INTERNATIONAL JOURNAL OF INTELLIGENT CONTROL AND SYSTEMS
VOL. 10, NO. 2, JUNE 2005, 152-161

Flexibility to Manufacturing Process Reengineering for Mass Customization

Naiqi WU

Abstract- **It is a trend to implement mass customization (MC) to meet customer demands and win the global competition. With mass customization, products can be produced with low cost, high quality, and in time as mass production. To implement MC, today's manufacturing process should be reengineered. However, it is believed that manufacturing process reengineering (MPR) is a highly risk job. A manufacturing system for MC should be highly flexible so as to meet customer demands. Flexibility in manufacturing systems has been recognized as one of the vital competitive priorities in manufacturing strategy. Flexibility should be taken into consideration in MPR to reduce the risk. Thus, flexibility analysis can be used as a tool in the MPR for MC. Consider that the existing theory of flexibility does not provide a guide in manufacturing reengineering for MC, this paper develops a measurement of flexibility in manufacturing systems for customization. This measurement measures not only the impact of manufacturing technology hardware but also the impact of the product design and process design, hence, it can be used as guide in manufacturing reengineering for MC. A case study is presented to show the use of the proposed approach.**

***Index Terms*—Manufacturing process reengineering, Mass customization, Manufacturing flexibility**

1. INTRODUCTION

During the past half century, tremendous changes were made for manufacturing enterprises. As pointed out in [17, 31], in the 1950's and 1960's, it was a seller's marketplace, manufacturers can sell whatever they produced. Manufacturers depended on high volume and low product mix to get economies of sale and keep cost down. However, today it is buyers' market. Customers want customized products. Thus, manufacturing enterprises have to switch to produce customized products in great variety and ultimately this will lead to one of a kind production [17, 31]. At the same time, to gain a competitive advantage, the products must be manufactured at lowest possible cost, with the highest possible quality, and in least possible time. This is a great challenge to manufacturing enterprises. However, today's manufacturing systems are mainly designed to produce standard products with high volume, low product mix. Faced with such severe market demand, companies have to reengineer the ill-conceived, poorly designed, and outdated manufacturing processes. Thus, process reengineering becomes popular.

Process reengineering or business process reengineering (BPR) is defined by Hammer and Champy [16] as "the fundamental rethinking and radical redesign of business processes to achieve dramatic improvements in … performance, such as cost, quality, service and speed." As pointed out in [14], "process reengineering has been fueled by such issues as customers and finance, better coordination and management, and productivity gains." Techniques are proposed to do process reengineering, such as [14, 11, 19, 25, 33]. Companies, such as Ford, IBM, Texas Instruments and others, have successfully reengineered [14]. However, some reengineering attempts failed [7, 21]. As pointed out by Fitzgerald and Siddiqui [13] "They all emphasize the radical nature of the activity and to varying degrees the enabling role of information technology" and "BPR is high risk and difficult and that failure rates are high." It is common that the failure rates are as high as 70% [32]. Fitzgerald and Siddiqui [13] argue that the reasons for this are: 1) the design is often based on current needs and does not address future needs sufficiently well; and 2) the processes and technology are not designed to be flexible. Thus, they suggest considering the flexibility in BPR.

One way to meet the demand of customer driven manufacturing is mass customization (MC) and it is believed that MC is the future manufacturing mode [24, 1]. Companies, such as Motorola, have successfully implemented mass customization for some products [12]. With MC, the customized products can be produced at the cost and in the time of mass production independent of the batch sizes. However, MC cannot be implemented by today's manufacturing systems and they need to be redesigned. While the existing versions of BPR mainly address the nature of activities and the role of information technology, product design and manufacturing process design for MC should also be reengineered. Especially, MC is to adapt to customer demands, flexibility is vitally important. Hence, it is wise to reengineer a manufacturing system for MC by taking flexibility into consideration. Although flexibility has been recognized as a competitive weapon for manufacturers and should be taken into consideration in BPR as suggested by Fitzgerald and Siddiqui [13] and there are theories about flexibility in manufacturing systems, there is no such report to do manufacturing process reengineering (MPR) with flexibility analysis being taken into account. In this paper, we make such an attempt.

With flexibility analysis, in this paper, a model is developed for MPR for MC. The paper is organized as follows. In the next section, we briefly introduce the basic concept of flexibility in manufacturing systems. The measurement of flexibility for customization is developed in Section 3. With a real case problem, in Section 4, we show how to apply the proposed method to reengineer a manufacturing processes so that mass customization can be

Manuscript received October 5, 2004; revised May 1, 2005.
N. Q. Wu is with School of Mechatronics Engineering, Guangdong University of Technology. 729 Dongfeng Road, Guangzhou 510090, China. (e-mail: nqwu@gdut.edu.cn).

implemented. Finally, conclusions are presented in Section 5.

2. CONCEPT OF FLEXIBILITY IN MANUFACTURING SYSTEMS

Flexibility is referred as to the capability of a system to adapt to changes that occur in its environment. However, this raises two questions: adaptation to what? and how? Thus, a variety of concepts of flexibility in manufacturing systems have been developed.

There are different changes to cope with in manufacturing systems and in different situations, different changes should be addressed. Based on different changes, researchers have defined a number of manufacturing flexibilities. Upton [29] defines manufacturing flexibility as the ability to change or react with little penalty in times, effort, cost or performance. Gupta and Goyal [15], and Tincknell and Radcliffe [28] all define manufacturing flexibility as the ability of a system to cope with changing circumstances. Cox [10] defines as the quickness and ease with which a plant responds to changes in the market conditions.

More specifically, Browne et al. [5] defines eight types of manufacturing flexibilities: machine, process, routing, volume, expansion, operation, and production flexibilities for enabling a system to cope with the following types of changes: switch between different part types in a given set of parts, produce a given part in a variety of different ways, move to a different set of products, handle machine breakdowns, vary the total volume of production, add to the total production capacity, switch the sequence of operations on a part type or add to the total set of possible part types. Three more types of manufacturing flexibilities named material handling flexibility, program flexibility and market flexibility are defined in [26]. Such lists of flexibilities in manufacturing systems show that flexibility measures probably should be multidimensional.

While a variety of manufacturing flexibility is defined, flexibility measures are needed for engineers and managers to understand the meaning of flexibility and to implement it. An entropic approach is developed in [20] to measure the routing, loading and operation flexibilities. The measurements for part, process, mix, volume and expansion flexibilities are proposed in [2]. Brill and Mandelbaum [3-4] defined a measure for machine flexibility by measuring a weighted normalized sum of task efficiency. Kochikar and Narendran [18] presents measure for product flexibility and routing flexibility focusing on the processing time of operations. Measurements for volume flexibility and expansion flexibility were also developed in [22]. By using the entropic approach, Chang et al. [8] presents the measurement for single machine flexibility by measuring the versatility and efficiency together. Adjustment degree was defined in [23] as the measure of manufacturing flexibility, which captures the system-environment relationship.

Although there are various approaches to measure manufacturing flexibilities, it is believed that flexibility is very difficult to measure and difficult to improve [30]. In discussing the difficulty in measuring manufacturing flexibility, Buzacott and Kahyaoglu [6] even raise the question: should flexibility be measured? and concluded that flexibility should only be measured with respect to a particular change or disturbance.

The existing theories of flexibilities can indeed measure how flexible a system is for different changes. But they are not very useful for answering the question: how the flexibility of a system should be improved to justify the investment. Thus, it is difficult to use these theories as a guide in MPR. It is this that motivates us to do this work. In MC, the manufacturing system is designed for a special type of products and the changes are particular. Following the conclusion in [6], we can analyze the particular changes for the type of products for the implementation of mass customization and then develop the measurement of flexibility for such systems to justify the MPR for the implementation of MC.

3. MASS CUSTOMIZATION AND FLEXIBILITY

Traditionally, manufacturing depends on high volume and low product mix to get economies of sale and keep its cost down. When customized product was required, customers are willing to pay more and wait for the product. However, with today's customer-driven market, customers want the customized products as well as the same low price, high quality and instant delivery as standard products. As pointed out in [Jagdev and Browne, 1998], for many manufacturers high quality is no longer the basis of competitive advantage, but a necessary precondition. Thus, cost and time to market are vitally important for competition, and manufacturers must produce customized products as efficiently as standard products.

3.1 Mass Customization

Before developing the measure of flexibility for manufacturing systems to implement MC, we should analyze how MC works. Considering the manufacturing process of customized products as shown in Figure 1. When customers order a product according to their likes, the product must likely contain some components (parts) that are standard and common to other products, and some components that are special for the ordered product. While the standard and common components can be manufactured without additional effort, additional time and cost are needed for manufacturing customized components. When both standard-common and customized components are available, then the product can be assembled for delivery.

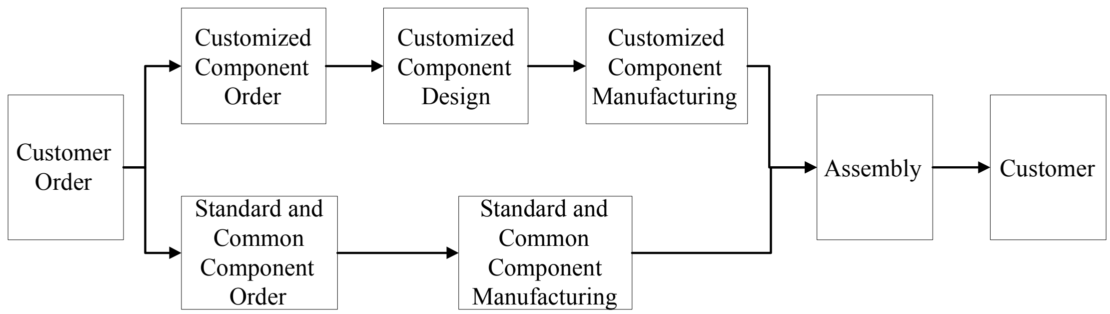

Figure 1. The manufacturing process of a customized product

With the observation of the manufacturing process of customized products, to make MC possible, it is necessary that the manufacturing system should be flexible enough to manufacture the customized components with low cost as standard components manufactured by mass production. This may be achieved by hardware, such as flexible manufacturing system, CAD/CAM, and automation. However, this is not enough, because this does not guarantee an instant delivery. In mass production, it is assumed that the market demand is known from forecast and the instant delivery of products is guaranteed by inventory. Thus, for customer driven manufacturing, even the customized components can be produced as quickly as the standard-common components, there must be a delay for delivery with respect to mass production since we can begin to manufacture the customized components only after the order for the product is made by a customer. Therefore, to implement MC some more techniques are needed.

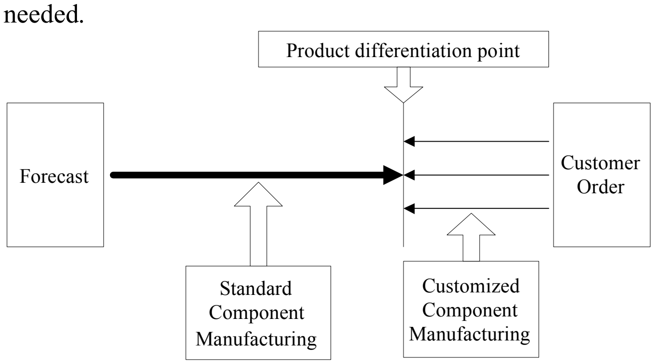

Figure 2. The push and pull phases in the manufacturing of a customized product

In customer driven manufacturing, the product differentiation point (PDP) in the manufacturing process plays an important role. PDP is a time point in the manufacturing process. Before this point, it involves only the manufacturing activities for standard-common components, but after this point, it involves manufacturing process for customization. In the viewpoint of supply chain management, before the PDP, the standard-common components can be manufactured based on forecast with a make-to-stock mode, and after this point it must be done with a make-to-order mode. Thus, a customized product can be manufactured with push and pull phases as shown in Figure 2, and the PDP is the boundary of these two phases. The PDP may be determined by a customized component or just operations involving customization. The PDP in the manufacturing process is heavily dependent on product design and manufacturing process design.

It is clear that if the PDP in a manufacturing process is closer to the time at which the product is sold (or sale point), it is more suitable for this type of products to be of customization, for we can respond to the customer order quickly by performing the operations before the PDP in advance before orders come. There are two ways to make the PDP closer to the sale point. One way is to standardize the components of the products. In this way, we can use as many standard and common components as possible to produce a type of products. Anderson and Pine II [1] point out that standardization is the necessary precondition for a type of products to be of MC. For example, one may use a standard transformer so that it can adapt to different power supply with voltage of 110 volts and 220 volts rather than use two different transformers.

With standardization, the product differentiation between customer orders for a type of products may not be large, but this does not necessarily imply that the PDP is made closer to the sale point than before, for PDP is also dependent on the operations relative to customization. The so-called postponement technique is the other way to delay the PDP. By postponement, the manufacturing process design is changed, so that some operations for the processing of customized components are delayed. To do so, some new manufacturing technology may be required. In this way, the PDP is delayed such that it is as close to the sale point as possible [9]. The goal of doing this is to have standard-common components for a most push phase. This can be achieved by designing an appropriate manufacturing process. By using this technique, Benetton develops a manufacturing technology that allows knitted garments to be dyed to the appropriate color. Thus, greige thread can be purchased, knitted, and assembled into greige garments, and the dyeing of the garments can be done when needed. It is seen that the differentiation among the products is the color, however, the performance difference is great by using different manufacturing process. With the improved one, MC can be implemented.

It should be pointed out that standardization and postponement involve product redesign and manufacturing process redesign. This is shown that product and process design take an important role in the MPR for MC. It can be seen that all the techniques for the implementation of MC are used to reduce effort, cost and time for customization and improve performance of the system. Hence, from the viewpoint of flexibility they can be measured by flexibility.

3.2 Measurement of Flexibility for Customization

Flexibility in manufacturing systems is to describe the versatility and efficiency, in terms of time and economy, or in some sense it measures the performance of a systems. With the discussion about MC, we know that for MC the manufacturing system must be able to produce customized products with the lowest cost and in the shortest time. This exactly matches what the flexibility is to describe. Thus, analyzing flexibility of a system can guide us in MPR for the implementation of MC. The problem is how to describe the flexibility for our goal.

To analyze the flexibility of a manufacturing system for the purpose of MPR for MC, a measurement is required. This measurement should provide an unambiguous meaning of the flexibility and can answer the question: how the flexibility should be improved in justifying the investment. Among flexibility measures, the measures for product, mix, and volume flexibilities seem related to the situation under investigation. These measures indeed say how easily the system can change for the manufacturing of a new product, but they do not tell what the best way is to improve the flexibility. For example, for the Benetton case, one may select to install a rigorous flexible manufacturing system rather than to postpone the product differentiation point, so as to improve the flexibility. Clearly, this is not an effective way to do so.

It is agreed that flexibility goals cannot be achieved by alone. Concurrent investments in human and organizational factors are required [30]. A manufacturing system should contain not only the hardware, but also the software such as product design and manufacturing process design. When the design of a product and/or manufacturing process can make customization easy, it makes a contribution to the flexibility. The design of a product and process may play a much more important role in contributing to the flexibility for MC than other factors do. In fact, the majority of cost for the manufacturing of a type of products depends on the design of the product and manufacturing process. This is shown in the discussion for MC above. However, the existing measurements of manufacturing flexibilities address mainly the flexibility due to the hardware upgrade. Thus, a new measure of flexibility for customer driven manufacturing should be developed, so as it can be used as a guide to MPR for MC.

In developing the measurement of flexibility for customer driven manufacturing systems, criteria are needed. To measure the flexibility for customization, the value of flexibility should increase (decrease) with the PDP close to (away from) the sale point; increase (decrease) with the increasing (decreasing) number of customized products that the system can produce; increase (decrease) with decreasing (increasing) setup time for the manufacturing of customized components; and increase (decrease) with the decreasing (increasing) fixed costs for the manufacturing of customized components.

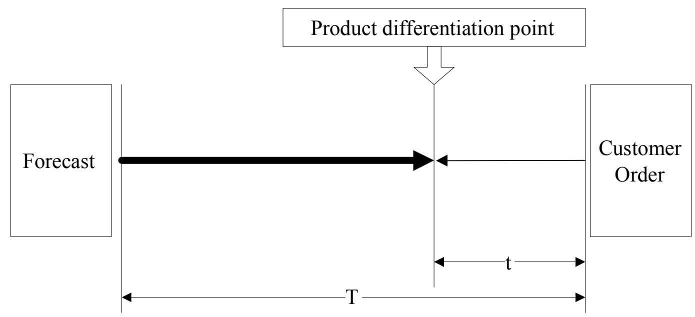

Figure 3. Illustration for product differentiation point flexibility

With the criteria in mind, we are now ready to develop the measurement of the flexibility for MC. According to the above discussion, this measurement should consider the factors: 1) PDP; 2) the number of different products for the product type; and 3) the efficiency in terms of time and cost. We first develop the measure that describes the impact of PDP. We call it the flexibility of PDP and denote it by PF. It is clear that the closer to the sale point the PDP is, the more flexible the system is, for in this case, it is easier to respond to a customer order. As shown in Fig. 3, we let the time from the PDP to the sale point be t and the total time needed to manufacturing a customized product be T. Then we define the PF as the ratio between T and t:

$$\mathrm{PF} = \frac{T}{t} \qquad (1)$$

It is reasonable to measure PF by expression (1), since it reflects the ability of the system to adapt to the product changes. If PF is large, the system is able to produce customized products easily and the system is more flexible. When the PDP goes rightward, then T increases and at the same time t decreases, this results in the increase of PF and the criteria are satisfied, and this shows improvement of flexibility. When T = t, PF = 1, we say the system has no such flexibility.

For customer driven manufacturing, a manufacturing system should produce a variety of customized products. Some systems may offer a limited number of product options, while the others may produce what the customers want for the same type of products. Clearly, the more the number of products a system can produce, the more flexible it is. We call this as versatility flexibility and denote it by VF. Let N denote the number of customized products that a system can produce. To measure this flexibility, we should take the value of N into consideration such that when N becomes infinity the flexibility can be measured appropriately. With this in mind, VF is defined as:

$$\mathrm{VF} = 1 - \frac{1}{N} \qquad (2)$$

With the VF defined above, it is sure that VF increases with N increasing. Further, if a system can produce what the customers want for the same type of products, N then approaches infinity and $\frac{1}{N} \to 0$. Hence, VF = 1, the largest flexibility of VF. However, if N is a limited number, then $\frac{1}{N} > 0$, and VF < 1. Note that N is never less than 1. By the definition this flexibility can be appropriately measured.

While the PF flexibility in the viewpoint of supply chain management measures the efficiency for the customization for the type of products as whole, we need also to measure the adaptability to manufacturing the customized components. According to the above criteria, this can be measured by the efficiency in terms of time and cost. The efficiency in terms of time in changeover to a new customized product can be measured by the setup time for manufacturing the customized components. We call it time efficiency flexibility and denote it as TF. In manufacturing a customized product, there are a number of customized components. However, among the customized components, there must be a component that makes the most contribution to the time delay for delivery, and we call this component a key component. Let T_{set} denote the setup time for manufacturing the key component, $T_{process}$ denote the time needed to process the key component with batch size to be one, and $T_{total} = T_{set} + T_{process}$. With the notion above, the TF is defined as:

$$\mathrm{TF} = \frac{T_{process}}{T_{total}} \qquad (3)$$

It is clear that this definition satisfies the criteria, since T_{total} decreases with the decrease of setup time T_{set}, and thus TF increases with the decrease of T_{set}. When $T_{set} = 0$, then TF = 1, the largest time efficiency flexibility. It should also be noticed that $T_{process}$ is the process time needed for one key component, so in some sense TF also measures the volume efficiency in terms of time.

Similarly, we can measure the efficiency in terms of economy in changeover to a new customized product. We call this cost flexibility and denote it by CF. Assume that there are k customized components (parts) for a new customized product. Let C^i_{fix} be the fixed cost for manufacturing the i-th customized component and C^i_{var} be the variable cost for manufacturing one of the i-th customized component. Further, let $C_{fix} = \sum_{i=1}^{k} C^i_{fix}$, $C_{var} = \sum_{i=1}^{k} C^i_{var}$ and $C_{total} = C_{fix} + C_{var}$, then CF can be defined as:

$$\mathrm{CF} = \frac{C_{var}}{C_{total}} \qquad (4)$$

After PF, VF, TF, and CF are defined, we can measure the flexibility of the total system F as the product of these four flexibilities:

$$F = PF \times VF \times TF \times CF \qquad (5)$$

This measurement describes system flexibility with the four factors considered together. It is seen that this measurement provides not only the evaluation of flexibility for customization, but also tells how the flexibility can be achieved. Because F is a product form, it tells us that we can improve the flexibility of customization by improving PF, VF, TF and CF, respectively. Thus, it can be used as a guide for MPR by effectively improving the system flexibility and to justify necessary investment in doing so.

3.3 Stages of Reengineering by Improving Flexibility

Applying the flexibility measurement for customer driven manufacturing developed above, the stages of reengineering for mass customization can be as follows:

1) Identify the potential changes for the customized products. To make MC possible, the products to be produced should be similar with something different. This differentiation should be clearly identified for the particular situation considered.
2) Identify the PDP in a manufacturing process. With the PDP identified we can examine whether we can postpone the PDP by reconsidering the product design and manufacturing process design so as to improve the PF. To do so some new technology may be needed. It should be pointed out that this stage is very important, because improving the product design and manufacturing process design are the most effective ways to improve the efficiency of the system in terms of cost.
3) Manage to improve flexibilities VF, TF and CF. To do so, some information technology may be needed, such as CIM as applied by Motorola for MC for some products. At the same time, some hardware may be installed. Such investment can be justified by examining the increase of VF, TF and CF.

4. A CASE STUDY

In this section we present a case study to show how flexibility measurement for customization in this paper can be used to help reengineer a traditional manufacturing system to implement MC.

4.1 Case Illustration

This case problem arises from a practical application scenario. A company at Guangzhou, China who produces motor-bicycle fittings for motor-bicycle companies has difficulties in dealing with customer orders. One type of products produced by the company is the motor-bicycle muffler. An illustration of this type of products is shown in Figure 4. In the company, there are facilities that are dedicated to the production of the mufflers. The mufflers produced are a series of products with different models. All the models have the same structure with different size for some parts as shown in Figure 4. Mainly, the product contains two components: main body and connection pipe. However, on the main body of the muffler, there must be a brand required by customers. Surely, different customers require different brands. This creates differentiation for customization. At the same time, the connector should be bent to different shape to adapt to different motor-bicycle for different customer orders. This is another differentiation. For mufflers with the same model, the main body is exactly the same except the brand on it. Similarly, for mufflers with the same model, the pipes to be bent to form the connection pipes are same.

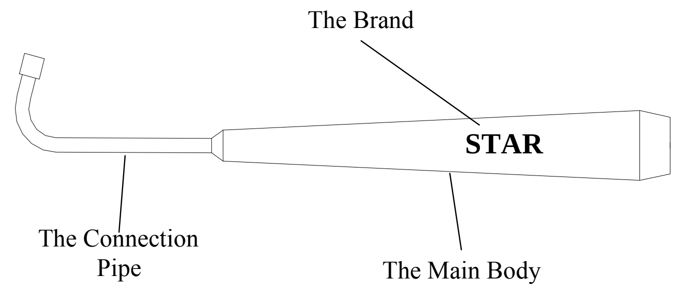

Figure 4. The motor-bicycle muffler

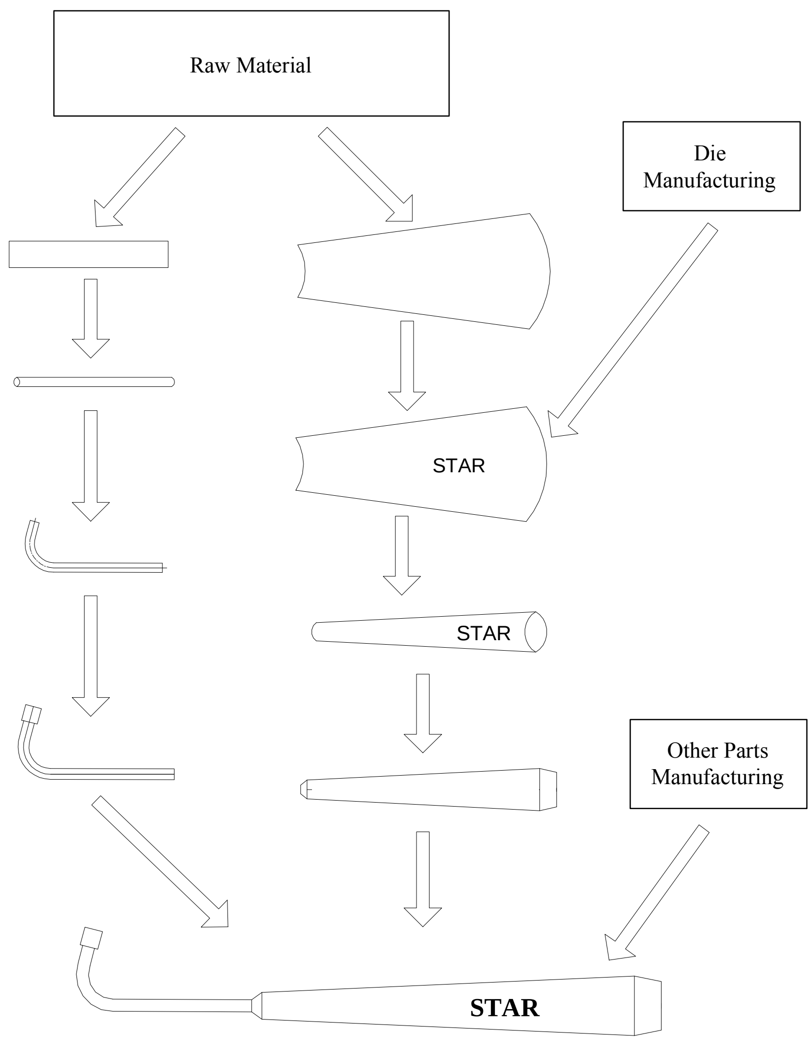

Figure 5. The brief manufacturing process before reengineering

Now we consider the manufacturing process of the products. We are interested in only the main lines, and we ignore the irrelative details. The brief manufacturing process in producing the mufflers is shown in Fig. 5. The main raw material for the products is the thin steel plate. Basically, the manufacturing process includes the manufacturing of the main body and connection pipe. In the manufacturing of the main body, first the sectors with required size for different models for forming the main body is cut from large steel plates by a punch machine. Then, a brand is made on the sectors by using a die as a tool on a punch machine. It can be imagined that the brand is special to the customer who orders the products. Thus, a special die must be manufactured for every order before the brand can be made. When the brand is made, the sectors are bent to form the main body. With other small parts available, the main body can be sub-assembled.

In the manufacturing of the connection pipe, rectangles are cut on a punch machine and pipes are made from the rectangles. With the data provided by the customer for particular orders, the pipes are bent to the required shape to form the connection pipe so as to adapt to the particular motor-bicycle models.

When both the main bodies and the connection pipes are ready, mufflers are then assembled for a particular order. The assembled mufflers are polished and followed by plating. After plating the mufflers are ready for delivery.

4.2 Problems Confronted

From the discussion about the manufacturing process of the products, we know that the products have to be produced in made-to-order mode. It can be seen that the operations before the brand is made on the sector and the operations before the bending of the pipes to form the connection pipes can be done in advance before the customer order is gotten, because these operations are independent of a special order. However, to make the brand on the sectors, a special die is necessary for every order. It takes at least one or two days to manufacturing the die for a simple brand, and occasionally more time is needed for a complex brand. Thus, it is not meaningful to perform these operations before the manufacturing of the die, because the die manufacturing takes much more time than the time needed for performing these operations. In this way, serious problems arise.

Every month, customer orders are concentrated on the first half of the month, and there are less customer orders in the second half. Furthermore, customers require shorter and shorter delivery time. Because of the capacity limit, the company cannot meet the delivery requirement for every order in the first half of the month if all the orders are accepted. Thus, a large number of orders are lost. At the same time, with less orders to come in the second half of the month, however, the facilities and employees are idle for a large part of time. Furthermore, the volume of each order is small, and often it is less than a hundred. This makes the situation even worse. Therefore, the profit of the company is declining.

The company may select to increase the capacity by installing more machines and hiring more employees so as to meet the capacity requirement in the first half of the month for accepting more customer orders. However, this will result in more loss in the second half of the month.

4.3 Reengineering for Mass Customization

To overcome the problems confronted, the company selects to reengineer the manufacturing process other than to expand its capacity. The question is how to reengineer. Following the stages presented in the last section, we successfully reengineered the manufacturing process, and MC is successfully implemented.

According to the proposed stages, the first thing to do is to identify the potential changes in the particular situation. With the description of the above product and manufacturing process, it is easy to do that for this case. The changes in this case are the brand and shape of the connection pipes for each different order. It is these changes that make the products customized.

After the changes are identified, the next step for reengineering a manufacturing process is to improve the PF, VF, TF and CF, respectively, so as to improve the flexibility of the whole system F. Now we examine the PF. From the above discussion, it is known that $T = t$ in the present manufacturing process, so $PF = 1$, or there is no such flexibility at all. Thus, it is an effective way to improve the flexibility of the total system by improving PF.

To improve the PF, we can do standardization in the product design, or redesign the manufacturing process, or both. After carefully examining the product design, we think it is well standardized, or no significant improvement of flexibility can be made by standardization. Thus, the question is whether we can postpone the PDP by redesigning the manufacturing process. There is an NC machine to bend the pipes to form the connection pipes, so this does not cause large delay for delivery. It is the making of the brand on the sectors that makes the great contribution to the major delay. Therefore, it had better to make the brand on the main body after the operation of polishing is performed. However, after the main body is formed and subassembled, it is impossible to make the brand on a punch machine by using a die. Thus, to do so, new technology is necessary. Via investigation, it is found that a laser machine can perform this operation after the muffler is assembled. Consider that if the operation of brand making is performed after the whole muffler is assembled and polished, then the operation of bending the pipes and the operation of brand making are performed in a serial way. In fact, they can be performed in parallel. Therefore, we redesign the manufacturing process so that the operation of brand making is performed after the main

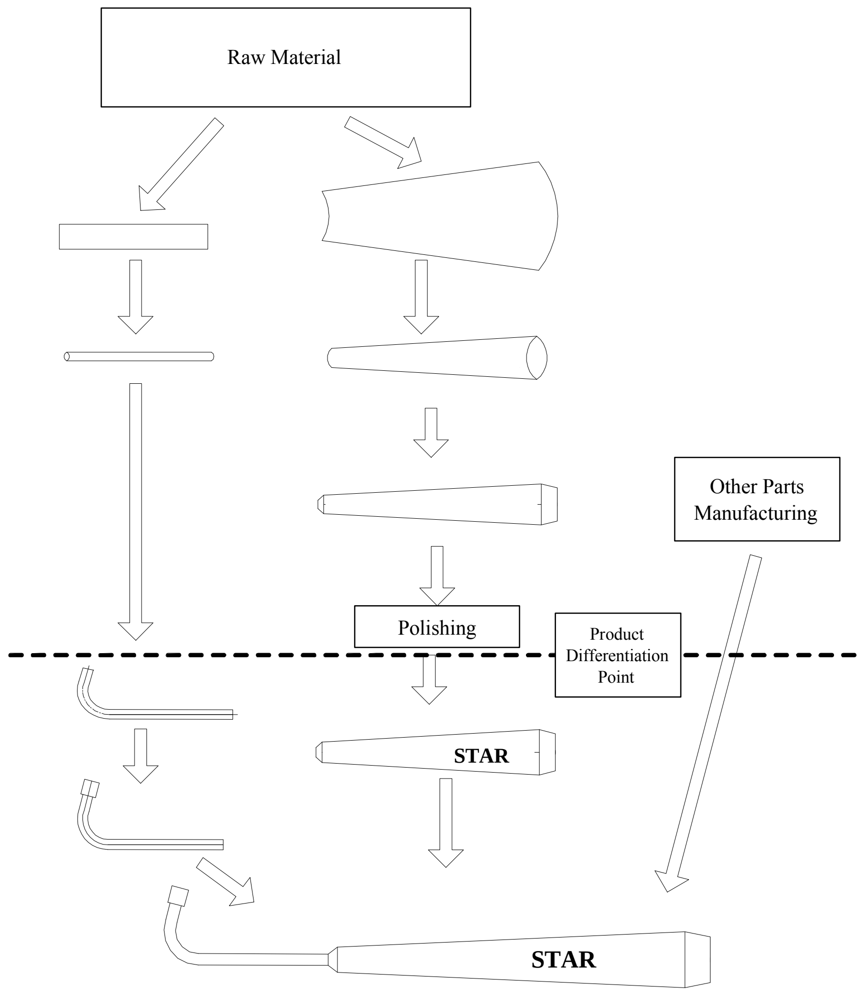

Figure 6. The brief manufacturing process after reengineering

body is subassembled and polished. At the same time the operation of pipe bending is performed. The reengineered manufacturing process is shown in Fig. 6. In Fig. 6, the dashed line represents the PDP. It can be seen that the PDP is much closer to the sale point than the original one, or there is a significant improvement of PF.

With the PF improved, then we consider the VF flexibility. As for VF, in our case we can make any brand as required by the customers, and we cannot enumerate the number of different products in this case. Thus, we think $N \to \infty$, and $\frac{1}{N} \to 0$, or VF = 1, the largest value. This means that we do not need to improve the VF.

Now it comes to examine TF and CF. In the original manufacturing process, the manufacturing of a die for the making of the brand takes much longer time and consumes much more money than performing the operation of making the brand, or we have $C_{total} \gg C_{var}$ and $T_{total} \gg T_{process}$, leading to very small TF and CF. In other words, it is meaningful to improve TF and CF.

In postponing the operation of brand making, a laser machine should be used to make the postponement possible. In this way, a die is no longer needed, this saves much money in making the brand. At the same time, it decreases the fixed cost, or C_{fix} decreases, and thus C_{total} decreases and CF increases as well. With a laser machine to make the brand, it needs to perform the design of the brand. Thus, to save the setup time, we need to reduce the time for designing the brand. Hence, we decide to install a laser NC machine that connects to a CAD/CAM system. In this way, for the brand making, T_{set} and T_{press} are comparable. By doing so, both TF and CF are improved significantly. In this way, the differentiation operations can be performed as quickly as mass production.

By improving PF, VF, TF and CF in the manufacturing process reengineering, respectively, the flexibility of the system is greatly improved. The operations in the push phase can be performed independently of the customer orders in mass production mode. At the same time, the differentiation operations can be performed as quickly as mass production. In this way, MC is implemented for the manufacturing of mufflers in the company. Now the company can deal with much more customer orders with the inventory of the standard-common components in the first half of the month, and at the same time, the facilities and employees need not to be idle in the second half of the month, for during this period, the standard and common components need to be produced for the use of the next month. Although there is an investment for installing the laser NC machine and the CAD/CAM system in the MPR, it is justified by considering the productivity and flexibility gains from the reengineering.

5. CONCLUSIONS

To meet the competition for customer demand in the global market, it is a trend for manufacturers to implement MC. To implement MC, MPR is required. However, although some companies are successfully reengineered, MPR is believed to be a high risk task.

For MC, high flexibility in the manufacturing system is required. At the same time, it is recognized that flexibility of manufacturing systems is one of the vital competitive priorities in manufacturing strategy. Thus, in reengineering a manufacturing process, flexibility should be taken into consideration so as to reduce the risk. There are theories about the definitions and measurements for various types of flexibilities in manufacturing systems. Nevertheless, they are difficult to use as a guide to MPR.

For the purpose of manufacturing reengineering for MC, in this paper, we define the flexibility of customization. Consider that both hardware and product design make contribution to the flexibility, this measurement is developed in considering both factors. Thus, the measurement can be used as a guide to MPR. A case study is presented to show the successful application of the proposed approach. Although the case problem is simple, it shows the way to reengineer the system for MC by using the proposed concept and method.

In developing the measurement of flexibility in manufacturing systems, we do not consider the contribution made by an information system. Information system may have great impact on the flexibility in manufacturing systems. It is the future work to do.

REFERENCES

[1] Anderson, D. M., and Pine II, B. J., *Agile Oroduct Development for Mass Customization*, McGraw-Hill, 1997.

[2] Benjaafar, S., and Talavage, J. J., "Process Flexibility in Manufacturing Systems: Models and Measurements", *Working paper*, School of Industrial Engineering, Purdue University, 1992.

[3] Brill, P. H., and Mandelbaum, M., "On Measures of Flexibility in Manufacturing Systems", *International Journal of Production Research*, vol. 27, no. 5, 747-756, 1989.

[4] Brill, P. H., and Mandelbaum, M., "Measurement of Adaptivity and Flexibility in Production Systems", *European Journal of Operational Research*, vol. 49, 325-332, 1990.

[5] Browne, J., Dubois, D., Rathmill, K., Sethi, S. P., and Stecke, K. E., "Classification of Flexible Manufacturing Systems", *The FMS Magazine*, vol. 2, no. 2, 114-117, 1984.

[6] Buzacott, J. A., and Kahyaoglu, Y., "Flexibility and Robustness in Manufacturing", *International Journal of Manufacturing Technology and Management*, vol. 2, nos. 1-7, 546-558, 2000.

[7] Cafasso, R., "Reengineering Projects: up, up and away", *Computer World*, vol. 27, no. 13, 1993.

[8] Chang, A.-Y., Whitehouse, D. J., Chang, S.-L., and Hsieh, Y.-C., "An Approach to Measurement of Single-Machine Flexibility", *International Journal of Production Research*, vol. 39, no. 8, 1589-1601, 2001.

[9] Chopra, S., and Meindl, P., *Supply Chain Management: Strategy, Planning, and Operation*, Prentice Hall, 2001.

[10] Cox, T. Jr., "Towards the Management of Manufacturing Flexibility", *Production and Inventory Management*, vol. 30, no. 1, 1989.

[11] Davenport, T. H., *Process Innovation: Reengineering Work through Information Technology*, Harvard Business School Press, Boston, 1993.

[12] Eastwood, M. A., "Implementing Mass Customization", *Computers in Industry*, vol. 30, no. 3, 171-174, 1996.

[13] Fitzgerald, G., and Siddiqui, F. A., "Business Process Reengineering and Fexibility: A Case for Unification", *The International Journal of Flexible Manufacturing Systems*, vol. 14, 73-86, 2002.

[14] Grant, D. A., "Using Existing Modeling Techniques for Manufacturing Process Reengineering: A Case Study", *Computer in Industry*, vol. 40, 37-49, 1999.

[15] Gupta, Y. P., and Goyal, S., "Flexibility of Manufacturing Systems----Concepts and Measurements", *European Journal of Operational Research*, vol. 31, no. 12, 119-135, 1989.

[16] Hammer M., and Champy J., *Reengineering the Corporation: A Manifesto for Business Revolution*, Harper Business, New York, NY, 1993.

[17] Jagdev, H. S., and Browne, J., "The Extended Enterprise ---- A Context for Manufacturing", *Production Planning and Control*, vol. 9, no. 3, 216-229, 1998.

[18] Kochikar, V., and Narendran, T., "A Framework for Assessing the Flexibility of Manufacturing Systems", *International Journal of Production Research*, vol. 30, no. 12, 2873-2895, 1992.

[19] Kromker, M., and Thoben, K.-D., "Reengineering the Ship Pre-Design Process", *Computers in Industry*, vol. 31, 143-153, 1996.

[20] Kumar, V., "Entropic Measurement of Manufacturing Flexibility", *International Journal of Production Research*, vol. 25, no. 7, 957-966, 1987.

[21] Ovans, A., "Should You Take the Reengineering Risk?" *Datamation*, (September 15, 1995), 39-44, 1995.

[22] Parker, R. P., and Wirth, A., "Manufacturing Flexibility: Measures and Relationships", *European Journal of Operational Research*, vol. 118, 429-449, 1999.

[23] Pereira, J., and Paulre, B., "Flexibility in Manufacturing Systems: A Relational and a Dynamic Approach", *European Journal of Operational Research*, vol. 130, 70-82, 2001.

[24] Pine II, B. J., *Mass Customization: The New Frontier in Business Competition*, Harvard Business School Press, Boston, 1993.

[25] Schnitt, D., "Reengineering the Organization Using Information Technology", *Journal of Systems Management*, 14-42, 1993.

[26] Sethi, S. K., and Sethi, S. P., "Flexibility in Manufacturing: A Survey", *International Journal of Flexible Manufacturing Systems*, vol. 2, 289-328, 1990.

[27] Teng, J. T. C., Grover, V., and Fieldler, K. D., "Business Process Reengineering: Charting a Strategic Path for the Information Age", *California Management Review*, vol. 36, no. 3, 9-31, 1993.

[28] Tincknell, D. J., and Radecliffe, D. F., "A Generic Model of Manufacturing Flexibility Based on System Control Hierarchies", *International Journal of Production Research*, vol. 34, no. 1, 19-32, 1996.

[29] Upton, D. M., "The Management of Manufacturing Flexibility", *California Management Review*, vol. 36, no. 2, 72-89, 1994.

[30] Upton, D. M., "What Really Makes Factories Flexible?" *Harvard Business Review*, July-August, 74-84, 1995.

[31] Wortmann, J. C., "Factory in the Future: towards an Integrated Theory for One of a Kind Production", In B. E. Hirsch and K. D.

Thoben (eds), *One of a Kind Production: New Approaches*, North-Holland, 37-74, 1992.

[32] Wysocki, R. K., and DeMicheill, R. L., *Managing Information across the Enterprise*, John Weley, New York, 1997.

[33] Zakarian, A., and Kusiak, A., "Process Analysis and Reengineering", *Computers & Industrial Engineering*, vol. 41, 135-150, 2001,.

Naiqi Wu received the M. S. and Ph. D. Degrees in Systems Engineering both from Xi'an Jiaotong University, Xi'an, China in 1985 and 1988, respectively.

He was with the Chinese Academy of Sciences, Shenyang Institute of Automation, China, during 1988-1995 and the Shantou University, Shantou, China, during 1995-1998. From 1991 to 1992, he was a Visiting Scholar in the School of Industrial Engineering, Purdue University, West Lafayette, USA. In 1999 and 2004, he was a visiting professor with the Department of Industrial Engineering, Arizona State University, Tempe, USA, and the Department of Electrical and Computer Engineering, New Jersey Institute of Technology, Newark, NJ, USA, respectively. He is currently a Professor of Industrial and Systems Engineering in the Department of Industrial Engineering, School of Mechatronics Engineering, Guangdong University of Technology, Guangzhou, China. His research interests include production planning and scheduling, manufacturing system modeling and control, discrete event systems, Petri net theory and applications, and information assurance. He has publications in International Journal of Production Research, IEEE Transactions on Systems, Man, and Cybernetics, IEEE Transactions on Robotics and Automation, IEEE/ASME Transactions on Mechatronics, Production Planning and Control, and Journal of Intelligent Manufacturing.

Dr. Wu is a senior member of IEEE, an associate editor of the IEEE Transactions on Systems, Man, & Cybernetics, Part C. He was a Program Committee Member of the 2003, 2004 and 2005 IEEE International Conference on Systems, Man, & Cybernetics, Program Committee Member of the 2004 and 2005 IEEE International Conference on Networking, Sensing and Control, and reviewer for many international journals.