Chapter 2
Changing and Evolving Products and Systems – Models and Enablers

H.A. ElMaraghy[1]

Abstract Many manufacturing challenges emerged due to the proliferation of products variety caused by products evolution and customization. They require responsiveness in all manufacturing support functions to act as effective enablers of change. This Chapter summarizes some recent findings by the author and co-researchers that address these issues.

A variation hierarchy for product variants, from part features to products portfolios, was presented and discussed. The evolution of products and manufacturing systems is discussed and linked, for the first time, to the evolution witnessed in nature. The concept of *evolving families* for varying parts and products is presented. A biological analogy was used in modeling of *products evolution* and Cladistics was used for its classification. This novel approach was applied to the design of assembly systems layouts with the objective of rationalizing and delaying products differentiation and managing their variations.

Process planning is part of the "soft" or "logical" enablers of change in manufacturing as the link between products and their processing steps. New perspectives on process planning for changing and evolving products and production systems are presented. *Process-neutral and process-specific products variations* were identified and defined. A recently developed innovative, and fundamentally different, method for *Reconfiguring Process Plans* (RPP) and new metrics for their evaluation are presented and their significance and applicability in various domains are summarized. The merits of reconfiguring process plans on-the-fly for managing the complexity and extensive variations in products families, platforms and portfolios are highlighted and compared with the traditional re-planning and pre-planning approaches.

The conclusions shed light on the increasing challenges due to variations and changes in products and their manufacturing systems and the need for effective solutions and more research in this field.

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[1] Intelligent Manufacturing Systems Center, University of Windsor

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2.1 Introduction and Motivation

Frequent and unpredictable market changes are challenges facing manufacturing enterprises at present. In the short term, there are many triggers for products changes including evolving over time due to innovation. Similarly, manufacturing systems frequently undergo incremental changes due to introducing products with new features. They also experience significant evolutions in the long term due to products and technological changes as well as introduction of new paradigms. There is a need, in the meantime, to reduce the cost and improve the quality of highly customized products. Agility, adaptability and high performance of manufacturing systems are driving the recent paradigm shifts and call for new approaches to achieve cost-effective responsiveness and increase the ability to change at all levels of the enterprise. It is important that the manufacturing system and all its support functions, both at the physical and logical levels, can accommodate these changes and be usable for several generations of products and product families.

Modern manufacturing paradigms aim to achieve these multi-objectives through: 1) pre-planned generalized flexibility as in Flexible Manufacturing Systems (FMS) designed and built-in a priory for pre-defined anticipated product variants over a period of time, 2) limited/focused flexibility to suit a narrower scope of products variation, or 3) customized flexibility on demand by physically reconfiguring a manufacturing system (RMS) to adjust its functionality and capacity. Many enablers are required for the successful implementation of these paradigms and achieving the desired adaptability. The flexibility, reconfigurability and changeability at the system hardware level are available to varying degrees today. However, the most challenging tasks encountered during their implementation include changes required, in light of the encountered variations, in the soft/logical support functions such as product/process modeling, process planning, production and capacity planning, control of processes and production, and logistics. These support functions must not only be in place but should also be adaptable, changeable and well integrated for any successful and economical responsiveness to changes in manufacturing to be realized (ElMaraghy, 2005).

A number of novel strategies and solutions to manage the inevitable products variations and related manufacturing changes are presented including new methods for modeling products evolution in manufacturing and designing their manufacturing systems accordingly as well as for reconfiguring process plans. An important contribution and a common theme utilized in the presented strategies is the use of natural evolution principles to develop new methods and solution to cope with variations and changes.

This chapter overviews the evolution of products and proliferation of their variants and highlights the need to effectively respond to these variations and the importance of modeling their evolution. It is essential to manage these changes in order to mitigate the resulting complexities as well as to prolong the life of their manufacturing systems and use their capabilities more effectively to produce the desired products variations. The concept of evolving parts and products families in changeable manufacturing is introduced as well as a modeling technique, inspired by laws of nature, to capture the evolutionary products changes and help design manufacturing systems accordingly; with an application for design of assembly systems. Focus is also placed on process planning and its functions as an important link between the features of generations of products/product families and the features, capabilities and configurations of manufacturing systems and their modules throughout their respective life cycles. A recently introduced innovative approach to re-configure process plans is highlighted as an enabler of the necessary changes in response to products and parts variations. It represents a fundamentally new concept of process planning as an effective means of managing the pervasive products variations while minimizing the resulting changes on the shop floor. Its rationale, characteristics, features and merits are discussed.

2.2 The Hierarchy of Parts and Products Variants

Customers' demands, innovation, new knowledge, technology and materials, cost reduction, environmental concerns and legislation's and legal regulations, drive the evolution of products. Product versions are developed over time in response to these requirements. Derivatives and variations in function, form and configuration lead to new product classes including Series of Products with different Functions, Series of Components with different Configurations and Series of Features with different Dimensions. This gives rise to product families that contain variants of the products and their parts, components and configurations.

It is informative to capture and classify the resulting products hierarchy, outline concisely the types and degrees of variation that occur at different hierarchy levels and consider ways of modeling them and their consequential effects on soft change enablers such as products and systems modeling and design and process planning among others.

An industrial example of automotive products is used, where information about the various products are readily available in the manufacturer's products information and open literature. Typical products, components and parts are selected and arranged/classified according to the suggested *variation hierarchy* for illustration as shown in Fig. 2.1.

There are eight distinguishable levels in the hierarchy: 1) Part Features, 2) Parts/Components, 3) Parts Family, 4) Product Modules or Sub-Assemblies, 5) Products, 6) Products Families, 7) Products Platform, and 8) Products Portfolios.

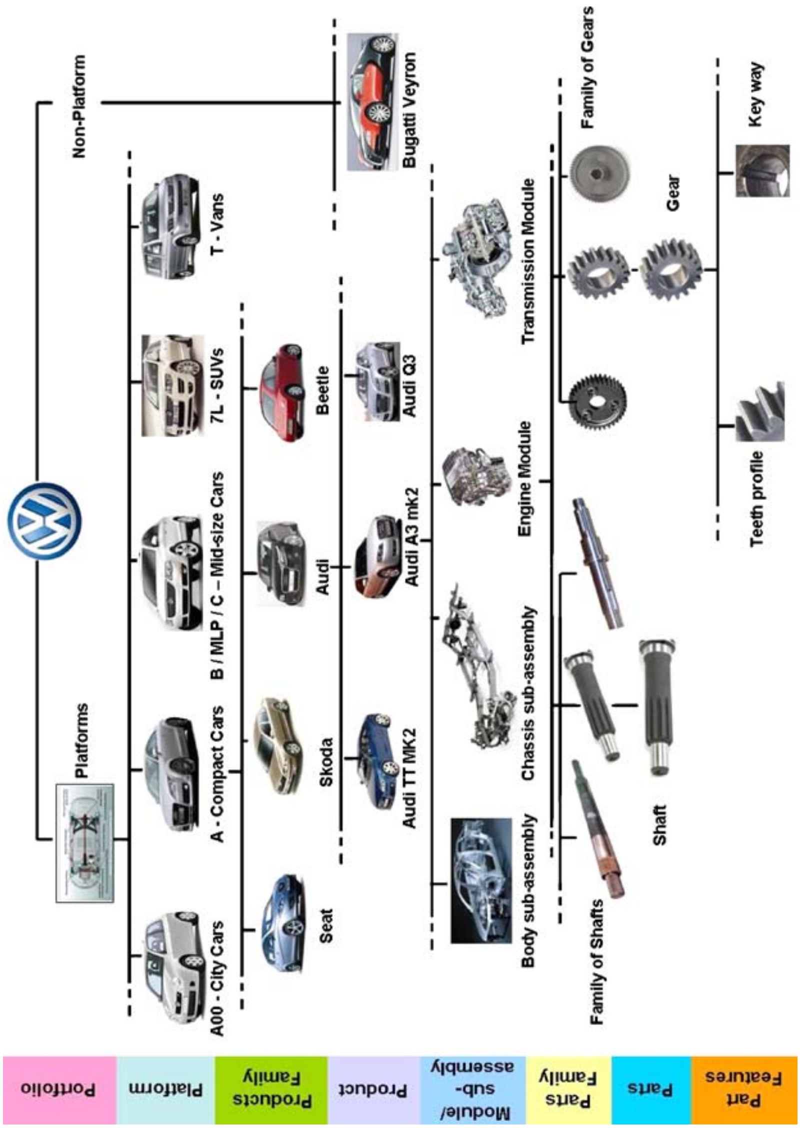

Fig. 2.1 An automobile products variation hierarchy

1) *Part Features* are either geometric features (such as flat, cylindrical and conical surfaces) or functional features (such as holes, slots/grooves, gear teeth, keyways, pockets, chamfers and threads). Features variations are easily illustrated; for example, holes may vary in dimensions, geometry and shape; they may be round or prismatic, smooth or threaded, stepped or having a constant diameter. The characteristics of the geometric and functional features are best-captured at the design level using variation geometry and parametric modeling techniques that reflect the changes within the features while respecting the geometric and dimensional constraints that express the functional requirements and designers intent. Subsequent analysis and manufacturing applications make good use of the similarities and parametric representation. Logical/soft support functions, at the process and machine levels, are directly affected by these variations. For example, in metal removal, micro/detailed process planning and tools/machines selection would utilize these models to account for the change in features.

2) *Parts/Components* are objects that are non-decomposable/non-divisible without loss of function. They contain both functional and non-functional features. Change at this level leads to parts/components variants within a class. The addition, removal and/or modification of part features require adaptation to these changes in upstream design and analysis applications as well as in downstream manufacturing logical support functions: a) at the process level such as macro- process planning (sequencing), planning of set-ups, and CNC programming, and b) at the system level such as the make/buy decisions.

3) *Parts Family* is a concept that was first introduced along with Group Technology (GT), where parts are grouped according to similarities in geometry and/or processing requirements. The objective is to capitalize on these similarities to increase the efficiency of many applications such as modeling and design, planning of fixtures and work holders, tools, production processes, parts/machine assignments, parts grouping into batches for production, and production flow management (e.g. manufacturing cells).

4) *Product Modules and Sub-Assemblies.* Modules represent functionally independent units that consist of more than one part or component and are meant to fulfill one or more technical function. A Sub-Assembly represents a number of strongly connected components and/or parts that may be considered as a single entity and is stable, in at least one direction, once assembled. A sub-assembly does not necessarily have an independent function, but is rather a convenient way of grouping parts and components into an intermediate assembly unit. Figure 2.1 illustrates instances such as the engine and transmission modules and the body and chassis sub-assemblies. A drive system for example contains many modules such as the engine, gearbox, stick shift, cooling and exhaust systems, electrical system, engine mounts, etc. (Shimokawa et al., 1997). These in turn contain common components; a gearbox for example consists of many parts such as the housing, gears, shafts, bearings, etc. that can be standard and modular. Determining the collection of parts/components that will form modules and sub-assemblies and defining their boundaries are important decisions, as they affect the extent of modularity and commonality and the

subsequent ability to interchange and combine modules into different products to offer the desired customization. In addition, they will affect the design and efficiency of the corresponding manufacturing systems. The choice of modules can also help manufacturers protect their intellectual properties by carefully planning the modules and making decisions to produce in-house, purchase or sub-contract their production.

5) *Products* are a collection of sub-assemblies and modules, the variation of which leads to different instances of that product. The dominant manufacturing activity at this level is the joining and assembly of modules and sub-assemblies into a final product. The same notion of grouping, based on similarities in features or processing steps, does apply to the modules and sub-assemblies that make up the product. At the process level, applications such as work holding, palletizing, and fixturing, parts feeding and orienting and assembly planning should benefit from the modularity and similarity between modules. Automation solutions at the system level can also be streamlined and rationalized as a result recognizing the nature and extent of similarities and variations.

6) *Products Families* is a concept similar to that of the parts families where variations in parts, sub-assemblies and modules produce different instances/members of a product family. The product family consists of related products that share some characteristic, components and/or sub-assemblies. These product families are meant to satisfy a variety of customers' demands and markets. This concept has been used more often in the context of products design and related analysis, and later for planning manufacturing processes, products platforms and market strategies. Examples of product families, some instances of which are shown in Fig. 2.1, include: the Audi Family [Audi A3 (3 and 5 doors), the Audi TT Coupe and Audi TT Roadster], the Seat Family [Toledo, Coupe, Station Wagon & Convertible], the VW Beatle Family, and the VW Golf Family.

Products variants within a family, as with parts variants, result from the modification, addition or removal of one or more modules. Macro-process planning, which determines the best sequence of assembly operations while respecting the logical and technological constraints, is dominant at the level of product modules/sub-assemblies, products and products families. The need for effectively changing macro-process plans at these levels did not receive much attention in literature to date. It can benefit greatly from novel methods for dealing with the variations while minimizing the consequential changes or disruptions in the manufacturing system as discussed in Sect. 2.6. At the system level, managing the products variation such as to provide as much variety to the consumer with as little variety as possible between the products manufacturing methods is very important to remain competitive. Delayed products differentiation is a key strategy that has been adopted to achieve this objective. A novel assembly system design method that exploits the similarities and commonalities among the product variants in a family is discussed in Sect. 2.5.

7) *Products Platform* is set of sub-systems/modules and their related interfaces and infrastructures, which forms a foundation used to produce a number of products that share common features. The platform features, parts and components remain

unchanged within a product family. Modules added to the platform serve to differentiate various products. This concept was originally introduced on the products level then extended to the products modules and component levels to achieve economies of scale through higher volume production of common product constituents. Modularity, standardization and commonality figure strongly at this level as manufacturers adopt the philosophy of products platforms to satisfy the desire for both products differentiation and customization. VW planned the “A” platform to produce 19 vehicles including all product variants of the VW Golf, VW Bora, VW Beetle, Skoda Octavia, Seat Toledo and Audi passenger cars. The chassis for the front wheel drive mid-size compact VW cars represents a fundamental module in a platform used to produce many product variants by adding and interfacing both common and different sub-systems. The body sub-system with its many components acts as one of the strong products differentiators. It is estimated that VW would save more than $1Billion/yr in capital investments, product development and engineering cost by using platforms.

Modularity promotes the exchange and re-use of components, helps the rapid introduction of new technologies, facilitates outsourcing and encourages more flexible allocation of production facilities locally and globally. This “Plug and Produce” approach to products design and manufacture supports more extensive variations in chasing customers’ satisfaction through maintaining maximum flexibility to achieve truly differentiated products while enabling controlled evolution of products identities.

The design and planning of these products platforms present many challenges throughout the life cycle of both products and manufacturing systems and have significant financial impact on the manufacturer. Products platforms must be planned, managed and updated over time to ensure the success of its derivative products and the efficiency of their production. Product-specific platforms limit the potential synergy and leveraging in products development, manufacturing technologies and processes, re-tooling, procurement of parts and equipment and marketing. Understanding products evolution and its impact on manufacturing systems design is discussed in Sect. 2.3 and 2.4.

8) *Products Portfolio* represents the range of different products offered by a company. It contains several, and sometimes quite different products and may include more than one product platform as well as non-platform products, such as the Bugatti in Fig. 2.1. The special niche products satisfy demands in certain smaller segments of the market, they do not benefit from the economies of commonality, they cost more to produce and sell for higher price and profit margins. A company decides on its products portfolio depending on its strategic goals, growth plans, market opportunities, market demands and emerging segments, competing products, risk tolerance, leverage possibilities, and economic considerations.

As the utilization and benefits of products platforms are directly influenced by the scope of its members and families, it is important to carefully plan the products, technologies or sub-systems selected for the platform and their degree of products similarity and differentiation they can support. However, many companies design new products individually without formal consideration of the whole range of products and families in their portfolios. This does not promote commonality, modularity and compatibility among products or ensure the best business justification. Ultimately it is a trade-off between commonality and distinctiveness, whereas extensively diversified platforms lead to product derivatives that lack distinctive character and do not serve well either the high or low end products, while sparsely populated platforms become inefficient, costly and thus unjustified.

In light of the above discussion and the presented products variation hierarchy, it is imperative to find ways of understanding and managing the formation of parts/products families and their variation and evolution, as well as capitalizing on their commonalities to achieve economic advantages in related activities such as product design, process planning, production planning, design of manufacturing systems and supply chain management.

2.3 Evolving and Dynamic Parts and Products Families

The classical notion of a *Static Parts/Products Families* was established in conjunction with the concept of Group Technology (GT) where members of the family have similarities in the design and/or manufacturing features. Flexible manufacturing systems relied on this definition of pre-defined and pre-planned parts and products families with non-changing boundaries for pre-planning the manufacturing system flexibility, processes and production plans according to the defined scope of variations within the family. Classification and group technology codes were introduced, such as OPITZ (1970), to make information retrieval and modification easier. In this case, a “Composite Part” that contains all features of the family members is 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 (Groover, 2008 and ElMaraghy, 1993 and 2006). The parts’ family concept is a pre-requisite for the success of flexible manufacturing where the similarity among members of a well-designed family helps achieve the economy of scale while realizing a wider scope of products.

In the current dynamic and changeable manufacturing environment, the products are frequently changed and customized, and it is also possible to reconfigure the manufacturing systems by changing their modules and hence their capabilities. Therefore, the notion of constant parts/products families is changing. This presents new challenges for related activities such as systems design and process planning to cope with both the variations on the product side and the changes in resources and their capabilities on the manufacturing side.

ElMaraghy (2007 and 2006) proposed a new class of “*Evolving Parts/Products Families*” where the boundaries of those families are no longer rigid or constant. The features of new members in the evolving families of parts/products overlap to varying degrees with some existing features in the original families; they mutate and form new and sometimes different members or families similar to the evolution of species witnessed in nature. Species is the theoretical construct that biologists use to explain why one population of organisms should be considered different from another. Species are the highest-ranked category of individuals, above which, all classes are abstract groupings of different species. Therefore, species are considered the unit of diversity in nature. This is illustrated for manufactured parts and products in Fig. 2.2. Since adding, removing, or changing manufacturing systems' modules changes their capabilities and functionality, a reconfigured system would be capable of producing new product features that did not exist in the originally planned product family. This allows the manufacturing system to respond to the rapid changes in products, their widening scope and faster pace of customization and support the evolving parts/products families.

Products evolution may be time or function based. Chronological Evolution develops gradually over time and represents a unidirectional natural progression as more knowledge and better technologies become available. It is unidirectional because as new and better solutions are obtained, there is no need to revert to older inefficient or flawed product designs. Functional Evolution is caused by significant and major changes in requirements, which are 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 would fulfill different functional requirements but would not necessarily render previous designs obsolete.

In summary, the introduced natural evolution metaphor (ElMaraghy, 2006 and 2007) is useful in explaining the concept of evolving parts/products families and finding solutions to the associated challenges. Static parts family members are seen as closely knit, having a strong core of common features where all parts/products variations are within the pre-defined boundaries (as would be applied in FMS). The concepts of Composite Parts, Master Plans and Retrieval/Variant Process Planning are both valid and useful in this case. After some parts/products generations, new parts (species) emerge and parts families gradually lose their roots as some features disappear and new (additional features) and different (modified features) branches are developed. The extent of difference between parts generations depends on the number and nature of features' changes until a clear differentiation of characters develops. The same evolution notion applies to products where parts, modules or

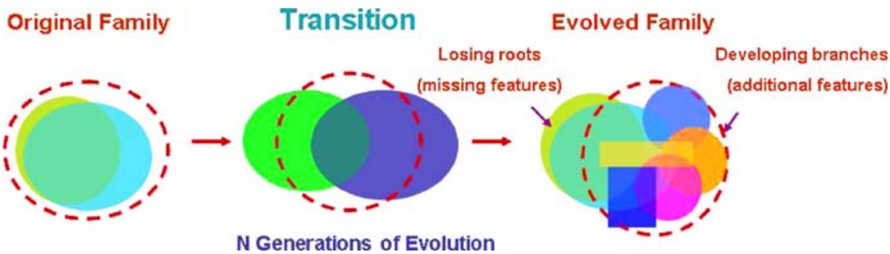

Fig. 2.2 Evolving parts/products families

sub-assemblies may be added, removed or changed causing the product and its family members to evolve. After many and different products generations, new product features and different products (species) and product families emerge with much less resemblance to the original parent family. In this case, many of the previously used and familiar rules and methods (e.g. for process planning) do not apply any longer. The magnitude of change and distance between new and old members of the parts/products families significantly influences the characteristics of the process plans in this new setting.

In light of the above discussion, 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, was introduced (Azab and ElMaraghy, 2007a and 2007b) and is discussed in Sect. 2.6.

2.4 Modeling Products Evolution – A Biological Analogy

The importance of understanding and managing the variation and evolution of parts/products families has been emphasized in previous sections. A novel biological analogy was introduced (ElMaraghy et al., 2008) and used for modeling evolution in manufactured products with the aim of extending it to their manufacturing systems and understanding the relationship between them.

Evolution does not only mean change, it marks modifications occurring over time, which can be inherited by descendants, in the process of developing new species. "Adaptation" is the main driver of evolutionary changes, which we contend can be observed in both nature and manufacturing. This approach was first proposed (ElMaraghy et al., 2008), to study evolution in the context of manufactured products, was demonstrated using the Cladistics analysis originally introduced by Hennig (1966) but only used to date in biological analysis. A family of engine cylinder blocks, two instances of which are shown in Fig. 2.3, was used as an exam-

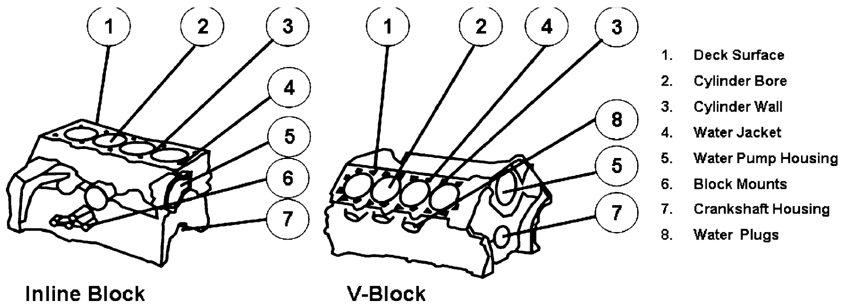

Fig. 2.3 Two members of the automobile engine cylinder blocks family – Inline and V-types (ElMaraghy et al., 2008)

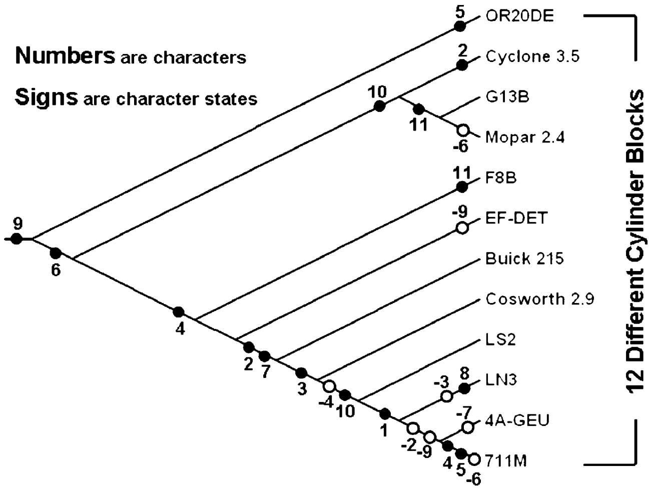

Fig. 2.4 Cylinder blocks Cladogram and product groups (ElMaraghy et al., 2008)

ple to demonstrate the developed application of Cladistics analysis and its merits. The cylinder block variants belong to automotive engines of different makes, material and types from Japan and North America, ranging in capacity from half a liter to six liters. The cylinder blocks are made of either Aluminum or Cast Iron. They belong to In-line or V-type, High-deck or Low-deck, Front or Rear Wheel Drive, Over Head Cam (OHC) or Over Head Valve (OHV) engines.

The Cladistics classification technique was shown to be capable of determining a logical representation of a group of automobile engine cylinder block variants and showing their path of evolution, in the most efficient way, using the parsimony analysis (ElMaraghy et al., 2008). The resulting Cladogram (Fig. 2.4) can yield additional useful information. These include potential possibilities of re-arranging existing product families to form more logical groupings, tracking their evolution trends, easily generating composite parts corresponding to a given set of product variants, identifying potential design and manufacturing latitudes, enhancing product design decisions and encouraging simplification, determining relevance of new variants to existing families, and anticipating future evolution directions of products design and development.

2.5 Design of Assembly Systems for Delayed Differentiation of Changing and Evolving Products

Customized and modular products allow manufactures to offer rich varieties to customers; however, this increases the complexity of both the products and manufacturing systems design. Delayed Product Differentiation (DPD) is a strategy introduced and adopted by companies to achieve the desired products variability while ensuring more manufacturing efficiency (e.g. He et al., 1998 and Xuehong et al., 2003). The objective is to postpone the stage in manufacturing where each of the products becomes differentiated and begins to have its own separate manufacturing path. Little work in literature has contributed methodologies for designing a physical manufacturing system that follows and implements the DPD strategy.

Clustering techniques are basic tools for establishing the different families of products. They are used to define the boundaries between the different families of products resulting in a number of differentiated sets, each containing a number of parts, components or products that are manufactured similarly, or have geometric likeness. Such techniques are used extensively in Group Technology (GT) and Cellular Manufacturing (CM). However, it has recently been proposed to use the commonality analysis as a fundamental method for analyzing each individual family of products for suitability to being produced in a DPD environment (AlGeddawy and ElMaraghy, 2008). Commonality analysis is mostly used with complete products composed of different parts, modules and sub-assemblies, rather than individual parts with different features. Its objective is to recognize commonality; it results in a metric of likeness among the products rather than identifying different sets of products. It should be noted that Cladistics were never used in the DPD literature, moreover, there is a lack of research in applying commonality analysis to products families in general, and in areas related to the DPD environment in particular.

The new framework offers a novel application of Cladistics applied to assembly lines design for Delayed product Differentiation. It: 1) uses products commonality schemes, and 2) complies with the precedence constraints that must be respected in sequencing assembly steps. It effectively links products design with the assembly line design. This model produced a set of unique Cladorams, as shown in Fig. 2.5,

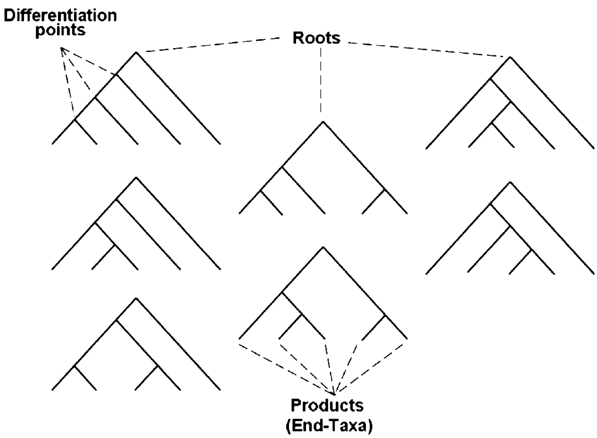

Fig. 2.5 Unique Cladograms representing assembly system layout schemes for the studied family of products (AlGeddawy and ElMaraghy, 2008)

which in fact schematically represent the possible physical assembly flow lines and their assembly steps/stations that can produce the analyzed family of five household products used for boiling water. It indicates where branching (i.e. product differentiation) takes place in each system alternative. The resulting flow line schemes would be further analyzed and compared using other performance and cost criteria and the best assembly system design would be selected.

Analysis of the resulting assembly line patterns reveals further information that should be considered to enable future improvements in the assembly line design and better management of the products variation while maximizing the delay in differentiation, including: 1) Re-sequencing of assembly operations by relaxing some precedence constraints for those similar and repeated assembly steps of closely related products, to allow these common steps to be moved up in the assembly line, and avoid their repetition, and 2) Re-designing products by adding commonly occurring characters/features to products that lack those characters, hence delaying branching out into different products on the assembly line.

The presented approach is a novel manufacturing system layout design method and a decision support tool for its further improvement. This design technique is not limited to assembly lines in one physical location but may be extended to the whole supply chain where products differentiation may be delayed till the point of delivery at distributed geographical locations. It helps manage the witnessed wide scope of products variation at the assembly level.

2.6 Process Planning – The Link Between Varying Products and their Manufacturing Systems

The process plans and planning functions are important links between the features of various generations and variations of products /product families and the features, capabilities and configurations of manufacturing systems and their components throughout their respective life cycles. One of the challenges for process planning in an environment characterized by change is to define methodologies and constructs that can be used consistently to respond to the variations observed in parts, products and families as well as changes in manufacturing resources and their availability on the shop floor. The efficient generation and adaptation of process plans is an important enabler for changeable and responsive manufacturing systems.

2.6.1 Existing Process Planning Concepts

The process planning activities have seen significant growth and development since the nineties. 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, within given constraints while optimizing some stated criteria (ElMaraghy, 1993).

Process planning techniques are now being applied in many domains such as metal removal, assembly/disassembly, inspection, robotic tasks, rapid prototyping, welding, forming, and sheet metal working. The process planning concepts and approaches are classified based on their level of granularity into: 1) Multi-Domain Process Planning to select the most suitable manufacturing technology to produce the part/product, 2) Macro-Process Planning, which selects the best sequence of multiple different processing steps and set-ups as well as the machines to perform those operations, and 3) Micro-Process Planning, which details each individual operation and optimise's its parameters. Process planning may be done manually or using Computer-Aided Process Planning (CAPP) systems. Automated process planning varies according to the type and degree of automation and includes: 1) Retrieval/ Variant Process Planning, which capitalizes on the similarity in design or manufacturing features among parts grouped into families, and revises existing master plans, 2) Semi-Generative Process Planning that benefits from retrieved "Master Process Plans" to make some "part-specific" decisions, but also optimize the operations to be performed and their parameters using algorithmic procedures assisted by CAD models, databases, decision tables or trees, heuristics and knowledge rules, and 3) Generative Process Planning that aims to generate an optimized process plan from scratch. Its success is predicated on the availability of 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 in this approach. A truly generative process planning system in any domain is yet to be realized. The major challenge is the availability of complete and reliable mathematical models of the various manufacturing processes and their characteristics as well as complete process planning knowledge and rules.

2.6.2 Process Plans Changeability

A change in products and/or manufacturing systems would not necessarily result in changes in process plans; the nature of change matters. The nature and extent of change in process plans depend on the type and degree of parts/products variations. Hence different process planning schemes would be needed for different scenarios. The products variation hierarchy shown in Fig. 2.1 can be used to illustrate the need for changeable process plans at the various parts/products families and levels. The following types of products variations can be identified along with the corresponding required changes in process plans.

Process-Neutral Products Variations that help create product identities and differentiation visible to the customer without changing the manufacturing process steps such as changing of automobile body colors, the color and material of the interior finish or type of special modules such as audio equipment. These and similar variations are observed at the products platforms, product families, products and sub-assemblies/modules levels where the macro-assembly process sequence and steps would not normally be affected by such changes in these cases.

Process-Specific Products Variations tend to be seen in the features of products modules, sub-assemblies and parts. These variations may affect the manufacturing process, as in the case of abandoning brushes and adopting brush-less technology in electric motors that would require major changes in the manufacturing processes, or affect the process sequence (macro-plan) as parts and features are changed, added or removed. The variations can be of a parametric nature where the detailed micro-plan would need to be adjusted accordingly. These parametric changes may be *small* and hence the same technology (e.g. metal removal) would still be used but with adapted parameters, or they may be *extreme* so as to call for a completely different manufacturing method. Some dimensional variations can lead to significant changes in the method of fabrication and would therefore require major process re-planning. For example, small variation, within limits, in the features and dimensions of a gear in the family of gears shown in Fig. 2.1 (e.g. gear teeth profile, key-way, and inner and outer diameters) would not lead to significant changes in the method of manufacture. Existing metal removal process plans can still be changed/adapted effectively using parametric variations, where group technology, composite parts and retrieval/variant process planning would be used. The addition or deletion of features affects the sequence of operations; and significant changes in macro-process plans would be required where all types of precedence constraints must be checked and satisfied. In addition, extreme reduction in dimensions may require micro-machining of the gear, and very large gears may have to be cast or forged first then machine finished. Both types of extreme variations call for different fabrication method/technology and complete process re-planning rather than adaptation.

Since not only products variations are increasing in scope and frequency and the families of manufactured parts are evolving, but also manufacturing resources on the shop floor and their functionalities are becoming changeable and reconfigurable (ElMaraghy, 2005), then "Reconfigurable Process Plans" are becoming an essential enabler of change.

There are some key criteria for reconfiguring process plans and commensurate techniques for their efficient re-generation when needed: 1) The utilization of the multi-directional and multi-faceted relationships and associations between the characteristics of product features, the process plan elements and all manufacturing system modules capable of producing them, 2) The process plan representation characteristics that facilitate adjusting and implementing optimally determined feasible and economical alterations in process plans to reflect the needed reconfiguration, 3) The ability to model process plans at varying levels of detail and granularity in order to, readily and appropriately, respond to changes at different levels (e.g. in products, technologies and systems), and 4) The availability of complete knowledge bases and rules for process planning and reconfiguration, accurate mathematical models of the various manufacturing processes and resources as well as meta-knowledge rules for using this knowledge to automate the plan reconfiguration. The optimality (time, quality, cost, etc.) of the evolved and reconfigured process plans should always be verified and maintained.

Some examples of newly developed approaches and methods for process planning for variation, based on the author's and her group's research are presented next for illustration.

2.6.3 Reconfiguring Process Plans (RPP) and Its Significance

The Reconfigurable Process Planning (RPP) approach represents an important enabler of changeability for evolving products and manufacturing systems. It addresses the new problem that arises due to the increased frequency and extent of changes in products and systems and the need to manage these changes cost effectively and with the least disruption of the production activities and their associated high cost.

A hybrid retrieval/generative reconfiguration model and algorithms for process planning (RPP) have been developed (see Azab and ElMaraghy, 2007a and 2007b for more details). The parts/products family, closest to the new part, would be identified and its composite part and corresponding master process plan are retrieved and missing features/operations are removed. Novel 0–1 Integer Mathematical Models and Mathematical Programming for reconfiguring these macro-level process plans were formulated and applied, for the first time, to the process planning/sequencing problem. It fundamentally changed it from an optimal sequencing to an optimal insertion problem. Reconfiguration of precedence graphs to optimize the scope and cost of process plans reconfiguration is achieved by inserting/removing features/operations iteratively in their string representation to determine the best location for added features and related operations in the operations sequence. This is akin to inserting new genes in a chromosome using the genetic evolution metaphor and lends itself to modeling and capturing the evolution of the parts/products features and corresponding processing operations and plans. The proposed RPP macro-process plan reconfiguration methodology readily supports evolving part families and manufacturing systems. Mathematical programming and formulations were presented, for the first time, to generate process plans that would account for changes in parts' features as they evolve beyond the scope of their original product families.

Two criteria were used in Reconfiguring Process Plans. First, the parts handling and re-fixturing time, when no value is added to the product, is minimized to arrive at a reconfigured and optimal process plan that minimizes the extent of reconfiguration and hence its implications. Second, a process plan Reconfiguration Index (RI), which is a Changeability Metric that captures the extent and cost of changes in the plan, was introduced as a new criterion to evaluate the reconfigured process plans. It can be used for choosing among alternate process sequences with substantially similar total cost by opting for the one that causes the least changes and disturbances on the shop floor (i.e. smallest RI). This saves other direct and indirect costs such as those related to changes in set-ups, tools, re-programming and associated errors and related quality issues. This tends to favor *limiting/localizing* the extent and effect of plan reconfiguration compared with the initial process plan, and it is *done by design.*

The weight given to the above two planning criteria, in practice, depends on the cost component that matters most in a given situation and different emphasis on initial vs. running cost in large volume and small series production as they are affected by frequent changes. The developed RPP model can use either criterion or a combination of both. Thus, the process planner would have the opportunity to consider which criterion matters most, based on experience and available data.

The RPP model has been applied in the metal removal domain, at the parts family level, for a family of single-cylinder aluminum engine front covers (Azab and ElMaraghy, 2007b) where the parts features changed. It was also applied in the assembly domain, at the products family level, for a family of small kitchen appliances (kettles) where the product features changed (Azab, 2008). These test cases clearly demonstrated the effectiveness of the proposed RPP methods.

The RPP approach is more advantageous than existing methods for dynamic, adaptive and non-linear process planning that utilize either pre-planning or re-planning methodologies. For the pre-planning methods, alternate process plans are developed and documented ahead of time in anticipation of future changes. In addition to the obvious cost and computational burden involved in this approach, future changes in products and technology cannot be fully predicted a priory. Moreover pre-planned process plans would likely become obsolete as the products, resources and technologies are changed. In re-planning, a whole new plan is created from scratch, without benefiting from currently available plans, set-ups, tooling, etc., every time some changes are made with the obvious added cost of not only re-planning, but also more importantly the potential major changes and disturbances on the shop floor as a result.

This new methodology for Reconfiguring Process Plans (RPP) is applicable to macro-process planning where determining the optimal sequence of operations and satisfying precedence constraints are important on the parts, modules and products levels. Effective macro-process planning, involving all manufacturing fabrication and assembly steps and their logical sequence, is important if the potential to offer greater product variety rapidly while reducing cost and risks is to be achieved.

2.6.4 Process Planning for Reconfigurable Machines

The RPP approach deals with variations in the process plans as a result of changing parts and products. Changes in process plans might require different machines assignment, depending on the available machines and their capabilities. Changes in machines, through purchase, replacement or reconfiguration would also trigger changes in process plans to utilize and benefit from the new capabilities. Therefore, a two-way mapping between the features of products and machine tools was devel-

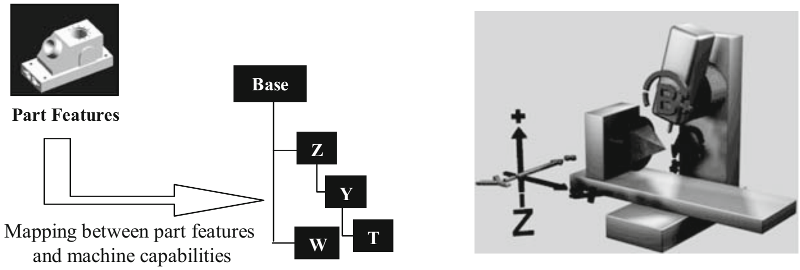

Fig. 2.6 Mapping between part features and machine capabilities (Shabaka and ElMaraghy, 2007)

oped and used for re-planning. The selection of 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 (Shabaka and ElMaraghy, 2007). The machine structure is represented as kinematic chains that capture the number, type and order of different machine tool axes of motion, which are indicative of its degrees of freedom and ability to produce certain geometric features as well as the size of workspace (Fig. 2.6). Operations are represented by a precedence graph and clustered according to the logical, functional and technical constraints.

Optimal process plans are generated using Genetic Algorithms (GAs) based on a constraint satisfaction procedure that ensures the feasibility of all produced plans. A rule-based semi-generative Computer-Aided Process Planning approach was introduced to adapt existing process plans through re-planning and account for changes in product requirements and/or availability of system resources. This approach minimizes the required hard-type reconfiguration on both the manufacturing system and machine levels if less costly soft-type adaptation of existing process plans can be performed instead. This research work advances the existing knowledge about process planning in the RMS domain with regards to macro-process planning (sequencing), operation selection and selection of machines and their configurations. It supports the process planer's decision making regarding the machine assignment/selection and sequencing activities at the initial stages of manufacturing systems design and subsequent changes in products features and scope. The developed approach is not limited to RMS and can be applied to other manufacturing systems such as FMS.

2.7 Discussion and Conclusions

The proliferation of products variants is wide spread due to the natural products evolution, which has been on the rise to satisfy customers' needs and specifications and benefit from advances in new materials and technologies as well as comply with imposed environmental legislation's and legal regulations. Products innovation and mass customization introduce many changes aimed at achieving products differentiation, which is an important key to surviving globalization and ensuring a competitive advantage. In addition, many engineering changes in products take place frequently throughout the product life and affect all types and sizes of manufacturers, from job shops, tool and die makers, to large automotive or aerospace companies. All product changes and revisions result in costly and significant changes in the design and manufacturing steps, setups, process plans, tools, fixtures and the used machines.

The increased products customization has also lead to a wider scope of products variants and increased their complexity as well as that of their manufacturing methods and systems. New manufacturing systems paradigms, such as flexible and reconfigurable manufacturing, evolved to achieve maximum products variety while remaining competitive, profitable and responsive to the frequent changes in markets and products.

This chapter presented a number of novel strategies and solutions to manage the inevitable products variations and related manufacturing changes.

A *Variations Hierarchy* was presented to classify variations at different levels from products families and platforms to individual parts and their features, and the implications of variation and commonality for both design and manufacturing were discussed.

A new class of "*Evolving Parts/Products Families*" was presented and contrasted with the traditional notions of static parts families. The implications of such evolution on planning products families and platforms were explored and its effects on downstream manufacturing support functions, such as process planning and assembly systems design were highlighted.

A novel approach for *modeling evolved products*, utilizing mechanisms analogous to those observed in nature, was presented. This innovative concept has the potential for modeling not only the evolution of products or their manufacturing systems but also their symbiotic co-evolution relationship. Its application, using Cladistics, to recognize and classify the commonalities among products and to design assembly systems layouts for delayed products differentiation was illustrated. The obtained results provide a promising foundation for future research in this domain.

An innovative method for *Reconfiguring Process Plans (RPP)* was presented. The new RPP method is also akin to the genetic evolution metaphor in manipulating the strings of ordered operations. It helps manage the complexity and variation of changing and evolving parts and products families and introduces innovative planning techniques that were demonstrated for both parts fabrication and products assembly. One of the main contributions of this method is the development of a new mathematical model for solving the classical problem of process planning through reconfiguration rather than sequencing. It limits the changes on the shop floor resulting from changing process plans by seeking a localized optimally reconfigured plan. Hence, process plans reconfiguration can be performed only when needed, where needed, and to the extent needed. This is done by design. It introduces an efficient way of coping with the frequent changes and allows this reconfiguration to take place on the fly. Hence, it reduces the need to keep, maintain and manage a huge number of process plans variants by manufactures. It demonstrates that process plans reconfiguration on demand is an effective management strategy to cope with variation.

In conclusion, the designers of products, processes and manufacturing systems as well as production planners should be cognizant of the coupling between generations and variations of products and manufacturing systems, its special nature and characteristics, and capitalize on its potential benefits for improving the productivity of the whole enterprise. This chapter presented a number of research contributions, which utilize this notion, towards providing enablers of change and achieving these goals.

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