Int J Adv Manuf Technol (2006) 29: 1002–1007
DOI 10.1007/s00170-005-2603-3

ORIGINAL ARTICLE

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Comparative influence of three flexibility types on manufacturing lead-time performance

Received: 19 April 2004 / Accepted: 2 February 2005 / Published online: 23 November 2005

Abstract This paper presents the results of a conceptual study and simulation experimentation aimed at understanding the impact of three important types of flexibility on the lead-time performance of a manufacturing system. The three flexibility types, viz. transformation flexibility, sequencing flexibility and product flexibility have been identified based on a new conceptual model for flexibility in manufacturing systems and supply chains. The influence of these three flexibility types has been studied using simulation models. The studies indicated that among the three, product flexibility has the greatest influence followed by transformation flexibility and the sequencing flexibility. The reasons for the inferior performance of sequencing flexibility is found to be reduction of dynamic flexibility levels as compared to its static flexibility levels and the reasons for superior performance of product flexibility is found to be the lower movement of products within the manufacturing system.

Keywords Lead-time performance · Product flexibility · Sequencing flexibility · Simulation studies · Transformation flexibility

1 Introduction

Flexibility refers to the ability to respond to changes in business environment. From a historical perspective, the notion of flexibility originated in economics literature, in the 1930s, in the context a firm's ability to accommodate greater variations in the demand for its outputs [1]. Later the idea was widened to encompass all forms of turbulence in the firm's environment. The concept of flexibility has been attracting the attention of many researchers and several authors made rich contributions to this domain [2–13]. Recently the focus of research is shifting to the flexibility of organizations and supply chains where more than one flexibility type are involved. With growing turbulence in the business environment, flexibility is considered as an important enabler for competitiveness.

Some flexibility types like "routing flexibility" have received the attention of several researchers [14–20], while there are many other flexibility types that are not even discussed in the literature. Also, studies encompassing more than one type of flexibility are very rare. Keeping this in view this paper addresses the comparative influence of three important types of flexibility in manufacturing systems and supply chains. The paper presents the above in three parts. The first part focuses on identification of the three flexibility types with the help of a new conceptual framework. Then the second part presents results of simulation studies on the influence of the above three flexibility types. The third part presents a comparison of the three flexibility types in terms of their influence on manufacturing lead-time and discusses about the possible reasons for inferior performance of sequencing flexibility and superior performance of product flexibility as compared with the performance of transformation flexibility. The last part is dedicated to conclusions.

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2 Identification of three flexibility types with the help of conceptual framework

The three flexibility types studied in this paper have been identified with the help of a new conceptual framework for flexibility in manufacturing systems and supply chains. The conceptual framework emerged as a result of an analysis of various possible inter-relationships between the key elements and the basic constructs of the manufacturing systems and supply chains as discussed below.

The most basic elements of the conceptual framework are products and resources, each of which is represented at three levels in the framework. In the case of products, the three levels of representation are: a given product, a set of products of a given product type and a set of products. In the case of resources, the three levels of representation are, a given resource, a set of resources of a given resource type and a set of resources. Both manufacturing systems as well as supply chains function by processing the set of products through the set of resources to meet the market demands. However, these two sets are related through number of intermediate constructs namely, product types, material type, transformation sequence, transformation type, process type and resource type. Many of these relationships give rise to flexibility. The purpose of this framework is to highlight these relationships to enable better understanding of flexibility.

Every product is of a particular product type and hence the relationship between the product and the product type has no flexibility. This is indicated through a rigid connection (horizontal bar) in the framework. The product type is related to the material type. Since it is possible that a given product type may be manufactured using more than one type of material, this relationship is shown as a flexible connection (vertical bar). For every combination of product type and material type, there will be a transformation sequence. However, it is possible to have alternative transformation sequences. Hence, this relationship is shown as a flexible relationship. The transformation sequence contains transformations of different types. Each type of transformation is connected with a type of process that is required to be performed to bring about the required transformation. Here again there is a possibility of alternative process types being able to perform the required transformation and hence this relationship is also shown to be flexible.

Process types are related to corresponding resource types that are capable of performing these processes. Since it is possible that more than one type of resources may be able to perform the same process or there may be resources with overlapped process capabilities, this relationship is also shown to be flexible. Beyond this, the relationship between the resource and the resource type is not flexible. There may be more than one identical resource. To cater for this the framework represents the set of resource of the same type with a separate construct. Thus, the framework pictorially represents the relationships among the key elements and the basic constructs and the flexibility built into these relationships. It is even possible to visually examine the framework to identify various types of flexibilities.

Based on the above framework several flexibility types have been identified. The framework considers there sources of flexibility; (1) The flexibility originated from the relationship between the key elements and basis constructs (2) flexibility originated from the magnitude of the basic constructs themselves and (3) the flexibility originated from the ability to change certain basic constructs. This analysis indicated the possibility of 174 flexibility types in the proposed conceptual framework. However, these are only possibilities, the actual existence of a flexibility types depends on the fulfilment of the certain conditions.

Among the various basic constructs identified above, the set of material types and the set of process types are more abstract in nature than the others. While the possibility of using alternate

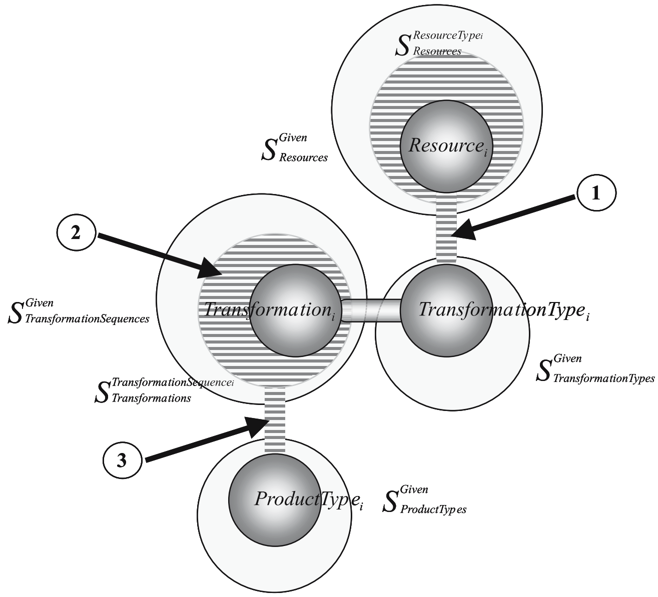

Fig. 1. A simplified conceptual framework for flexibility types

materials for a given product type in a dynamic manner during manufacturing exists, making this concept operational in real life requires considerable effort. It is clearly a distant possibility. Similarly, for many practitioners it is difficult to distinguish between a process and a transformation. In practice they are used in a synonymous manner. Keeping this in view, a simplified conceptual framework has been evolved as shown in Fig. 1.

Based on the simplified conceptual framework we can identify three important flexibility types. Firstly, flexibility of a given transformation type with reference to a set of resources, which may be referred to as ‘transformation flexibility’. Secondly, the flexibility of interchanging the sequence of transformations within a transformation sequence, which may be referred to as ‘sequencing flexibility’. Thirdly, the flexibility of a given product type with reference to the set of transformation sequences, when the transformation flexibility and sequencing flexibility are constrained, this will be equivalent to the flexibility of a given product type with reference to the set of resources. This may be referred to as ‘product flexibility’. In order to demonstrate the usefulness of the proposed framework we have modelled these three flexibility types of a manufacturing system and studied their influence on the lead-time performance of the manufacturing system, with the help of simulation experimentation. The results of the simulation experimentation are discussed below.

3 Results of simulations experimentation

3.1 Influence of transformation flexibility on the manufacturing lead-time

From the results the following observations may be noted: (1) The manufacturing lead-time monotonously decreases with increasing of the transformation flexibility level (TFL). This indicates that transformation flexibility negatively influences manufacturing lead-time. (2) The influence of transformation flexibility on the manufacturing lead-time appears to be strong ($F = 660.99$) and highly significant ($p < 0.000$). (3) The influence is not uniform at all the levels of flexibility. The results indicate a lead-time reduction of 2508 units of time, for a change in the flexibility levels from a condition of no-flexibility (TFL = 1) to a condition of full-flexibility (TFL = 6), in a diminishing manner as shown in Fig. 2 and Table 1.

The above observations imply that: (1) Manufacturing systems that use transformation flexibility are likely to achieve shorter lead-times as compared to those that do not use it. (2) Manufacturing systems that use greater levels of transformation flexibility are likely to achieve shorter lead-times, but the benefit diminishes with increasing levels of flexibility. (3) The first level of transformation flexibility (TFL = 2) provides the greatest benefit, followed by fewer and fewer benefits at subsequent levels. The lead-time accomplished with the first level of flexibility (TFL = 2) is closer to the lead-time accomplished with full-flexibility (TFL = 6) rather than to the lead-time under the conditions of no-flexibility (TFL = 1). Similarly, the lead-time accomplished with the second level of flexibility (TFL = 3) is closer to the lead-time accomplished with the full-flexibility (TFL = 6) rather than to the lead-time accomplished with the first level of flexibility (TFL = 2). This pattern continued throughout. (4) Since it is generally expected that the levels of investment, magnitude of transition penalties and the performance penalty of having and using flexibility increase with increasing levels of flexibility, the above pattern of lead-time reduction has two implications. Firstly, at lower levels of flexibility the benefits due to flexibility may always outweigh the penalty of using flexibility. Secondly, at higher levels of flexibility the penalty of using flexibility may outweigh the benefits due to flexibility. Hence, there is a need to arrive at judicious levels of flexibility to balance the penalties and benefits.

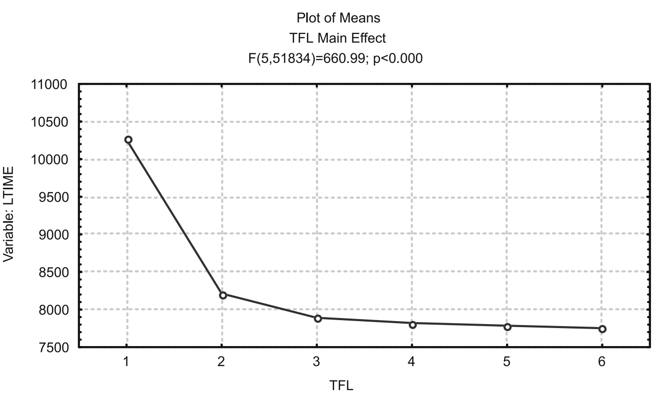

Fig. 2. Pattern of lead-time reduction with transformation flexibility

Table 1. Pattern of lead-time variation with the increasing levels of transformation flexibility

Lead-time variation		To (TFL)				
		2	3	4	5	6
From (TFL)	1	−81.63%	−94.45%	−97.26%	−98.68%	−100%
	2		−12.86%			
	3			−2.77%		
	4				−1.43%	
	5					−1.36%

3.2 Influence of sequencing flexibility on the manufacturing lead-time

Among the several flexibility types of the manufacturing system, there is a distinct type of flexibility called the "sequencing flexibility" originated from the product design characteristics. Keeping in view the possibility that building flexibility into product designs may sometimes be more cost effective than making manufacturing resources flexible, this part of the paper focuses on the influence of sequencing flexibility on the lead-time performance of manufacturing systems.

The potential of sequencing flexibility in enhancing the manufacturing system performance has been recognized by the researchers but very few efforts are reported in the literature. For example, Rachamadugu et al. [21] studied the effects of sequencing flexibility on the performance of various scheduling rules in environments such as job shops and flexible manufacturing systems. Benjaafar and Ramakrishnan [8] introduced several representations and measurement schemes for sequencing flexibility and studied the relationship between sequencing flexibility and system performance under a variety of design assumptions and operating conditions. However, beyond this, no studies could be found in literature on the influence of sequencing flexibility. For instance, how sequencing flexibility differs from other flexibility types in terms of its influence on the manufacturing lead-time, is not discussed in literature. This paper intends to bridge this gap.

From the results the following observations may be noted: (1) The manufacturing lead-time monotonously decreases with increasing of the sequencing flexibility level (SFL). This indicates that sequencing flexibility negatively influences manufacturing lead-time. (2) The influence of sequencing flexibility on the manufacturing lead-time appears to be weak ($F = 2.13$) but significant ($p < 0.0590$). (3) The influence is not uniform at all the levels of flexibility. The results indicate a lead-time reduction of 148.60 units of time, for a change in the flexibility levels from a condition of no-flexibility (SFL = 1) to a condition of full-flexibility (SFL = 6), in a diminishing manner as shown in Fig. 3 and Table 2.

The above observations imply that: (1) Manufacturing systems that use sequencing flexibility are likely to achieve shorter lead-times as compared to those that do not use it. (2) Manufacturing systems that use greater levels of sequencing flexibility are likely to achieve shorter lead-times, but the benefit diminishes with increasing levels of flexibility. (3) The first level of sequencing flexibility (SFL = 2) provides the greatest benefit, followed by lesser and lesser benefits at subsequent levels. (4) The lead-time accomplished with the first level of flexibility (SFL = 2) is closer to the lead-time accomplished with full-flexibility (SFL

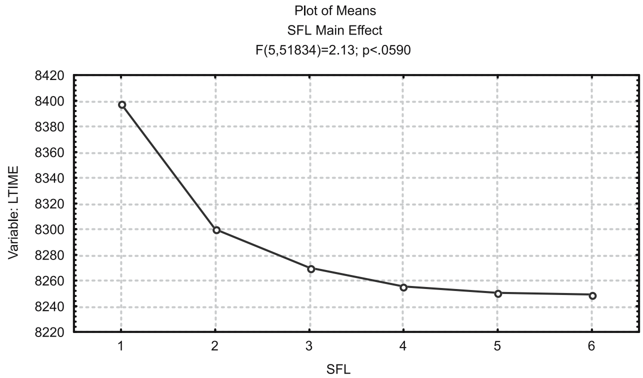

Fig. 3. Pattern of lead-time reduction with sequence flexibility

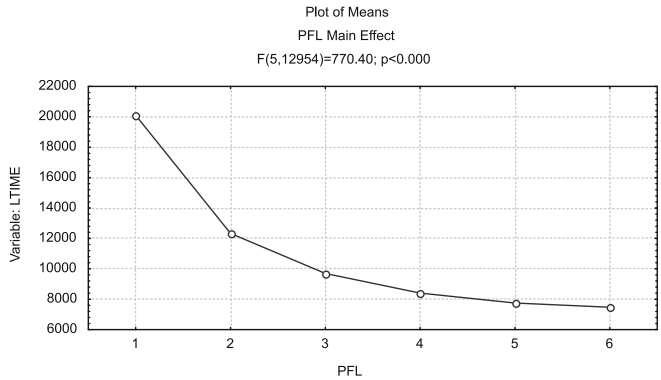

Fig. 4. Pattern of lead-time reduction with product flexibility

Table 2. Pattern of lead-time variation with the increasing levels of sequencing flexibility

Lead-time variation		To (SFL)				
		2	3	4	5	6
From (SFL)	1	−65.81%	−85.95%	−95.80%	−99.13%	−100%
	2		−20.14%			
	3			−9.85%		
	4				−3.33%	
	5					−0.87%

Table 3. Pattern of lead-time variation with the increasing levels of product flexibility

Lead-time variation		To (PFL)				
		2	3	4	5	6
From (PFL)	1	−61.54%	−82.41%	−92.64%	−97.81%	−100%
	2		−20.86%			
	3			−10.23%		
	4				−5.17%	
	5					−2.19%

= 6) rather than to the lead-time under the conditions of no-flexibility (SFL = 1). Similarly, the lead-time accomplished with the second level of flexibility (SFL = 3) is closer to the lead-time accomplished with the full-flexibility (SFL = 6) rather than to the lead-time accomplished with the first level of flexibility (SFL = 2). This pattern continued throughout.

3.3 Influence of product flexibility on the manufacturing lead-time

From the results the following observations may be noted: (1) The manufacturing lead-time monotonously decreases with increasing of the product flexibility level (PFL). This indicates that product flexibility negatively influences manufacturing lead-time. (2) The influence of product flexibility on the manufacturing lead-time appears to be strong ($F = 770.40$) and highly significant ($p < 0.000$). (3) The influence is not uniform at all the levels of flexibility. The results indicate a lead-time reduction of 62.82%, for a change in the flexibility levels from a condition of no-flexibility (PFL = 1) to a condition of full-flexibility (PFL = 6), in a diminishing manner as shown in Fig. 4 and Table 3.

The above observations imply that: (1) Manufacturing systems that use product flexibility are likely to achieve shorter lead-times as compared to those that do not use it. (2) Manufacturing systems that use greater levels of product flexibility are likely to achieve shorter lead-times, but the benefit diminishes with increasing levels of flexibility. (3) The first level of product flexibility (PFL = 2) provides the greatest benefit, followed by lesser and lesser benefits at subsequent levels. (4) The lead-time accomplished with the first level of flexibility (PFL = 2) is closer to the lead-time accomplished with full-flexibility (PFL = 6) rather than to the lead-time under the conditions of no-flexibility (PFL = 1). Similarly, the lead-time accomplished with the second level of flexibility (PFL = 3) is closer to the lead-time accomplished with the full-flexibility (PFL = 6) rather than to the lead-time accomplished with the first level of flexibility (PFL = 2). This pattern continued throughout.

4 Comparative influence between transformation flexibility, sequencing flexibility and product flexibility

The comparative influence of the three types of flexibility on manufacturing lead-time is presented in Table 4.

From Table 4, it may be observed that all three flexibility types influence lead-time. There are a number of similarities and many differences. The important similarities include: (1) all three flexibility types influence lead-time in a negative manner, i.e. the lead-time decreases with increasing levels of flexibility, (2) in all the cases, the benefit due to flexibility diminishes with increasing levels of flexibility, and the first level of flexibility always gives the greatest benefit, (3) in all three cases, the lead-time after the first level is closer to the condition of full-flexibility rather than to the condition of no-flexibility, (4) the possible mechanism of lead-time reduction appears to be the same in all three cases, i.e. with an increase in flexibility levels, concurrency increased and load-unbalance decreased and thus lead-time reduced.

Table 4. Relative influence of transformation flexibility vis-a-vis sequencing flexibility vis-à-vis product flexibility

	Transformation flexibility	Sequencing flexibility	Product flexibility
	Influence on lead-time		
Nature of Influence on Lead-time	Negative (Lead-time reduces with the increase in flexibility)	Negative (Lead-time reduces with the increase in flexibility)	Negative (Lead-time reduces with the increase in flexibility)
Strength and Significance of Influence	Strong and very significant ($F = 660.99$, $p < 0.000$)	Weak but significant ($F = 2.13$, $p < 0.0590$)	Strong and very significant ($F = 770.40$, $p < 0.000$)
Magnitude of Lead-time reduction from the condition of no-flexibility to the condition of full-flexibility.	24.44% of lead-time under no-flexibility condition	01.77% of lead-time under no-flexibility condition	62.82% of lead-time under no-flexibility condition
Diminishing benefit with increasing levels of flexibility	Yes	Yes	Yes
	Pattern of lead-time variation		
From the condition of no-flexibility (FL = 1) to the first level (FL = 2)	−81.63%	−65.81%	−61.54%
From the first level of flexibility (FL = 2) to the second level (FL = 3)	−12.86%	−20.14%	−20.86%
From the second level of flexibility (FL = 3) to the third level (FL = 4)	−2.77%	−9.85%	−10.23%
From the third level of flexibility (FL = 4) to the fourth level (FL = 5)	−1.43%	−3.33%	−5.17%
From the fourth level of flexibility (FL = 5) to the fifth level (FL = 6)	−1.36%	−0.87%	−2.19%

Important differences include: (1) the magnitude of the influence on lead-time is different for all three flexibility types, (2) product flexibility has the greatest influence on lead-time followed by the transformation flexibility and sequencing flexibility, (3) the influence of product flexibility is more than double the influence of the transformation flexibility which in turn is more than double the influence of sequencing flexibility, (4) the benefit due to the first level of flexibility is the greatest for transformation flexibility and lowest for the product flexibility. This is true at all levels. Nevertheless the actual lead-time reduction is always higher for product flexibility, at all levels. (5) While the general mechanism of lead-time reduction appears to be the same, the role of the standard deviation of concurrency appears to be different for different flexibility types. In general, it has a greater role in the transformation flexibility as compared to the product flexibility.

4.1 Possible reasons for the poor performance of sequencing flexibility in terms of its influence on lead-time

In the case of sequencing flexibility, the dynamic flexibility level is different from the static flexibility level. There are two reasons: (1) as more and more transformations are being completed, the flexibility level decreases, as shown in Table 5 and Fig. 5. With the completion of each transformation the level of flexibility will reduce by one, and (2) at any level, the number of transformations remaining to be completed limits the maximum possible flexibility level. Thus the actual flexibility available under SFL is far less as compared to the flexibility available under TFL. This could be one possible reason for its poor performance.

4.2 Possible reasons for the superior performance of product flexibility in terms of its influence on lead-time

In the case of product flexibility, the movement of the products is restricted to only one resource. Whatever may be the number of transformations, all will be performed by the same resource. Under the conditions of more flexibility, a product may be routed to a different resource, but still it will visit only one resource.

Table 5. Pattern of reduction of flexibility levels with the completion of transformations

Dynamic flexibility level	Number of transformations completed 0	1	2	3	4	5	6
Static flexibility level	1	1	1	1	1	1	0
	2	1	1	1	1	1	0
	3	2	1	1	1	1	0
	4	3	2	1	1	1	0
	5	4	3	2	1	1	0
	6	5	4	3	2	1	0

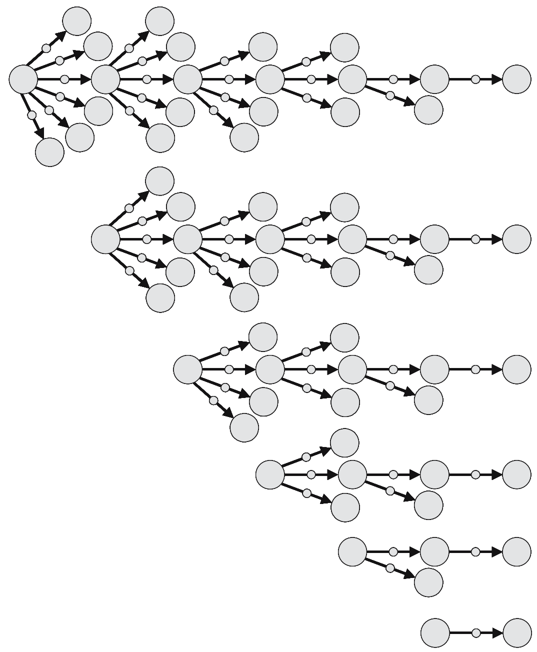

Fig. 5. Pattern of reduction of flexibility levels with the completion of transformations

Where as in the case of transformation flexibility, a product needs to visit multiple resources. As the transformation flexibility level increases, this movement may reduce but will not be completely eliminated. Thus the reduced movement of the products result in a superior performance of product flexibility as compared to the transformation flexibility.

5 Conclusions

This paper presented the results of a conceptual study and simulation experimentation aimed at understanding the impact of three important types of flexibility on the lead-time performance of a manufacturing system. The paper presented the results in three parts: first identification of three flexibility types, influence of the three flexibility types on the lead-time, comparative performance and reasons for performance variance. The three flexibility types, viz. transformation flexibility, sequencing flexibility and product flexibility have been identified based on a new conceptual model for flexibility in manufacturing systems and supply chains. The influence of these three flexibility types has been studied using simulation models. The studies indicated that among the three, product flexibility has the greatest influence followed by transformation flexibility and the sequencing flexibility. The reasons for the inferior performance of sequencing flexibility is found to be reduction of dynamic flexibility levels as compared to its static flexibility levels and the reasons for superior performance of product flexibility is found to be the lower movement of products within the manufacturing system. These observations are important for the designers and managers of flexible supply chain systems to arrive at appropriate types and judicious levels of flexibility to attain a given lead-time performance.

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