IEMS Vol. 3, No. 1, pp. 52-58, April 2004.

Hierarchical Evaluation of Flexibility in Production Systems

Hitoshi Tsuboner · Tomotaka Ichimura
Tokyo Metropolitan Institute of Technology
Asahigaoka, Hino-city, Tokyo 191-0065, JAPAN

Mitsuyoshi Horikawa† · Mitsumasa Sugawara
Iwate Prefectural University
152-52, Takizawa-aza-sugo, Takizawa, Iwate 020-0193, JAPAN
Tel: +81-19-694-2460, E-mail: horikawa@soft.iwate-pu.ac.jp

Abstract. This report examines the issue of designing an efficient production system by increasing several types of flexibility. Increasing manufacturing flexibility is a key strategy for efficiently improving market responsiveness in the face of uncertain market demand for final products. The manufacturing system comprises multiple plants, of which individual plants have multiple manufacturing lines that are designed to produce limited types of products in accordance with their size and materials. Imbalance in the workload occurs among plants as well as among manufacturing lines because of fluctuations in market demand for final products. Thereby, idleness of some manufacturing lines and longer lead times in some manufacturing lines occur as a result of the high workload.

We clarify how these types of flexibility affect manufacturing performance by improving only one type of fl exibility or by improving multiple types of flexibility simultaneously. The average lead time and the imbalance i n workload are adopted as measures of manufacturing performance. Three types of manufacturing flexibility are interrelated: machine flexibility, routing flexibility, and process flexibility. Machine flexibility refers to the vario us types of operations that a machine can perform without requiring the prohibitive effort of switching from one order to another. Routing flexibility is the capability of processing a given set of part types using more than one l ine (alternative line) in the plant. Process flexibility results from being able to build different types of final produ cts at the same plant.

Keywords: flexibility, manufacturing system, lead time

1. INTRODUCTION

Manufacturing flexibility is an important element of a firm's manufacturing strategy. It provides the capability to respond quickly to shifting market requirements. Increasing manufacturing flexibility is an essential strategy for improving market responsiveness efficiently in the face of uncertain market demand for final products. Over the last decade, many studies have defined various types of flexibility in manufacturing systems (Browne *et al*., 1984; Sethi and Sethi,1992; Toni and Tohchia,1998) and specified measures of flexibility (Benjaafar, 1994; Brill and Mandelbaum, 1990).

Some types of flexibility are evaluated and compared in terms of manufacturing performance in various shop environments when only one type of flexible method is introduced (Bhandra and Tombak, 1992; Tsubone and Horikawa, 1999-a, 2000). However, little thorough investigation has been done into the relationships among flexibility types despite their great potential for managerial insights into flexibility competitiveness. That is, some types of flexibility are not independent but interrelated, such as machine flexibility, routing flexibility, and process flexibility (Hyun and Ahn, 1992; Newman *et al*, 1993; Tsubone and Horikawa, 1999-b). Machine flexibility is required when routing flexibility is to be improved. Additionally, both machine and routing flexibilities are necessary when process flexibility is required to be improved. Therefore, these types of flexibility have a hierarchical structure. Machine flexibility (*Mf*) refers to various types of operations that the machine can perform without requiring the prohibitive effort of switching from one order to another. Routing flexibility (*Rf*) is the capability of processing a given set

† : Corresponding Author

of part types using more than one line (alternative lines) in the plant. Process flexibility (*Pf*) refers to the ability to build different types of final products at the same plant.

We consider a made-to-order production system where plastic products such as sprays, polyethylene terephthalate (PET), and shampoo are manufactured. These products vary greatly in shape, size, and market requirements in quantities. The manufacturing system comprises multiple plants. Individual plants have multiple manufacturing lines that are designed to produce limited types of products in accordance with their size and materials. Orders for individual final products arrive at each plant randomly every day. Imbalance in the workload occurs among plants as well as among manufacturing lines because of market fluctuations for final products, thereby engendering idleness of some manufacturing lines and longer lead times in some manufacturing lines.

We clarify how these types of flexibility affect the manufacturing performance, by answering the following questions.

1) To what extent can manufacturing performance be increased by improving:
   i) only machine flexibility,
   ii) both machine flexibility and routing flexibility, and
   iii) process flexibility as well as machine flexibility and routing flexibility simultaneously?
2) To what extent can additional production capacity, as a design parameter, be decreased by improving the above types of flexibility?

The average lead time and the imbalance in workload are adopted as measures of manufacturing performance. Results will provide manufacturers with better insight and guidelines for determining the scale or scope of the different types of flexibility and their implementation.

2. PRODUCTION SYSTEM

2.1 Orders

Two distinct types of orders exist for individual final products, which arrive at each plant randomly every day. One is a group of orders with normal delivery dates. The other is a group of emergent orders. The ratio of the number of emergent orders *ER* is defined as the ratio of the number of emergent orders *NE* to the total number of orders *N*.

$$ER = NE/N \tag{1}$$

2.2 Manufacturing System

The manufacturing system comprises multiple plants.

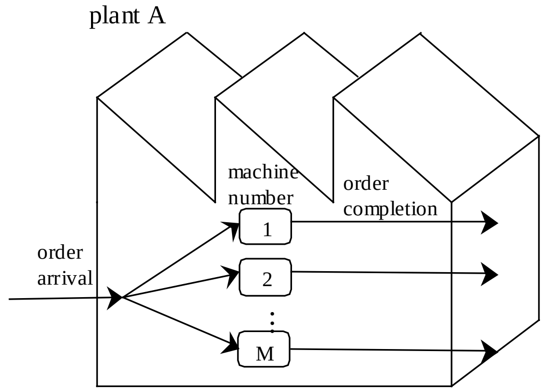

Figure 1. Manufacturing system

The total number of plants in the manufacturing system is *P* (*p*=1, 2, …, *P*). In addition, an individual plant has multiple processing lines that are designed to produce limited types of products in accordance with their size and materials (as shown in Fig. 1). Although a processing line comprises multiple machines in series, it can be regarded as only one machine because each order is output automatically as a final product at the last machine after assigning the order to the first machine. Therefore, it is assumed that each individual plant has *M* processing lines, each of which has only a single machine (*m*=1, 2, …, *M*) to produce limited types of products.

2.3 Planning Model

A two-level planning model, which is hierarchically linked, is used to determine the production capacity and timing of order release to the shop floor, that is, the weekly planning and the daily planning, respectively.

2.3.1 Weekly Planning

Weekly planning determines the production capacity of individual plants at the end of week (*w*-1). Assigning orders in the main plant with a high workload to an alternative plant can decrease an imbalance in workloads among plants. In the initial step of planning, the planning model assigns orders that cannot be processed at an alternative plant to the main plant. In the second step, the planning model assigns orders that can be processed at an alternative plant to an alternative plant with a low workload to minimize the workload imbalance among plants (See Appendix A). This algorithm minimizes the expression below.

$$\sqrt{\sum_{p=1}^{P}\left(f_{p_{\max}}(w-1)-f_p(w-1)\right)^2} \rightarrow \min \tag{2}$$

$$f_p(w-1) = \sum_{i=1} OT_i^p \tag{3}$$

$f_p(w-1)$ is the workload at the end of week (w-1) for the plant p, $p_{\max}$ is a plant which is the highest workload of all plants, and OT_i^p is the processing time of order i. In the third step, the required production capacity for each plant in the upcoming week is determined by introducing the parameter for setting the production capacity γ, on the basis of the workload of an individual plant as the following.

$$F_p(w) = f_p(w-1) + \gamma \cdot \hat{D}_p(w) \tag{4}$$

Therein, $F_p(w)$ is the production capacity required for plant p in the week w, $f_p(w-1)$ is the workload at the end of week (w-1) for the plant p after the orders have been assigned using the algorithm in Appendix A, γ is the parameter for setting the production capacity $(0 \le \gamma)$, and $\hat{D}_p(w)$ is the expected workload of orders that will arrive during the upcoming week w.

$$DT_p(t) = F_p(w)/(M \cdot L) \tag{5}$$
$$(w = 1, 2, \cdots, W), (m = 1, 2, \cdots, M)$$

Here, $DT_p(t)$ is the working time of plant p available on day t in planning week w, and L is the number of working days in w.

2.3.2 Daily Planning

The daily planning model handles the release of orders onto the shop floor. Orders are immediately released to the plant upon arrival. Orders cannot be assigned to alternative plants on the daily planning level. With regard to machine flexibility, when orders are in the queue for those that can be processed without initial setup of the machine, they are given priority as the next processing operation by grouping them. Such prioritization improves machine flexibility. When orders cannot be grouped, the first come first served (FCFS) rule is adopted as the dispatching rule. With regard to routing flexibility, when an order can be assigned to alternative machines to improve routing flexibility, workloads among the main machines predetermined for processing and alternative machines are compared each time an order arrives or is completed. Thereby, the order is processed on the machine with the smallest workload. When an order has no alternative machine, the FCFS rule is adopted.

An emergent order is processed immediately after the order that is currently being processed is completed.

3. FLEXIBILITY

3.1 Machine Flexibility Index

It is assumed that the machine flexibility can be applied to each machine. The machine flexibility index MF is defined as the ratio of the number of orders that can be processed without changing the setup when switching from one order to another order, to the total number of orders.

$$MF = N_m / N \tag{6}$$
$$\{ n \mid n \in MS, n \in N \}$$
$$MS = \{1, 2, \cdots, N_m\},\ n = \{1, 2, \cdots, N\}$$

MS is the set of orders that can be processed without changing the setup if the orders to be processed are grouped; N_m is the number of elements in MS and N is the total number of orders.

3.2 Routing Flexibility Index

The routing flexibility index RF is defined as the ratio of the number of orders performable on alternative machines to the total number of orders. We assume that if the order on main machine m can be processed on alternative machines, the order can be assigned to the alternative machine (m-1) or (m+1). However, when the order can be processed on main machine 1 or M, the order can be assigned to the alternative machine 2 or (M-1).

$$RF = N_r / N \tag{7}$$
$$\{ n \mid n \in RS, n \in MS, n \in N \}$$
$$RS = \{1, 2, \cdots, N_r\}$$

RS is the set of orders that can be assigned to alternative machines and N_r is the number of elements in RS.

3.3 Process Flexibility Index

The process flexibility index PF is defined as the ratio of the number of orders performable on alternative plants to the total number of orders. We assume that if the order in the main plant can be processed in alternative plants, the order can be assigned to the total number of plants not including the main plant.

$$PF = N_p / N \tag{8}$$
$$\{ n \mid n \in PS, n \in RS, n \in MS, n \in N \}$$
$$PS = \{1, 2, \cdots, N_p\}$$

PS is the set of orders that can be assigned to alternative plants and N_p is the number of elements in *PS*.

Not all of these flexibility types are independent. In fact, they are linked. This study subsumes that orders can be processed on alternative machines without changing the setup when switching from one order to another, and that the order which can be processed at alternative plants can be processed using alternative machines in an alternative plant without changing the setup when switching from one order to another.

$$PS \subseteq RS \subseteq MS \quad (9)$$

4. CRITERIA

The following two criteria assess manufacturing performance.

1) Average lead time

Lead time is the time from the arrival of the order to completion of the order.

$$ALT = \sum_{i=1}^{N} LT_i \Big/ N \quad (10)$$

LT_i is the actual lead time of order i ; N is the total number of orders that actually arrived.

2) Imbalance in workload

Imbalance in the processing workload can be represented as the imbalance in workload between individual machines.

$$IW = \sqrt{\frac{\sum_{p=1}^{P}\sum_{m=1}^{M}\left(PD_{p,m}(w) - AMT\right)^2}{P \cdot M}} \Big/ AMT \quad (11)$$

$$AMT = \sum_{p=1}^{P}\sum_{m=1}^{M} PD_{p,m}(w) \Big/ P \cdot M \quad (12)$$

$PD_{p,m}(w)$ is the total processing time in planning week *w* and *AMT* is the average processing workload.

5. NUMERICAL EXPERIMENT

5.1 Purpose

This experiment is intended for two purposes. One is to analyze how the manufacturing performance can be improved numerically upon introducing three types of flexibility. The other is to clarify how manufacturing performance will be affected by emergent orders.

5.2 Experimental Conditions

The number of plants *P* is set to three. The number of machines *M* is also set to three. Orders arrive according to a Poisson distribution with an average of 20 orders per day per machine. The processing times of orders are generated based on an Erlang distribution with an average of 1.0 and a phase of 1.0. The setup time required to switch from one order to another is set to 0.1. The number of working days *L* is fixed at 5.

5.3 Experimental Results

Experimental results are represented as values of

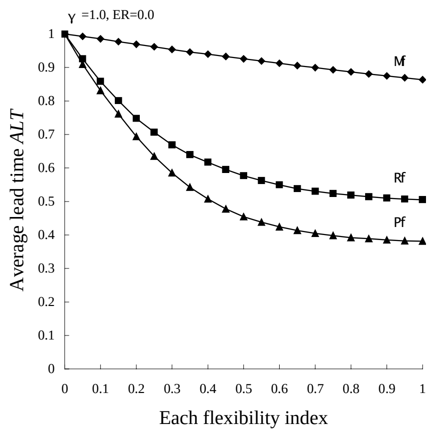

Figure 2. The relationship between each flexibility index and the average lead time

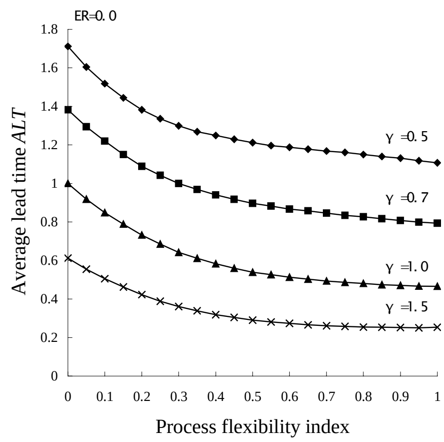

Figure 3. The relationship between the process flexibility index and the average lead time

performance measures for each level of flexibility normalized by the observed lead time of each level obtained under the condition that all flexibility indexes are set to 0 and that γ is set to 1. These average lead times are plotted in Figs. 2–5.

Figure 2 shows the relationship between each flexibility index and the average lead time when there are no emergent orders. As the machine flexibility index increases, the average lead time decreases because orders can be processed continuously by grouping them, thereby decreasing the setup time. With an increasing routing flexibility index, the average lead time decreases more markedly than that in the case of machine flexibility because the imbalance in workload among machines can be decreased. However, with an increasing process flexibility index, the reduction of the average lead time is similar to that in the case of routing flexibility.

Figure 3 shows the relationship among the parameter for setting the production capacity γ, the average lead time, and the process flexibility index. When $\gamma = 0$, the production capacity on week w is determined only on the basis of the work in process (orders not completed) at the end of the planning week (w-1). As the γ value increases, the average lead time can be decreased without increasing flexibility because the production capacity in the forthcoming week is set at a higher level by anticipating the arrival of orders.

Figures 4 and 5 show the relationship between the respective machine and process flexibility indexes and the average lead times, under the condition that emergent

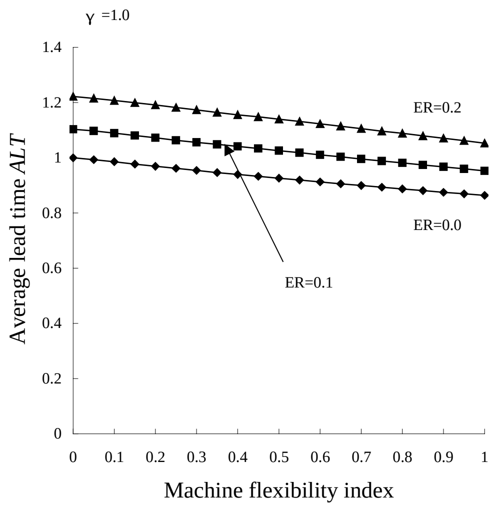

Figure 4. The relationship between the machine flexibility index and the average lead time

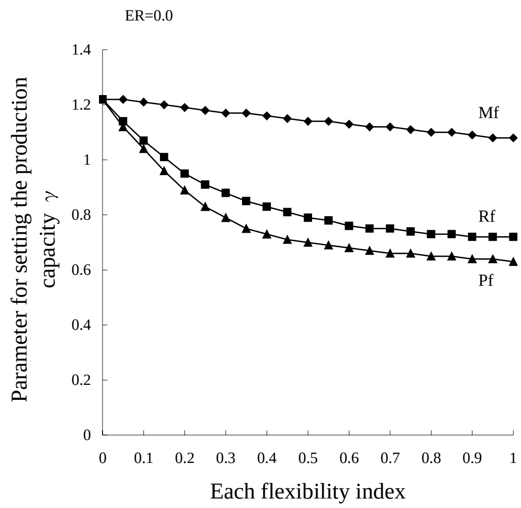

Figure 6. The relationship between each flexibility index and the parameter for setting production capacity.

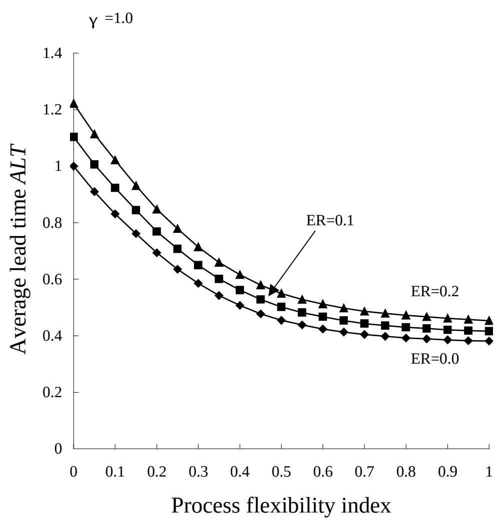

Figure 5. The relationship between the process flexibility index and the average lead time

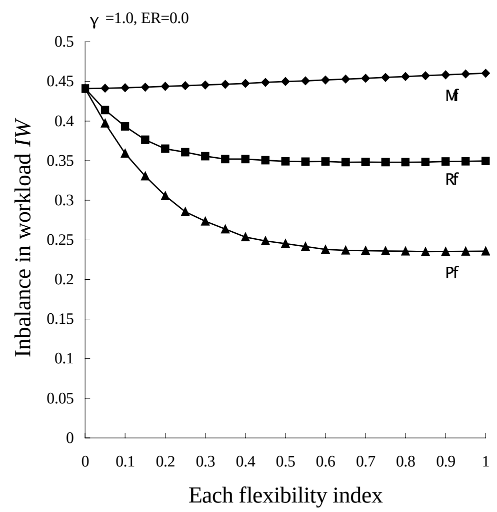

Figure 7. The relationship between each flexibility index and the workload imbalance

orders arrive. Regarding enhancing the flexibility, the average lead time under the condition that emergent orders arrive approaches the lead time under the condition that emergent orders do not arrive.

Figure 6 shows the relationship between each flexibility index and the parameter for setting the production capacity γ, which can control the normalized average lead time within a certain value of *ALT*. A trade-off exists between the flexibility indexes and the parameter for setting the production capacity.

Figure 7 shows the relationship between each flexibility index and the workload imbalance. Even if the machine flexibility index increases, the workload imbalance does not decrease because orders cannot be interchanged among machines. Therefore, machine flexibility does not decrease workload imbalance. However, on increasing the routing flexibility index, the reduction rate of the imbalance in workload increases because orders can be processed on alternative machines in the plant. When the process flexibility index is increased, the reduction rate of the imbalance in the workload becomes higher because orders can be processed not only at alternative machines, but also in alternative plants. However, the reduction rate of the imbalance of workload gradually decreases as either the routing flexibility index or the process flexibility index increases.

5.3 Summary of Experimental Results

The following points are noted based on experimental results.

(1) Upon increasing the machine flexibility index, the average lead time decreases because the orders can be processed continuously by grouping them. Thereby, the setup time decreases. Upon increasing the routing flexibility as well as the machine flexibility, the reduction rate of the average lead time becomes greater than that of increasing only the machine flexibility because the workload imbalance among the machines can be decreased.

(2) When the parameter for setting the production capacity increases, the average lead time decreases without increasing flexibility. Increasing the flexibility can be considered to have the same effect as increasing the production capacity.

(3) With increasing flexibility, the average lead time under the condition of emergent orders approaches the average lead time under the condition of no emergent orders.

(4) Machine flexibility does not decrease the workload imbalance because orders cannot be interchanged among machines. The imbalance in workload decreases as either the routing flexibility index or the process flexibility index increases. However, the reduction rate of the imbalance of workload gradually decreases.

6. CONCLUSIONS

Effects of enhancing manufacturing flexibility differ, depending not only on the environment surrounding the manufacturing system, but also the types of flexibility considered. We investigated the impact of three types of flexibility – machine flexibility, routing flexibility, and process flexibility – upon manufacturing performance when these types of flexibility have a hierarchical structure. Results from a series of experiments indicated the relationship between the three types of flexibility indexes and the parameter for setting additional production capacity by which the average lead time can be controlled within an acceptable upper limit. These experimental results provide better insight into potential benefits of the different types of flexibility and their implementation in manufacturing systems.

APPENDIX A

The following is an algorithm assigning orders to an individual plant:

1. Note rows of the *P* matrix (the number of plants) which contain all zeros. Assign the largest of the orders indicated by these rows if more than one exists.
2. Note the order numbers in the row of the *F* matrix, which corresponds to the assigned order, and go to the rows of *P* indicated by these numbers. Replace the assigned order's identification number with a zero. Matrix *F* contains the immediate preceding elements of each individual order.
3. Continue assigning orders following the procedures of 1 and 2 above, adhering to the restriction that Max $E_i(p) \le S_p$. $E_i(p)$ is a rational division of the total work content and S_p is the actual amount of orders assigned to a specific plant. The problem has been solved when the *P* matrix contains all zeros.

REFERENCES

Browne, J., Dubois, D., Rathmill, K. Sethi, S. P., and Stecke, K.E. (April 1984) Classification of Flexible Manufacturing Systems, *The FMS Magazine*, 114–117.

Chandra, P. and Tombak, M. (1992) Models for the Evaluation of Routing and Machine Flexibility, *European Journal of Operational Research*, **60**(2), 156–165.

Benjaafar, S. (1994) Models for Performance Evaluation of Flexibility, *International Journal of Production Research*, **32**(6), 1383–1402.

Brill, P. H. and Mandelbaum, M. (1990) Measurement of Adaptively and flexibility in Production Systems, *European Journal of Operational Research*, **49**(3), 325–340.

Hyun, J. and Ahn, B. (1992) A Unifying Framework for Manufacturing Flexibility, *Manufacturing Review*, **5**(4), 251–260.

Newman, W. R., Hanna, M. and Maffei, M. (1993) Dealing with the Uncertainties of manufacturing: Flexibility, Buffer and Integration, *International Journal of Operations & Production Management*, **13**(1), 19–34.

Sethi, A. K. and Sethi, S. P. (1992) Flexibility on manufacturing – a survey, *International Journal of Flexible Manufacturing Systems*, **2**(4), 289–328.

Toni, A. D. and Tohchia, S. (1998) Manufacturing flexibility: a literature review, *International Journal of Production Research*, **36**(6), 1587–1617.

Tsubone, H. and Horikawa, M. (1999-a) A Comparison Between Machine Flexibility and Routing Flexibility, *International Journal of Flexible Manufacturing Systems*, **11**(1), 64–83.

Tsubone, H. and Horikawa, M. (2000) Comparison between machine flexibility and routing flexibility with bottleneck job shop, *Journal of Engineering Valuation and Cost Analysis*, (to appear).

Tsubone, H. and Horikawa, M. (1999-b) Impact of various flexibility types in a hybrid fabrication/assembly production system, *International Journal of Production Economics*, **60/61**, 117–124.