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Paper:

Task Scheduling of Material-Handling Manipulator for Enhancing Energy Efficiency in Flow-Type FMS

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Energy savings and reduction in environmental burdens are necessitated to enhance sustainable manufacturing performances. Not only should energy consumption in the factory be visualized, but also a mechanism, by which in-process production and energy-related information measured in the shop floor are fed back into planning/scheduling decision-making, must be established to improve the energy efficiency during manufacturing execution. This study addresses the effect of scheduling on the improvement of energy efficiency in manufacturing by connecting a developed measurement and control platform with a real manufacturing system. The manufacturing system testbed utilized in this study forms a simple flow-type flexible manufacturing system composed of automated manufacturing cell with a CNC lathe, material-handling manipulator, and vertical machining center. We focus on the task scheduling of the material-handling manipulator, which yields a job sequence, and the effect of task scheduling of the manipulator on the energy efficiency and productivity of the entire manufacturing system.

Keywords: energy-efficiency, productivity, manufacturing system, scheduling, industrial robot

1. Introduction

Energy savings and reduction in environmental burdens are necessitated to enhance manufacturing sustainability as the global society becomes more conscious of the environmental health. In the manufacturing industry, the development of factory energy management systems is promoted to achieve green manufacturing [1] aimed at optimizing the procurement of raw materials as well as energy supply and consumption to reduce manufacturing costs and CO_2 emissions. Green manufacturing is one of the eight key areas in Industry 4.0 [2], and it has been investigated in the last decade [3]. In most practical situations of implemented factory energy management systems, only the "visualization" of energy consumption in the entire factory has been provided, and actual energy conservation activities are still performed by to human workers. Therefore, it is necessary to build a system that can autonomously maximize both productivity and energy efficiency, by which in-process production and energy-related information acquired from the manufacturing shop-floor can be fed back into the planning/scheduling decision-making process. Hence, Yonemoto and Suwa developed a cyber-physical manufacturing simulator for energy-efficient scheduling [4] based on a measurement and control platform [5]. The simulator can evaluate in-process manufacturing energy efficiency and productivity through real-time measurements of the physical material flow and power consumption. A miniature factory model was utilized as a physical system directly connected to a developed simulator, and a simple scheduler unit was implemented in the simulator. Through the physical simulation, they discovered a tradeoff between manufacturing lead time and total energy consumption on an optimized schedule [4].

This study, as an extension of our previous study, addresses the effect of scheduling on the improvement in energy efficiency in manufacturing by connecting a developed measurement and control platform to a real manufacturing system. The target manufacturing system testbed forms a simple flow-type flexible manufacturing system (FMS) composed of a two-axis CNC lathe equipped with a six-axis material-handling manipulator and a three-axis vertical machining center. In this study, we focused on the task scheduling of a material-handling manipulator that directly affects typical machine scheduling, i.e., the sequence of job processing, and investigate the effect of manipulation task scheduling on the energy efficiency and productivity of the entire manufacturing system based on electric power consumption data obtained through our developed measurement platform.

2. Related Studies

Duflou et al. [3] discussed resource and energy efficient manufacturing by introducing three decomposition levels in manufacturing industries; the machine, line/multi-machine (refers to manufacturing systems in this study), and factory/plant levels. At the machine level, technologies have been developed to reduce energy consumption for both the primary function and auxiliary devices of the machine tool, such as servo motors, hydraulic pump units, and cooling units [6]. Furthermore, the electric energy required for feed drive motors, main spindle motor, and lubrication can be reduced by conducting high-speed machining and optimizing the cutting tool path, resulting in a shorter machining time [6, 7]. Shudeleit et al. [8] provided a component-mapping-based approach to evaluate the efficacy of such energy-saving techniques by the value-adding energy efficiency, which is the ratio of the value-adding power demand to the total power demand and energy intensity. Moreover, innovative technologies for energy savings have been developed in other manufacturing processes, such as EDM and injection molding [9], and the energy-efficient use of industrial robots has been investigated [10–12].

At the factory or plant level, factory energy management systems have been developed in the last decade [13]; these systems collect and visualize in-process information associated with energy consumption and production in every area in the factory through industrial IoT devices. In fact, the visualization of energy consumption encourages human workers to realize energy savings and sustainability; however, if manufacturers attempt to establish higher energy efficiency as well as flexibility and smartness in manufacturing, a system must be developed that enables energy information obtained in the manufacturing shopfloor to be fed back to the upper decision-making unit to enhance both energy efficiency and productivity. Computational simulations are a suitable technique to implement such a feedback methodology in the manufacturing system. Hibino et al. proposed computational simulation methods to evaluate the energy consumption of manufacturing systems [14–16].

Herrmann et al. developed an energy-aware manufacturing system simulation tool using AnyLogic [17]. Kohl et al. proposed a methodology to enhance material-flow discrete-events on a plant simulation to predict the energy consumption of individual products and their variants [18]. Garwood et al. reviewed modeling approaches and simulation tools combining elements in multiple layers in manufacturing from the perspective of machine, process, and factory building [19].

From a broader perspective of the factory/plant level, simulation techniques have been proposed for life cycle assessments from materials to reuse through the manufacturing process. Case studies of product lifecycle systems for EVs, PHEVs, and lithium-ion batteries have demonstrated the effectiveness of simulation techniques [20]. Mizuno et al. analyzed the future of sustainable manufacturing in Japan using scenario-based simulations [21].

From the perspective of the line/multi-machine level, including design and planning, the association between planning and manufacturing execution phases has been addressed. Isnaini et al. developed a computer-aided process planning decision support system that was connected seamlessly with CAD and CAM systems [22]. Research regarding energy-efficient scheduling has been addressed in the last decade [23, 24], almost all of which were based on the framework of traditional scheduling theory and a mathematical programming approach was adopted. Artigues et al. reported a scheduling problem maximizing the energy efficiency under the electric supply constraint and defined a cumulative scheduling problem based on a parallel machine scheduling problem [25]. Zhang et al. integrated process planning and production scheduling by minimizing the energy consumption of the manufacturing system [26]. However, it is noteworthy that the simulation approaches and theoretical energy-efficient scheduling mentioned above tend to oversimplify the power consumption behavior of production facilities; consequently, the energy consumption models become simplified without the consideration of physical power consumption.

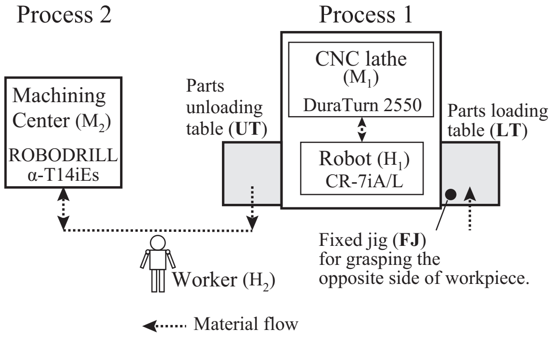


Fig. 1. Manufacturing system testbed with two machining stages.

3. System Configuration

3.1. Manufacturing System Testbed

The physical manufacturing system used in this study forms a flow-type FMS comprising of a CNC lathe (DuraTurn 2550, DMG MORI), three-axis machining center (ROBODRILL α-T14iES, FANUC), and material-handling manipulator (CR-7iA/L, FANUC), as shown in **Fig. 1**. The first machining process is turning by an automated turning cell, as shown in **Fig. 2**, which is composed of a two-axis CNC lathe (M_1) and a six-axis material-handling manipulator system (H_1) equipped with a gripper with three claws. The CNC lathe is interlocked with the material-handling manipulator, and a demand signal from the manipulator to the CNC lathe or vice versa invokes the mount/dismount of a workpiece, execution of the NC program, and open/close operation of the sliding door of the lathe. The material-handling system comprises two worktables on both sides of the manipulator: the parts (workpieces) loading table (LT) and unloading table (UT). The loading table has a fixed jig (FJ) to reverse the workpiece. The second process involves a three-axis vertical machining center (M_2). Suppose that a human worker (H_2) manages a workpiece between the UT and M_2, and mounts a workpiece on M_2 and then dismounts it.

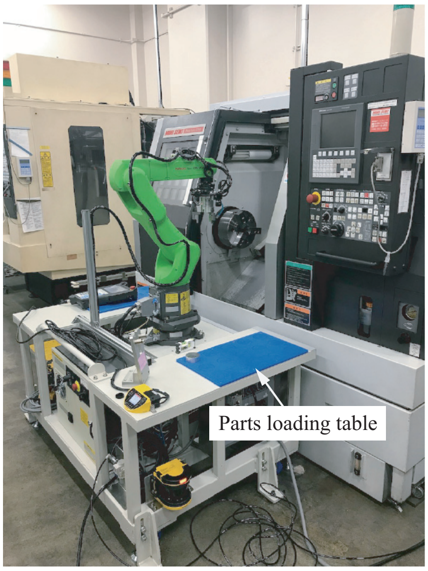


Fig. 2. Material-handling manipulator system comprising an automated manufacturing cell by connection with CNC lathe.

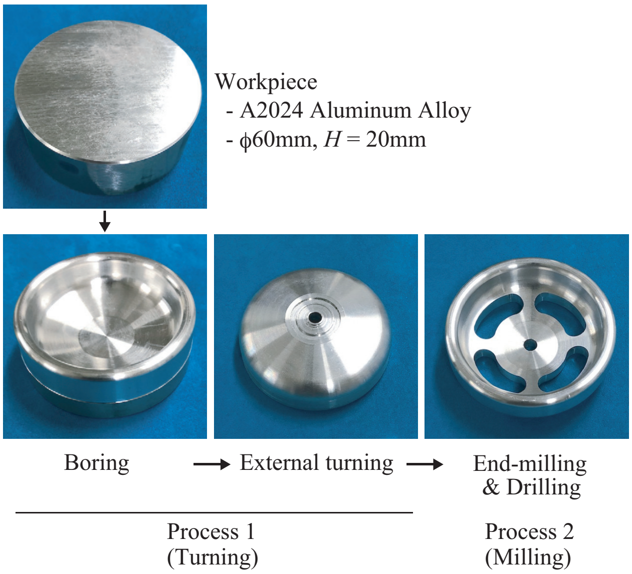


Fig. 4. Workpiece and postulated machining processes.

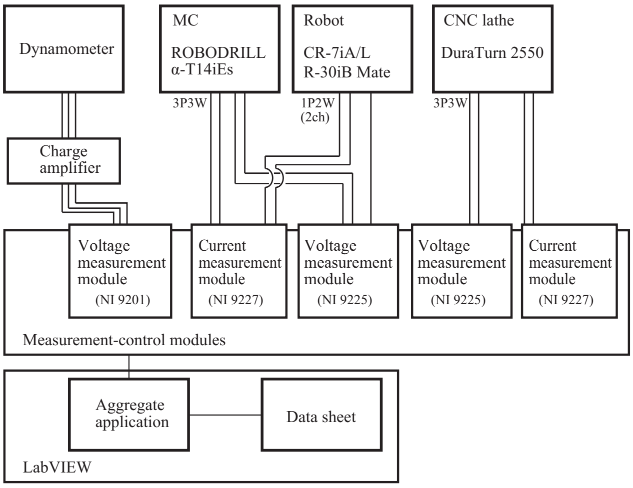


Fig. 3. Connection between platform and physical systems.

3.2. Measurement of Power Consumption

The measurement and control platform [4, 5, 27] (known as the measurement system for simplicity) is composed of a 4ch analog current input module (NI9227), 3ch analog 300 V voltage input module (NI9225), 8ch analog ±10 V voltage input module (NI9201), and 32ch digital 24 V voltage input/output module (NI9375) on the main platform (cRIO-9064 or cDAQ-9178). LabVIEW was utilized to control the measurement system.

Figure 3 depicts the connection between the measurement system and the physical manufacturing system introduced in Section 3.1. The machine tools were connected to the measurement system with a 3P3W connection to input to the power source cables; three measuring points using a clamp sensor for the currents and two points using clump terminals were established for the voltages. The measurement system was connected to the material-handling manipulator with 1P2W connections because the material-handling manipulator required a single phase 200 V. All of the analog voltage/current data from the manufacturing system testbed can be synchronized between them on the main platform, and imported into a PC via a USB device (at the bottom of **Fig. 3**). The analog voltage/current data were measured at a sampling rate of 1000 Hz; subsequently, the active power was calculated at intervals of 1 s. The measurement system calculated the mean power by the second.

4. Process and Scheduling on Manufacturing Testbed

4.1. Processes

We considered a machining process in which cylindrical A2024 aluminum alloys with a diameter of 60 mm and a height of 20 mm were cut to produce specified parts in the manufacturing system testbed introduced in Section 3.1. The machining process was composed of two subprocesses; turning (process 1) and milling (process 2). As depicted in **Fig. 4**, boring and external turning were performed in process 1 on M_1, whereas in process 2, four circular-arcs on a workpiece were milled using M_2. Various inner, outer, and hole designs were created for the produced parts. However, only one design, as depicted in **Fig. 4**, was employed to focus on the effect of task scheduling of the manipulator on the energy efficiency of the entire system.

Table 1 summarizes the identifiable tasks for planning a product schedule for the target production. Tasks 1, 2, and 3 executed on the machine tools correspond to cutting operations, whereas tasks V, W, X, and Y processed by the material-handling manipulator correspond to the mount, dismount, and convey workpieces. The hu-

Table 1. Machining and manipulation tasks.

Tasks	p_k	Description
Machining:		
1	160	Boring machining on M_1
2	130	External turning on M_1
3	120	End-milling and drilling on M_2
Material handling:		
V	40	$M_1 \rightarrow$ UT by H_1 (Dismounting and placing)
W	30	UT $\rightarrow$ FJ by H_1 (Picking and placing)
X	110	$M_1 \rightarrow$ FJ $\rightarrow M_1$ by H_1 (Dismounting, switching of grasping direction and then chucking)
Y	60	LT $\rightarrow M_1$ by H_1 (Picking and chucking)
Z1	30	UT $\rightarrow M_2$ by H_2 (Picking and chucking)
Z2	10	$M_2 \rightarrow$ UT by H_2

man worker (H_2) must perform two tasks: Z1 conveys a workpiece from process 1 to 2, and Z2 mounts/dismounts it. In **Table 1**, the operator $\rightarrow$ expresses a locational conversion, e.g., LT $\rightarrow M_1$, which is the transition of a workpiece placed on the loading table to the CNC lathe in process 1. The symbol p_k in **Table 1** denotes the estimated machining or manipulation time of task $k \in \{1, 2, 3, \mathrm{V}, \mathrm{W}, \mathrm{X}, \mathrm{Y}, \mathrm{Z1}, \mathrm{Z2}\}$ based on the actual measurement values obtained from the preliminary experiments. It is noteworthy that the minimal unit of p_k was set to 10 s, which indicates that a deviation might exist between the planned and actual production schedules. Every task began and ended at a designated mechanical home position. The trajectory of task V, for example, can be expressed as O $\rightarrow M_1 \rightarrow$ UT $\rightarrow$ O; however, the movement from/to the home position was excluded in **Table 1** for simplicity.

4.2. Cyclic Scheduling Based on Material-Handling Operations

Suppose that the manufacturing of a set of four aluminum alloy parts (as shown in **Fig. 4**), i.e., the two final products are repeated a definite number of times; this implies that a cyclic scheduling problem is considered. A *job* refers to the manufacturing of one part; let T_{jk} and T_{jl} denote the *machining task* of job j ($j = 1, 2, 3, 4$) on M_k ($k = 1, 2$) and the *manipulation task* of the material-handling manipulator, respectively, where $l \in \{\mathrm{V}, \mathrm{W}, \mathrm{X}, \mathrm{Y}, \mathrm{Z1}, \mathrm{Z2}\}$. The symbols $\prec$ and $\Rightarrow$ are introduced to express a precedence relation between tasks and the consecutive processing of tasks, respectively. For instance, $A \prec B$ means that task B is never processed before task A is completed, and $A \Rightarrow B$ indicates that task B is processed immediately after task A is completed (no tasks are assigned between tasks A and B). The manufacturing system introduced in Section 4.1 is considered as a two-machine flow shop system, and $T_{j1} \prec T_{j2}$ must hold.

Table 2. Preempted tasks X1 and X2.

Tasks	p_k	Description
X1	60	$M_1 \rightarrow$ FJ (Dismounting and placing)
X2	50	FJ $\rightarrow M_1$ (Picking and chucking)

We first consider a normal cyclic schedule denoted by S1 involving typically implemented material-handling operations in practice; subsequently, we propose an enhanced cyclic schedule, namely S2, by separating a specific task into two to enhance the manipulator utilization to achieve a higher energy efficiency.

- Normal schedule S1: Each part is processed according to the sequence shown in **Fig. 4**, i.e., the sequence on M_1 is

  $$T_{11} \prec T_{12} \prec T_{21} \prec T_{22} \prec T_{31} \prec T_{32} \prec \cdots .$$

  Jobs on the manipulator comprises three tasks X, Y, and V, yielding the following sequence for job j ($1 \leq j \leq 4$):

  $$T_{j\mathrm{Y}} \Rightarrow T_{j1} \Rightarrow T_{j\mathrm{X}} \Rightarrow T_{j2} \Rightarrow T_{j\mathrm{V}},$$

  The sequence of tasks of jobs j' and $j'+1$ ($j' = 1, 2, 3$) on the manipulator is expressed as

  $$T_{j'\mathrm{V}} \Rightarrow T_{j'+1,\mathrm{Y}}.$$

- Enhanced schedule S2: Task X expressing $M_1 \rightarrow$ FJ $\rightarrow M_1$ by H_1 is separated into two tasks, X1 and X2, as shown in **Table 2**: Tasks X1 and X2 instead of preempted task X are employed to enhance the utilization of the material-handling manipulator, by which a reduction in energy consumption is expected. The sequence of tasks on M_1 is:

  $$T_{11} \prec T_{21} \prec T_{12} \prec T_{22} \prec T_{31} \prec T_{41} \prec \cdots ,$$

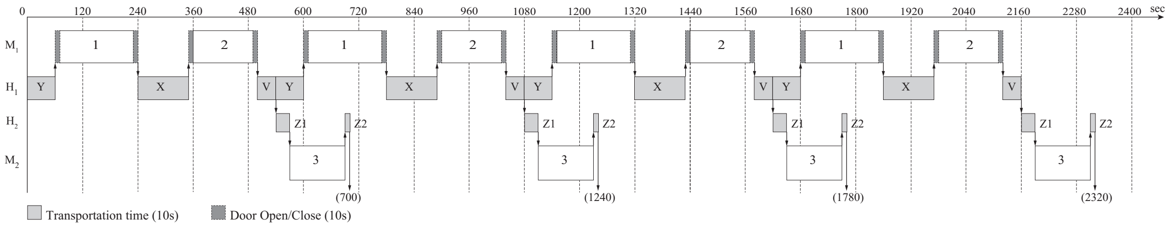
  which indicates that two tasks belonging to task 1 (T_{*1} of job $*$) are processed consecutively, and then two tasks belonging to task 2 (T_{*2}) are processed in a row. Regarding material handling, the sequence of job j ($j = 1, 3$) is

  $$\begin{aligned} T_{j\mathrm{Y}} &\Rightarrow T_{j1} \Rightarrow T_{j\mathrm{X1}} \Rightarrow T_{j+1,\mathrm{Y}} \Rightarrow T_{j+1,1} \\ &\Rightarrow T_{j+1,\mathrm{V}} \Rightarrow T_{j\mathrm{X2}} \Rightarrow T_{j2} \Rightarrow T_{j\mathrm{V}} \\ &\Rightarrow T_{j+1,\mathrm{X2}} \Rightarrow T_{j+1,2} \Rightarrow T_{j+1,\mathrm{V}} \end{aligned}$$

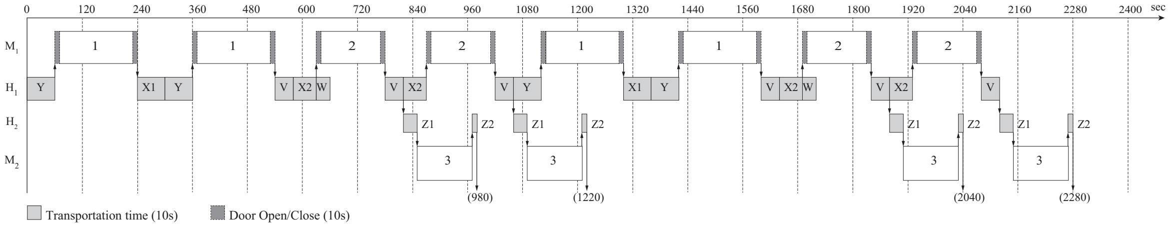
  and

  $$T_{j+1,\mathrm{X2}} \prec T_{j,\mathrm{W}} \prec T_{j+1,\mathrm{V}}.$$

Figure 5 depicts a Gantt chart example of schedules S1 and S2, in which the dark gray square expresses the time required for the door opening/closing of M_1 at the beginning and the end of tasks on M_1; the duration was set to

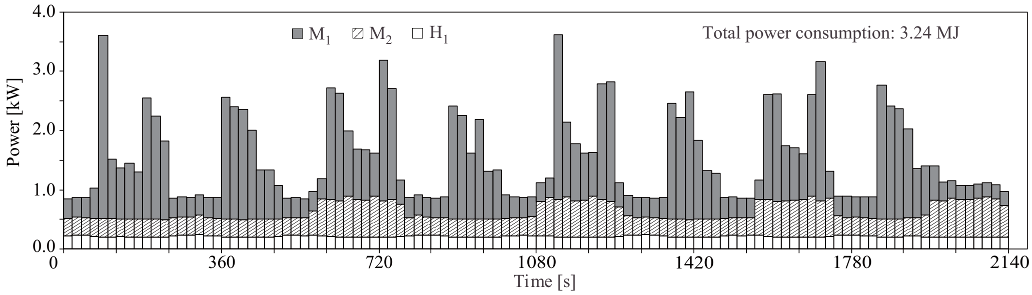


(a) Schedule S1

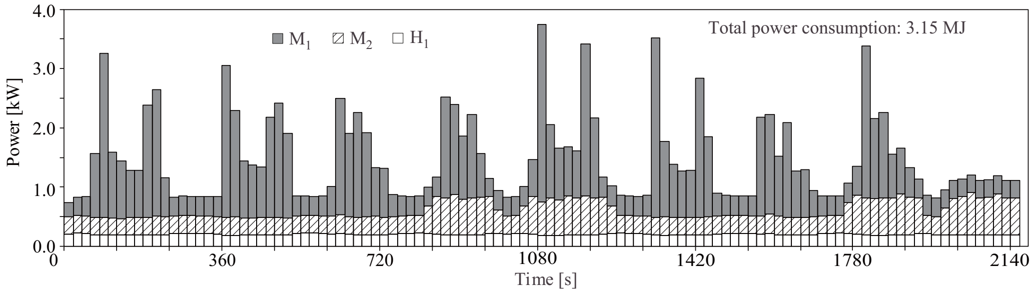


(b) Schedule S2

Fig. 5. Two patterns of predictive schedules.



(a) Schedule S1



(b) Schedule S2

Fig. 6. Measured power consumption in manufacturing based on schedules S1 and S2.

10 s. It is noteworthy that H_1 is always in an idle state when M_1 performing cutting on S1, whereas task W occurs simultaneously with T_{12} on S2. Schedules S1 and S2 exhibit the following characteristics in terms of their productivity performance under an ideal environment without any uncertainty:

- The makespan, i.e., the schedule length, of S1 is 2320 s, which is longer than that of S2 (2280 s).
- The material-handling manipulator utilizations on S1 and S2 are 37.0% and 40.6%, respectively.
- The average flow time (or manufacturing lead time) of S1 is 1510 s, better than that of S2 (1630 s), while all jobs are ready at the beginning of the manufacturing execution.

5. Experiments

5.1. Physical Scheduling Simulations and Results

We measured the electric power consumed by the manufacturing system testbed during the manufacturing of four parts, based on each of the two schedules. The obtained energy distribution over time is depicted in **Fig. 6** where the horizontal axis expresses the elapsed time, and the vertical axis indicates the average consumed power of

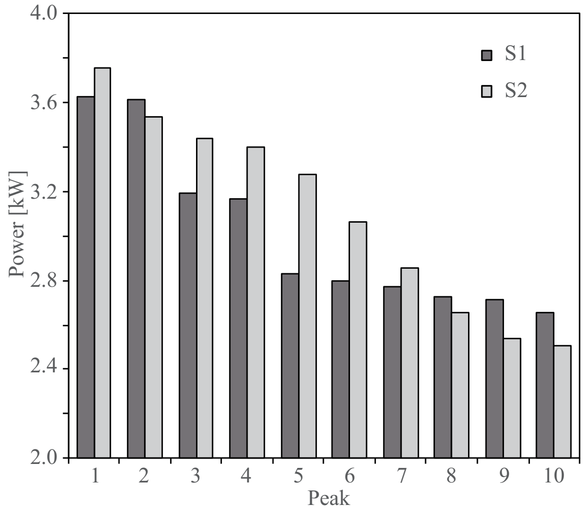


Fig. 7. Ten largest power peaks.

M_1, M_2, and H_1 aggregated every 20 s.

The actual results of S1 and S2 differed from the predicted ones under an ideal environment without any uncertainties. The total energy consumptions measured in S1 and S2 were 3.24 MJ and 3.15 MJ, respectively, and S2 resulted in a relatively lower energy consumption. The consumed electric energy by M_1, i.e., the CNC lathe constituted the largest portion of that by the entire system. As shown in **Fig. 6**, both energy distributions exhibited multiple power peaks owing to machining by M_1. **Fig. 7** shows the 10 largest power peaks in the actual results of manufacturing based on S1 and S2. To avoid the power peak during the in-process state, schedule S1 might be preferable; however, the distribution of power peaks between S1 and S2 was not significantly different.

Table 3 summarizes the average consumed power [kW] for the manipulation/machining tasks and during idle time periods in manufacturing based on S1 and S2. S2 reduced the power consumption during the idle state of the machine tools, whereas the consumed power between the two schedules during the idle states of the manipulator was the same. The consumed power measured at manipulator H_1 was considerably lower than that measured at the machine tools. Holistically, not the behavior of the material-handling manipulator, but its operation schedule can affect the energy savings of the entire system.

5.2. Computational Simulations

The observations above were based on the measured values of power consumption in the manufacturing of two products. It is easily predictable that the behavior of energy consumption of the system will exhibit a cyclic property because the manufacturing involved is cyclic. Therefore computational scheduling simulations were conducted based on the measured values to investigate the productivity and energy efficiency of the target manufacturing system. We considered 100 jobs (200 tasks) for the scheduling simulation.

Figure 8 shows the calculated energy efficiency and production rate, where the energy efficiency is defined as the duration (lead time) for manufacturing one product [pcs] divided by the consumed energy [kJ] [4]. The production volume efficiency was investigated based on the enhanced schedule S2. It was discovered that the task scheduling of the material-handling manipulator can enhance the energy efficiency of the entire manufacturing system under the situation investigated in this study.

6. Concluding Remarks

This study investigated the effect of the task scheduling of a material-handling manipulator on the energy efficiency and productivity of a manufacturing system based on measured electric power consumption obtained through a developed measurement system. The results and discussion are summarized as follows:

- The manipulator operations (physical movements) did not affect the power consumption of the entire manufacturing system because the power consumed by the manipulator, as expected, was much lower than by the machine tools in operation.
- Based on numerical simulations, the proposed enhanced schedule that aimed at enhancing the manipulator utilization outperformed a typically implemented schedule in terms of energy efficiency by performing a simple job sequence.
- The results above demonstrated that the task scheduling for the manipulator enhanced the energy efficiency while maintaining the productivity of the system during manufacturing. This implied the importance of a smooth linkage between the planning and manufacturing execution phases in manufacturing.

Future studies include the development of generic optimization techniques, such as mathematical programming, to generate a suitable set of manipulation tasks while considering the reduction in energy consumption of the entire manufacturing system, and application to more complicated situations, such as high-mix varied volume production.

Acknowledgements

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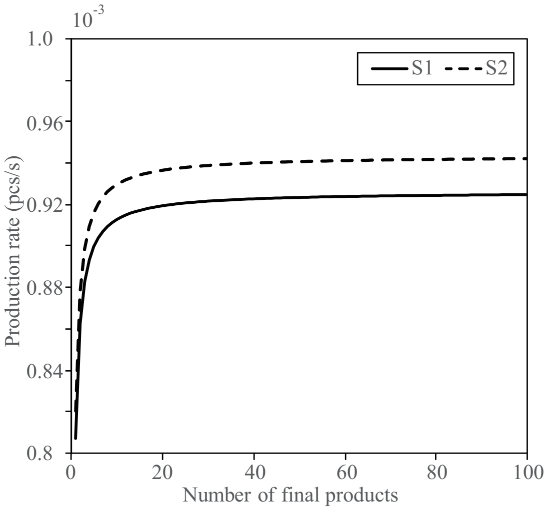
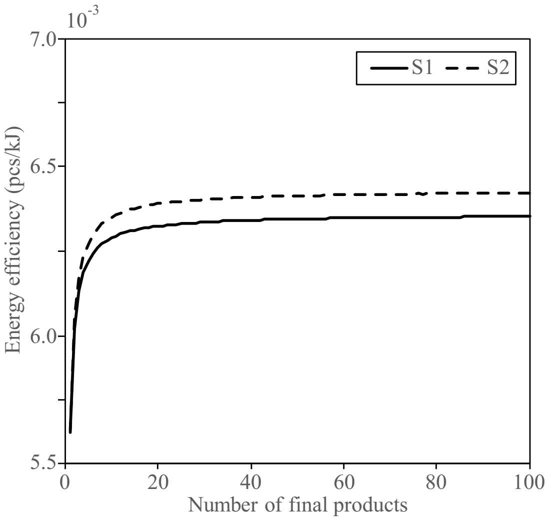
Table 3. Average power consumption [kW] every 20 s on machining/manipulation tasks and idle times.

	In-process				Idle state		
Schedule	H_1 tasks	T_{j1}	T_{j2}	T_{j3}	H_1	M_1	M_2
S1	0.217	0.338	1.355	1.361	0.194	0.306	0.622
S2	0.218	0.329	1.442	1.152	0.194	0.304	0.616



(a) Production speed [pcs/s]



(b) Energy Efficiency [pcs/kJ]

Fig. 8. Simulation results of producing 100 products based on schedules S1 and S2 in terms of measured power consumptions.

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