Proposal of an Efficiency Index for Supporting System Configuration Design

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Abstract. Demands for various miniature mechanical parts and products such as mobile phones, medical devices and so on, will increase more and more. Contrarily, manufacturing systems for those devices are becoming larger and more complicated. AIST developed the first prototype of a machineable microfactory which consisted of miniature machine tools and robots in 1999 as a countermeasure for the situation. An expected advantage of the microfactory was that the microfactory can reduce environmental impact and costs of miniature mechanical fabrication. However, the effect of the microfactory in reducing environmental impact and costs, or enhancing system efficiency have not been quantified. So, an appropriate index to evaluate microfactories by considering environmental impacts, costs and system throughput, simultaneously, is necessary. In the paper, the authors propose an evaluation index, based on the required time for each process, machine cost, operator's cost and environmental impact, using the microfactory as an example. The calculation shows that the proposed efficiency index is useful in evaluating the system configuration.

Keywords. Microfactory, System configuration, Environmental impact, Throughput

1 Introduction

"Microfactory" was a concept of a future manufacturing system, which was proposed in the Japanese national R&D project named "Micro Machine Project [1]". The original concept of the microfactory was "a super-miniature factory consists of micro machines and capable of producing miniature products anytime and anywhere". In 1999, AIST developed the first prototype of a microfactory that consists of miniature machine tools for parts fabrication and miniature manipulators for parts transfer and assembly. (Figure 1) The microfactory was able to perform a series of fabrication and assembly on a small desktop [2,3]. The result of the test production led us to conclude that the microfactory had considerable capability of micro mechanical fabrication. Some other microfactories [4-6] have

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been proposed and "microfactory" has become a rather common concept. An expected advantage of the microfactory was that the microfactory would reduce environmental impact and costs of miniature mechanical fabrication, especially for "diverse-types-and-small-quantity production". Since the smallness of the machines enables flexible layout changes, it can control the increase of the costs when the product designs have been modified. And, by replacing conventional manufacturing systems to microfactories, electrical power can be reduced. However, since there have been no effort to evaluate effect of microfactories quantitatively, abovementioned advantages are still uncertified. In recent world where "green manufacturing" is strongly required, environmental aspect of microfactories should be examined. The purpose of this research is to propose a simple efficiency index for a microfactory-like system to support its system configuration design.

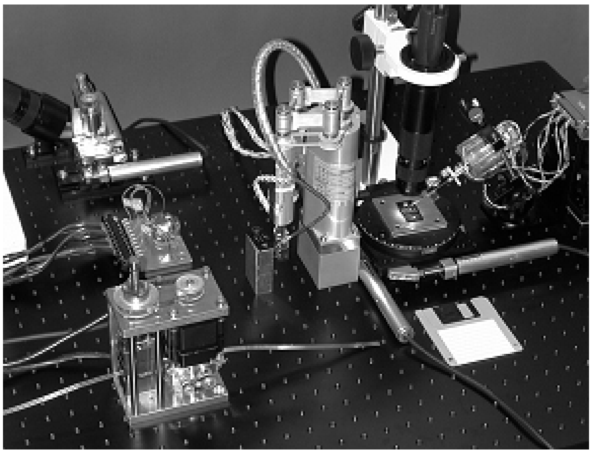

Figure 1. Microfactory

2 Overview of the Microfactory

The microfactory shown in Figure 1 consisted of five miniature machines. The five components were a lathe, a milling machine and a press machine for parts fabrication, and a transfer arm and a micro-hand for assembly. Every component is well-designed and extremely smaller than the corresponding conventional item. To show the capability of the microfactory as a manufacturing system, test production was executed. The test product was a miniature ball bearing, which was 900 microns in diameter, and consisted of 4 kinds of parts. The parts and the test product is shown in Figure 2. All the parts except steel balls were fabricated using the miniature machine tools, and assembled using the manipulators. As the result of the fabrication, the microfactory was capable to assemble the test product. Therefore, it can be said that the microfactory has possibility as a future manufacturing system to produce many varieties of extremely miniature machine parts. However, it still has some problems, such as the low throughput or the difficulty of the fixture of the product. To improve the throughput, an appropriate system configuration should be considered. To fabricate the miniature ball bearing shown in Figure 2, manufacturing process in Figure 3 was applied. Every part starts from the material shown in the left side, passes through some sub-processes shown in the block and reaches the assembly processes written in the right side. From the figure it is easily imaginable that the assembly processes are very time-consuming, because the manufacturing processes should be done sequentially under a microscope using the micro-hand. Table 1 indicates the average process time of the corresponding processes in Figure 3, after operators have been skilled enough. Number of operators required for each process is also shown in the table.

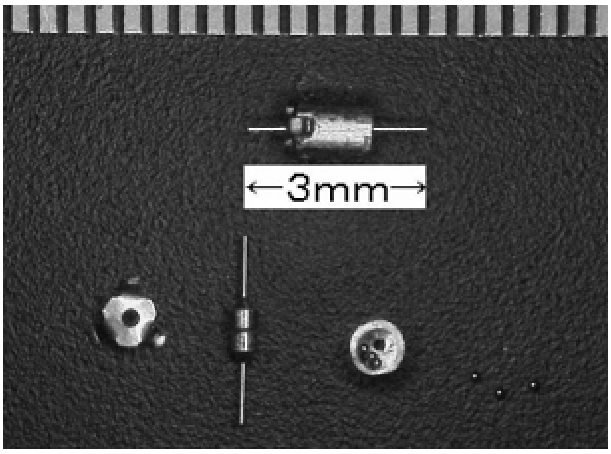

Figure 2. Miniature ball bearing

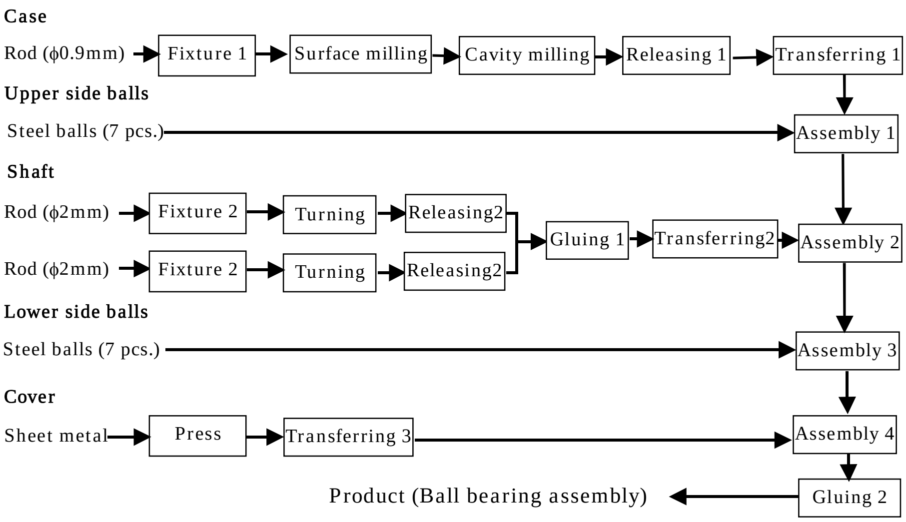

Figure 3. Manufacturing process of the test product

Table 1. Process time and number of operators for each process per unit

Sub Process	Process time in seconds	Number of operator
Fixture 1	10 sec.	1
Fixture 2	5 sec.	1
Surface &cavity milling	3 min.	1
Turning	2 min.	1
Press	0.2 sec.	0
Releasing 1	10 sec.	1
Releasing 2	5 sec.	1
Transferring 1	1 sec.	0
Transferring 2	1 sec.	0
Transferring 3	1 sec.	0
Assembly 1-4 (total)	48 min.	1
Gluing 1	1 min.	1
Gluing 2	2 min.	1

According to Figure 3 and Table 1, it is evident that the assembly operations will be the bottlenecks for the throughput. Machine and labor costs are also important for manufacturing. Table 2 shows the rough estimation for the cost of the machines used in the microfactory. And also the energy consumption of each machine is an important factor to consider system efficiencies. Table 3 shows the average power consumption of the machines during the operation.

Table 2. Machine costs

Machine	Milling	Turning	Press	Arm	Hand
Cost in million yen	0.7	1.2	2.0	3.0	5.0

Table 3. Energy consumption

Machine	Milling	Turning	Press	Arm	Hand
Average power in Kw	0.25	0.3	0.05	0.2	0.4

3 Proposal of a System Efficiency Index

Hereby, the paper tries to define an index to evaluate the efficiency of manufacturing process. In an existing research [7], there was a proposal of an index to evaluate total performance of products by considering product values, costs and environmental impacts, through product life cycle. Functionality per cost is often used to evaluate product performance in quality engineering field. And functionality per environmental impact, so-called eco-efficiency [8,9] is also a common index in recent design for environment [10], for evaluating another aspect of product performance. However, these existing evaluation indexes cannot evaluate the environmental and economical aspects simultaneously. Because the design engineers and manufacturers have long histories of serious effort to reduce cost of manufacturing, they might not accept an index without evaluating cost and functionality. The proposed index is the simplest combination of “eco-efficiency” and “functionality per cost”. To evaluate the efficiencies of manufacturing systems, the same idea can be applied. Efficiency index defined by Equation (1) is used in the following sections.

$$Ef = \frac{F}{\sqrt{C}\sqrt{E}} \tag{1}$$

Ef: system efficiency index, *F*: system functionality,
C: cost of the system (yen/hour), *E*: environmental impact (kg-$CO2$/hour)

Instead of the total performance of a product defined in the original index, “*Ef*” which is an index to express system efficiencies is introduced. “*F*” is the sum total of the value of the various products created within a certain time. But, since the target product is not changed in this case, “*F*” can be simply represented by the system throughput. By defining the throughput by number of products assembled in an hour, the efficiency index for the microfactory can be calculated. “*C*” can be calculated by a sum total of machine costs, labor costs and electricity cost during the corresponding time. Labor cost is assumed to be 5.0 (million yen) per person per year. For “*E*”, many indexes have been proposed to estimate it. In the microfactory, since it isn't necessary to consider special waste, equivalent $CO2$ emission will be a good index to estimate environmental impact. So, “*E*” can be expressed by the sum of $CO2$ emission cased by electricity shown in table 3 and machine material. (1kwh =0.38kg-$CO2$)

4 Efficiency Analysis of the Microfactory

Analysis of the manufacturing process mentioned in the former section showed that the assembly processes performed by “micro-hand” is critical both for throughput and environmental impact. When the number of components or operators is not limited to be 1, a simple strategy to enhance system efficiency will be to increase the number of the “hands”. According to table 1, total process time of assembly and gluing (gluing is also executed by micro-hands) will be 51 min. So, when the system has one operator for machining and one for assembly, number of the product produced in an hour is 60/51=1.18. And when the number of hands and assembly operators is i, throughput will be 1.18i. By assuming the annual operation time of the system is 1600 hours, the efficiency is calculated by Equation (2). When the number of the “hand” is more than 6 and the system has only one machining operator, the turning process becomes the bottleneck and the efficiency index can be calculated by Equation (3). This value is lower than that of the case in which there are 5 hands and one machining operator. By adding one more machining operator to the system, again the bottleneck will be the assembly process. When the system has i hands, j machining operators, k lathes and l milling machines, the system efficiency is expressed by Equation (4). Figure4 shows the behavior of the system efficiency calculated by these equations.

$$Ef = \frac{1.18i}{\sqrt{(6.9+10i+5)\times 10^6/1600}\sqrt{(0.8+0.4i)\times 0.38}} \quad (1 \le i \le 5) \tag{2}$$

$$Ef = \frac{6.4i}{\sqrt{(6.9+10i+5)\times 10^6/1600}\sqrt{(0.8+0.4i)\times 0.38}} \quad (6 \le i) \tag{3}$$

$$Ef = \frac{1.18i}{\sqrt{(5+10i+5j+1.2k+0.7l)\times 10^6/1600}\sqrt{(0.25+0.4i+0.3k+0.25l)\times 0.38}} \tag{4}$$

i: number of hands and assembly operators, *j*: number of machining operators, *k*: number of lathes, *l*: number of milling machines

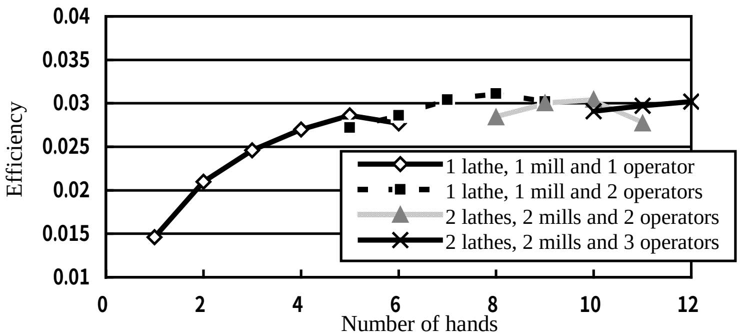

Figure 4. Behavior of the efficiency index

In the figure, since press and transferring processes are not significant for the overall throughput, the figure shows the behavior of the efficiency indicator according to the change of the number of hands, lathes and mills. ("Operators" means number of operators for machining processes.) According to Figure 4, it can be said that there are some local maximums. The result suggested some simple strategies. For example when the system had a lathe, 2 machining operators and 6 hands, the efficiency was higher than that of the case having 1 lathe and 5 hands. The results showed that having 6 hands and one machining operators won't be efficient. Usually, the configuration of the system is mainly determined by the required throughput. But the calculation indicates that covering the shortage of the throughput by extending the operation time of the factory will be a better solution in the aspect of green manufacturing.

5 Comparison with a Conventional Factory

Focusing on "diverse-types-and-small-quantity production" of micro mechanical products, the final goal of this research is to prove that a microfactory-like system is more suitable than a large mass production manufacturing system. When frequent layout change of the system is necessary, high flexibility may cover low throughput. The paper tried to compare system efficiency of the microfactory with that of a conventional mass production line. A rough estimation says the maximum throughput of a typical manufacturing system of miniature ball bearing is about 100 thousand units per month. By assuming the system runs 20 days a month and 8 hours a day, it is equivalent to 625 units per hour. Initial cost of the system is about 200 million yen and the power consumption is estimated to be about 200kw. Considering the environmental impact of machine material, die-set and electricity, the efficiency can be calculated. Figure 6 shows the rough estimation of the efficiency of the mass production system, corresponding to lifetime length of the system, and average demand.

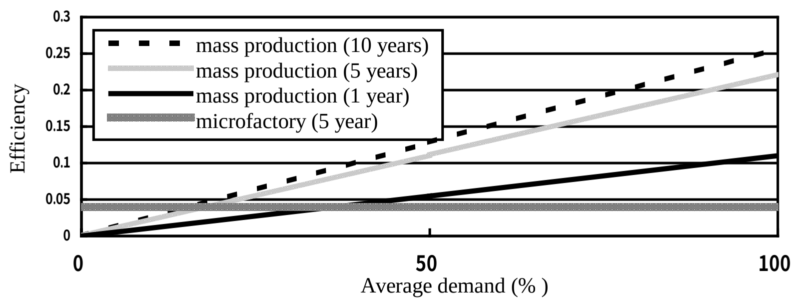

Figure 5. Efficiency of a mass production system

The figure indicates that the microfactory is rather efficient when the demand is low and the lifetime of the system is relatively short. When the system lifetime is 5 years, the efficiency of the microfactory in its suitable configuration is about 0.04. So, when the average demand is lower than 20% of the maximum throughput, the microfactory is more efficient than the mass production system. Although more precise comparison is necessary, it can be said that “microfactory” has a good possibility for diverse-types-and-small-quantity production of miniature mechanical products.

6 Conclusion and future work

A simple index to evaluate the system efficiency of a microfactory-like system was proposed by considering system throughput, machine costs, labor cost, and $CO2$ emission caused by machine material and electricity. As the results of the analysis of the test production process of the microfactory, it was able to show that the system had some suitable configurations. By using the evaluation result, it was possible to design the system configuration of microfactory-like systems.

The result was compared with a rough estimation of the efficiency of a conventional manufacturing system of ball bearing. The comparison indicated that the efficiency index of the microfactory was lower than that of a mass production line. However, when the lifetime of the system is relatively short and the demand is low, efficiency of the microfactory can be higher than that of a mass production line. The fact shows although "microfactory" is not a suitable system for mass production, it will be a good solution for "diverse-types-and-small-quantity production".

As the future work, more precise comparisons with mass production systems are required in order to prove the effectiveness of microfactory-like system. In addition, modification of efficiency index to consider frequent change of demand and product design may become necessary to estimate the feature of microfactory-like systems.

7 Reference

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