



On flexibility investment in manufacturing system: A multi-objective decision making method

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ABSTRACT

In today's market, flexibility has received much concern of companies because of its important role in responding to the ever-changing environment. Most of the research in the literature on flexibility investment is focused on one objective, i.e. profit maximization. However, more and more company managers and customers pay much attention to another objective, i.e. production efficiency maximization. There is a need to develop flexibility investment strategy by considering these two objectives simultaneously. In this paper, we propose a multi-objective decision making method to derive the optimal flexibility investment strategy. Both efficiency and profit are taken into account as objectives when making flexibility investment decisions. The proposed method is a hierarchical method which composes of two-level models. Based on the characteristics of the models, a guideline is presented to help managers conveniently find out the optimal flexibility investment strategy. Simulation experiments are performed to verify the validity of the proposed models and guideline. The results of the simulation illustrate that the flexibility configuration obtained by following the guideline leads to benefit very close to total flexibility configuration, and much higher than 2-Skill Chain configuration; while the cost much less than total flexibility configuration, and even less than 2-Skill Chain configuration.

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1. Introduction

Global competition and shortened product life cycles bring to the diversification of customer demand and the increasing complexity of the production environment (Chan, Bhagwat, & Wadhwa, 2007). Faced with these pressures, more and more companies invest on flexible manufacturing systems (FMS). Typically, flexibility refers to the ability that machines can process various parts without requiring a prohibitive effort in switching from one part to another (Chen & Chung, 1996; Jordan & Graves, 1995). Flexibility provides companies the ability to match production to market demand (Sethi & Sethi, 1990), thereby increasing profits, capacity utilization and customers' satisfaction. Despite of its benefits, however, flexibility comes at the expense of increased cost of requiring flexible manufacturing capacity, as compared with dedicated or nonflexible capacity (Fine & Freund, 1990). Thus how to invest for flexibility in a manufacturing system is an important problem for decision makers.

The extant literature on flexibility investment strategies can be approximately categorized into two groups. Researches in the first group start with building a flexibility measure, followed by finding out the configuration with satisfactory flexibility but not much

investment cost. Examples in this kind include Jordan and Graves (1995), Graves and Tomlin (2003), Iravani, Van Oyen, and Sims (2005), Hua and He (2010a, 2010b), etc. Jordan and Graves (1995) propose an index to measure the process flexibility of a system configuration. Based on the index, they find that few and long chains can have nearly the same performance (expected sales quantity) as total flexibility configuration. Following this work, Graves and Tomlin (2003) find that the chaining structure is also effective for supply chains. Iravani et al. (2005) propose a set of measures for structural flexibility by solving maximal flow problems. They also verify that the chaining structure performs rather well. Considering bill of material (BOM) constraints, Hua and He (2010a) present a set of hierarchical measures for process flexibility of production line and manufacturing system. Based on these measures, Hua and He (2010b) propose some flexibility investment guidelines for decision makers.

Researches in the second group identify the flexibility investment strategies by directly solving flexible capacity investment or production programs. For example, Fine and Freund (1990) present a model of the firm's flexible manufacturing investment decision. With the aid of the model, they characterize the necessary and sufficient conditions for a firm to invest in flexible capacity to protect efficiently against uncertainty in demand for all of its products. Van Mieghem (1998) highlights the important role of price and cost mix differentials, which significantly affect the

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investment decision and the value of flexibility. Akşina and Karaesmen (2007) identify preferred flexibility structures in service or manufacturing systems, by solving a network flow type model. They find out general structural properties of flexibility design pertaining to the marginal values of flexibility and capacity. Gong and Hu (2008) develop a product mix flexibility model, in which the product mix flexibility is measured by an economic index. They identify the bottlenecks that affect the flexibility most. Chou, Chua, Teo, and Zheng (2009) give some analytical results on the performance of chaining strategies vis-à-vis the total flexibility system.

The literature reviewed above investigates the flexibility investment problem with the only objective of profit maximization (or equivalently cost minimization). In the competitive market of today, there is another objective that companies also pay much attention to, i.e. production efficiency. Production efficiency is an important factor that affects customer satisfaction. In today's market, time-based competition makes more and more companies focus on production efficiency (Koufteros, Vonderembse, & Doll, 1998). Production efficiency is mainly determined by the time spent to complete the production of all the demand. However, time and cost are often inversely related (Gupta & Goyal, 1989). In most cases, time and cost have their trade-off and time might be more important than cost (Chang, Whitehouse, Chang, & Hsieh, 2001). For non-homogeneous machines and parts (i.e. the unit processing cost as well as processing time is different for different machine-part pairs), different flexibility configurations lead to different system performance (in terms of profit-efficiency mix). Considering these two objectives, the flexibility investment methods reviewed above are not applicable. It is necessary to build a multi-objective method (Wang & Zeng, 2010; Wu, Sukoco, Li, & Chen, 2009) on flexibility investment for companies.

This paper aims to propose a multi-objective decision making method for guiding flexibility investment. The rest of the paper is organized as follows. In Section 2 we define the problem to be investigated, and develop a two-level multi-objective programming model. Section 3 presents a guideline for constructing flexibility configuration based on the proposed model. Section 4 discusses the way the weights of multiple objectives can be determined. A set of simulation experiments is performed in Section 5 to verify the proposed models and guideline. Section 6 concludes this paper.

2. Model

In this section, we formally define the problem, and propose a two-level method to help managers on flexibility investment decisions. The higher level corresponds to flexibility investment decisions, while the lower level corresponds to production planning decisions. At the lower level, optimal production decisions are made by a multi-objective model, with any given system configuration and demand realization. Based on this model, the improved system performance with given flexible configuration compared with rigid configuration is obtained. At the higher level, another model is developed to search for the optimal flexible configuration which brings the maximal net benefit (improved performance minus the flexibility investment cost) to the system. The optimal solution of the higher level model is the flexibility investment strategy for system managers.

2.1. Problem description and notations

Faced with various customer demand and complicated production environment, managers of many companies are increasingly interested in investing flexible technologies. Flexible machines can switch from producing one part to another without much cost,

according to the changing demand of parts. Flexibility makes the system better satisfying customer demand and simultaneously improves capacity utilization of machines (Jordan & Graves, 1995). By flexibility investment we mean making one or more machines able to process more than one part. This investment does not increase the machine's total working time but only increases its capability set. In this paper, we define a flexibility investment strategy to be a set of decisions on the capability set of each machine.

For a rigid manufacturing system, there are numerous flexibility investment strategies to change it to a FMS. As argued in the first section, different flexibility investment strategies may lead to different system performance on multiple objectives. The most suitable one for a specific company depends on the additional benefit and cost brought by the flexibility investment strategy, as well as the weights on each objective imposed by the system manager.

Consider a manufacturing system which has K machines available for processing P parts. For the convenience of description, we define rigid manufacturing system as that one machine can only process one part, in case of $K = P$. If $K \neq P$, we define "rigid" manufacturing system as the manufacturing system before flexibility investment. The manufacturing system is a Make-to-Order (MTO) system, i.e. it produces part after receiving demand information in each planning horizon. Demand of each part is uncertain, but the total work time of each machine is fixed. Unfilled demand in each planning horizon is assumed to be lost and there is no penalty for the unfilled demand. Setup time and setup cost are taken into account when machines switch between producing different parts.

Notations are defined as follows.

Parameters:

k : index of a machine, $k = 1, \dots, K$

p : index of a part, $p = 1, \dots, P$

D_p : demand realization of part p in a planning horizon

T_k : total working time of machine k in a planning horizon

t_{pk} : operation time for machine k to process one unit of part p

c_{pk} : operation cost for machine k to process one unit of part p

S_{pk} : setup time for machine k to switch from producing other part to part p

C_{pk} : setup cost for machine k to switch from producing other part to part p

v_p : market price of one unit of part p

N : number of planning horizons that the manufacturing system works

r : interest rate for a planning horizon

ρ : discount rate for a planning horizon; $\rho = 1/(1+r)$

λ : cost for a machine to add one capability for processing a part

Decision variables:

A_{pk} : indicator; $A_{pk} = 1$ if machine k is able to process part p ;

$A_{pk} = 0$ otherwise

Q_{pk} : the number of part p processed by machine k in a planning horizon

$\delta(Q_{pk})$: indicator; $\delta(Q_{pk}) = 1$ if $Q_{pk} > 0$; $\delta(Q_{pk}) = 0$ if $Q_{pk} = 0$

2.2. Multi-objective model for production planning

At the lower level of the proposed method, a multi-objective model is built to find the optimal production decision, according to the multiple objectives set by decision-makers.

Before we introduce the multi-objective model, it is necessary to define the objectives considered in our model. In general, profit is an obvious objective pursued by any company. In each planning horizon, the profit of a manufacturing system depends on the

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