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Evaluating flexibility in discrete manufacturing based on performance and efficiency

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ABSTRACT

Recent economic developments indicated that greater flexibility in manufacturing is more important than ever and we consider flexibility as a key objective of many manufacturing systems. The ability to provide a certain degree of flexibility of production systems must be prioritized in future manufacturing. The purpose of this paper is to present an applicable approach for the evaluation of flexibility in discrete manufacturing. Therefore, we developed a two-dimensional model to capture the performance and the efficiency of batch production systems. As a result, to evaluate manufacturing flexibility, we calculate a coefficient of variation from the deviations of the production order lead times. In addition, we compute an efficiency coefficient that indicates whether increased flexibility results from the manufacturing performance or from production waste, such as excessive inventory levels and/or excess capacities. The current flexibility model shows how to determine the degree of manufacturing flexibility and how to illustrate different flexibility situations and any improvements in flexibility. Our evaluation approach is based on readily available data and it is applicable to any batch production system with discrete manufacturing processes. Finally, we provide a clearly arranged guideline for practitioners clarifying the evaluation procedure and the computational steps to evaluate the manufacturing flexibility. The practical feasibility and the application of the current approach are demonstrated by an example that shows exactly how to evaluate the manufacturing flexibility and how to measure an improvement of flexibility in business practice.

1. Introduction

Many companies are shaped by customer-driven markets, short innovation cycles and increasingly rapid technological leaps. Consequently, rapidly changing customer requirements and accelerated innovation cycles are leading to shorter product lifecycles and greater product variety. Moreover, many companies in cyclic industries are increasingly facing volatile demand and must adjust their production volume within short time spans without incurring major costs. Prospectively, in many industries, only highly flexible manufacturing companies will be able to meet customer demand rapidly by responding effectively to changing customer requirements (Bordoloi et al., 1999; Koufteros et al., 2002; Winkler, 2009; Winkler and Seebacher, 2011). As a result, manufacturing systems must become much more adaptable to changing conditions regarding product variety and production volume (De Toni and Tonchia, 1998; Zhang et al., 2003). In fact, stable performance under changing conditions depends on a manufacturing system's ability to handle fluctuations in production volume by remaining volume-flexible while maintaining low inventory levels (Jack and Raturi, 2002). Furthermore, a high level of product flexibility is required to provide customized products without cost or time penalties to the company (Koste and Malhotra, 1999; Jacobs and Swink, 2011).

Consequently, manufacturing companies must improve their manufacturing flexibility to potentially obtain a sustainable competitive edge in the future. Hence, for many companies, manufacturing flexibility is an important strategic success factor that must be designed and enhanced in a targeted manner. However, this strategy presupposes the existence of comprehensive flexibility management that allows for a requirement-oriented design of the necessary flexibility in manufacturing (Sethi and Sethi, 1990; Ketokivi, 2006; Winkler and Seebacher, 2012a). Thus, target-oriented flexibility management must be considered a key issue in future manufacturing. On one hand, this practice requires a seamless identification of the crucial drivers and constraints of manufacturing flexibility (Narasimhan et al., 2004; Winkler and Seebacher, 2012a). On the other hand, it is essential to be able to assess the current flexibility in manufacturing (Shuiabi et al., 2005;

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Tierney et al., 2012). Assessment is a major challenge for manufacturing companies because it is extremely difficult to measure and evaluate manufacturing flexibility. This difficulty exists mainly because manufacturing flexibility depends on numerous interdependent factors, whose mutual influence is particularly difficult to reproduce (Pagell and Krause, 1999). To date, different scientific approaches have been published on how to calculate a flexibility measure for a single machine or certain groups of machinery and equipment (e.g. Abdel-Malek and Wolf, 1991; Chang et al., 2001; Wahab et al., 2008; Baykasoglu, 2009, Chang, 2009). Other approaches focus either on the measurement of the process flexibility or on the routing flexibility within an existing manufacturing system (e.g. Das and Nagendra, 1997; Chang, 2007; Wahab and Stoyan, 2008; Ahkioon et al., 2009; He et al., 2012). Manufacturing flexibility, however, depends on a variety of other factors as well, such as in-plant transport times, waiting times, quality level, capacity utilization, and inventory levels. Although previously published approaches attempt to evaluate the parts of systems or the system as a whole, they neglect flexibility related processes, such as handling and/or queues in the order processing. Finally, different scientific approaches have been developed to assess either the volume flexibility or the product mix capability of a manufacturing system (Berry and Cooper, 1999; Bengtsson and Olhager, 2002; Jack and Raturi, 2003; Gaimon and Morton, 2005; Gong and Hu, 2008; Hasuike and Ishii, 2009).

However, it is more practical to assess manufacturing flexibility independently of any variants and regardless of the processes and resources employed in manufacturing. Moreover, most of the current mathematical and stochastic approaches to evaluate or measure the flexibility in manufacturing are far from the cases met in the industry because of the underlying constraints. It is precisely for this reason a priority task in flexibility research to provide a measurement approach that is easy to implement in practice. Thus, this paper provides an application-oriented approach to evaluating manufacturing flexibility. Our evaluation model enables any manufacturing company to determine the flexibility of its discrete manufacturing system. Furthermore, we present a brief numerical example showing how to apply our flexibility model and how to measure the flexibility of a manufacturing system. In addition, we show how to evaluate an improvement in manufacturing flexibility.

2. Theoretical foundation and model development

2.1. Review of flexibility in manufacturing

Considerable efforts have been made to define flexibility and to examine its determinants. Flexibility can be defined as the ability to respond to changing conditions within a very short time and with little penalty in cost and performance (Upton, 1995). The importance of manufacturing flexibility has been widely discussed in the academic literature as well (e.g. Slack, 1988; Gerwin, 1993; Koste and Malhotra, 1999; Vokurka and O'Leary-Kelly, 2000; Cousens et al., 2009; Camisón and López, 2010; Esturilho and Estorilio, 2010; Lucas and Kirillova, 2011; Patel, 2011; Winkler and Seebacher, 2012a; Patel et al., 2012; Seebacher and Winkler, 2013). It is important to note that the literature agrees on the need for manufacturing flexibility to address internal changes and external uncertainties. Internal changes that might require greater manufacturing flexibility include equipment breakdowns, variable task times, queuing delays, rejections, and rework (Buzacott and Mandelbaum, 1985; Shanthikumar and Yao, 2007; Wahab and Stoyan, 2008). External uncertainties may exist regarding the level of demand, product prices, product mix, and the availability of resources. These uncertainties may arise from various sources, including the actions of competitors, changing customer preferences, and technological innovations. Thus, flexibility must be viewed as a key objective of any manufacturing system, and the issue of manufacturing flexibility is an increasingly important competitive strategy in an ever more rapidly changing business environment. Sethi and Sethi (1990) defined manufacturing flexibility as the ability to reconfigure manufacturing resources to produce different products of adequate quality efficiently. Basically, it describes the ability to adjust the manufacturing system in order to handle the instability induced by internal changes and external uncertainties without any perceptible loss of performance (D'Souza and Williams, 2000). Because of the multidimensional nature of manufacturing flexibility and a multiplicity of interdependent factors, many different types and dimensions of manufacturing flexibility have been defined and discussed in the academic literature. Browne et al. (1984) defined eight flexibility types, including operational, process, production, routing, and equipment flexibility. Subsequently, Gerwin (1987) emphasized the significance of material handling and changeover flexibility in manufacturing. Sethi and Sethi (1990) identified 11 dimensions of manufacturing flexibility and provided a three-stage system of flexibility dimensions. Koste and Malhotra (1999) provided a hierarchical structure of 16 flexibility dimensions on five different levels ranging from the strategic level to the flexibility of the individual resources in manufacturing. This framework has been empirically tested by Koste et al. (2004) to measure the dimensions and to better understand manufacturing flexibility. There is a vast literature that provides empirical measures of manufacturing flexibility. In brief, there have been persistent attempts to empirically measure the dimensions of manufacturing flexibility and to examine its influencing factors. Furthermore, empirical research has focused on the relationship between uncertainty, manufacturing flexibility and performance (Collins et al., 1998; D'Souza and Williams, 2000; Pagell and Krause 1999, 2004; Narasimhan et al., 2004; da Silveira, 2006; Allmayer and Winkler, 2012; Patel et al., 2012; Chauhan and Singh, 2013).

2.2. Review of operational flexibility metrics, gaps and motivation

Many researchers noted that there is a lack of operational metrics of manufacturing flexibility and that the existing approaches and schemes had not been adopted by manufacturing companies (Gerwin, 1993; Berry and Cooper, 1999; Koste et al., 2004; Shuiabi et al., 2005; Kristianto et al., 2012). Nevertheless, various mathematical models and stochastic approaches to evaluate flexibility in manufacturing have been developed and published thus far, and there have been persistent attempts to measure flexibility in manufacturing (e.g. Pereira and Paulré, 2001; Beskese et al., 2004; Shuiabi et al., 2005; Wahab et al., 2008; Wahab and Stoyan, 2008; Tierney et al., 2012; Bertsimas et al., 2014). Brill and Mandelbaum (1989) proposed measuring the efficiency with which the manufacturing equipment performs its tasks. Therefore, different criteria, such as quality, throughput, setup times, and the number of different tools, have been considered to assess the efficiency of the manufacturing equipment. Depending on a particular set of efficiently executable tasks, the flexibility is calculated based on the efficiency of the manufacturing equipment (Brill and Mandelbaum, 1989). Equipment efficiency and the efficient design of production processes have been repeatedly used to measure the flexibility in manufacturing (e.g. Mathur et al., 2011). For instance, Wahab's (2005) work focused on the measurement and valuation of equipment flexibility. The author noted that a high level of equipment flexibility implies a high degree of product flexibility (i.e., more product variants can be produced because more processes are feasible). According to Wahab (2005), a flexible production system is characterized by production