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Impact of reconfiguration characteristics for capacity investment strategies in manufacturing systems

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ABSTRACT

The increasing frequency of new product introductions force today's companies to continuously upgrade their production capacities. The frequent revision of production capacities and the capacity loss during the reconfiguration period increase the importance of ramp up duration in evaluating capacity investments. This paper aims to explore how a firm should optimally allocate its capacity investments among dedicated manufacturing systems (DMSs), flexible manufacturing systems (FMSs) and reconfigurable manufacturing systems (RMSs) considering the capacity evolution in ramp up period. The proposed model addresses a firm making multiple products for which demand is deterministic and has a specific life cycle. Furthermore, the duration of reconfiguration period is modeled as a function of the amount of capacity change.

1. Introduction

Manufacturing paradigm has shown rapid changes in the past decades due to an aggressive market competition on a global scale. Manufacturing system paradigms have evolved from mass production (dedicated lines), which focuses on the reduction of product cost; to lean manufacturing, which improves product quality while decreasing product costs; and then to flexible manufacturing systems (FMSs), which address changes in work orders, production schedules, part programs, and tooling for production of a part family. FMS is able to make a variety of products on the same system but the disadvantages of a flexible manufacturing system include a high initial investment, fixed hardware, and fixed but programmable software. These disadvantages cause a major problem for manufacturers who want to adapt to the new technologies. Mehrabi et al. (2000) review available manufacturing techniques; their key drivers and enablers; and their impacts, achievements, and limitations. According to the survey conducted by the authors, around 73% of manufacturers are looking for a system that could accommodate an incremental increase to their existing production system's capacity rather than the extra functionality delivered by an FMS. To cope with this limitation, a new manufacturing system technology must provide minimum lead time for launching and integrating new technologies while having the capability to upgrade quickly to new functionality.

A reconfigurable manufacturing system (RMS) is defined as a comprehensive system which provides exact required functionality and capacity. RMS has better scalability than dedicated and flexible manufacturing systems. The key rule for RMS is to meet the uncertainties of the open system architecture at the machine, shop floor and system levels. In other words, RMS promises to have a modular structure (software and hardware) that allows for the ease of reconfiguration as a strategy to adapt to market demands. Moreover, the modular structure of RMS enables the system to integrate/remove new software/hardware modules without affecting the rest of the system. Thus, RMS possesses the advantages of both DMS and FMS and occupies a middle ground between them in terms of quantity and variety. RMS could be a solution to industries in search of a system that is more adaptable to changes in terms of capacity and gradual changes in functionality.

Although reconfigurable manufacturing system is a new paradigm in manufacturing systems, it might not be the best option and solution for all industries and manufacturers. There may be two main reasons for this. First, technology selection depends on different factors such as the scalability characteristics of the manufacturing system, product life cycles, market behavior, frequency of new products to market, and the cost of acquiring new capacity, as well as market economy and political situations. For instance, due to monopoly and lack of competitors, some markets such as chemical industries might benefit more from the dedicated manufacturing systems. In contrast, in markets, such as the electronic industry, where the frequency of new products is

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high, Flexible Systems might be more advantageous. Furthermore, when either excess capacity or shortage of product is vital for a firm from the strategic point of view, the characteristics of the manufacturing systems must be evaluated in the selection of a system.

Secondly, agility is the premise of RMS in responding to unexpected market changes quickly. Therefore, ramp up time and reconfiguration period are important characteristics to assess the responsiveness of RMS. In other words, reconfiguration period is the major factor in assessing the agility of RMS and its capability to capture the market demand. Therefore, while selecting the manufacturing system alternatives, companies should consider the impact of reconfiguration and the relevant RMS cost structure.

In this paper, we develop a decision model based on dedicated, flexible, and reconfigurable manufacturing characteristics to explain how product life cycle and frequency of new product introductions could affect the selection of manufacturing systems. The ramp up time and reconfiguration period of RMS is incorporated in the model as a function of the amount of added or removed capacity. Thus, through an analysis of parameters such as excess capacity cost, shortage cost, reconfiguration speed, we examine how the capacity portfolio of manufacturing systems is selected.

The paper outline is as follows: Section 2 reviews the relevant literature. In Section 3, the problem statement is presented along with the assumptions and characteristics of each manufacturing system. In Section 4, we represent the characteristics of dedicated, flexible, and reconfigurable manufacturing systems by a mathematical model. In Section 5, we solve the model to understand which manufacturing system is desirable under what condition(s). Numerical results are discussed in Section 6. Conclusion and future research directions are presented in Section 7.

2. Literature review

Capacity planning and management usually consists of determining the type of production systems as well as capacity expansion/contraction times. Julka et al. (2007) mention that the first opportunities in capacity planning area lie in expanding the set of factors deemed important for capacity expansion. Luss (1982) categorizes the major factors affecting the capacity management as: size, time, location, cost, demand, differing expansion, decision maker constraints, and capacity modification. With the increasing volatility of demand and more frequent product introductions, the planning of capacity becomes even more important for capital intensive industries. This problem can be analyzed at the strategic, tactical and operational levels (Wu et al.;2005). While the strategic level approach focuses on capacity investment decisions from the supply chain perspective and strategic interactions between two or more players, the operational level focuses on product and firm-specific operational environment.

Dedicated, flexible, or reconfigurable systems represent different characteristics in terms of scalability, especially from the perspective of lead time during capacity changes. The differentiating factor of scalability and ramp up pattern will have the most visible impact on tactical level decision making in terms of capacity expansion decisions and production allocation to each capacity type. Therefore, we focus on the tactical level analysis of capacity planning from a firm's perspective by differentiating capacity types such as dedicated, flexible, and reconfigurable systems. In this section, we review the literature on capacity planning models that incorporate the lead time behavior and capacity scalability at strategic, tactical, and operational levels.

At the strategic level, most of the studies are performed using dynamic stochastic optimization models to incorporate randomness and to account for the tradeoff between excess capacity costs and lost sales during capacity expansions. Van Mieghem (2003) provides a detailed review on capacity management where factors such as risk aversion, multiple capacity types, hedging and demand stochasticity are modeled. Ryan (2004) considers an option pricing based model which takes into account uncertain exponential demand growth and expansion lead times. In an extension of this work, Ryan and Marathe (2009) formulate a model to minimize expected discounted expansion cost under a service level constraint for infinite horizon. In both of these works, the authors consider only the capacity expansion and ignore the effects of capacity reduction. Moreover, the capacity expansion lead time is considered fixed; therefore, these studies ignore the partial capacity that can be available during the expansion period.

In addition to incorporating lead time effects, the capacity scalability or lumpiness of capacity of manufacturing systems is also considered at the strategic level by several authors. Narongwanich et al. (2002) develop a model, which optimally allocates capacity investments between dedicated systems (DMSs) and reconfigurable systems (RMSs) in different demand scenarios. The result of their model shows that firms should keep a portfolio of dedicated and reconfigurable machines tools, and the mix should be driven by relative costs of each, considering the frequency of new products to market and the stochastic nature of demand level. They argue that ISD policy is valid when the capacity comes in discrete increments rather than continuous and is optimal when the DMS and RMS modules have identical module sizes. Equality of DMS and RMS modules is not a valid assumption since RMS aims to provide better scalability. In order to highlight the importance of the scalability factor, Deif and ElMaraghy (2007) propose a model to manage capacity scalability on the RMS at system level according to total investment cost. The proposed model relaxes the assumption of fixed capacity increments, thereby giving the system designers ability to decide when to reconfigure the system according to the scale of capacity and by how much to scale it in order to meet the market demand in a cost-effective way. However, this model assumes that the lead time is zero and ignores the ramp up period.

At the tactical and operational level, most of the previous works focus on multiple period problems using mixed integer programming or stochastic programming approach to account for the demand uncertainty. Ceryan and Koren (2009) show how a range of investment cost parameters, product revenues and demand uncertainties influence capacity portfolio by considering dedicated and flexible manufacturing systems which have different scalabilities. Authors analyze multiple products' demand for three consecutive periods using stochastic programming approach; however, they do not integrate the lead times for capacity modifications.

The optimal control theory based works by Asl and Ulsoy (2003), Matta et al. (2007) develop an optimal policy where reconfiguration periods are considered in a single product with random demand environment. In the model proposed by Matta et al. (2007), the ramp up is limited to a maximum of 50% of the available period. While this work is one of the better representations of ramp up periods, the duration of the ramp up is independent of the amount of capacity increase. According to Terwiesch and Bohn (2001), who investigate the impact of learning on the duration of ramp up, the time to reach full capacity decreases as learning is achieved through the experiments performed during ramp up periods. These prior works show that the throughput performance of manufacturing systems is affected by the activities during the ramp up period.