility

Fig.4 Histogram of no-load running periods in solder reflow facility

5. Conclusion

In this paper, we proposed a simulation environment for sustainable manufacturing systems considering the productivity and energy consumption. A state transition model, a simulation system and a visualization system were proposed and implemented considering the necessary items and requirements for the simulation environment. Finally, case studies for a middle-scale semiconductor manufacturing line was conducted to confirm the efficiency of the proposed simulation environment.

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