

# RECONFIGURABLE PROCESS PLANS FOR RECONFIGURABLE MANUFACTURING

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*This keynote paper focuses on the process plans and planning functions as the important link between the features of generations of products/product families and the features, capabilities and configurations of manufacturing systems and components throughout their respective life cycles. The challenges presented by the paradigm shift in manufacturing systems and their increased flexibility and changeability require corresponding responsiveness in all support functions. Process planning is part of the “soft” or “logical” enablers of changeability in this new environment. New perspectives on process planning for Flexible (FMS) and Reconfigurable (RMS) manufacturing systems in integrated digital manufacturing enterprises are presented. Process plans reconfiguration and their pre-requisites, characteristics, modeling and solution approaches, potential automation, and integration with both products and systems models as they evolve are discussed. New concepts of “Evolving Products Families” and “Reconfigurable Process Plans” are introduced and their ramifications for process planning approaches are outlined. The distinguishing features of process plans and planning methodologies in flexible, reconfigurable and changeable manufacturing systems, for both planned and un-planned products changes, are highlighted. Future research directions and challenges in process planning, being one of the enablers for changeable and responsive manufacturing systems, are presented.*

## 1. INTRODUCTION

Global competition and unpredictable frequent market changes are challenges facing manufacturing enterprises at present. There is a need for reducing cost and improving quality of highly customized products. Responsiveness, agility and high performance of manufacturing systems are driving the recent paradigm shifts and call for new approaches to achieve cost-effective responsiveness at all levels of the enterprise. It is becoming important that the manufacturing system and all its support functions, both at the physical and logical levels, can accommodate these changes and be usable across several generations of products and product families.

Modern manufacturing paradigms aim to achieve these multi-objectives. For example, flexible manufacturing systems (FMS) provide pre-planned generalized flexibility built-in a priori, while reconfigurable manufacturing systems (FMS) aim at providing customized flexibility by offering the functionality and capacity needed when needed. Many enablers are required for the successful implementation of these paradigms and achieving the desired adaptability. The flexibility, changeability and reconfigurability of the hardware components and systems are essential. However, more often what represents the most formidable challenge is the soft or logical support functions, such as product / process modeling, process planning, process and production control strategies and logistics, which must not only be in place but also be adaptable and well integrated for any successful and economical responsiveness to changes in manufacturing to materialize.

## **2. CLASSIFICATION OF PROCESS PLANNING CONCEPTS**

The process planning activities have seen significant growth and development since the nineties, which have been reviewed in a number of publications where details can be found. Planning is concerned with generating the set of steps required to reach a specified goal, within given constraints, while optimizing some stated criteria. Manufacturing process planning seeks to define all necessary steps required to execute a manufacturing process, which imparts a definite change in shape, properties, surface finish or appearance on a part or a product (ElMaraghy, 1993).

A classification of the various process planning concepts and approaches, based on their level of granularity, degree of automation, and scope, as outlined below, is helpful in highlighting the current challenges and future directions.

### **2.1 Process Plans Granularity**

#### *2.1.1 Multi-Domain Process Planning*

At the highest level, planning seeks to select the most suitable manufacturing domain or technology for producing a feature, a part or a product (e.g. metal removal, material addition, forming or joining). A planner, for example, would determine whether a certain cavity would be produced by EDM rather than milling, or that a near net shape forming or casting would be used to produce the initial component rather than machining it from a block. Multi-domain process planning is concerned with this initial choice of the manufacturing technology or type of equipment to be used and the assessment of feasible alternatives. This type of planning has seen little automation to date.

#### *2.1.2 Macro-Process Planning*

It is concerned with selecting the best sequence of multiple different processing steps and set-ups as well as the machines to perform those operations. For example determining the individual operations to be performed for rough and finish machining a cylinder block casting and their sequence is a typical Macro-level process planning. In a high volume dedicated manufacturing system, it is carried out once at the system design stage to optimize the overall process. However, in a flexible or reconfigurable manufacturing system, Macro-planning has to be done frequently as the machines/ products and their modules are changed.

### 2.1.3 Micro-Process Planning

At this level the details of each individual operation are optimized to determine the best process parameters. For metal removal the feed, speed, depth of cut, tools, fixtures, cutting path, etc. are determined to optimize process time, and cost and avoid undesirable behavior such as tool breakage and chatter. More detailed planning is carried out to specify the machining execution instructions and NC program steps.

## 2.2 Process Planning Automation

### 2.2.1 Manual Process Planning

Process planners often possess extensive experience and knowledge that are used to establish process plans at any level of granularity. However, manual planning lacks consistency, standardization and optimality and does not lend itself to computerization and automation.

### 2.2.2 Computerized Process Planning

It capitalizes on the increasing capabilities of computers to facilitate storage, retrieval and use of data, models, and knowledge to speed up computation and allow user interaction and participation in decision-making. This is called Computer-Aided Process Planning (CAPP) and is not to be confused with automated process planning.

### 2.2.3 Automated Process Planning

Automated process planning is by nature also computerized. However, the following classification is more concerned with the type and degree of automation.

#### 2.2.3.1 Retrieval /Variant Process Planning

The variant approach marks the beginning of automating process planning activities, and is basically a computerized database retrieval approach. The fundamental concept is that parts that bare similarity in design or manufacturing features are grouped into part families, a unique Group Technology code is generated for each part, a composite part that contains all the features in the family, and a standard optimized master process plan for each family of parts are developed beforehand. The planning of a new part is performed by identifying and retrieving existing plans for similar parts, using the GT code, and making the necessary modifications.

A *dynamic process planning* system is a retrieval type, which allows adaptation of pre-determined process plans (or portions of) to changes in the manufacturing facilities (machines failure, material and tools shortage, order changes, etc.). This adaptation may be done at both Macro- and Micro- process planning levels.

#### 2.2.3.2 Semi-Generative Process Planning

Semi-generative process planning was the next automation step wherein the "standard master process plan" concept was *augmented* by algorithms capable of making some "*part-specific*" decisions about the operation to be performed and their parameters. It combines both retrieval and algorithmic procedures assisted by CAD models, databases, decision tables or trees, heuristics and knowledge rules. This allowed process plans to be partially customized for individual parts, particularly when new features are added.

#### 2.2.3.3 Generative Process Planning

A totally generative process planning system aims at generating an optimized process plan from scratch given sufficient input about all relevant data. It relies heavily on complete and accurate models of the parts and processes, and their behavior, constraints and interactions. Automated reasoning, knowledge-based systems and Artificial Intelligence techniques are essential to the success of this approach. Some CAM/CNC application programs claim to be moving in this direction, mostly in the metal cutting domain. However, a truly generative process planning system in any domain is yet to be realized. The major challenge is the complete mathematical modeling of the various processes and their characteristics.

#### 2.2.3.4 Distributed, Web-based, Networked Process Planning

A trend is evolving for distributed and more decentralized process planning systems. These would be a collection of process planning sub-systems, each with a limited function or scope and more specialized nature, which are loosely connected to form a "system of systems" with an overall supervisory system to coordinate their interaction and the flow of control and data between them. These systems could reside on one or more computers and may fall under any of the above classifications according to their degree of automation and level of granularity. There are a number of factors, which motivate this trend including the globally distributed manufacturing facilities, the wide spread use of the Internet, and the application of agent-based techniques.

### **2.3 Scope of Process Planning**

Process planning of metal cutting processes received a great deal of attention over the years due to their widespread use and importance. However, the increased emphasis on reducing the cost of the total manufacturing process, the advent of many new production methods and technologies, and the desire to compete globally highlighted the need to carefully plan all steps of manufacturing. Hence, process planning principles and techniques are now being applied to non-traditional domains such as assembly/disassembly, inspection, robotic tasks, rapid prototyping, welding, forming, and sheet metal working. Process planning classification, approaches and solution methods are applicable across these domains. However, the process nature, specific knowledge and constraints vary greatly and hence some of the terminology, logic and criteria used in their planning.

Several application programs have been developed using many of the process planning approaches classified in this section and many have been used in industry to date. A review of specific systems or solutions is beyond the scope of this paper.

## **3. EVOLUTION OF MANUFACTURING SYSTEMS**

Manufacturing systems have evolved from job shops, which feature general-purpose machines, low volume, high variety and significant human involvement, to high volume, low variety dedicated manufacturing lines driven by the economy of scale. In the eighties the concept of flexible manufacturing was introduced in response to the need for greater responsiveness to changes in products, production technology, and markets. Flexible manufacturing systems address mid-volume, mid-variety production needs. Similarities between parts in design and/or manufacture, and the

concepts of static Product Families and Group Technology were used to achieve economy of scope. Flexible manufacturing systems (FMSs) anticipated these variations and built-in flexibility a priori. Optimality, agility, waste reduction, quality, and lean manufacturing were identified as key drivers and goals for ensuring survival in a globally competitive market.

The reconfigurable manufacturing concept has emerged in the last few years in an attempt to achieve changeable functionality and scalable capacity (Koren, *et al.*, 1999 and Fujii, *et al.*, 2000). It proposes a manufacturing system the modules of which can be added, removed, modified, or interchanged as needed to respond to changing requirements. It has the potential, when implemented, to offer a cheaper solution in the long run compared to FMSs, as it can increase the life and utility of a manufacturing system. However, hardware reconfiguration also requires major changes in the software used to control individual machines, complete cells, and systems as well as to plan and control the individual processes and production (ElMaraghy, 2005).

### 3.1 Manufacturing Systems Life Cycle

In the context of manufacturing systems, one can also envisage a life cycle (ElMaraghy, 2005). It has several phases including the initial system design to implementation, use / operation, re-design / reconfiguration and re-use as well as sale / retirements of some of its modules. Both “soft” and “hard” reconfiguration and flexibility can be used to achieve capability and capacity scalability and extend the utility, usability, and life of manufacturing system. Hard or physical reconfiguration includes adding/removing machines and machine elements, material handling equipment, buffers and storage devices as well as changing their location and layout. Soft or logical reconfiguration can be achieved in variety of ways including re-programming, re-routing, re-planning, re-scheduling, and capacity changes through sub-contracting, utilization of shifts (time) and operators (human resources).

## 4. EVOLUTION OF PARTS AND PRODUCTS

The evolution of products is driven by customer demands, innovation, availability of new knowledge, technology and materials, cost reduction, environmental concerns, and legal regulations (Figure 1). There are many examples of products variations that were developed over time in response to these demands. Derivatives and variations in function, form and configuration lead to products classes including Series of Products with different Functions, Series of Components with different Configurations and Series of Features with different Dimensional and Time Versions. The result is a product family that contains variants of the product, its components and their configuration. One such example is the high bypass ratio turbine fan engine - CFM56, which has been under development since 1970s ([www.cfm56.com](http://www.cfm56.com)). The family consists of six series (sub-sets): 2, 3, 5A, 5B, 5C, 7, ordered chronologically. They feature four fan sizes, ranging from 60 to 72 inches, produced thrust ranging from 18,500 to 34,000 pounds. The fan family, configured for the cfm56 engine family, contains fans produced in four sizes: 60”, 61”, 68”, and

72”. The variation of fan form is in response to changes in functional requirements such as thrust, fuel efficiency, noise attenuation, and maintainability.

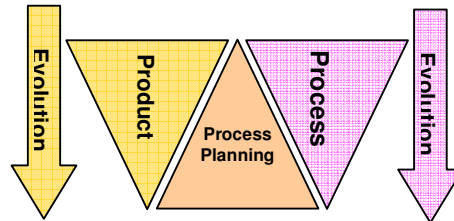


Figure 1 - Evolution of products and processes calls for evolvable process plans

#### 4.1 Static Parts/Products Families

The classical notion of a parts/products family was established in conjunction with the concept of Group Technology where members of the family have similarities in the design and/or manufacturing features. Flexible manufacturing systems relied on this definition of pre-defined parts/products families with non-changing borders to achieve the economy of scale by pre-planning the manufacturing system flexibility according to the defined scope of variations within the family. In this case, a “*Composite part*” that contains all features of the family members can be considered and a “*Master Process Plan*” is devised and optimized, in anticipation of the pre-defined variations, for use in “*Variant Process Planning*” and other manufacturing related activities. The cylinder block for an automobile engine is an example of a product family with well-defined and pre-planned boundaries, where variations in the number, orientation, size and characteristics of cylinder bores, as well as size, mounting bosses, oil gallery, bolt holes, etc. produce different members of the family such as V6, V8 and V10 cylinder blocks for different vehicles.

#### 4.2 Evolving Parts/ Products Families

In the current dynamic and changeable manufacturing environment, the products are frequently changed and customized, and it is possible to reconfigure the manufacturing systems as needed and when needed by changing their modules and hence their capability and capacity. Therefore, the notion of constant parts/products families is changing. This presents new challenges for related activities such as process planning.

We propose a new class of “*Evolving Parts/Products Families*”. Since adding, removing, or changing manufacturing systems’ modules changes its capabilities and functionality, the system would be capable of producing new product features that did not exist in the original product family. This allows it to respond to the rapid changes in products, their widening scope and faster pace of their customization. The features of new members in the evolving families of parts overlap to varying

degrees with some existing features, they mutate and form new and sometimes different members or families as shown in Figure 2.

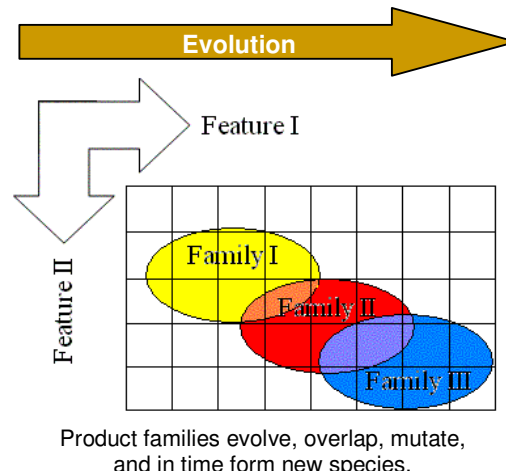


Figure 2 – Evolving parts/products families

It is suggested that this evolution occurs in two modes (Al Geddawy, 2006):

- **Chronological Evolution:** this type of product evolution develops gradually over time and represents a unidirectional natural progression as more knowledge and better technology become available. It is unidirectional because as new and better solutions are obtained it does not make sense to revert to older inefficient or flawed designs. For example, the engine cylinder height range of an automobile engine has been changing over time, based on research, to achieve optimum engine performance.
- **Functional Evolution:** This type of evolution is caused by a significant and major change in requirement, which is normally forced by many factors. It is often selective and discrete although a major overhaul is also possible. This type of change may be bi/multi-directional as the new product fulfills different functional requirements but does not necessarily render previous designs obsolete. For example, the engine cylinder height may be changed within its pre-determined optimum range, to obtain desired engine capacity.

In summary, and to use the natural evolution metaphor:

- a) **In a Flexible Manufacturing System:** The parts family members are closely knit, have a strong core of common features, and all variations are within the pre-defined boundaries. The concepts of Composite Parts, Master Plans and Variant/Retrieval Process Planning are both valid and useful.
- b) **In Transition:** After a few generations, new product families gradually lose their roots (missing features) and develop new and different branches (additional features). The extent of difference between product generations depends of the number and nature of features changes.

- c) In a Reconfigurable Manufacturing System: After many and different products generations, new product features and different families / Species emerge with much less resemblance to the original parent family. In this situation many of the familiar rules do not apply. The magnitude of change and distance between new and old members of the family significantly influences the characteristics of process plans and process planning techniques that would be required in this new setting.

We would like, in light of the above discussion, to introduce the concept of “*Evolvable and Reconfigurable Process Plans*”, which are capable of responding efficiently to both subtle and major changes in “*Evolving Parts/Products Families*” and changeable and Reconfigurable manufacturing systems.

## 5. RECONFIGURABLE PROCESS PLANS

The process plans and planning functions are important links between the features of various generations of products /product families and the features, capabilities and configurations of manufacturing systems and its components throughout their respective life cycles. The relationships between process plans and both products characteristics and manufacturing systems attributes are closely intertwined. The efficient generation and reconfiguration of process plans is an important enabler for changeable and responsive manufacturing systems.

Since the manufacturing resources and their functionalities are becoming reconfigurable, the products variations are increasing in scope and frequency and, as has been demonstrated, the families of manufactured parts are also changeable and evolvable, therefore, some of the familiar rules and earlier approaches, which assume unchanged product families, are no longer applicable. Hence, the concept of “Reconfigurable Process Plans” is being introduced in this paper, which applies to both Macro and Micro plans.

There are some key criteria for achieving reconfigurable process plans and commensurate techniques for their efficient regeneration when needed. The relationships between the product features, process plan elements and all manufacturing system modules capable of producing them must be clearly established. These are many-to-many or multi-directional relationships. Modeling methods including classes, hierarchies, reconfiguration rules and knowledge, associations and relationships in the form of rules, functions, constraints, tables, and the like must be developed. Emphasis should be placed on utilizing process plans representations that would facilitate their reconfiguration. Appropriate models should be developed for the representation and use of: parts geometry (geometric models, and design and manufacturing features), parts technological constraints (hierarchies, precedence, association, datums), manufacturing resources constraints, both static and dynamic (e.g. capabilities, limitations, capacity, size, number, alternatives, and availability), and process knowledge (mathematical models, rules, heuristics, expert systems, intelligent agents, etc.). New algorithms for re-planning and reconfiguring process plans should also be developed to ensure the efficiency of this process.

The reasoning and mapping mechanisms for recognizing the need for, triggering and achieving a reconfiguration of the process plan in response to both pre-planned

and evolutionary changes in the product and/or system must be established. The optimality (time, quality, cost, etc.) of the evolved and reconfigured process plans should also be verified and maintained.

Some examples of newly developed approaches and methods for reconfiguring process plans are presented next for illustration of the proposed concepts.

### 5.1 Semi-Generative Macro Process Planning for Reconfigurable Manufacturing

A practical semi-generative process planning approach suitable for both reconfiguration of the products and manufacturing systems has been developed (Azab *et al.*, 2006). The macro-level process plan is formulated as a sequence of operations corresponding to a set of features in the part. The interactions between the part's different features/operations are modeled using Features/Operations Precedence Graphs (FPG/OPG). The FPG/OPG graphs of a part family's composite part are modified to account for the missing as well as the added features. A random-based heuristic was developed to obtain optimal or near-optimal operation sequences. A validation scheme was developed and used to maintain the specified precedence relationships and constraints.

The developed method was applied to an industrial example of a single cylinder, air cooled, overhead valve engine front cover family of parts defined by a composite cover and a corresponding master process plan. The developed method was used to generate a new macro-level process plan for a new cover, the features of which differ (new, missing and modified) from those that exist in the original family's composite part. The manufacturing system machines had to be reconfigured accordingly to be capable of producing the new features in the new front cover.

It has been illustrated that a hybrid system, which is variant in nature yet capable of generating process plans for parts with machining features beyond those present in the current part family's composite part best meets the current challenges [Azab *et al.*, 2006].

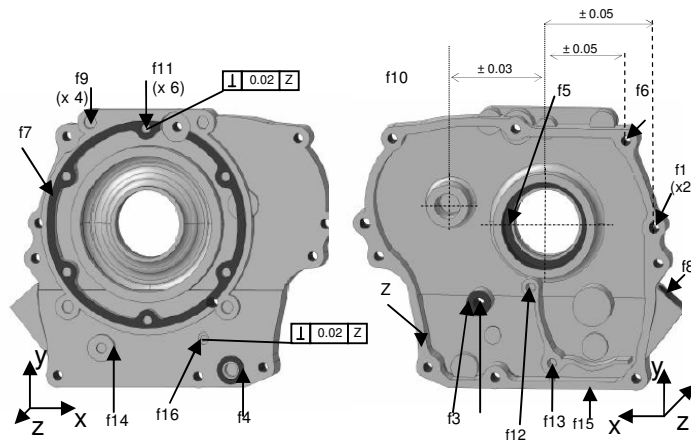


Figure 3 - The composite cylinder front cover

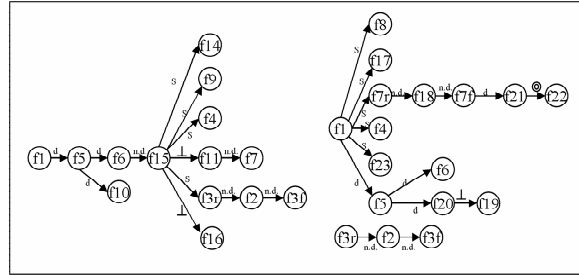


Figure 4 - Feature precedence graph (FPG) of the original composite and new cylinder front cover

### 5.2 Mapping Products Machining Requirements and Machine Tools Structure Characteristics in RMS

This work establishes a two-way mapping between the features of products and machine tools. An approach for selecting the different types of machine(s) and their appropriate configurations to produce different types of parts and features, according to the required machine capabilities was developed (Shabaka and ElMaraghy, 2005 & 2006). The machine structure is represented in a format similar to kinematic chains and captures the number, type and order of different axes of motion, which are indicative of its ability to produce certain geometric features.

The operations required for manufacturing a part are represented by a precedence graph and clustered according to the logical, functional and technical constraints. More than one machine configuration is generated for a single operation cluster, which provides alternatives and increases the flexibility in machine tool selection and process sequence planning. The developed mapping approach is general in nature and not limited to RMS. Knowing the candidate machine(s) for each operation is a typical requirement for generating a process plans. In RMS, the capabilities of the machines and manufacturing system change with each configuration. Therefore, the presented approach for selecting the different types of machine(s) and their appropriate configurations to produce different types of parts and features, according to the required machine capabilities is a fundamental building block in generative planning of manufacturing processes.

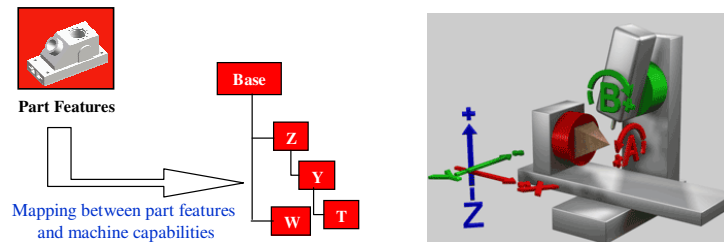


Figure 5 - Mapping between part features and machine capabilities

### 5.3 Reconfigurable Process Planning Modeling

A new and novel mathematical model and algorithms for reconfigurable process planning are introduced in this work (Azab and ElMaraghy, 2006). An automated iterative reconfiguration process is devised to account for new, modified or missing features. The reconfiguration logic has been developed taking into consideration the new part, its precedence graph and corresponding operations precedence graph, the current generation of parts family and manufacturing system and their attributes. The overall proposed method scales well with the problem size, hence, it lends itself readily to optimization.

A practical case study of an engine cylinder block family for V6, V8 and inline engines is used to test the proposed algorithm and process plans reconfiguration scheme. The advantage of the proposed method for reconfigurable process plans have been demonstrated since the algorithm is linear in the amount of the required modifications whereas re-planning provides global solutions by solving an exponentially growing NP-complete problem, which requires far more computational effort.

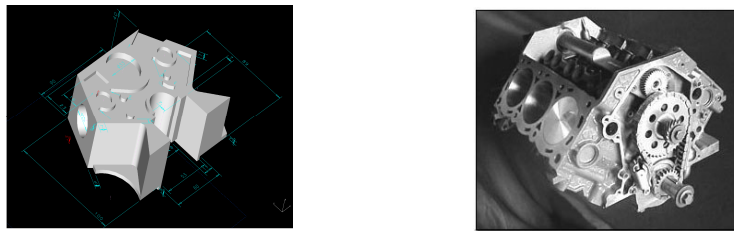


Figure 6- Cylinder block and its model used in reconfigurable process planning

## 4. CONCLUDING REMARKS

Responsiveness, agility and high performance of manufacturing systems call for new approaches to achieve cost-effective adaptability at all levels. It is becoming increasingly important that the manufacturing system and all its support functions, both at the physical and logical levels, can accommodate these changes, and are usable across several generations of product families and manufacturing systems.

In particular, process planning and production control strategies and logistics present a formidable challenge in this changeable environment. These must not only be in place but also be adaptive and well integrated at many levels for any successful and economical responsiveness to changes in manufacturing to materialize.

The designers of products, processes and manufacturing systems as well as production planners should be cognizant of the coupling between generations of products and systems and capitalize on its potential benefits in improving the productivity of the whole enterprise.

Well-defined relationships between parts, manufacturing processes and systems can help facilitate the automatic evolution of process plans as an important link and enabler of effective changeability

A classification of the various process planning concepts was presented. The evolution of manufacturing paradigms and the manufacturing system life cycle were discussed. The evolution of products was illustrated and classified. A new class of “*Evolving Parts / Products Families*” was proposed and contrasted with the traditional notions of static parts families, composite parts and master process plans. The new concept of “*Reconfigurable Process Plans*” was introduced, and the need to link their evolution and reconfiguration to the changes and evolution of both products and manufacturing systems was highlighted. The new rules and challenges of reconfigurable process plans were discussed.

Research implementations, using examples of real products, were briefly described to demonstrate applications of the presented new concepts. These include: 1) Semi-generative reconfigurable process planning and their optimization, 2) Automated mapping between products features and machines capabilities for use in configuring both the process plans and machines when needed as the products are reconfigured, and 3) A modeling technique and novel algorithm for reconfiguring process plans.

The new manufacturing paradigms and need for responsiveness and adaptability are highlighting the importance of developing new process planning approaches that can support the objectives of the new environment. This paper shed light on the many remaining research challenges and pointed to several potential and exciting opportunities for improving manufacturing productivity and competitiveness that will inspire renewed interest in the important area of process planning research.

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