Abstract: The objective of this paper is to explore the state-of-the-art in generative process planning as it seems most suitable for the concept of Mass Customization (MC). Particular importance is attributed to special requirements of MC on the practice of process planning as it becomes an integral part of the value chain. Based on the literature review and the extended requirements of MC, the need for future research is derived. This paper also gives a brief introduction on the concept of MC and explains why current discussions often fail to address important issues such as manufacturability and cost of individualized products.
1 Introduction

It is often claimed that customized goods will guarantee higher margins especially in markets with growing saturation. So far little attention has been paid to the requirements such a strategy imposes from the manufacturing point of view. This paper discusses the process planning as a vital function for the production of individualized, complex products. In this paper, a literature review on process planning is presented. The main objective is to provide an overview of the developments that emerged in the last decade. Based on the current state-of-the-art of process planning, future research directions are derived, based on the extended requirements imposed by Mass Customization (MC). Furthermore special requirements and limitations caused by the nature of truly individualized products are discussed. In literature the meanings of many terms are very case sensitive and can vary considerably. Therefore the most crucial definitions are stated briefly as they are used in the course of this paper.

Products considered in this context are complete and functioning goods that are comprised of (sub-)assemblies and/or single parts. (DIN 6789). Assemblies are complete groups consisting of two or more parts and/or subassemblies of lower hierarchy (DIN 6789). Parts are entities that cannot be divided any further (DIN 6789). Based on that, the definition of variants is derived: Variants of a product or an assembly are the changes to a basic product by removing or adding single parts.

MC is defined as a system that uses information technology, flexible processes, and organizational structures to deliver a wide range of products and services that meet specific needs of individual customers (often defined by a series of options), at a cost near that of mass-produced items (Hart, 1995; Kay, 1993; Joneja / Lee, 1998).

Mass customization promises to deliver products that are truly individualized and go beyond mere variants. Therefore MC has to exceed the assembly of prefabricated components that are configured based on customers’ choices. By reviewing current literature on mass customized products it becomes evident that there is a lack of distinction between mass customization and assemble-to-order production:

One group of example describes assembled-to-order products as mass-customized products (Jiao, 1998; Vasilash, 1997), the other group of examples proclaims that products that are produced according to customers’ biometric data are true examples of mass customization (Piller, 1997). The first group clearly does not fall into the category of mass-customization as discussed in this paper, because they represent an approach for variant producers that has been successfully implemented by a number of companies. True customization as it is regarded in this paper can only be achieved if customization becomes possible on a specific part of the product. Therefore process planning for MC products does not only consider the components selection in an individualized assembly process but also the parameters of manufacturing operations based on the customer’s choices.

Traditionally, process planning is only performed for new products. In the automotive industry new products are typically developed every 7 years on average. The main challenge for a mass customizing company is the fact that every product represents a new product that requires new process plans and resource allocation. So far, car manufacturers act as producers of variants based on a platform strategy. This concept is limited by default to a basic structure, in which certain components can be altered, left out or added. The industry has largely evolved to a make-to-order process in which the customer can configure his “almost-unique” car with a number of possible combinations beyond $10^{32}$ variants (Reithofer, 2003). Although a huge variety of different cars are produced every day, the process chains mainly stay the same and...
only different components are assembled in the same order of process steps. Therefore the basic manufacturing processes to build a car remain in a constant sequence. Variety is only achieved by having the choice to implement certain features like leather seats instead of regular ones. The order at which point of the production process a seat is implemented is not affected by the option itself. The customer is limited in his choice by the variety offered upfront by the manufacturer. Demanding true customization as offered by the pre-industrial craft systems, the customer would also be able to demand over-sized seats for example. Such seats could probably not be assembled into the car in the “usual” way. They would either necessitate the assembly order or the structure of the surrounding parts to be altered.

According to Pine (2000), in MC each customer is recognized as an individual and offered attractive “tailor-made” features. This basic concept clearly goes beyond a platform strategy, in which all choices can be pre-planned as for the automotive industry. The scenario of mass customization has to assume that different products necessitate different process steps with different parameters. Therefore each new product requires detailed process planning comparable to the planning for a new product model of a traditional variant producer. Because of this, the act of process planning is transformed from a supporting secondary activity to a primary activity that has to be undergone for every single product.

Figure 1: Own modified value chain for mass customized products based on Porter (1985) and Piller (1998)

In mass customization the planning of processes becomes an integral part of the production of all customized goods. As

Figure 1 demonstrates, mass customization necessitates an additional process step in the value chain. Therefore new methods have to be derived how to perform this step with as little additional cost as possible in order to compete with variant producers on a comparable level of price. One important argument of how to achieve this aim is presented by Younis and Wanab (1997) stating that only 15% of the process planner’s time is spent on technical decision making while the remaining time is equally spent between gathering data, calculating and preparing documentation. Therefore the main focus should not be attributed to complex, artificial intelligence approaches trying to imitate the human decision making process but rather to minimize the time needed for retrieving data. This reveals the need for an integrated information model in which all
relevant data is instantaneously available. The following paragraph provides a brief overview of the state-of-the-art in CAPP with a special emphasis on the modeling of necessary data followed by a discussion of specific needs for individualized products.

2 State of the art in computer aided process planning

According to a study led by Maropoulos (1995) about research projects in computer-aided process planning, the most research aims at different aspects of generative planning. The other two main approaches namely variant and semi-generative are not further investigated in this paper because they would necessitate a high level of interaction from a human process planner, that would make these approaches too cost-intensive. Maropoulos distinguishes four important problems/issues to be solved in generative:

- Development and management of tools as well as fixtures,
- modeling of processes (methods and tools for modeling, integrated modeling of products and processes, automatic feature recognition),
- the actual process planning (as the bridge between product design and the execution of production processes, the distributed process planning, the feature based product development and process planning) and
- the integration of computer aided design, process planning and manufacturing (CAD/ CAPP/ CAM).

In the following section different approaches and methods are described that have been used by a variety of researchers to address the four main areas as described above. For the development and selection of tools and fixtures various approaches were followed in a roughly chronological order: mathematical models, linear optimization, heuristics, artificial intelligence, expert systems, hybrid systems and object-oriented knowledge representation (Rasch / Rolstadas, 1971; Mathieux, / Bourdet, 1987; Giusti / Santochi, 1986). Modeling resources, the object-oriented approach has been widely adopted to represent production capabilities and capacities (Ali / Motavalli, 1993; Gu / Zhang, 1994; Yut et al., 1994). The modeling of products serves the purpose of storing important information on a product during its life cycle. Because of that, a multitude of diverse requirements arise. Single, dispersed efforts were not suitable to sufficiently solve this issue (Kang / Nnaji, 1993; Giacometti / Chang, 1991); therefore STEP (The STandard for the Exchange of Product model data) was developed by an international committee including major CAD vendors. Because of the many requirements of the product model, different views on the product, the so-called Application Protocols (AP) were developed. For process planning the AP224 was especially defined. Although STEP is widely dispersed throughout a multitude of different industries, it does not fully satisfy the needs of a CAPP system, especially not one focusing on individual products. One major shortcoming is for example the lack of hierarchies in the feature structure, furthermore STEP224 has a strong focus on metal cutting and would have to be extended to incorporate other operations especially assembly (Sharma / Gao, 2002). The STEP224 format is not yet fully supported by CAD system vendors. Important information such as tolerances are not supported by many systems. Because of that Kang et. al (2003) have proposed a data structure to store various types of tolerance and surface finish data. This information can be utilized by a CAPP system to extract manufacturing
information contained in STEP AP224 file more easily, regardless of the CAD systems use.

The strong focus on metal cutting stems from the fact that in engineering CAD based drawings are common for this kind of products. Furthermore CAM is also widely spread by highly computerized CNC-machines. Consequently a highly automated CAPP in this environment would clearly establish a highly automated process chain. But even focusing only on metal cutting, successful systems were only implemented for very limited spectrums of single parts. The major reason for this stems from the fact that design features can often not be directly transformed into manufacturing features (Houten, 1991; Kanai et al., 1996; Burghardt, 1996).

This literature review has revealed that there is a strong trend towards generative process planning on the basis of feature technology. Giving a comprehensive overview on feature technology is clearly out of the scope of this paper; see (Han et al., 2000) for a thorough survey. So far research works have mainly been directed towards metal-cutting operations. Special research considering the implication of mass customization on process planning has been very limited so far. Two selected works are referred to in the following chapter, which deals with the special requirements of MC on process planning.

3 Special requirements imposed by Mass Customization

In order to understand the special requirements imposed by a mass customization process chain on the process planning, a brief description of the interaction between customer and manufacturer in a MC environment is given:

The manufacturer defines to what extent customers may customize their order. This includes the selectable design elements as well as their possible ranges. The customers feed back the information on their choice of design elements. The following sequence of steps describes the activities involved in establishing a customer-manufacturer communication link:

- defining a solution space of options to be offered to customers;
- collecting and saving information on customer choices;
- transferring data from retail to manufacturer; and
- mapping customer choices with product design features and manufacturing processes.

MC is typically concerned with the fulfillment of end users’ needs. Therefore these products mostly consist of many different parts that have to be assembled to create a product that fulfills the special customers’ needs. In contrast to most work as described in the state-of-the-art in process planning, where a main focus is attributed to single prismatic parts, complex individualized products are the main focus of MC and therefore addressed in this paper.

MC has to be supported by enabling technologies based on computer-integrated manufacturing (CIM) (King, 1998). An important aspect is to achieve an integrated process chain from computer-aided design (CAD) to computer-aided manufacturing (CAM). Specifications on design elements are fed from CAD to CAPP systems, where they are converted into production instructions (Kotha, 1995; Spira, 1996; Choi /
It is evident that the success of MC implementations is heavily dependent on the existence of a computerized manufacturing environment. This is hardly surprising since MC relies on flexibility and quick responsiveness.

CAM is often achieved by numeric control (CNC) and flexible manufacturing systems (FMS). Many researchers consider these technologies to be essential to MC implementation (Pine et al., 1993; Kotha, 1995). Examples from industry such as the NBIC (Kotha, 1995), Motorola (Eastwood, 1996), and Perkins (Vasilash, 1997) emphasize the important role of these enablers. Motorola for example used CIM-related technologies such as Cartesian and gantry robots to implement MC factories. Perkins based their MC system on a hybrid CAD/CAE (computer-aided engineering) system with flexible manufacturing assembly lines.

Although process planning is crucial for the implementation of MC, special necessities derived from MC have not been researched in much detail. The planning for MC products not only faces the same obstacles as for mass-produced products, but also clearly exceeds these. One important difference is the product itself, which is mostly of a complex nature. Product families have been recognized as an effective enabler for mass customization as shown by Ulrich (1995) and Sawhney (1998), because they provide a good solution how to deal with the risen complexity of individual products. The product families can be managed in a so-called product variant structure that shows the "part-of"- and the "is-a"-relationships between different parts. These two aspects are modeled in two interwoven structures. In order to handle product complexity and the relationships between different components of a product Jiao et al. (1998) have proposed the product family architecture (PFA) as a basis for the derivation of customized goods. Their graph representation of the configuration structure for a product family can be compared to a traditional gozinto graph not going further than to a component level. In their approach they assume that parts are pre-fabricated and the graph merely expresses the logical relationship between different components. Assuming that each part of a complex product can be customized in its geometry and size leads to a variety of new questions to be solved. How is the assembly sequence influenced by the geometry of the parts of the assembly? How does the customization of a single part affect adjacent parts of the product? These issues have not been addressed in MC literature so far.

Typically customized goods are produced close to the market because of short logistical ways and consequently shorter delivery times of the made-to-order products. Therefore the concept of the so-called mini-factory has been derived (Reinhart et al., 2000). These mini-factories are to produce the goods with similar but not necessarily the same manufacturing resources. In high-wage countries a higher level of automation can be assumed. Therefore the process planning has to take different production settings into account. So far neither the literature of process planning nor of MC has considered this aspect in a satisfying way.

Tu et al. (2000) have developed a framework that includes reference architecture for structuring a CAPP system in virtual networks; they describe a CAPP method and an optimal/rational cost analysis model. Their method and model include three data models for data modeling and structuring of the product, the process, and manufacturing plants. In their research Tu et al. claim to have developed a new approach called the incremental process planning (IPP). Based on the product’s features a similar process plan is derived based on a Group Technology (GT) code, that is further modified to accommodate all specific features. Their approach is theoretical in nature and not explained in a very detailed way. Important aspects such as the assemblibility have not been covered at all. Furthermore, the extraction of
processes based on GT code does not seem suitable, because the GT code is usually based on rough geometric dimensions that do not provide the necessary details to derive a valid process plan (Markus et al., 1996).

Given a part geometry in the form of a CAD-file, Computer Aided Process Planning (CAPP), the bridge between Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM), generates a sequenced set of instructions to manufacture the specified part. To do that, CAPP has to extract manufacturing information such as machining features and precision specifications including surface roughness, as well as dimensional and geometric tolerances in order to select the possible processes and production resources. Although there has been considerable effort in the past to interlink design and process planning, sharing of manufacturing information still remains a bottleneck (Kang et al. 2003).

4 Modeling for integrated process planning

The majority of researchers base modern approaches for process planning on object-oriented design, because it is a concept that is natural for human beings and can easily be adapted to changes. A variety of researchers have suggested object-oriented approaches for Process Planning (Usher, 1997).

Although a large number of these approaches have lead to the creation of diverse prototypes, so far no standard could be achieved. This is partly due to the fact that process planning is a complex and case specific task. Because of this fact, the involved knowledge has to be clustered and implemented in customizable and reconfigurable models. This section explores the requirements on product, process and resource models.

There are three different ways of product modeling that have been researched so far: Design by features models the part based on predefined and parameterized form-features. The main disadvantage of this approach stems from the fact that the designer is limited in his design by these predefined elements. In contrast to this, the second approach, namely the feature recognition permits to design classically. Features are later extracted from the geometrical representation using different techniques. Although much effort has been made in this area only limited success for a well-defined set of parts could be achieved. The third approach is based on one model for the design solution and several models of domain applications like for example one for process planning (Salomons et al., 1994).

In a reference model of manufacturing processes, these can be classified as primary, secondary and tertiary processes (Candadai, 1994). Primary processes are main-shape generating processes such as casting and forging. Primary/secondary processes generate both the main shape of the part and the manufacturing features. Tertiary processes do not affect the geometry and comprise mainly grinding or finishing operations.

Modeling resources, the object-oriented approach has been widely adopted to represent production capabilities and capacities (Ali et al. 1993; Gu et al., 1994; Yut et al., 1994, Mak et al, 1999). Unlike STEP for the representation of products, no standard for the description of resources has been established so far. Nevertheless the trend in factory planning also directs to object-oriented approaches as they are embraced by commercial systems such as eM-Planner (Tinham, 2003). There is the substantial need to integrate factory planning and process planning, because a digital model of the factory has already been developed in the early planning stages of a factory. This
model should have the capability to be used as a common ground for process planning. This idea is also expressed by Westkämper and Briel (2001) as followed: “Work planning and factory planning have to be integrated on a common multi-scale data base, which allows to change the time scale as well as the details of data for the different tasks of planning and usage of computerized planning tools.”

Extensive research has been done in the area of process planning. Nevertheless no system has been developed that is able to cater for all the needs. One reason for this lies in the many proprietary standards that have been utilized by researchers in the past. Only recently there seems to be a trend towards standardization. This trend has clearly been sparked off by the standardization initiated by the STEP-format for product modeling. Based on this standard, several researchers have worked with the AP224 [Sharma and Gao, 2002; Usher, 1997; Proctor et. al, 2003], which has a special focus on process planning for metal removal and bending. So far no comparable standard has been established for the product modeling of complex, individualized parts. This paper has revealed the necessities of the extension of the STEP-format. Similarly a comparable standard for the description of resources has to be established.

Process planning has to provide the optimal mapping between products, processes and manufacturing resources. Based on this knowledge, process planning should focus on its primary role, which is to determine the best possible sequence of operations based on the product to be produced and the capabilities and capacities on the shop-floor. The modeling of the product has to be undertaken by the designer in a standardized model like STEP that can be used for down-stream processes like manufacturing and assembly. The resource model depends on each production side, therefore it is referred to as plant-specific. The initial planning of manufacturing resources is not focus of process planning itself, but lies in the hands of factory planning or system design. Therefore the digital models that have been used for the initial planning of a factory should be utilized for the process planning.

Considering that process planning is the fundamental mapping between the domains of products, processes and resources these dependencies can be expressed by simple “if- / - then” statements. This kind of knowledge representation clearly indicates the use of an expert system to automate the mapping process (Zha et al., 2001; Arezoo et al., 2000)

5 Limitations to MC from a manufacturing point of view

Although computer aided process planning has the capability to effectively map products with processes and resources, practical limitation and technical restrictions for the planning of individualized products have to be addressed. It is important to note that the offer of choices, although essentially customer driven, must be coherent with the manufacturer's technological development and cost of production (McCarthy, 1997). This aspect is sometimes neglected in the discussion of the potential of MC implementation. It is often argued that MC practice offers cost savings based on modularity and postponement. In fact both modularity and postponement are only strategies to cope with the additional cost of a high product variety. In fact a high modularity of products means that additional assembly process steps have to be included in the creation of a product. A more integrated and therefore less flexible design would reduce the number of assembly steps and therefore reduce the cost of production. Zipkin (2001) advises to carefully assess the technology and the market demand for customization before embracing a strategy of mass customization. This
advice has to be taken seriously, because most product designs are optimized for production. Even minor changes by the customer can lead to high increases of manufacturing costs. Many researches especially from the field of business studies argue that CNC-machines provide the necessary flexibility for the creation of individualized products. While this might be true to a certain extent, it has to be taken into account that a wide range of changes means that the block of raw material has to be substantially larger than the end product. Otherwise many different shapes of raw material would have to be used that create an enormous cost of inventory. Metal chips that have been removed in a cutting process are mostly cut with the help of coolant liquids. Therefore they cannot be re-used as raw material but in fact have to undergo an expensive recycling process. Based on these arguments even flexible CNC-machines created substantial cost for MC products based on higher costs of material (increased waste of material), tool wear (increased volume to be cut per part), manufacturing time and cost for the disposal of metal chips.

Manufacturing processes are too complex and context sensitive for a single methodology to generate flexible, agile, and focused systems. In order to implement MC it is necessary to integrate different manufacturing technologies into a structured framework capable of combining human and technological factors (Silveira et al. 2001). CAPP systems can be seen as possible enablers and integrators of these different technologies. It can further provide the necessary knowledge sharing that is key for the success of distributed local factories. Nevertheless a critical view on related cost has to be taken compared to additional customer satisfaction and willingness to pay a premium price for an individualized product.

6 Conclusion

This paper has demonstrated a state-of-the-art-overview on process planning. Furthermore the special role of process planning for the concept of Mass Customization has been demonstrated. Special requirements derived from MC have been specified, namely the integration of process planning and assembly planning and the integration of process planning and factory planning. These integrations can only be achieved on the basis of a consistent data model. Object-oriented modeling seems to be the logical choice for this modeling task. An overview of current modeling practice has been given which clearly points into the direction of standardization in order to integrate different hierarchies and domains of process planning. Although the field of computer aided process planning will clearly evolve to more standardized solutions also for Mass Customization, manufacturing related obstacles referred to in chapter five remain an impediment to the implementation of MC in practice. It is highly doubtful that MC is the right strategy for every kind of product or even industry. Excessive customer choice is far from desirable and will probably not be economically feasible for most products. A critical view has to be taken towards promises of advantages over traditional mass production. It is often proclaimed that product choice is only limited by the customers’ imagination. Process planning as an effective link between design and manufacturing can provide a more realistic view as an effective means to estimate the consequences of changes to the product by the customer.
References


