Thesis Report

Master's Degree

A Plan-Based Design Similarity Approach for Hybrid Process Planning

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ABSTRACT

Title of Thesis: A PLAN-BASED DESIGN SIMILARITY APPROACH FOR HYBRID PROCESS PLANNING

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A process plan describes the steps necessary to manufacture a product. Because creating a process plan is a time-consuming activity, researchers have developed methods that reduce the time and effort required. The hybrid process planning approach builds on the strengths of the variant and generative process planning approaches while overcoming their individual drawbacks. The variant approach identifies useful process plans from a database that contains existing designs and their process plans. The retrieved plans are then merged and modified as necessary to generate a plan for the new design. To find these designs and process plans, one must define a design similarity measure that evaluates the similarity between an existing design and the new design. The hypothesis of the variant planning approach is that similar designs have

similar process plans. However, existing design similarity measures are not plan-based. Consequently, the retrieved process plans may not be useful when building the new design's process plan. This thesis presents a systematic approach to formulate a precise and consistent plan-based design similarity measure that ensures that designs are classified as similar if and only if they have similar process plans. We do not assume *a priori* that similar designs have similar process plans. The proposed approach identifies functions that map design parameters to critical process planning attributes. We assume that there is a one-to-one correspondence between the designs and the corresponding process plans. Mapping functions identify those design parameters that must be similar for critical process plan attributes to be similar. Design similarity is thus a function of process plan similarity. This plan-based design similarity measure ensures that similar designs will have similar process plans. The generality of the proposed design similarity approach is validated by developing hierarchical and continuous design similarity measures using this approach.

A PLAN-BASED DESIGN SIMILARITY APPROACH FOR

HYBRID PROCESS PLANNING

by

Gurdip Singh

Thesis submitted to the Faculty of the Graduate School of the
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DEDICATION

To my parents, my sister, and

my teachers

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Chapter 1

Introduction

The Integrated Product and Process Design and Development (IP^2D^2) process aims at translating a product concept into a manufacturable and profit-earning product that satisfies customer requirements. The IP^2D^2 process takes the design team through a series of intermediate steps to meet the above stated goals. One of the most crucial steps in this process is taking the final design embodiment's part characteristics and generating the corresponding process and production variables. The process and production variables corresponding to a design are usually outlined in a process plan (also referred to as a routing sheet) for use on the shop floor. The process plan describes unambiguously the type and sequence of manufacturing operations that the operators need to perform in order to transform the stock into the proposed design embodiment. In addition, the design team may generate process plans for intermediate designs and conduct a plan-based manufacturability evaluation.

A process planner must take into account the available resources, process capabilities, batch size, tolerance standards, material standards, cost, and time in order to generate a good process plan. Thus the process planner spends a significant amount of time in data collection and document preparation.

Traditionally, experienced personnel perform the task of process planning. Significant research has been targeted in the recent past at reducing the effort needed to generate a process plan by automating the data collection and plan generation process. Computer Aided Process Planning (CAPP) tools have made significant contributions to the industrial workplace. There are two primary approaches to CAPP: variant planning and generative planning.

Variant process planning is based on the hypothesis that similar parts will have similar process plans. A variant process planning system searches for an existing design that is similar to the proposed design and retrieves the existing design's process plan. The process planner then manually modifies the retrieved plan to make it feasible for the proposed design. To search for similar designs, the system must use a product classification scheme and a design similarity measure. Traditionally, Group Technology (GT) coding and classification schemes have been used to classify similar designs. Despite the popularity of the commercial variant process planning systems, this approach has some significant drawbacks. The variant process planning technique is explained in detail in Section 2.1.1.

In generative process planning, the planning system attempts to synthesize a process plan directly for a new design. For machined parts, the typical approach is to do the planning on a feature-by-feature basis. Candidate processes from the manufacturing knowledge repository are selected, based on geometric and manufacturability feasibility analyses. These processes are then combined into a process plan for the proposed design.

Unfortunately, generative process planning has proven quite difficult. An evaluation of the generative process planning approach is presented in Section 2.1.2.

A next logical step in the development of CAPP is to develop a hybrid variant-generative approach to process planning that would build on the strengths of the two primary process planning techniques while overcoming their individual drawbacks. One such hybrid approach has been proposed by Elinson, Herrmann, Minis, Nau and Singh [1997]. The application domain of this approach is machined parts. The basic steps of this approach are summarized below:

1. Create a solid model *D* of the final design embodiment using standard Computer Aided Design (CAD) software.

2. Add annotations such as batch size, material, and tolerances to the CAD model through a user interface.

3. Use the feature extractor to recognize the unique set of primary machining features *M(D)* corresponding to the design *D* [Gupta, 1995].

4. Create a feature graph *G(N, E)* using the primary feature set *M(D)* and the annotated CAD model *D*, such that the nodes correspond to the primary machining features and the edges denote important manufacturing and geometric relations between the features (nodes).

5. Divide the feature graph into subgraphs. Each design subgraph *P(n, e)* will represent a collection of primary machining features and the important manufacturing and geometric relations among these features.

6. Using a measure of design similarity, extract from the repository of existing designs design subgraphs (S_1, S_2, ..., S_k) that are similar to the design subgraphs created in above step.

7. Combine the process plan slices that correspond to these similar designs into a process plan for the proposed design.

8. Verify the feasibility of the synthesized process plan to generate the physical embodiment of the proposed design. Use generative process planning techniques to modify and update the synthesized process plan to suit the proposed design.

A hybrid variant-generative approach offers significant advantages over existing process planning techniques. Although an exact match may not exist for the proposed design, portions of different existing designs may exactly match some portion of the proposed design. The hybrid approach exploits these similar subdesigns. Synthesizing a process plan from the process plan slices corresponding to each of the similar subdesigns would yield a plan that requires fewer modifications because it is more suitable to the proposed design than the single process plan retrieved during a variant search procedure. The hybrid approach uses generative process planning techniques to create process plan slices for subdesigns of the proposed design for which there were no similar existing subdesigns. Since these subdesigns will be simpler, generating process plans for them should also be easier.

From the above discussion, the proposed hybrid approach appears promising and likely to overcome some of the major drawbacks of the two existing primary approaches.

A necessary component of such a hybrid approach is the ability to retrieve process plan slices that are useful to synthesize the complete process plan for the proposed design. Since these slices result from the search for similar subdesigns, we need to develop a measure of design similarity that has the following characteristics:

- The design similarity measure must reflect the similarity between process plans. A plan-based design similarity measure will yield more useful process plans. This, in the hybrid approach, will yield more useful process plan slices and a complete process plan for the proposed design that requires fewer modifications.

- The design similarity measure must allow us to classify and retrieve, precisely and consistently, existing designs based on their similarity.

This thesis will address the following research question: How can one define a consistent, precise design similarity measure that will be rational and useful when applied to the proposed hybrid variant-generative approach for process planning under the assumption that there exists a one-to-one correspondence between a design and its process plan? Previous design similarity measures are based on the similarity of GT codes or upon the similarity of design attributes (Section 2.2). Although these attributes do encode manufacturing knowledge, the similarity measures defined do not explicitly relate to process plan similarity. In our approach we use a process plan similarity measure to define the design similarity measure. This plan-based measure should yield more useful plans when used in the variant or hybrid process planning approaches.

In addition to the above research question, several other interesting questions and research issues appear when considering the hybrid approach to process planning. This thesis will address the following questions: What is a process plan? What manufacturing information framework does process planning require? Answering these questions provides insight into the original research question. However, this thesis does not answer the following questions: How are the process plan slices synthesized into the complete process plan for the proposed design? How is the complete process plan used to carry out a plan based evaluation of the proposed design? What factors ensure the feasibility of the complete process plan? We leave these questions for future researchers to explore.

The remainder of this thesis is organized as follows: Chapter 2 presents a review of existing literature in relevant fields. An overview of process planning techniques, and traditional design similarity measures is presented. Chapter 3 describes an approach to define a design similarity measure based on the similarity between process plan slices. Chapter 4 describes the structure and content of a process plan. An explicit description of a process plan and the framework necessary to support such a plan on the shop floor will remove some of the ambiguity surrounding the definition of a process plan. Chapter 5 describes a hierarchical process plan similarity measure which is then used to define a hierarchical design measure. Chapter 6 defines a continuous design similarity measure based on a continuous process plan based similarity measures. Finally, Chapter 7 presents the conclusions from this research and the contributions of this study to the design and maufacturing community. Research issues not addressed in this thesis and directions for further research are also outlined in this chapter. The Appendix explains the concepts of strict feature interactions resulting from datum dependent tolerances and approachability constraints.

Chapter 2

Review of Related Research Work

This chapter presents a review of work related to the research question addressed in this thesis. There is a vast body of literature that addresses the issues involved in automating process planning. Several commercial software systems are available to help the process planner work more efficiently, quickly and accurately. Section 2.1 describes the traditional variant and generative approaches to process planning. This section also describes some recent efforts at combining the two traditional approaches for planning to overcome the drawbacks associated with the traditional techniques. Section 2.2 describes briefly the various design classification techniques in use in industry and academia. This section describes in detail the two approaches to design classification using Group Technology (GT) coding and classification schemes. GT codes have in fact become the *de facto* standard for design classification in the variant approach. No attempt is made in this section to exhaustively explore the several GT coding schemes that have been developed. Instead, the philosophy behind the use of GT codes for classifying designs is underscored. Section 2.3 presents some observations on the traditional approaches to design classification described in the preceding sections.

2.1 Process Planning Techniques

2.1.1 Variant Process Planning

The hypothesis of the variant process planning technique is that similar designs will have similar process plans. The variant process planning system provides the process planner with a standard process plan for the family of products to which the proposed design belongs. This standard plan is then modified to ensure its feasibility for the proposed design.

The variant process planning technique was one of the first approaches to be used for computerized process planning. Several variant process planning systems are commercially available. They currently support almost all practical implementations of CAPP. Typical systems are MIPLAN, MITURN, and MAYCAPP (Alting, and Zhang [1989]). The variant process planning approach involves the following three steps:

1. The process engineer uses a Group Technology (GT) coding scheme to map a proposed design D into an alphanumeric code.
2. This code is then used as an index into a database to retrieve a process plan P_O for a design D_O similar to D, or for the family F_O to which D belongs.
3. The planner then modifies the process plan P_O manually to produce a plan P for the design D.

Some of the reasons why the variant process planning technique is popular are:

1. The total time spent by the planner in generating a complete process plan for the proposed design is reduced because the planner's work is reduced to modifying the retrieved plan.
2. Since this approach avoids "redesigning the wheel" for the most part, the planner is not burdened with assigning a reason for selecting a process, a machine tool, etc., since it is assumed that this reasoning was carried out while creating the process plan for the existing design. This leaves the planner with more time to generate and evaluate alternate process plans for design features in the proposed design which differ from the retrieved design.
3. This approach has been successfully implemented in several practical CAPP systems.

Despite the popularity of variant process planning systems, it has some significant drawbacks:

- This approach will prove ineffective for a truly unique or first-of-its-kind design since the designer will have to generate the complete process plan for the proposed design.
- This approach will prove ineffective when production quantities change significantly, because the retrieved process plans will specify inappropriate processes.
- The approach will be ineffective when the manufacturing process has changed because the retrieved process plans will specify outdated processes.

2.1.2 Generative Process Planning

In generative process planning, the planning system attempts to synthesize a process plan directly for a new design. For machining, the generative process planning process typically involves the following steps:

1. Extract the manufacturing features of the proposed design.

2. Use the manufacturing knowledge repository, rules of thumb, and heuristics to generate candidate process plans for each of the necessary manufacturing features.

3. From the candidate process plans for each feature, select the optimal process plan. The complete plan must reflect the geometric and manufacturing constraints imposed on the part.

A generative process planner that provides a realistic process plan for a reasonably wide spectrum of products would have made a great impact on industrial practice. Thus a great deal of research has been done on generative approaches, and a number of experimental systems have been developed for various aspects of process planning (Mantyla, Opas and Puhakka [1989], Kambhampati, Cutkosky, Tennenbaum, and Lee [1993], Gupta, Nau, Regli and Zhang [1994])

Unfortunately, generative process planning has proved quite difficult. Difficulties arise from interaction with various aspects of the problem, such as, process selection and process sequencing. Moreover, it is very difficult to address some important issues such as jig/fixture selection using this approach, because of the complexity of such tasks. As a result, most existing systems work only in restricted domains. Although one generative system PART system (Geelink, Salomons, Slooten, Houten, and Kals [1995] and http://www.wb.utwente.nl/pt/projects/part) is being marketed commercially, generative systems have not really achieved significant industrial use.

Even in the absence of complete and comprehensive solutions to the entire process planning problem, generative process planning techniques can be useful in Design for Manufacturing (DFM) (Boothroyd [1994]), in which the designer tries to take manufacturability considerations into account during the design stage.

2.1.3 Hybrid Planning Process Planning

In the past, some researchers have explored the feasibility of merging the two traditional approaches to process planning to create a more robust approach to tackle the problem of automated process planning. In this section two such approaches are described.

Kumar [1988] describes an enhanced variant process planning system. This approach uses AI techniques to include automated plan modification modules in the planning system. A knowledge base provides expert manufacturing information which then serves as a model to modify the searched plan and make it feasible for the proposed design. This approach aims at reducing the need for extensive manual intervention in the plan modification stage of the variant process planning approach.

Marefat and Britanik [1994] describe a process planning system which attempts to combine the advantages of the two traditional approaches. Their system is a case-based process planner. The domain of implementation is 3D prismatic parts. The process plan corresponding to a feature is generated by the case-based planner by recalling similar features the planner may have encountered in the past. Similarity here is hierarchical: the feature must be the same type, then the same dimensions, then the same tolerances. The planner learns from experience and generates better and more suitable process plans with time. Hierarchical plan merging techniques are then used to combine the process plans corresponding to each of the features into a global process plan for the complete design.

2.2 Design Similarity Measures

2.2.1 An Overview of Design Similarity Measures

The most popular design classification schemes in use today are the Group Technology (GT) coding and classification schemes. GT codes have been in use for the last thirty to thirty-five years, ever since they were popularized by Mitrofanov [1966] and Opitz [1970]. One of the main reasons why GT codes are so useful in the manufacturing industry, is that they allow the economy of scale usually associated with mass production to be associated with small and medium-sized production runs, by grouping products with similar production routes together. In addition, GT codes have been widely and very successfully used to design and operate cellular manufacturing systems (Snead [1989]). GT codes have also been used in materials management, tool management, process planning and product standardization (Snead [1989]).

Although manufacturing engineers have put the GT code to innovative use in the industry, it is widely acknowledged that GT codes suffer from several drawbacks, not the least of which is the tremendous effort and time they inherently require to initially set up the database, and then constantly update it to ensure its usefulness. Several researchers are trying to automate the task of GT code generation and thus reduce the overhead associated with creating and maintaining GT code databases (Kalyanapasupathy, Lin and Minis [1997]). However, since GT codes were initially meant to be human interpretable, sometimes the rules that the GT classification schemes use to create the code can be interpreted differently, and so attempts to automate GT code generation have not always been successful (Ames [1988]).

Another approach to classifying designs is to use geometric properties of solid and Computer Aided Design (CAD) models. Although this approach is currently not very widely used in the manufacturing industry, it does offer some potential solutions to the problem of automating the task of classifying designs.

2.2.2 Design Classification Approaches for Group Technology

GT codes are broadly classified into three categories hierarchical (monocode), chain type (polycode), and hybrid (semi-polycode). Monocodes are GT codes in which the information contained in a particular position of the code can be interpreted only on the basis of the information contained in the preceding positions of the code. This form of the GT code most closely resembles decision trees. Polycodes are GT codes in which the information contained in a position of the code is independent of any other position of the code. Hybrid GT codes use features from both previously mentioned types of GT codes. Most GT codes are hybrid in nature.

Two formal methods of classifying designs for group technology are Production Flow Analysis (PFA) and Parts Coding and Classification Analysis (PCA). PFA uses the product routing information to classify products into families, while PCA uses the product's design information to classify products.

In the PFA approach as shown in Figure 2.1, an incidence (part-machine) matrix is created. This matrix provides the part's routing information. Usually, clustering algorithms such as Rank Order Clustering or (ROC, King [1980]), or mathematical formulations (Kusiak [1987]) are used to classify parts into families on the basis of their routings. Variant process planning systems often use the PFA approach to create part families. Then, the GT code for each part in the part family is stored in a part-family matrix (Chang and Wysk [1985]). A part-family matrix describes for each position of the

GT code, all possible values that members of that family have. Thus, a new design belongs to a particular family if the GT code for the new design has in each position, a value that exists in that family's part-family matrix. Although there is a perfectly logical reasoning for designs with similar routings to be classified into a family, there seems to be some inconsistency in using the GT codes of the products to create the part-family matrix, using the information stored in the part family matrix to decide whether a new design is similar to a family of designs, and then asserting that the new design has a process plan similar to the plans for that family. This inconsistency appears because there is no direct link between the GT code of a product and its routing. Although the GT code of a product captures some manufacturing information of the product, it does not explicitly capture the product's routing information. So, the use of GT codes, although convenient for classification in this approach, cannot be described as entirely consistent.

In the PCA approach to group technology as shown in Figure 2.2, part families are created using the GT codes of the parts. GT codes store the product's geometric and manufacturing information. One such approach has been described in Offodile [1990]. A part-attribute matrix is created using the GT codes of the products. A single linkage clustering algorithm is then used to group the products into families at different thresholds of similarity. A rational measure of design similarity, using the GT code of the products as the input, is used to evaluate the threshold similarity values. Although the PCA approach of classifying designs is consistent in its entirety, the use of this approach to search for designs with similar process plans would be inappropriate because no direct link has been

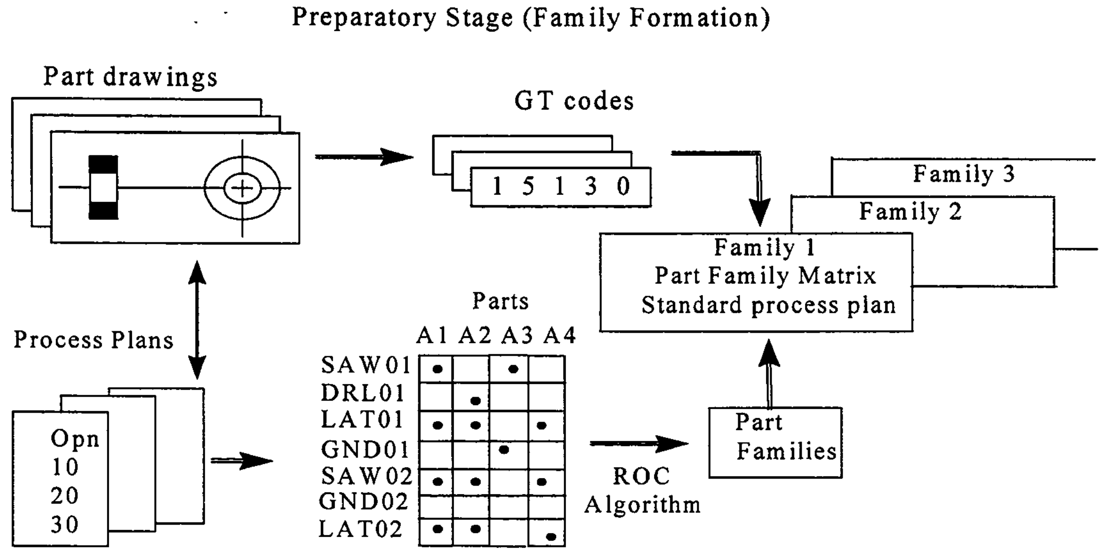


Figure 2.1 The family formation stage of the PFA approach

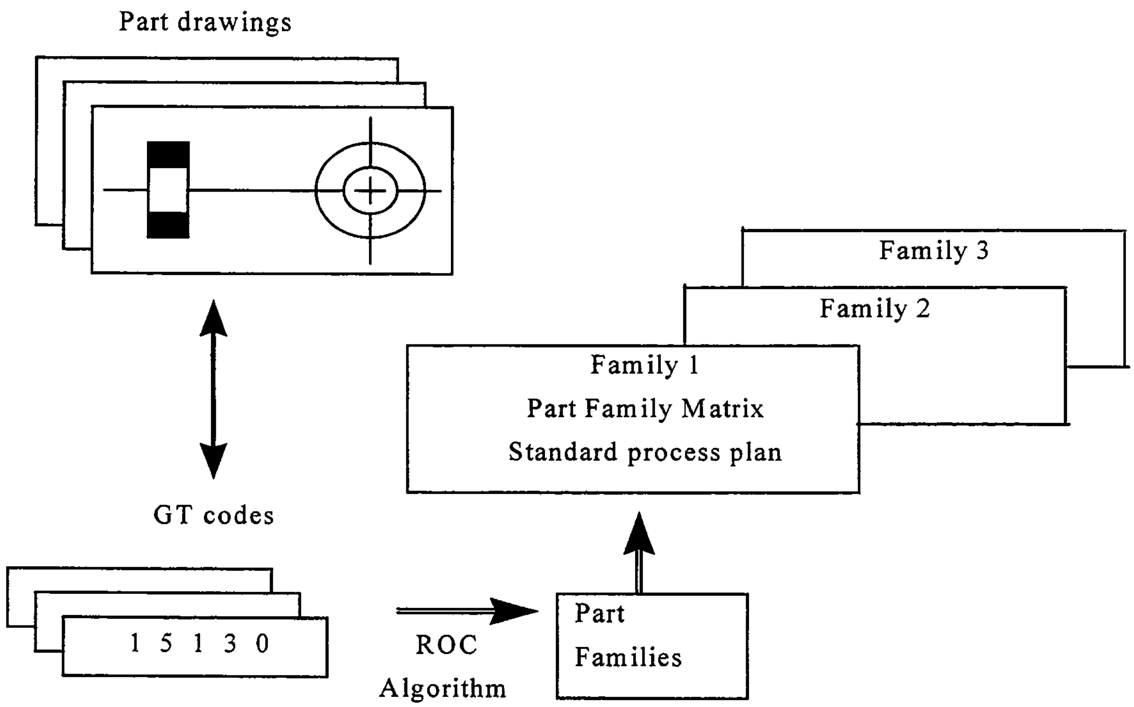


Figure 2.2 The family formation stage of the PCA approach

established between the GT code based measure of design similarity and the process plans of the parts.

2.2.3 Geometric Approaches for Design Similarity

Many of today's CAD/CAM systems use either constructive or boundary models to represent solids. Thus a possible basis for classifying designs is to use geometric properties of solid and CAD models as defined by the solid models. A good description of some of these efforts is provided in Elinson, Nau and Regli [1997].

The ready availability of Constructive Solid Geometry (CSG) trees as a basic representational scheme in most solid modelers, and the underlying similarity between the removal volumes associated with machining features and the volumetric CSG trees, makes the use of CSG trees for classifying designs an obvious choice. However, the approach suffers from two drawbacks. First, the CSG representation for a design is not unique. Second, the CSG primitives that would be involved in such a representation do not necessarily correspond to the manufacturing operations that would be used to manufacture the design and thus the classification might not be very useful for manufacturing purposes.

Sun *et al.* [1996] have described a similarity measure for solids based on properties of their boundary representations. As a new measure of "relaxed" geometrical similarity their work looks very interesting, but there are several difficulties to be overcome before it can be useful as a classification scheme for manufacturing. First, the measure of similarity is defined only for polyhedral objects. This implies that a design has cylindrical or sculpted faces will have to be approximated with planar approximations. The result of such an approximation on the actual similarity of designs is unknown and may cause some difficulty. Second, and perhaps more importantly, the measure in its current form does not address any manufacturing considerations, such as approachability, operation interference, or fixturing. There also seems to be no obvious way to include these considerations in the design similarity measure.

2.3 Discussion

Previous attempts at defining design similarity measures characteristically have overlooked the following three issues:

1. The definition of a process plan
2. The framework in which that plan is applicable
3. The usefulness of the design similarity measure in the realm of variant or hybrid process planning.

It is important to interpret the geometric and manufacturing constraints a design seeks to convey in a consistent manner without losing vital information by relying on fixed length alphanumeric GT codes. Also, the design similarity measure must be machine interpretable so as to facilitate automation.

Chapter 3

Design Similarity Approach

In most jobshop environments, an expert process planner generates the process plans for proposed designs. The planner spends a significant portion of time collecting information about standards and preparing the final process plan document. Computer Aided Process Planning (CAPP) systems have greatly reduced the time needed to generate a process plan by automating most of the routine tasks of the planner. Unfortunately, most present day CAPP systems do not generate process plans that can be used directly on the shop floor. The expert process planner must manually modify the process plans before releasing them to the shop floor.

Most successful commercial process planners use the variant approach to process planning. Variant process planning is based on the hypothesis that similar designs will have similar process plans. So, let us examine some of the reasons why the output generated from commercial process planners is not being used directly on the shop floor. Let us start at the beginning, by examining the hypothesis of the variant process planning approach: Similar designs have similar process plans.

The question that comes to mind while examining the hypothesis of the variant process planning approach is: Do similar designs necessarily have similar process plans?

Not always do similar designs have similar process plans. It is the design similarity measure defined for the variant search process which determines whether similar designs will have similar process plans.

In the variant or the hybrid process planning approach, we must ensure that similar designs have similar process plans. This can be achieved by defining the design similarity measure appropriately. In this domain we define a design similarity measure such that it classifies designs with similar process plans as similar.

Section 3.1 presents the motivation behind the proposed approach. A brief review of existing techniques helps outline the drawbacks and limitations of these approaches. The characteristics of a good design similarity measure for the variant or the hybrid process planning approach are presented at the end of this section. Section 3.2 presents the proposed approach. Section 3.3 presents an example to illustrate the usefulness of the proposed design similarity approach in defining a design similarity measure that gives the process planner, useful and precise data about the similarity between two process plans. A discussion of the proposed approach is presented in Section 3.4.

3.1 Motivation

A review of previous research efforts in the field of variant process planning shows us that the current working hypothesis is: Similar designs have similar process plans. In this section we will review the different design similarity approaches for the variant search and classification schemes, and also define the characteristics that a good design similarity measure to be used in a variant search and classification scheme must have.

In the Parts Coding and Classification Analysis (PCA) approach, a Group Technology (GT) code is used to classify designs into families. A standard process plan is created for each family and serves as the process plan to be used for a new design with a similar GT code. However, since there is no explicit mapping of the GT code of a product onto its process plan, it is not clear why such a classification and search technique should at all result in a useful process plan for the new design.

In the Production Flow Analysis (PFA) approach, the product designs are classified into families, based on their routings through the machine shop. However, the use of the GT code and the part-family matrix to determine whether a new design has a similar routing is not consistent with the classification technique. Since there is no direct relation between the GT code of a product and its routing, there is no reason why such an approach should yield a useful process plan for the new design.

The other possible approach for classifying designs is to use geometric properties of solid and Computer Aided Design (CAD) models. However, the applicability of product geometry-based design similarity measure to a variant classification and search technique for process planning, is at least as questionable as the use of the GT based classification and search techniques in the PCA and PFA approaches. This is because although product geometry plays a significant role in determining the process plan for a given design, without examining the accompanying manufacturing concerns, only a partial correspondence between a design and its process plan can be established. Thus even though a product geometry-based design similarity measure will prove effective for simple designs with little or no manufacturing constraints, its success in real world scenarios, involving complex manufacturing and geometric constraints is highly doubtful.

Recent approaches exploiting the strengths of the Artificial Neural Net (ANN) technique (Leung, Hines, and Raja [1994]) to associate a product's attributes with its process plan, have proved promising. Although no explicit design similarity measure is used in this particular approach, there is an implicit mapping of the product's attributes to the associated process plan. However, the process planning systems developed using this technique have not yielded consistent results. Since the results yielded by variant search process are greatly dependent on the ANN technique used and the sample data used to train the net, it is difficult to analyze or predict the performance of the search process.

There have been other approaches using neural nets to classify designs. The form recognition problem has formed the basis of nearly all these studies (Wu, and Jen [1996]). This approach can be viewed as another geometric approach for classifying designs and shares the same drawbacks associated with the geometric approach.

From the appraisal of existing approaches for classifying designs, it can be seen that there is a need for a design similarity measure that identifies designs with similar process plans. Such a design similarity measure should have the following characteristics:

1. The design similarity measure should be plan based. There should be a correspondence between the process plan similarity measure and the design similarity measure. In fact, two designs should be similar if and only if their process plans are similar. This alone will ensure that the hypothesis of the variant process planning approach is true.

2. The design similarity measure must convey information to the process planner in an unambiguous manner. This means that:

    - The design similarity measure must be precise. Given the value of the design similarity measure between two product designs, the process planner should know precisely what attributes of the two process plans are similar and by how much.

    - The design classification and search techniques should be consistent. If the value of design similarity measure between a pair of product designs is equal to the value of the design similarity measure between another (different) pair of product designs, then the same or an equivalently important set of process plan attributes should be similar in both pairs of process plans.

3.2 Approach

In this section we describe an approach for developing plan-based design similarity measures. In doing so, we will incorporate the characteristics of a desired similarity measure for the variant search process described in Section 3.1. Our working assumption is that there is a one-to-one correspondence between a design and its process plan. We use the term "process plan attribute" to describe such characteristics as operations and features. We use the term "design attribute" to describe such attributes as features and dimensions.

Step 1

In Step 1, we define the set of variables to be used in our approach. In this regard, we define the precisely the process plan corresponding to each design being considered for classification. Further details on how to precisely define a process plan and the need to do so will become apparent in Chapter 4. For the moment, let us assume that we can capture all the information that a process plan contains and that will be used to determine process plan similarity.

1. $P_1, P_2, \ldots, P_n$ are process plans corresponding to designs $D_1, D_2, \ldots, D_n$, respectively
2. $A_{1p}, A_{2p}, \ldots, A_{kp}$ are the process plan attributes corresponding to the process plan P_p
3. $P_p \equiv (A_{1p}, A_{2p}, \ldots, A_{kp})$ is the vector of process plan attributes corresponding to the process plan P_p
4. $X_{1p}, X_{2p}, \ldots, X_{np}$ are the design attributes corresponding to the design D_p

5. $D_p \equiv (X_{1p}, X_{2p}, ..., X_{np})$ is the vector of design attributes corresponding to the design D_p

Step 2

In Step 2, we define a mapping function g_i for each $i = 1, ..., k$, that describes the correlation between the design attributes of product D_p, and the process plan attribute A_{ip} of the process plan P_p.

$$A_{ip} = g_i(X_{1p}, X_{2p}, ..., X_{np}) = g_i(D_p)$$

For notational purposes we also define a vector function $g(D_p)$ as follows:

$$g(D_p) = (g_1(D_p), g_2(D_p), ..., g_k(D_p))$$

Step 3

In Step 3, we define $f(P_i, P_j)$ as the plan similarity measure between process plan P_i and process plan P_j, the process plans for designs D_i and D_j respectively.

$$f(P_i, P_j) = f\{(A_{1i}, A_{2i}, ..., A_{ki}), (A_{1j}, A_{2j}, ..., A_{kj})\}$$

Note that this is a function of the identified process plan attributes.

Step 4

Finally, in Step 4, we define $h(D_i, D_j)$ as the plan-based design similarity measure between designs D_i and D_j.

$$h(D_i, D_j) = f(g(D_i), g(D_j))$$

$$= f\{(g_1(D_i), g_2(D_i), \ldots, g_k(D_i)), (g_1(D_j), g_2(D_j), \ldots, g_k(D_j))\}$$

$$= f\{(g_1(X_{1i}, X_{2i}, \ldots, X_{ni}), g_2(X_{1i}, X_{2i}, \ldots, X_{ni}), \ldots, g_k(X_{1i}, X_{2i}, \ldots, X_{ni})),$$

$$(g_1(X_{1j}, X_{2j}, \ldots, X_{nj}), g_2(X_{1j}, X_{2j}, \ldots, X_{nj}), \ldots, g_k(X_{1j}, X_{2j}, \ldots, X_{nj}))\}$$

Thus we see that the plan-based design similarity measure is a function of design attributes.

In a variant process planning approach, $f(P_i, P_j)$ is defined for the entire process plan and $h(D_i, D_j)$ is defined for entire designs. In a hybrid process planning approach, $f(P_i, P_j)$ is defined for process plan slices and $h(D_i, D_j)$ is defined for subdesigns.

3.3 Analysis

Let us consider why the above approach to defining a design similarity measure is a good approach.

Let there be a Group Technology (GT) code with three positions, indicating length, width and height of the product. Let each position of the code take a value from 00 to 99, indicating the range of each dimension. Let us compare three designs with the following codes:

$D_1 = 20\ 50\ 70$

$D_2 = 30\ 50\ 85$

$D_3 = 25\ 55\ 100$

One could define a GT code measure of design similarity as described in Offodile [1990]:

$$S_{ij} = \frac{\sum_{k=1}^{K} s_{ijk}}{\sum_{k=1}^{K} d_{ijk}}$$

$$s_{ij} = 1 - \frac{|x_{ik} - x_{jk}|}{R_k}$$

$$d_{ijk} = \begin{cases} 1 & \text{If comparison between components } i \text{ and } j \text{ is possible for attribute } k \\ 0 & \text{Otherwise} \end{cases}$$

where

S_{ij} = similarity between component i and component j

s_{ijk} = score between component i and component j on attribute k

x_{ik} = value assigned to component i for attribute k

x_{jk} = value assigned to component j for attribute k

R_k = range of attribute k taken over the population space

K = number of attributes

Then,

$$S_{12} = \frac{(1 - \frac{10}{99}) + (1 - \frac{0}{99}) + (1 - \frac{15}{99})}{3} \approx 0.916$$

$$S_{13} = \frac{(1-\frac{05}{99})+(1-\frac{05}{99})+(1-\frac{20}{99})}{3} \approx 0.899$$

$$S_{23} = \frac{(1-\frac{05}{99})+(1-\frac{05}{99})+(1-\frac{15}{99})}{3} \approx 0.916$$

Let us consider how precise and consistent this measure is. This raises the following questions: What information do the similarity values convey to the process planner? Do these similarity values tell the process planner what attributes of the two process plans are similar? Is it possible that two other designs that have the same design similarity value (e.g. $S_{12} \approx 0.916$ and $S_{23} \approx 0.916$) are similar to each other in a completely manner?

Let us now use the approach developed in the Section 3.2 to define a plan-based design similarity measure. We assume that the planner is only interested in the fixture size.

Let

A_{1x} = Smallest appropriate fixture (process plan attribute for process plan P_x)

X_{1x} = Length of product (product design attribute for product design D_x)

X_{2x} = Width of product (product design attribute for product design D_x)

X_{3x} = Height of product (product design attribute for product design D_x)

Let us define a function, g_1, that relates the design attributes X_{1x}, X_{2x}, and X_{3x} of a product to its process plan attribute, A_{1x} and a function g, as shown in the approach. Then,

$$
\begin{aligned}
A_{1x} &= g_1(D_x) \\
&= g_1(X_{1x}, X_{2x}, X_{3x}) \\
&= \min \{f \in F : X_{1x} X_{2x} \leq S_f, X_{3x} \leq H_f\}
\end{aligned}
$$

where

S_f = Maximum surface area that fixture f can hold

H_f = Maximum height that fixture f can hold

$F = \{1, 2, ..., m\}$ is a set of m possible fixtures

And, $S_f \leq S_{f+1}$, $H_f \leq H_{f+1}$, $f = 1, 2, ..., m - 1$

We define two process plans, P_i and P_j, to be similar if they have the same value of the process plan attribute A_1 i.e. they can use the same fixture. Thus,

$$
f(P_i, P_j) = \begin{cases} A_{1i}, \text{ if } A_{1i} = A_{1j} \\ 0, \text{ Otherwise} \end{cases}
$$

From the approach developed in Section 3.2, the corresponding measure of design similarity to be used during a variant search process is:

$$
h(D_i, D_j) = \begin{cases} g_1(D_i), \text{if } g_1(D_i) = g_1(D_j) \\ 0, \text{ Otherwise} \end{cases}
$$

Let F be comprised of four fixtures:

Fixture $f \in F$	**S_f, the maximum surface area (units^2)**	**H_f, the maximum height (units)**
1	500	50
2	1000	75
3	1500	100
4	2000	125

Table 3.1 The set F of existing fixtures

Designs, D_x	$X_{1x}X_{2x}$	X_{3x}	$g_1(D_x)$
D_1	1000	70	2
D_2	1500	85	3
D_3	1375	100	3

Table 3.2 The mapping function g_1 for the three designs

The mapping function g_1 is evaluated for each of the three designs. Then, using the plan-based design similarity measure described above, we can evaluate the design similarity measure for each of the designs as:

$h(D_1, D_2) = 0$

$h(D_1, D_3) = 0$

$h(D_2, D_3) = 3$

Let us consider what information this design similarity measure conveys to the process planner. Recall that, for the purpose of this example, we have assumed that the process planner is interested in only one process plan attribute, the fixture. The plan-based design similarity measure tell us that designs D_2 and D_3 use the same fixture (fixture number three (3) from our set of fixtures F) but design D_1 uses a different fixture (fixture number two (2) in F) and so is not similar to designs D_2 and D_3. We can view the above results graphically as shown in Figure 3.1.

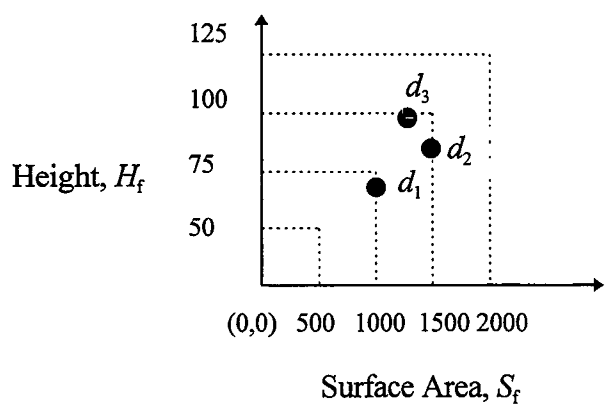


Figure 3.1 The surface area and height of the three designs

From the above example, we can see that the use of GT codes for defining a measure of design similarity suffers from at least two drawbacks:

- The design similarity measure is not plan-based: it does not necessarily convey any overt information to the process planner as to the similarity between their respective process plans.

- The information conveyed by the design similarity measure is ambiguous: it does not convey to the planner the precise attributes that are similar. It is not necessary that a certain value of the design similarity measure always implies that the same set of attributes are similar. The planner is thus forced to interpret the resulting similarity value.

Let us now verify that the plan-based design similarity measure developed using the approach proposed in Section 3.2 has the characteristics of a good design similarity measure as described in Chapter 1, and overcomes the drawbacks associated with traditional GT code-based design similarity measures.

- The design similarity measure is plan-based. In the above example we see that the two designs are classified as similar if and only if they have the same smallest appropriate fixture, an important variable in the process plan.

- The information conveyed to the process planner is precise. Unlike the GT code-based design similarity measure, in this case the planner knows precisely what information the design similarity measure conveys. The design similarity measure tells the process planner whether the designs being compared use the same smallest appropriate fixture.

- The design similarity measure is consistent. Any pair of designs having the same value of the design similarity measure necessarily use the same fixture.

The above example only serves to highlight how the proposed design similarity approach can overcome the drawbacks of existing GT code based approaches. In practice, a multi-attribute hierarchical process plan similarity measure will have to mapped onto the design attributes to define a practical design similarity measure to be used in a variant process planning environment.

3.4 Conclusions

The proposed approach for defining a design similarity measure for the variant search process seeks to overcome the drawbacks of the existing design similarity approaches. Existing design similarity approaches work under the hypothesis that similar designs have similar process plans. So they define a design similarity measure that allows the process planner to search for similar designs. However by using GT codes and geometric-based design similarity measures to accomplish their task, they do not necessarily capture the relationship between the design and its process plan. In the proposed approach, the accent is on defining a design similarity measure that will help the process planner search for useful process plans for the proposed design, as opposed to finding designs similar to the new design. This is accomplished by defining the design similarity measure as function of the process plan similarity measure. This ensures the applicability of the resulting similarity measure to the domain of process planning. This approach conveys precise and consistent information about the process plan similarity to the process planner.

Chapter 4

Structure and Framework of a Process Plan

A process plan specifies the manufacturing steps necessary to create the physical embodiment of the proposed product in the required quantity, with the desired finish and accuracy. In order to generate a good process plan, the planner must take several manufacturing issues into account. These include the capabilities of the manufacturing facility in terms of man, machine and environment, production quantity, desired finish and accuracy of the product, material and tolerance standards, and time available to meet the order. As a result, the process planner spends a significant amount of time and effort to gather information about standards, and existing manufacturing facilities. This problem becomes even more acute in a job shop environment where the total time available for process planning is much less than the time available for process planning in a repetitive manufacturing environment, despite the complexity of the planning activity being far greater in the job shop (Halevi and Weill [1995]). To simplify the planner's task and reduce the total time spent in gathering the necessary information and generating the process plan, several CAPP systems are now commercially available. However, there is a reluctance on the part of the manufacturers to rely on the process plans generated from CAPP systems. It is the ambiguous description of a process plan, which is at the root of the incompatibility of many automated process planning systems with their manufacturing environments. One reason why researchers and others working on CAPP systems are faced with this problem can be traced to the different ways in which different segments of the manufacturing community define a process plan. This implies that for the CAPP system to be of any real use to manufacturers, it must be customized for use in a particular manufacturing environment.

Section 4.1 describes the process plan, and process planning activity, as viewed by different experts in the manufacturing community. Section 4.2 presents a manufacturing information framework. The process planner must be aware of the information framework for the process planning activities and for the product itself. Section 4.2.1 presents a possible framework for the information required for the process planning function. Section 4.2.2 presents a possible framework for the product database which itself serves as a member of the process plan information framework. Once a possible framework for the process planning activity has been defined, it is now possible to unambiguously describe the structure of the process plan. Section 4.2.3 presents a hierarchical process plan structure, suitable for the manufacturing information framework described in section 4.2.1. Section 4.3 summarizes the advantages of systematically defining a process plan and its manufacturing information framework as described in this chapter.

4.1 Definitions of a Process Plan

There exist several definitions for process planning and process plans in literature. A few of these definitions are cited below.

The Society of Manufacturing Engineers (Alting and Zhang [1989]) defines process planning as "the systematic determination of the methods by which a product is to be manufactured economically and competitively."

Link [1976] broadly defined process planning as "the subsystem responsible for the conversion of design data to work instruction."

Chang and Wysk [1985] define process planning as "that function within a manufacturing facility that establishes which machining processes and parameters are to be used (as well as those machines capable of performing these processes) to convert (machine) a piece part from its initial form to a final form predetermined (usually by a design engineer) from an engineering drawing." In addition, they define process planning as "the act of preparing detailed work instructions to produce a part." The authors mention that the other commonly used names for process plans include operation sheet, route sheet, operation planning summary, or other synonyms. The details to be specified and included in the process plan are the operations, the sequence in which the operations are to be performed, the work centers or machine tools to be used, the tools, jigs, and fixtures needed to carry out the operations, and the process parameters. The authors also describe the process plan as an instruction sheet to produce the part.

Niebel, Draper and Wysk [1989] define process planning as "a process that evolves the sequence of operations required to manufacture a part, the times required to accomplish the operation, the machining and the toolings required, and evaluates tolerance stacking problems that accrue from multiple cuts and/or multiple components that comprise a part."

Kalpakjian [1989] defines process planning as "an activity concerned with the selection methods of production, tooling, fixtures and machinery, sequence of operations and assembly."

Chang [1990] defines process planning as "an act of preparing detailed processing documentation for the act of manufacture of a piece part or assembly." Chang differentiates between rough and detailed process plans. Rough process plans contain the name and sequence of operations. Detailed process plans contain more detailed information, such as, the tooling and fixturing data, and the process parameters for the operations.

Bedworth, Henderson, and Wolfe [1991] define process planning as "preparing a set of instructions that describe how to fabricate a part or build an assembly which will satisfy engineering design specifications. The resulting set of instructions may include any or all of the following: operation sequence, machines, tools, materials, tolerances, notes, cutting parameters, processes (such as how to heat treat), jigs, fixtures, methods, time standards, setup details, inspection criteria, gauges, and graphical representations of the part in various stages of completion."

Zhang and Wang [1993] define process design (known as process planning) as "the conversion of the design specifications into manufacturing instructions." They describe the role process engineers play in determining the processes and the process parameters. According to the authors, the major decisions involved in process planning include selecting the processes, determining the sequence in which the processes are carried out, determining the process parameters, and verifying that the necessary dimensions, accuracy, and tolerances will be obtained.

Gupta [1994] generates machining plans (process plans) from feature based models. He defines a process plan (referred to as a machining plan in his thesis) as a set of machining operations with their recommended cutting parameters in an ordered sequence.

Halevi and Weill [1995] describe process planning as "an important link in the manufacturing cycle that defines in detail the process that transforms raw material into the desired form." The authors use a flow chart to give a detailed explanation of their understanding of the activities involved in process planning and the sequence in which these operations must be carried out.

These definitions of process planning and process plans are by no means exhaustive but merely serve to highlight the different ways in which experts chose to interpret the definitions of a process plan and the process planning activity. The reason why such a variety of interpretations are all equally valid is the different context in which each of these definitions is applicable. In fact, it can very well be argued that there is no single definition of a process plan, or the process planning activity. And yet, the process plans which are handed to the operators on the shop floor are accurate and complete instructions for the operators to carry out their tasks. There is nothing ambiguous, or uncertain about the way in which the process plan documents are to be used by the operators. This is in sharp contrast to the ambiguity in the definition of a process plan and the process planning activity, as witnessed by their different interpretations presented above. Why then is it so difficult, well nigh impossible to assign a definition to a process plan and to the process planning activity?

The answer to this question lies in understanding how a manufacturing system is designed and controlled. The process plan is a small, albeit necessary part of the information transferred to the shop floor. The process plan fits into a bigger picture in which the Bill of Materials (BOM), the Work Order, and the other databases, all convey different parts of the information necessary for the operator to perform his tasks correctly. Thus it is very difficult to accurately describe a process plan without first defining the framework in which the process plan must function. Section 4.2 presents a possible manufacturing information framework.

4.2 Manufacturing Information Framework

In order to define the process plan unambiguously, it is important to first define the manufacturing information framework in which that process plan will be used. In the following sections we describe a possible framework for organizing the information needed to generate a process plan. Our focus will be on a jobshop environment using machining operations (milling and drilling) to manufacture the part.

Section 4.2.1 presents a typical manufacturing information framework in a machine shop. It outlines the flow of information from the customer to the operator on the shop floor. Section 4.2.2 focuses on the product database. The product database allows the operator on the shop floor to access key information such as the part drawing, the BOM associated with that part, the work order and the process plan. Section 4.2.3 specifies a hierarchical structure for the process plan document.

Because different manufacturers have different manufacturing information frameworks in place, a clear understanding of the overall manufacturing information framework will explain why different planners include the same data in different formats in their respective process plan documents, and also why sometimes the data found in one process plan document is not included in another.

4.2.1 The Overall Manufacturing Information Framework

A process plan cannot be generated directly from the Computer Aided Design (CAD) file of the product. The process planner must have the answer to several key questions before he/she can generate a useful process plan. Some of the important questions are: How many parts need to be manufactured ? What is the process capability of the available machine tool ? When is the order due? What are the available cutting tools? This information is provided to the process planner from different sources or databases, and from existing standards repositories.

As described in Section 4.1, there are many definitions of what constitutes a process plan. Despite this characteristic ambiguity associated with the definition of a process plan, once the process plan is released onto the shop floor, the operator should be in a position to create the end product by following the set of instructions included in the process plan. Also, given the overall framework in which a particular process plan exists, and the process plan document, there should be no ambiguity as to how the process plan has been generated.

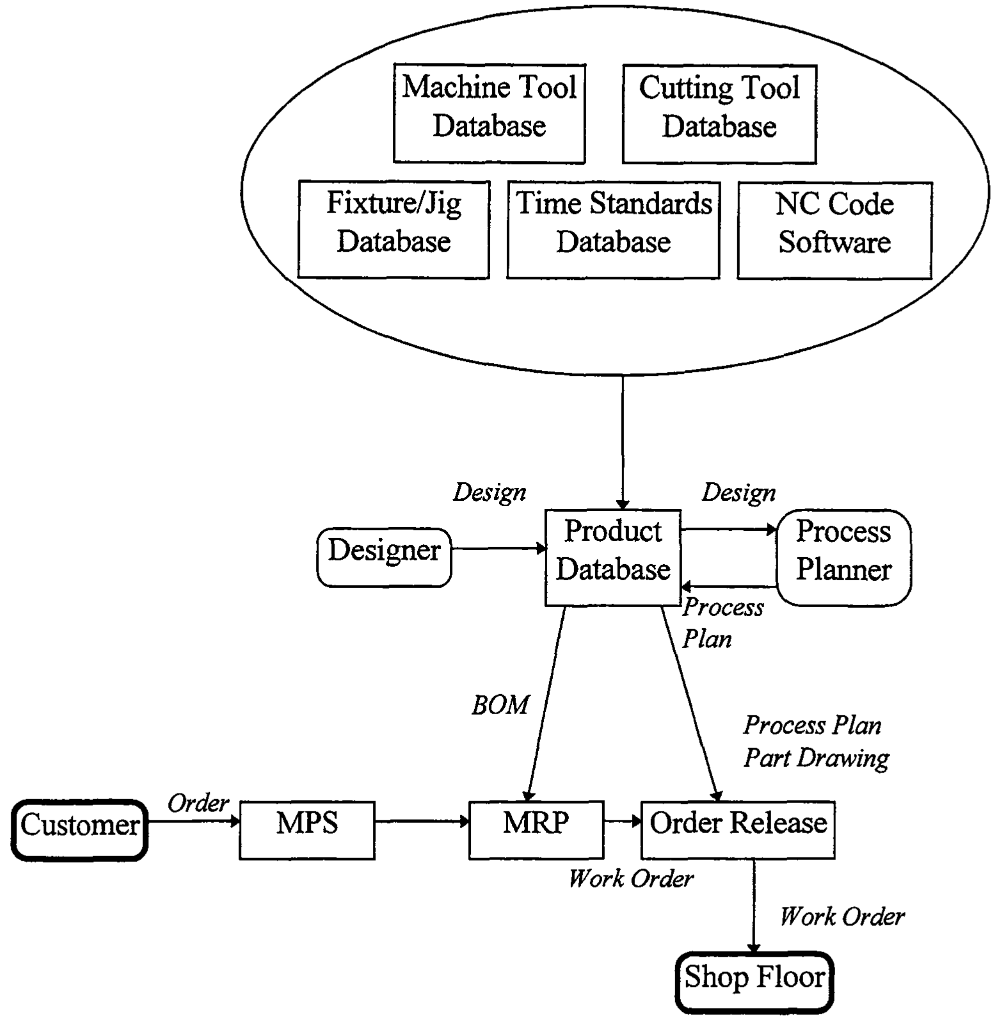


Figure 4.1 Manufacturing Information Framework

Figure 4.1 describes a typical manufacturing information framework in a machine shop. The Master Production Schedule (MPS) receives the customer order. It passes on the information to the Materials Requirement Planning (MRP) Module, which translates the customer order to a work order. The key input to the MRP system is the BOM from the Product Database. The Product Database stores the designs created by the designer.

The design from the Product Database together with information from the Process Capabilities Information Repository (comprising of the Machine Tool Database, the Cutting Tool Database, the Jig/Fixture Database, the Time Standards, and the NC Code Generation Software) are the inputs provided to the process planner for generating the process plan. The due date information from the work order, and the run and setup time information from the product's process plan are then used by the Order Release system to determine the job's release and completion dates. Finally, the work order (with the process plan, the part drawing and the BOM) is released onto the Shop Floor.

4.2.2 The Product Database

The product database is structured as shown in Figure 4.2. Associated with the product's part number are the product's final and stage drawings, the BOM and the work order. After the process plan has been generated, it must be referenced in product database with respect to the product's part number, and if necessary, the work order. If generated, the stage drawings which depict the results of operations performed on the stock are stored and referenced along with the final drawings of the part.

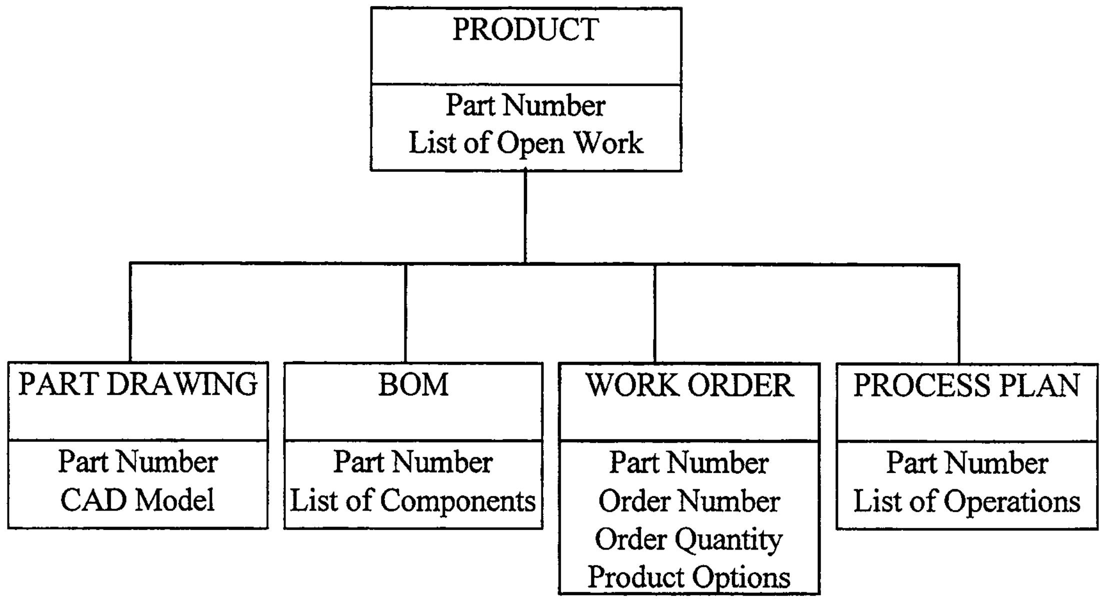


Figure 4.2 Product Database

The product database shows only one process plan. In some cases there may exist alternative process plans that the manufacturer uses when the order quantity changes or when a preferred machine is unavailable. In this case, the work order must specify which plan alternative that order will follow. In this thesis we will assume that the product has only one process plan.

Here is a brief description of the elements of the product information framework shown in Figure 4.2:

The Drawings (Final and Stage Drawings)

The final drawing is a solid model of the product that the operator is expected to machine from the stock. The stage drawings depict the transformation of the stock through a series of steps to the final product. The stage drawings may or may not be included for all the operations. The final and stage drawings can be represented in the **ST**andard for the **E**xchange of **P**roduct model data (STEP) format with tolerance and surface finish information included in the file.

The Bill of Materials (BOM)

The following assumptions have been made while defining attribute information that is useful in the bill of materials.

1. Since we are dealing with machining operations only, it is assumed that the final product does not require any assembly operation

2. Only one product will be machined per blank.

Attributes Stock identification number

Stock size and specification

Stock material

The operator will need this information to select the stock. Since this document includes details of the size and the specification of the stock it will be possible for the operator or the inspector to check on them if necessary.

The Work Order

Attributes Part number

Quantity

Order number

Product options

This document will tell the operator how many parts he needs to machine and the due date for delivery of the job. This information is not included in the process plan document itself as it will be accessible to the operator through the work order released to the shop floor.

The Process Plan

This document contains the all the necessary information and instructions that the operator needs to transform the stock into the final physical embodiment. This is the instruction sheet released to the shop floor by the process planner.

4.2.3 Process Plan Structure

Once the manufacturing information framework is in place, it is possible to define the process plan unambiguously. We have defined a hierarchical structure for the process plan as shown in Figure 4.3. The list of operations in the high level process plan is an ordered sequence of machining operations which will result in the transformation of the stock to the end product. This is the high level process plan. Each operation in the list of operations, points to another level of detail which will provide the operator with all the necessary information under the existing manufacturing information framework to machine the product. This is known as the detailed process plan. Each operation points to:

1. A machine tool capable of carrying out that operation on the designated stock.
2. The cutting tool that will be used during that particular machining operation.
3. The fixture/jig that will be used during the operation and the clamping and location positions.
4. The setup and run times needed to complete the operation.
5. An NC code that the machine tool will use if it is a CNC machining environment.
6. The cutting parameters that the operator will need to setup in order to carry out the machining operation. In an NC machining environment the operator should not need to setup the cutting parameters but will need to ensure that those parameters are not being violated at the start, or during the machining process. The cutting parameters are approach direction, feed, speed, depth of cut, and number of passes.

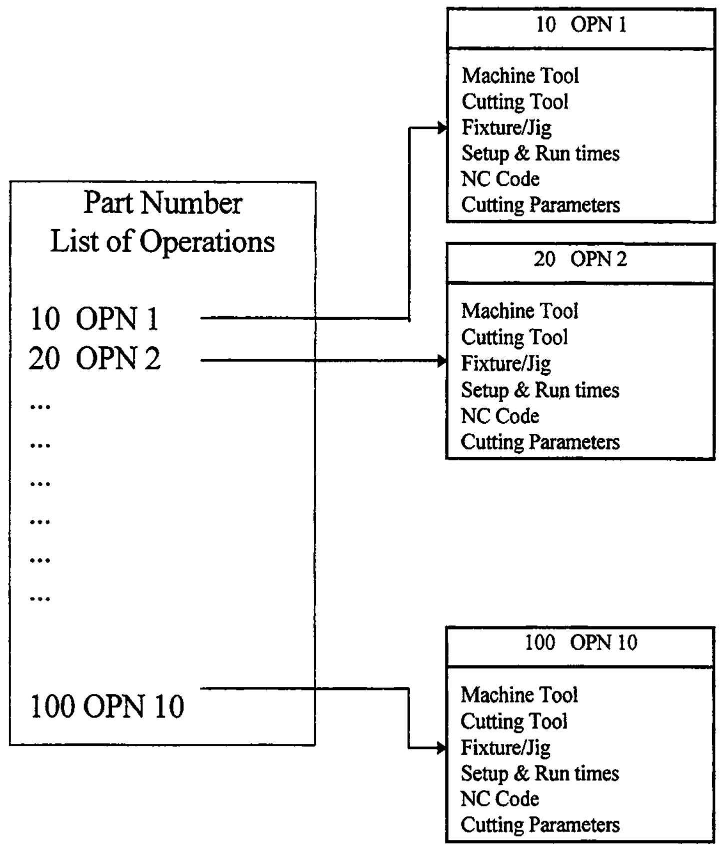


Figure 4.3 Hierarchical Process Plan Structure

4.3 Discussion

The proposed manufacturing information framework and the hierarchical structure for the process plan represents only one of the possible framework-structure combinations possible in a manufacturing environment. The proposed framework and structure are consistent and lead to an unambiguous planning environment for the process planner. This is important in an automated planning environment to overcome the drawbacks of existing Computer Aided Process Planning (CAPP) systems.

By allowing the user to define the overall manufacturing information framework surrounding the process plan, it is possible to automatically generate a process plan that can function in the customized manufacturing environment. Imagine a manufacturing environment in which there is no machine tool database. In this case, the process plan document will have to explicitly specify the type and other details associated with the machine tool for each operation. Thus, the process plan document will in effect reflect the manufacturing information framework and so ensure that the automated process planner will generate a process plan that will be suitable for the manufacturing environment in which it functions.

Although there are certain obvious advantages associated with a formal framework and structure, especially in the context of automated process planning, there is also an overhead associated with maintaining structured information. However, it is our belief that an organized framework and structure will help the manufacturing environment not only with greater automation, but also with greater control over the manufacturing and planning activities.

Chapter 5

A Hierarchical Design Similarity Measure

The necessary task in the design similarity approach is to define a process plan similarity measure. The process plan similarity measure is used to define the design similarity measure as shown in the design similarity approach proposed in Chapter 3. In Chapter 4, we defined a process plan as a document that specifies the manufacturing steps necessary to create the physical embodiment of the proposed product in the required quantity, with the desired finish and accuracy. From the many definitions of the term available in literature, we know that this is only one of the many possible and equally correct descriptions of a process plan. In Chapter 4, we also defined a possible manufacturing information framework and a structure for the process plan. Understandably, this is only one of several ways in which a manufacturing information framework and corresponding process plan structure can be defined. We will use the manufacturing information framework and process plan structure defined in Chapter 4 to demonstrate our approach.

Section 5.1 presents a binary process plan similarity measure. The binary plan similarity measure is then mapped into a hierarchical process plan similarity measure by arranging the process plan attributes in a hierarchical sequence. Section 5.1.1 presents the hierarchical process plan similarity measure. This section also includes an example to illustrate the use of the hierarchical process plan similarity measure. Section 5.2 uses the design similarity approach presented in Chapter 3 to define a hierarchical design similarity measure. This section includes an example to illustrate the use of the hierarchical design similarity measure. Finally, Section 5.3 summarizes the hierarchical design similarity approach and introduces the continuous similarity measure to be presented in Chapter 6.

5.1 A Binary Process Plan Similarity Measure

There are many different ways of defining process plan similarity. One approach is a binary plan similarity measure. In this approach we divide the set of all process plans into disjoint subsets such that two plans are in the same subset if and only if they have the same values on a predefined set of attributes. Thus a plan is similar to identical plans only.

$$f\left(P_i, P_j\right) = \begin{cases} 1, \text{ If } A_{1i} = A_{1j}, \ \ldots, \ A_{ki} = A_{kj} \\ 0, \text{ Otherwise} \end{cases}$$

where

$f\left(P_i, P_j\right)$ is the process plan similarity measure between process plans P_i and P_j,

$A_{1p}, A_{2p}, A_{3p}, \ldots, A_{kp}$, are the process plan attributes corresponding to process plan P_p.

5.1.1 A Hierarchical Process Plan Similarity Measure

This hierarchical process plan similarity measure organizes the discrete subsets of the binary process plan similarity measure (described above) into a hierarchy of subsets such that the similarity between plans indicates the smallest subset to which both plans belong.

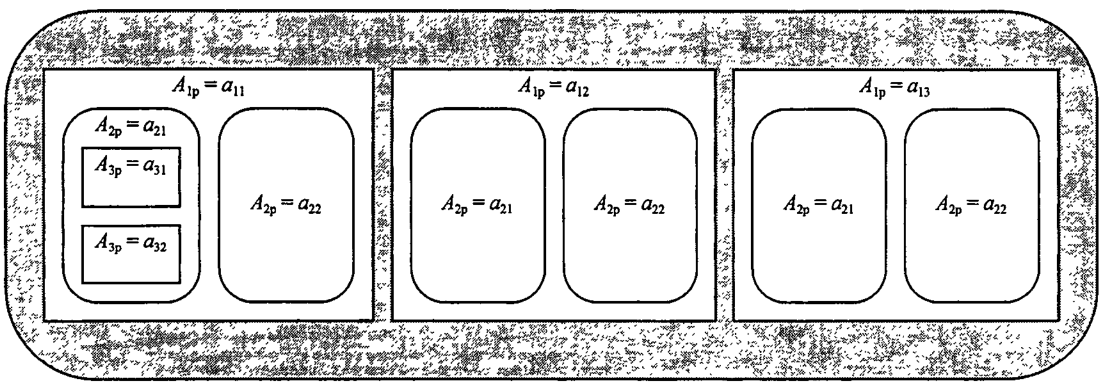


Figure 5.1 A hierarchical arrangement of process plan subsets

Figure 5.1 shows a set of process plans in which the independent subsets are arranged hierarchically. On the left hand side of the figure is the subset of process plans P_p having the attribute $A_{1p} = a_{11}$ which contains two subsets, one with the plans P_p such that attribute $A_{2p} = a_{21}$ and the other with the plans P_p such that attribute $A_{2p} = a_{22}$. The first subset ($A_{2p} = a_{21}$) contains subsets of process plans with attribute $A_{3p} = a_{31}$ and with $A_{3p} = a_{32}$. The subsets of plans with $A_{1p} = a_{12}$ and $A_{1p} = a_{13}$ contain similar subsets. Thus one can see a hierarchical structure in the process plan classification scheme described above.

More formally, we sequence the process plan attributes as $A_{1p}, A_{2p}, A_{3p}, \ldots, A_{kp}$. The hierarchical process plan similarity measure is defined as:

$$f_h(P_i, P_j) = m, \text{ if } A_{1i} = A_{1j}, \ldots, A_{mi} = A_{mj}, A_{(m+1)i} \neq A_{(m+1)j}$$

where,

$f_h(P_i, P_j)$ is the hierarchical process plan similarity measure

As an example, we will apply the above hierarchical plan similarity measure to the five process plans shown in Table 5.1. These process plans correspond to the five designs shown in Figure 5.2. $P_p = (O_{1p}, \ldots, O_{np})$ are the operations. $O_{jp} = i$ if and only if O_{jp} is an operation of type *i*. Let us consider the attributes of the process plan for the purpose of determining the similarity between them. For the sake of brevity and simplicity, we consider only the following attributes of a plan P_p:

1. A_{1p} represents the type of operations in plan P_p.

$A_{1p} = (x_{1p}, \ldots, x_{bp})$, where $x_{ip} = 1$ if P_p contains any operations of type *i*, and $x_{ip} = 0$ otherwise.

2. A_{2p} is the number of times each operation occurs.

$A_{2p} = (y_{1p}, \ldots, y_{bp})$, where y_{ip} is the number of operations of type *i* in P_p.

3. A_{3p} is the sequence of the operations.

$A_{3p} = (O_{1p}, ..., O_{np})$, the sequence of operations.

$f_h(P_i, P_j) = 1$, if the two process plans have the same types of operations, but the number of times each operation type occurs in the two process plans is different.

i.e. $x_{ai} = x_{aj} \forall\ a = 1, \ldots, b$

but $\exists\ a$: $y_{ai} \neq y_{aj}$

$f_h(P_i, P_j) = 2$, if the types of operations present and the number of times each operation type occurs in the two process plans are same, but the sequence in which the operations occur in the two process plans is different.

i.e. $y_{ai} = y_{aj} \forall\ a = 1, \ldots, b$ but $\exists\ a$: $O_{ai} \neq O_{aj}$

Since $x_{ai} = 0$ iff $y_{ai} = 0$, this condition implies that $x_{ai} = x_{aj} \forall\ a = 1, \ldots, b$

$f_h(P_i, P_j) = 3$, if the types of operations present, the number of times each operation type occurs, and the sequence of operations in the two process plans are identical.

i.e. $O_{ai} = O_{aj} \forall\ a = 1, \ldots, b$

This condition implies that

$x_{ai} = x_{aj} \forall a = 1, \ldots, b$ and $y_{ai} = y_{aj} \forall a = 1, \ldots, b$

Part	Plan	List of Operations
D_1	P_1	Operation 10 Mill pocket
		Operation 20 Drill hole
		Operation 30 Drill hole
D_2	P_2	Operation 10 Drill hole
		Operation 20 Mill pocket
		Operation 30 Drill hole
D_3	P_3	Operation 10 Mill pocket
		Operation 20 Drill hole
D_4	P_4	Operation 10 Mill pocket
		Operation 20 Drill hole
		Operation 30 Drill hole
D_5	P_5	Operation 10 Drill hole
		Operation 20 Drill hole

Table 5.1 The list of operations in the process plans P_p corresponding to the designs D_p

Table 5.1 presents the list of operations for plans P_p for the designs D_p shown in Figure 5.2. Let us classify the above set of process plans using the hierarchical classification scheme described above. Table 5.2 lists the attributes A_{1p}, A_{2p}, and A_{3p} for each process plan P_p. Note that there are $b = 2$ operation types.

Then, $x_{1p} = 1$, if P_p contains any milling operations, and $x_{2p} = 1$, if P_p contains any drilling operations. Also, y_{1p} is the number of milling operations in P_p, and y_{2p} is the number of drilling operations in P_p. And, $A_{3p} = (O_{1p}, ..., O_{np})$ is the sequence of operations in P_p.

For the process plans P_1 and P_2 the hierarchical similarity measure $f_h(P_1, P_2) = 2$. As shown in Table 5.2, both process plans consist of milling and drilling operations and in both process plans, the milling operation occurs once and the drilling operation occurs twice. However the sequence in which the operations occurs in the two plans is different.

For the process plans P_1 and P_3 the hierarchical similarity measure $f_h(P_1, P_3) = 1$. As shown in Table 5.2, both process plans consist of milling and drilling operations. However the drilling operation occurs only once in process plan P_3, while it occurs twice in process plan P_1

	P_1	P_2	P_3	P_4	P_5
A_{1p}	(1,1)	(1,1)	(1,1)	(1,1)	(1,0)
A_{2p}	(1,2)	(1,2)	(1,1)	(1,2)	(2,0)
A_{3p}	(1,2,2)	(2,1,2)	(2,1)	(1,2,2)	(1,1)

Table 5.2 The attribute values for the five process plans.

For the process plans P_1 and P_4 the hierarchical similarity measure $f_h(P_1, P_4) = 3$ As shown in Table 5.2, both process plans consist of milling and drilling operations, in both plans the milling operation occurs twice and the drilling operation occurs once, and the sequence in which the operations occur is the same in both the plans.

For the process plans P_1 and P_5 the hierarchical similarity measure $f_h(P_1, P_5) = 0$ As shown in Table 5.2, P_1 has milling and drilling operations, while P_2 only has milling operations.

Now that we have defined a process plan similarity measure we are in a position to use the proposed design similarity approach to define a design similarity measure. Section 5.2 presents a hierarchical design similarity measure for the proposed hierarchical process plan similarity measure.

5.2 A Hierarchical Design Similarity Measure

In this section we will develop a hierarchical design similarity measure using the general approach presented in Section 3.2. We will apply this measure to the five designs shown in Figure 5.2. Let us consider the four steps previously defined.

Step 1

1. $P_1, \ldots, P_5$ are process plans corresponding to designs $D_1, \ldots, D_5$.
2. A_{1p}, A_{2p}, A_{3p} are the process plan attributes corresponding to the process plan P_p
3. $P_p \equiv (A_{1p}, A_{2p}, A_{3p})$ is the vector of process plan attributes corresponding to the process plan P_p

4. X_{1p}, ..., X_{4p} are the design attributes corresponding to the design D_p

5. $D_p \equiv (X_{1p}, ..., X_{4p})$ is the vector of design attributes corresponding to the design D_p

We define the following set of design attributes corresponding to the design D_p:

X_{1p} is the set of machining feature types that occur in design D_p. We assume that the design D_p has a set of features $\{F_{1p}, F_{2p}, ..., F_{np}\}$, and each feature is a pocket (a type 1 feature) or a hole (a type 2 feature).

$X_{1p} = (x_{1p}, x_{2p})$, where $x_{ip} = 1$ if feature of type i is present and 0 otherwise

X_{2p} is the number of each feature type in design D_p.

$X_{2p} = (y_{1p}, y_{2p})$, where y_{ip} is the number of feature type i in design D_p (i.e. y_{1p} is the number of pockets. y_{2p} is the number of holes).

$$X_{3p} = \begin{cases} \{(i,j)\}, \text{ a set of feature precedences. } (i,j) \in X_{3p} \text{ if and only if} \\ F_{ip} \text{ satisfies a necessary manufacturing or geometric precondition} \\ \text{for } F_{jp} \end{cases}$$

$$X_{4p} = \begin{cases} \{(i,j)\}, \text{ a set of feature precedences. } (i,j) \in X_{4p} \text{ if and only if} \\ F_{jp} \text{ deletes a necessary manufacturing or geometric precondition} \\ \text{for } F_{ip} \end{cases}$$

Step 2

Function g_i relates the process plan attribute A_{ip} of the process plan P_p and the design attributes of product $D_{p.}$.

$$A_{ip} = g_i(X_{1p}, X_{2p}, ..., X_{np}) = g_i(D_p).$$

For notational purposes, we define $g(D_p) = (g_1(D_p), g_2(D_p), ..., g_k(D_p))$.

For this example, we define the functions g_{1p}, g_{2p}, and g_{3p}, which map the attributes of the design D_p (X_{1p}, ..., X_{4p}) to the attributes, A_{1p}, A_{2p}, and A_{3p} of the process plan P_p. Thus for each process plan attribute defined in Section 5.1.1, we define a mapping function. Note that these functions assume that pockets require milling operations and holes require drilling operations:

$$A_{1p} = g_1\ (D_p)$$

$$= g_1(X_{1p}, X_{2p}, X_{3p}, X_{4p})$$

$$= X_{1p}$$

g_1 maps the set of feature types to the set of operation types.

$$A_{2p} = g_2(D_p)$$

$$= g_2(X_{1p}, X_{2p}, X_{3p}, X_{4p})$$

$$= X_{2p}$$

g_2 maps the number of each feature type to the number of each operation type.

$$A_{3p} = g_3(D_p)$$

$$= g_3(X_{1p}, X_{2p}, X_{3p}, X_{4p})$$

We define g_3 such that it yields a completely ordered sequence of $\{F_{1p}, F_{2p}, ..., F_{np}\}$ that satisfies the precedence constraints of X_{3p} and X_{4p}. We can obtain such an ordering by using a topological sorting algorithm (Corman, Leiserson, and Rivest [1990]). g_3 maps the two types of feature precedences to the operation sequence.

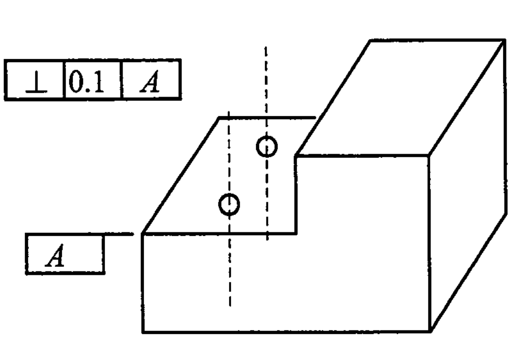
Step 3

$f_h(P_i, P_j)$ is the hierarchical plan similarity measure between process plan P_i and process plan P_j, the process plans for designs D_i and D_j respectively. We have defined such a hierarchical process plan similarity measure in Section 5.1.1.

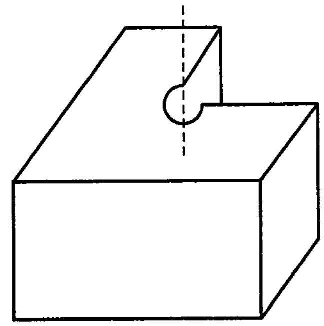
Step 4

Based on the hierarchical process plan similarity measure defined in Step 3, we define the hierarchical design similarity measure as follows:

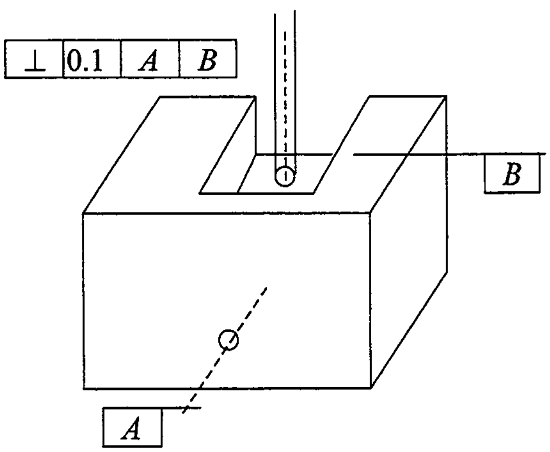
$$h_h(D_i, D_j) = m, \text{ if } g_1(D_i) = g_1(D_j), \; ..., \; g_m(D_i) = g_m(D_j), \; g_{(m+1)}(D_i) \neq g_{(m+1)}(D_j)$$



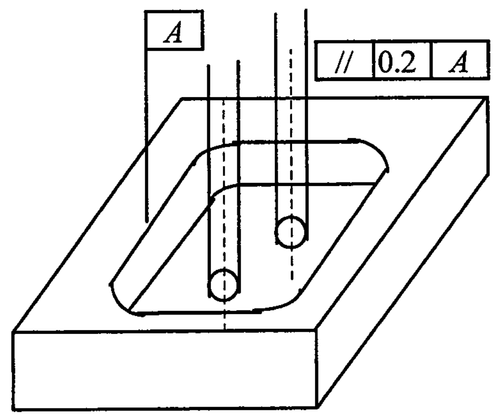
Design D_1



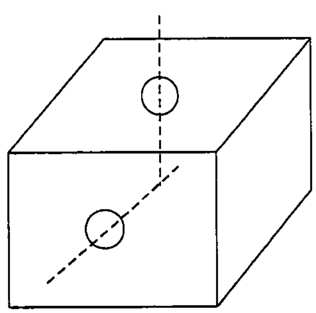
Design D_3



Design D_2



Design D_4



Design D_5

Figure 5.2 The set of designs D_1, D_2, D_3, D_4, and D_5

Let us evaluate the design similarity measures for designs D_1, D_2, D_3, D_4, and D_5, which have the process plans P_1, P_2, P_3, P_4, and P_5. For a detailed explanation of the datum dependent precedence constraints, tolerances, and strict precedence constraints such as the approachability constraint, please refer to Appendix A.

Design D_1 has a perpendicularity tolerance (the two holes must be perpendicular to face A, the bottom of the pocket) that implies that forming the pocket must precede forming the holes.

$X_{11} = (1, 1); X_{21} = (1, 2); X_{31} = \{(\text{pocket, hole}_1), (\text{pocket, hole}_2)\}; X_{41} = \{\}$

Thus, $g_1(D_1) = (1,1)$; $g_2(D_1) = (1,2)$; $g_3(D_1) =$ (pocket, hole$_1$, hole$_2$) or $g_3(D_1) =$ (pocket, hole$_2$, hole$_1$)

Design D_2 has a perpendicularity tolerance (hole h_1 must be perpendicular to the axis A of hole h_2, and the face B, the bottom of the pocket) that implies that hole h_2 and the pocket must be machined before the hole h_1.

$X_{12} = (1, 1); X_{22} = (1, 2); X_{32} = \{(\text{pocket, hole}_1), (\text{hole}_2, \text{hole}_1)\}; X_{42} = \{\}$

Thus, $g_1(D_2) = (1,1)$; $g_2(D_2) = (1,2)$; $g_3(D_2) =$ (hole$_2$, pocket, hole$_1$) or $g_3(D_2) =$ (pocket, hole$_2$, hole$_1$)

Design D_3 has an approachability constraint: milling the pocket renders the approach face for the drilling operation incomplete. This implies that drilling the hole must precede milling the pocket.

$X_{13} = (1, 1); X_{23} = (1, 1); X_{33} = \{\}; X_{43} = \{(\text{hole, pocket})\}$

Thus, $g_1(D_3) = (1,1)$; $g_2(D_3) = (1,1)$; $g_3(D_2) =$ (hole, pocket)

Design D_4 has a parallelism tolerance (the two holes must be parallel to face A, the side of the pocket) that implies that forming the pocket must precede forming the holes.

$X_{14} = (1, 1); X_{24} = (1, 2); X_{34} = \{(\text{pocket, hole}_1), (\text{pocket, hole}_2)\}; X_{44} = \{\}$

Thus, $g_1(D_4) = (1,1)$; $g_2(D_4) = (1,2)$; $g_3(D_4) =$ (pocket, hole$_1$, hole$_2$) or $g_3(D_4) =$ (pocket, hole$_2$, hole$_1$)

Design D_5 has no precedence constraints associated with the holes. This implies that the two holes can be drilled in any order.

$X_{15} = (0, 1); X_{25} = (0, 2); X_{35} = \{\}; X_{41} = \{\}$

Thus, $g_1(D_5) = (0,1)$; $g_2(D_5) = (0,2)$; $g_3(D_5) =$ (hole$_1$, hole$_2$) or $g_3(D_5) =$ (hole$_2$, hole$_1$)

Let us use the proposed hierarchical design similarity measure to measure the similarity between the designs shown in Figure 5.2.

Let us compare designs D_1 and D_2. $g_1(D_1) = g_1(D_2)$ because both designs have pockets and holes. $g_2(D_1) = g_2(D_2)$ because both designs have the same number of pockets and the same number holes. Thus, the similarity of designs D_1 and D_2, $h_h(D_1, D_2) = 2$ (or 3 if $g_3(D_1) = g_3(D_2)$). Likewise, the similarity of designs D_1 and D_3, $h_h(D_1, D_3) = 1$. The similarity of designs D_1 and D_4, $h_h(D_1, D_4) = 3$. The similarity of designs D_1 and D_5, $h_h(D_1, D_5) = 0$.

Thus we have defined a hierarchical design similarity measure using the approach described in Chapter 3. Note that the design similarity of designs D_1 and D_2, $h_h(D_1, D_2) = 2$ or 3 may differ from the process plan similarity of process plans P_1 and P_2. A more complex similarity measure may better capture the precise relations between operations and features.

The following conclusions can be drawn from the above set of results:

1. The process plans corresponding to the designs D_4 and D_1 will have identical values for all the three process plan attributes because $h_h(D_1, D_4) = 3$.

2. The process plans corresponding to the designs D_2 and D_1 will have identical values for the first two process plan attributes and the process plans corresponding to the designs D_3 and D_1 will have identical values for the first process plan attribute.

3. The process plans corresponding to the designs D_5 and D_1 will not have identical values for any of the process plan attributes.

Let us now apply a GT classification scheme to the above five designs to determine their similarity. One of the popular GT codes in use in the industry is the Multi-M GT coding and classification scheme (OIR Multi-M GT Code Book and Conventions, [1986]). It uses an 18 digit code to capture some of the most important characteristics of a design. In order not to bias the GT code the following assumptions were made:

1. Each design's function was unknown.
2. All stocks were cubes measuring 10 units to a side.
3. The material properties of each stock were identical, and for the purpose of classification came under the category "other."
4. The raw material for each stock was the same, and for the purpose of classification came under the category "others."
5. Between 1 to 5 parts of each design were to be manufactured.

Table 5.3 presents a brief description of each position of the Multi-M GT code. Using the information provided in Table 5.3 and the list of assumptions, we can determine the GT codes for the five designs. Table 5.4 lists the Multi-M GT codes for the five designs shown in Figure 5.2.

	Description
Position 1:	Description of main shape configuration e.g. a value of "7" implies not more than one slanted side and /or one curved side in any one view of perimeter.
Position 2:	Description of design views (top, and side/bottom) e.g. a value of "1" implies a U, L, or V shape.
Position 3:	Description of symmetry e.g. a value of "3" describes symmetry in one or two planes
Position 4:	Description of machined secondary elements e.g. a value of "3" indicates the presence of holes, flats and/or slots.
Positions 5 & 6:	Description of function e.g. a value of "00" indicates that the function is unknown.
Positions 7 & 8:	Description of the length e.g. a value of "10" indicates that length is 0.375 inches.
Positions 9 & 10:	Description of width e.g. a value of "10" indicates that width is 0.375 inches.
Positions 11 & 12:	Description of height or thickness e.g. a value of "10" indicates that height is 0.375 inches.
Position 13:	Description of tolerances e.g. a value of "9" indicates the presence of datum dependent tolerances.
Positions 14 & 15:	Description of material chemistry e.g. a value of "00" indicates that the material is of type "other".
Position 16:	Description of raw material e.g. a value of "0" indicates that the material is of type "others".
Position 17:	Description of production quantity e.g. a value of "0" indicates that between 1-5 parts are to be manufactured.
Position 18:	Description of machined secondary element orientation e.g. a value of "1" indicates that the secondary elements are perpendicular to the top plane.

Table 5.3 A brief description of each position of the Multi-M code

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
D_1	7	1	3	3	0	0	1	0	1	0	1	0	9	0	0	0	0	1
D_2	7	1	3	3	0	0	1	0	1	0	1	0	9	0	0	0	0	3
D_3	7	1	2	3	0	0	1	0	1	0	1	0	9	0	0	0	0	1
D_4	7	5	3	8	0	0	1	0	1	0	1	0	9	0	0	0	0	1
D_5	7	5	0	1	0	0	1	0	1	0	1	0	0	0	0	0	0	3

Table 5.4 Multi-M GT Codes

Table 5.5 lists the similarity values between design D_1 and the other four designs using Offadile's formula (refer Chapter 3).

	Design similarity value
S_{12}	0.983
S_{13}	0.915
S_{14}	0.923
S_{15}	0.923

Table 5.5 A summary of the design similarity values using Offadile's measure

From these design similarity values we can draw the following conclusions:

1. Designs D_1 and D_2 are the most similar. The only identified difference is the orientation of the secondary elements.

2. Designs D_4 and D_5 are equally similar to design D_1.

3. Of the four designs under consideration, design D_3 is least similar to design D_1.

Let us now compare the conclusions that can be drawn from the plan-based hierarchical design similarity measure to the conclusions that can be drawn from the GT code-based design similarity measure.

- The GT-code based design similarity measure assigns a similarity value greater than 0.9 to each pair of designs. Yet, we know that the process plans for designs D_1 and D_5, have no similar process plan attribute.

- The designs D_4 and D_5 have a similarity value of 0.923 with respect to the design D_1. However, their process plans are quite different as shown in Table 5.1 and Table 5.2. The process plans for designs D_1 and D_4 have three identical process plan attributes, while the process plans for designs D_1 and D_5 have no identical process plan attributes. Also, this particular example clearly illustrates the inconsistent and imprecise nature of the GT code-based design similarity measure (as discussed in Chapter 3).

We can see from this above example why a plan-based hierarchical design similarity measure is better than a GT code based design similarity such as the one proposed by Offadile for the purpose of design classification for variant process planning.

5.3 Discussion

Chapter 3 presented a generalized design similarity approach. In this Chapter, we took advantage of the well defined process plan and process plan framework in Chapter 4, to define a hierarchical process plan similarity. Based on the hierarchical process plan similarity we defined a hierarchical design similarity measure. The example described in Sections 5.1.2 and 5.2, illustrates a precise, consistent plan-based design similarity measure. The process planner who must use such similarity measures to extract useful process plans for a new design, is now equipped with a measure of design similarity that allows him to precisely recognize how similar designs are in terms of the similarity of their process plans.

Some process plan attributes are related to non-geometric design attributes. Though not considered in this example, the proposed approach could include such non-geometric design attributes (e.g. product quantity).

To illustrate the robustness of our approach we will define a continuous design similarity measure in Chapter 6, using the same approach presented in Chapter 3 and used in Chapter 5 to define a hierarchical design similarity measure. There are some disadvantages associated with a continuous design similarity measure. However, by defining a continuous design similarity measure we will be in a position to develop a far more useful hybrid design similarity measure. We will briefly touch upon the hybrid design similarity measure at the end of Chapter 6.

Chapter 6

A Continuous Design Similarity Measure

In Chapter 5 we defined a hierarchical design similarity measure. In this Chapter we will define a continuous design similarity measure. The approach used will be that proposed in Chapter 3 and successfully used in Chapter 5 to define a hierarchical design similarity measure.

Section 6.1 presents a continuous process plan similarity measure. This section also includes an example to illustrate the use of the continuous process plan similarity measure. Section 6.2 uses the design similarity approach presented in Chapter 3 to define a continuous design similarity measure. This section includes an example to illustrate the use of the continuous design similarity measure. Finally, Section 6.3 summarizes the continuous design similarity approach. A hybrid design similarity measure is proposed in this Section which makes use of the hierarchical and continuous design similarity measure described in previous sections in this thesis.

6.1 The Continuous Process Plan Similarity Measure

In this section we define a function that calculates a similarity measure based on the difference of the attribute values.

$$f(P_i, P_j) = F(A_{1i} - A_{1j},\ \ldots,\ A_{ki} - A_{kj})$$

where

F is a function having a value between 0 and 1, that calculates a process plan similarity value ($F(0, 0, \ldots, 0) = 1$)

Some of the advantages associated with using a numerical similarity measure are:

1. For those attributes of the process plan for which there is no clear sequence or hierarchy, a numerical process plan similarity measure will be easier to implement.

2. For some attributes, such as the feed, speed, and depth of cut of the cutting tool, a binary measure of similarity does not fully capture the closeness of the attribute values in the plans being compared. For such attributes, a continuous measure of similarity is more appropriate.

The continuous process plan similarity measure is also a function of the attributes of the process plan defined in Section 5.1. For each process plan attribute we define a similarity function, f_q. (If $A_{qi} = A_{qj}$, $f_q(A_{qi}, A_{qj}) = 1$.)

$$f_q(A_{qi}, A_{qj}) \in [0, 1], \forall\, q = 1, 2, ..., k$$

We then assign weights, $w_1, w_2, ..., w_k$ to each process plan attribute such that $\sum_{q=1}^{k} w_q = 1$ and define the continuous process plan similarity measure as follows:

$$f_c(P_i, P_j) = \sum_{q=1}^{k} w_q f_q(A_{qi}, A_{qj})$$

where

$f_c(P_i, P_j)$ is the continuous process plan similarity measure for the process plans P_i and P_j

As an example, we will apply the above continuous similarity measure to the process plan defined in Chapter 4. Let us consider the following attributes of the process plan for the purpose of determining the similarity between them. For the sake of clarity and simplicity, we restrict ourselves to the following attributes:

- A_{1p} represents the number of times each operation type occurs. Let i = 1, 2, ..., b be all the possible types of operations.

$A_{1p} = (y_{1p}, ..., y_{bp})$, where y_{ip} is the number of type i operations in process plan P_p

- A_{2p} is the sorted set of cutting tool diameters used in process plan P_p.

$A_{2p} = (d_{1p}, ..., d_{np})$

where

$d_{1p} \leq d_{2p} \leq \ ... \ \leq d_{np}$

$n = \sum_{i=1}^{b} y_{ip}$

- A_{3p} is the sorted set of cutting speeds (in revolutions per minute) used in the process plan P_p.

$A_{3p} = (S_{1p}, ..., S_{np})$

where

$S_{ip} =$ the average cutting speed used for the operation O_{ip} in process plan P_p

$S_{1p} \leq S_{2p} \leq \ ... \ \leq S_{np}$

Let us define the process plan similarity functions for the attributes of the process plans. Consider two process plans P_p and P_q with n and m operations each. Let us also assume that all cutting tools are high speed steel (HSS) tools.

$$n = \sum_{i=1}^{b} y_{ip}$$

$$m = \sum_{i=1}^{b} y_{iq}$$

Similarity Function for Attribute A_1

$$f_1(A_{1p}, A_{1q}) = 1 - \sum_{i=1}^{b} \frac{|y_{ip} - y_{iq}|}{\max(y_{ip}, y_{iq})}$$

Similarity Function for Attribute A_2

$$f_2(A_{2p}, A_{2q}) = 1 - \sum_{i=1}^{\min(n,m)} \frac{|d_{ip} - d_{iq}|}{\max(d_{ip}, d_{iq})}$$

Similarity Function for Attribute A_3

$$f_3(A_{3p}, A_{3q}) = 1 - \sum_{i=1}^{\min(n,m)} \frac{|S_{ip} - S_{iq}|}{\max(S_{ip}, S_{iq})}$$

Weights

Let $w_r = \frac{1}{3}$, $r = 1, 2, 3$

Thus the continuous similarity function between process plans P_p and P_q is defined as:

$$f_c(P_p, P_q) = \sum_{r=1}^{3} \frac{f_r(A_{rp}, A_{rq})}{3}$$

6.2 Continuous Design Similarity Measure

Let us now use the approach proposed in Chapter 3 to formulate a continuous design similarity measure h_c between the designs D_i and D_j.

Step 1

1. $P_1, ..., P_p$ are process plans corresponding to designs $D_1, ..., D_p$.
2. A_{1p}, A_{2p}, A_{3p} are the process plan attributes corresponding to the process plan P_p
3. $P_p \equiv (A_{1p}, A_{2p}, A_{3p})$ is the vector of process plan attributes corresponding to the process plan P_p
4. $X_{1p}, ..., X_{5p}$ are the design attributes corresponding to the design D_p
5. $D_p \equiv (X_{1p}, ..., X_{5p})$ is the vector of design attributes corresponding to the design D_p

We define the following set of design attributes corresponding to the design D_p:

X_{1p} is the material to be used to manufacture the product with the design D_p

X_{2p} represents the types of features that are present in the design D_p (i.e. pockets, holes, etc.)

$X_{2p} = \{x_{1p}, x_{2p}, ..., x_{bp}\}$, where $x_{ip} = 1$ if the feature of type i is present in the design D_p and 0 otherwise. Let $i = 1, 2, ..., b$ be all the possible types of features in any design.

X_{3p} is the number of each feature type in design D_p (i.e. number of pockets, number of holes, etc.)

$X_{3p} = \{y_{1p}, y_{2p}, ..., y_{bp}\}$, where y_{ip} is the number of type i features in design D_p.

X_{4p} is the sorted set of minimum corner radii corresponding to each and every machining feature of the design D_p, which has $N = \sum_{i=1}^{b} y_{ip}$ features.

$X_{4p} = \{d_{1p}, d_{2p}, ..., d_{Np}\}$

where

$d_{1p} \leq d_{2p} \leq \ ... \ \leq d_{Np}$

X_{5p} is the sorted set of machining feature types corresponding to the sorted set of corner radii X_{4p}.

$X_{5p} = \{z_{1p}, z_{2p}, ..., z_{Np}\}$

where

$z_{ip} \in \{1, 2, ..., b\}$, the set of machining feature types. Thus the feature with corner radius d_{ip} is a feature of type z_{ip}.

Step 2

Function g_i relates the process plan attribute A_{ip} of the process plan P_p and the design attributes of product $D_{p.}$.

$$A_{ip} = g_i(X_{1p}, X_{2p}, \ldots, X_{np}) = g_i(D_p).$$

For notational purposes, we define $g(D_p) = (g_1(D_p), g_2(D_p), \ldots., g_k(D_p))$.

For this example, we define the functions g_{1p}, g_{2p}, and g_{3p}, which map the attributes of the design D_p $(X_{1p}, \ldots, X_{5p})$ to the attributes, A_{1p}, A_{2p}, and A_{3p} of the process plan P_p i.e. for each of the process plan attributes defined in Section 6.1, we define a mapping function. We assume that type *i* operations make type *i* features.

$$A_{1p} = g_1(D_p)$$

$$= g_1(X_{1p}, X_{2p}, X_{3p}, X_{4p}, X_{5p})$$

$$= X_{3p}$$

The cutting tool diameters (A_{2p}) are a function of the minimum corner radii (X_{4p})

$$A_{2p} = g_2(D_p)$$

$$= g_2(X_{1p}, X_{2p}, X_{3p}, X_{4p}, X_{5p})$$

$$= 2X_{4p}$$

A_{3p} is the sorted set of recommended cutting speeds. $A_{3p} = (S_1, S_2, ..., S_n)$, is a function of the product material (X_{1p}), the operation types (X_{5p}), the cutting tool material (which is assumed to be HSS), and the cutting tool diameters (which are a function of the minimum corner radii, X_{4p}). The mapping function g_3 comes from a standard handbook or knowledge database such as the Tool Engineer's Handbook [1949].

$$A_{3p} = g_3(D_p)$$

$$= g_3(X_{1p}, X_{2p}, X_{3p}, X_{4p}, X_{5p})$$

$$= g_3(X_{1p}, X_{4p}, X_{5p})$$

$$= (S_1, S_2, ..., S_n)$$

Step 3

$f_c(P_i, P_j)$ is the continuous plan similarity measure between process plan P_i and process plan P_j, the process plans for designs D_i and D_j respectively. We have defined such a continuous process plan similarity measure in Section 6.1.

Step 4

Based on the continuous process plan similarity measure defined in Step 3, we define the hierarchical design similarity measure as follows:

The similarity functions for the functions g_1, g_2 and g_3 are identical to the similarity functions for the attributes A_{1p}, A_{2p} and A_{3p}.

$$f_1(A_{1p}, A_{1q}) = f_1(g_1(D_p), g_1(D_q))$$

$$f_2(A_{2p}, A_{2q}) = f_2(g_2(D_p), g_2(D_q))$$

$$f_3(A_{3p}, A_{3q}) = f_3(g_3(D_p), g_3(D_q))$$

We define the design similarity function as follows:

$$h_c(D_p, D_q) = \sum_{r=1}^{3} \frac{f_r(g_r(D_p), g_r(D_q))}{3}$$

The Analytical Hierarchy Process (AHP) is a useful tool to determine the relative weights of the attribute similarity functions. Using the AHP to determine the weights will ensure that the relative weights assigned to the attribute similarity functions result in a consistent and meaningful continuous process plan similarity measure. For details on the theorems and axioms supporting the AHP, please refer Saaty [1980, 1986] . Refer to Iyer and Nagi [1994] for an illustration of the use of the AHP to retrieve and sort similar parts in agile manufacturing.

6.3 Discussion

This chapter presented the continuous design similarity measure. Although the hierarchical similarity measure is a precise and consistent measure that can be used to classify process plans, it is necessary to sequence the attributes in order to classify the set of process plans into independent subsets. Moreover, each attribute has a binary similarity measure. This sequencing may be difficult to achieve, and binary measures are undesirable for continuous attributes.

Implementing the continuous process plan similarity measure on the other hand may be an easier task since it is a weighted similarity measure.

However, it is difficult to determine what attribute differences a certain continuous process plan similarity value implies. Thus, even if two process plans are equivalently similar to a given plan, their attributes may be completely different. Also, because a weighted measure is being used, it is likely that the resulting continuous process plan similarity function will be sensitive to the weights associated with the attribute similarity functions.

Thus the continuous similarity measure does have some drawbacks, but it proves useful when the hierarchical similarity measure cannot be implemented or does not produce good results.

So far we have described two completely different similarity measures. The purpose of this exercise was to demonstrate the robustness and wide applicability of the general design similarity approach.

It may prove beneficial to combine the hierarchical and continuous measures to exploit the unique advantages each has to offer. Consider the following hybrid measure:

Let $f_h(P_i, P_j)$ be the hierarchical process plan similarity measure between process plans P_i and P_j

Let $f_c(P_i, P_j)$ be the continuous process plan similarity measure between process plans P_i and P_j

Then if the threshold hierarchical process plan similarity measure is set at k, ($A_{1i} = A_{1j}$, ..., $A_{ki} = A_{kj}$), then the process plan similarity measure $f(P_i, P_j)$ can be defined as:

$$f(P_i, P_j) = f_h(P_i, P_j), \text{ if } f_h(P_i, P_j) < k$$

$$f(P_i, P_j) = f_c(P_i, P_j), \text{ if } f_h(P_i, P_j) = k$$

The hybrid process plan similarity measure described above is only one of several possible hybrid approaches.

In general, one can even view a hierarchical measure as a special type of continuous (weighted) measure. That is, there exists attribute similarity measures and weights such that the continuous measure and the hierarchical measure form equivalent classes. We will describe process plan similarity measures since the design similarity measure is a function of the process plan similarity measure.

Let $(A_{1i}, A_{2i}, \ldots, A_{mi})$ be the m attributes of interest for a process plan P_i. Given the following hierarchical similarity measure between process plans P_i and P_j:

$$h_h\left(P_i, P_j\right) = k, \text{ if } A_{pi} = A_{pj}, \forall p = 1,2,\ldots,k \text{ and } A_{(k+1)i} \neq A_{(k+1)j}$$

Let us define the continuous similarity measure $h_c(P_i, P_j)$ between process plans P_i and P_j as follows:

$$h_c(P_i, P_j) = \sum_{k=1}^{m} w_k F_k\left(A_{ki}, A_{kj}\right)$$

where

$$F_k\left(A_{ki}, A_{kj}\right) = \begin{cases} 1, \text{ if } A_{ki} = A_{kj} \\ 0, \text{ otherwise} \end{cases}$$

$$w_k = 2^{m-k}$$

Let $T_K = \sum_{k=1}^{K} 2^{m-k},\ k = 1,\ 2,\ \ldots,\ m$. Then we define two process plans to be "K-similar" if

$$T_K \le h_c(P_i, P_j) < T_{K+1}$$

Thus if two process plans are K-similar then ,

$$\sum_{k=1}^{K} 2^{m-k} \le \sum_{k=1}^{m} 2^{m-k} F_k\left(A_{ki}, A_{kj}\right) < \sum_{k=1}^{K+1} 2^{m-k}$$

Since $\sum_{k=K+1}^{m} 2^{m-k} = 2^{m-K}(1 - \frac{1}{2^{m-K}}) < 2^{m-K}$,

We know that

$$F_k\left(A_{ki}, A_{kj}\right) = 1, \forall\ k = 1,\ \ldots,\ K \text{ and}$$

$$F_{(K+1)}\left(A_{(K+1)i}, A_{(K+1)j}\right) = 0$$

Thus,

$$A_{ki} = A_{kj}, \forall p = 1,2,\ldots,K, \text{ but } A_{(K+1)i} \ne A_{(K+1)j}$$

Therefore, $h_h(P_i, P_j) = K$. Thus we have defined a continuous similarity measure that will result in the same classification scheme as that provided by the hierarchical design similarity measure.

Despite this proof we believe that a hierarchical design similarity measure provides an intuitive way to measure the similarity between two designs. The weighted design similarity measure requires an additional step to provide the same information.

Chapter 7

Application & Conclusions

The proposed design similarity approach will form part of a hybrid variant-generative process planning (HVGPP) system. Section 7.1 gives a brief description of the software system. Section 7.2 describes the contributions of this research, and its anticipated impact on the manufacturing process planning community. Section 7.3 lists some of the interesting research areas that this thesis does not address, along with a few recommendations for future research.

7.1 Application to the HVGPP

A proof of concept automated process planning system is being developed using the proposed hybrid variant generative process planning approach. A team of researchers (Elinson, Herrmann, Minis, Nau, and Singh, 1997) are developing this system at the Computer Integrated Manufacturing Laboratory of the Institute for Systems Research, University of Maryland, College Park, Maryland. Figure 7.1 shows the steps in the hybrid-variant generative process. Figure 7.2 shows how Steps 1, 2, and 3 have been implemented. We developed an algorithm to slice the process plans into independent process plan slices and the designs into independent subdesigns. To date we have, using the design similarity approach described in Chapter 3, implemented Steps 4 and 5 for complete graphs. Figure 7.3 explains Step 6 of the hybrid process planning process in greater detail. Future work will address the following extensions:

1. **A generative process planning module:** In order to complete the hybrid process planning system, first and foremost, a process plan slice merging, and generative process planning module will have to be developed. For example, several interesting cases arise when one attempts to merge the process plan slices into one plan.

2. **Automated design improvement:** After generating the complete process plan for a proposed design, the next step is to automatically formulate suggestions for design improvements based on the cost, quality and time associated with the process plan generated for the design. Although a fully automated design improvement module would be difficult to create, since it would imply capturing the designer's original intent and the design's functionality, design modifications based on the manufacturability of the proposed design would be feasible.

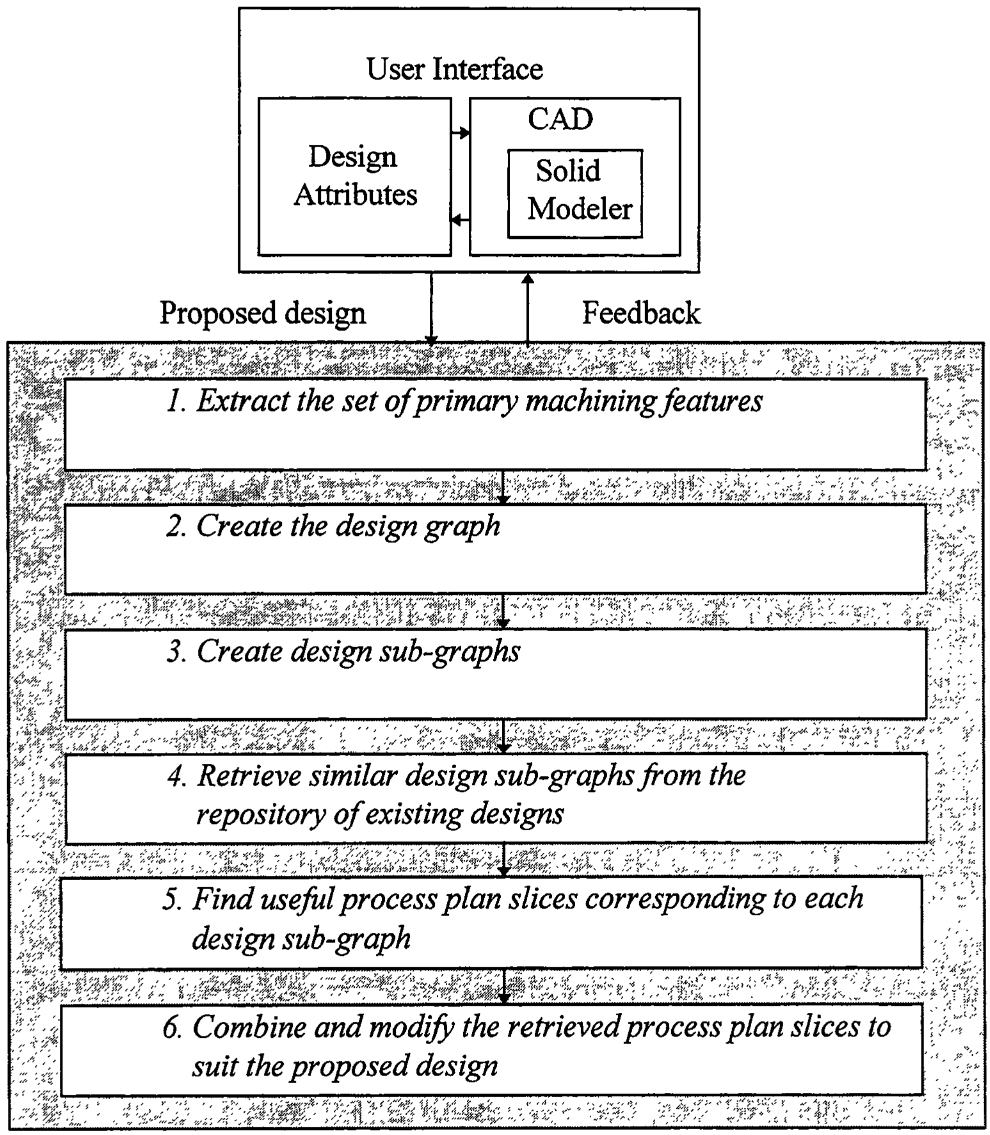


Figure 7.1 Steps in the hybrid variant-generative approach

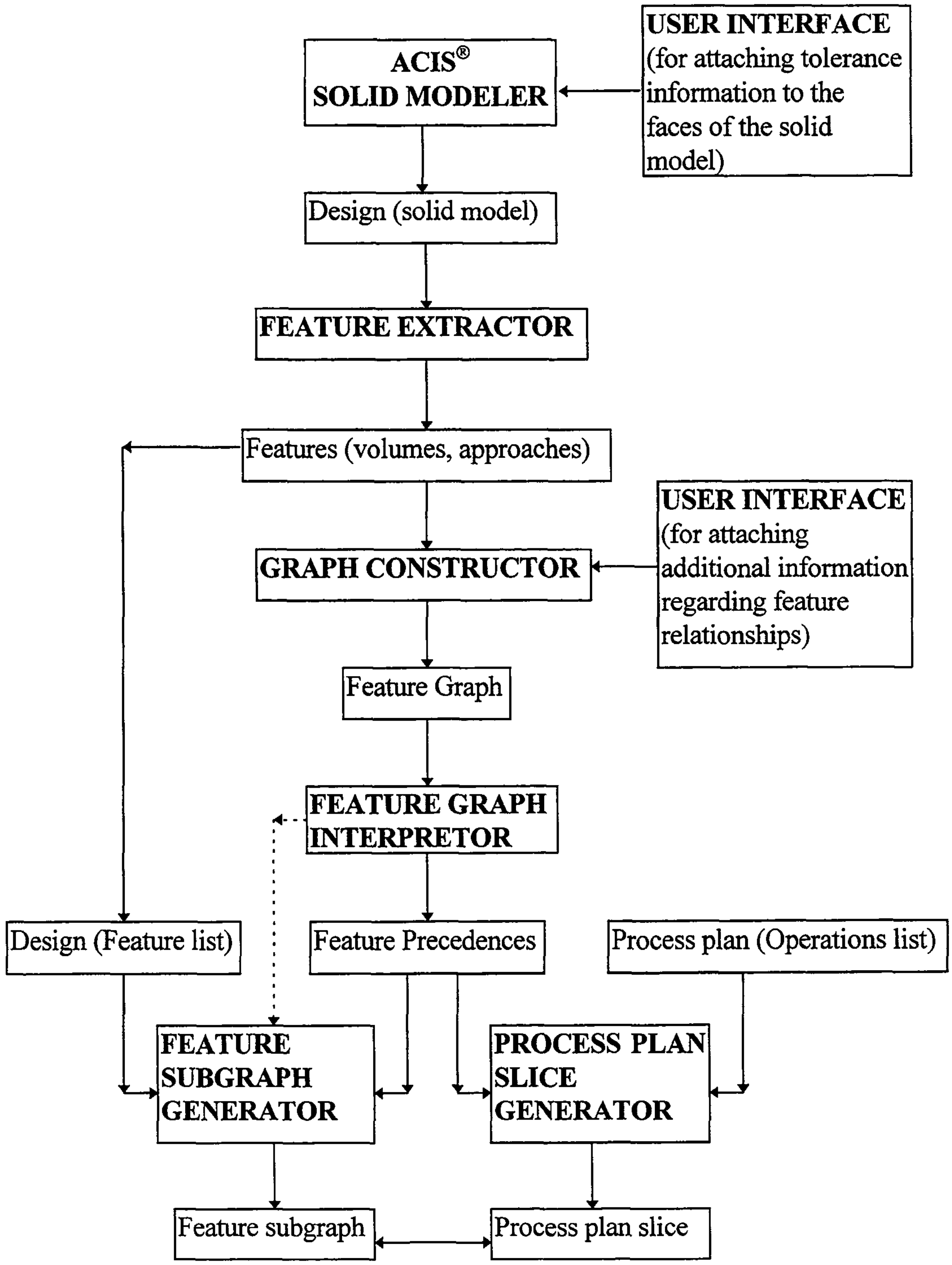


Figure 7.2 Steps 1, 2, and 3 in detail

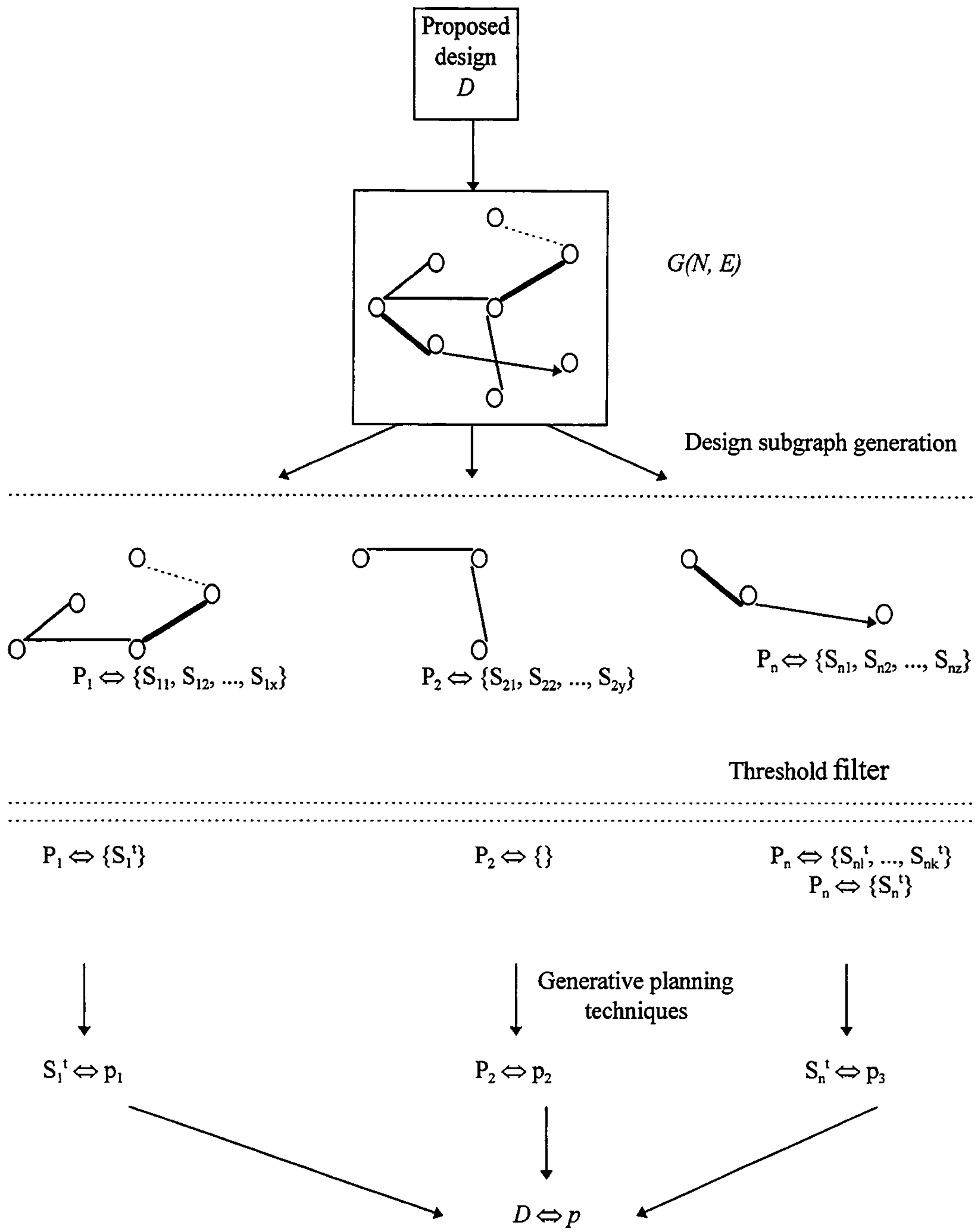


Figure 7.3 A graphical representation of Step 6

7.2 Contributions and Anticipated Impact

The preceding chapters have presented a systematic approach for computing a design similarity measure based on process plan similarity under the assumption that there is a one-to-one correspondence between a design and its process plan. This research has tried to identify a rational approach to the process of design classification to be used for the purpose of automated process planning.

This thesis presents a systematic approach to construct a precise, consistent plan-based design similarity measure. Moreover, by looking at the problem from the manufacturing system point of view, this approach tackles the problem from the perspective of the eventual user of any design classification scheme for the purpose of process planning. This user is the process planner, the cog in the manufacturing system responsible for generating the process plan for the new design (or for an existing design under a new set of manufacturing conditions).

The proposed plan-based design similarity approach makes the following contributions:

1. This approach systematically compares designs for the purpose of hybrid and variant process planning. It is expected that this research will improve the productivity of

process planners by reducing the time spent searching for useful process plans from a database of existing designs. Since the process plans culled from the set of existing designs will be more useful to the process planner as a result of the proposed approach, the process planner will be free to devote his time to problems that cannot yet be solved in an automated manner with good results.

2. Two designs are said to be similar for the purpose of variant process planning because they have attributes that can be manufactured by similar process plans. We do not assume that designs have similar process plans because they have superficially similar design attributes. This approach alone guarantees the presumption of the variant process planning philosophy: Similar designs have similar process plans.

3. The proposed approach, as shown in our examples, yields a more meaningful design similarity measure than GT-code based approaches. GT-code based approaches, like Offadile's do not focus on the critical design information that is correlated with process plan attributes. The proposed approach explicitly captures these relations.

4. The proposed approach does not require exact mappings. If we had used a set e of exact rules to generate the process plan attributes given the set of design attributes, the resulting plan-based design similarity measure, $h^{*}(D_i, D_j) = f(e(D_i), e(D_j))$, would accurately calculate the similarity between designs as required for variant process planning. However, we have already acknowledged the difficulty in determining the set e precisely. Moreover, it is well known that process planning is a function not only

of design attributes but also of several external, hard to define, and dynamic considerations. Thus, using approximate mapping functions g will yield a sufficient design similarity measure, $h(D_i, D_j) = f(g(D_i), g(D_j))$.

7.3 Recommendations for Future Work

This section describes future work that would improve and extend the plan-based design similarity measure. Future work in this area should address the following issues:

- **One-to-one correspondence between a design and its process plan:** This is an assumption that we have made while developing our approach. However, as mentioned in Chapter 4, it is quite possible that there may exist more than one process plan for a given design at any given time. Assuming that such a situation existed in a manufacturing environment which tried to use our approach to classify their designs for the purpose of variant process planning, it would be necessary to define complex mapping functions that would capture such a discontinuity. Future work should address this problem and develop intelligent mapping functions that realize that this one-to-many correspondence between the design domain and the process plan domain.

- **Mappings from the design domain to the process planning domain:** This very important issue needs to be addressed before the proposed design similarity approach can be used in a meaningful way. This thesis described a few mappings from the design domain to the process planning domain, e.g. the mapping from the features' minimum corner radii to the cutting tool diameters. In order to develop a complete and comprehensive design similarity measure it is important to capture all relevant mappings. Although these mappings are similar to rules that generative process planning uses to determine the process plan for a given design, it is important to note that these mappings are different in at least one important way. Generative process planning rules must precisely determine the process plan attribute values and capture manufacturing interactions. The mappings only describe (perhaps approximately) the correlation between design parameters and process plan attributes. While not adequate for generative process planning these mappings do identify the design attributes that must be similar in order for certain process plan attributes to be similar. Still, formulating such mappings can be a difficult task, and more work is needed to capture the relevant mappings for any given domain.

- **The sequence of attributes:** In practice, the relative importance of process plan attributes is not necessarily obvious. In fact, under a different scenario, a different sequence of the same process plan attributes may represent a more suitable hierarchy (a similar, though even more complex problem exists when assigning weights to different attributes for a continuous similarity measure). Clearly, the hierarchy of process plan attributes will influence the results obtained from a search for similar designs. Future work in this area should address automatically generating the similarity measure's attribute sequence.

- **Hybrid similarity measures:** At the end of Chapter 6, we very briefly touched upon one hybrid design similarity measure. Given the inherent characteristics of the process planning attributes (some are discrete while others are continuous, viz. the cutting speed, feed and depth of cut), the most useful design similarity measure might be a hybrid design similarity measure that will better capture how process plans and designs are similar. In this regard, the equivalence (under very special circumstances) of the hierarchical and continuous similarity measures, as described in Chapter 6, might help implement a practical hybrid design similarity measure.

We expect that these suggestions will enhance the usefulness of the proposed approach and will result in the development of a fully automated process planning system incorporating a plan-based design similarity approach.

APPENDIX A

A.1 Design Tolerances

In this thesis we are only interested in those tolerances that directly influence the task of process planning for machined prismatic parts. So, we will describe in detail only those dimensional and geometric dimensional tolerances that are of direct interest to us, while briefly mentioning the other design tolerances. To understand the impact of design tolerances on process planning, it is important to understand the importance of datum dependency as explained in Gupta [1995].

A.1.1 Datum-dependency

To understand the datum dependency relationship between two features, it is important to understand two basic issues: How is a machining feature modeled? What is a machining feature? The following sections give the definitions to most of the terms pertaining to features as defined in Gupta [1995].

A.1.1.1 Geometric Modeling of Machining Operations

The *tool volume* is that portion of the cutting tool and the machine tool which is of interest to us, because it gets close to the work piece. It is denoted by the solid *T*. To perform a cutting operation, the tool volume is given a relative cutting motion with respect to the work piece. This motion is represented by a *sweep* s_v. Let T_V denote the solid generated by the sweep s_v to the solid T. For the purpose of locating the tool, a particular point p_d of T_V is selected as the *datum point*. The boundary $b(T_V)$ is naturally partitioned into the following three types of surfaces :

1. The *separation surface*, i.e., the portion of $b(T_V)$ that connects to the machine tool.

2. The *cutting surface*, i.e., the portion of $b(T_V)$ that is capable of cutting the material.

3. The *non-cutting surface*, i.e., the portion of $b(T_V)$ that is not capable of cutting the material.

To perform a machining operation one sweeps the volume T_V along some *cutting trajectory t*. A cutting trajectory is defined by a space curve. The trajectory *t* is *feasible* only if sweeping T_V along *t* does not cause interference problems between the non-cutting surface of T_V and the work piece.

Let the *approach surface* π be a surface touching solid T_V and containing T_V to one of its sides. This surface is either planar or cylindrical depending upon the machining operation. the side containing T_V is called *accessibility side*. The other side is called *removal side*. The approach surface π partitions T_{SV} into two parts. Only the portion of T_{SV} that lies on the removal side actually corresponds to the volume that can be removed by the machining operation.

A.1.1.2 Definition of Machining Features

A *machining feature* is the portion of the work piece affected by a machining operation. A machining feature will be created by some machining operation op(*f*), using a cutting tool tool(*f*). To perform the machining operation, one sweeps the tool along some trajectory that is characterized by some set of parameters param(*f*). However only a portion of this swept volume corresponds to the volume that can be removed by the machining feature. This volume is called *removal volume* rem(*f*). The approach face, a(*f*) = $\pi \cap T_{SV}$, separates the removal volume from the accessibility volume. The *accessibility volume*, acc(f), is the remaining portion of the tool swept volume. The volume removed by *f* from a give work piece *W* is not necessarily *f*'s removal volume. Instead it is *f*'s *effective removal volume* with respect to *W*, which is defined as eff(*f*, *W*) = $W \cap^{*}$ rem(*f*).

A.1.1.3 Strict Precedence Constraints

Let f and g be two features corresponding to any two machining operations in the list of operations L. The following strict machining considerations result in strict precedence constraints between f and g. A strict precedence constraint must be observed in a process plan and cannot be violated.

Datum-dependency: If f and g have different approach directions and f creates the datum surface for the position tolerance of g, then f must be machined before g. These types of precedence constraints can be determined by a pair-wise examination of the features.

Approachability: If machining f does not permit the machining of g, then f is said to destroy the approachability of the feature g with respect to the workpiece. Since the approachability of a feature is determined with respect to the workpiece, it might not always be possible to determine the approachability of a feature by pair-wise comparisons.

A.1.2 Tolerances and Fits

Dimensions describe the details of a part so that it can be manufactured to the proper size. Dimensions show the sizes and locations necessary to manufacture and inspect the part.

In this section are a few important definitions associated with tolerances and fits as defined in Jain [1990] are listed.

Tolerance is the magnitude of permissible variation of a dimension or other measure or control criterion from the specified value.

Tolerances are essential because they account for the inevitable variation from the specified value as a result of human fatigue, machine inaccuracies, or material variation. The primary purpose of tolerances is to permit some variation from the specified value without complete degradation of the functionality of the part. Any attempt to completely eliminate the causes of such deviations from the specified value would be prohibitively expensive and highly impractical.

Limits are the extreme permissible sizes for any dimension.

When two parts are to be assembled, the relation resulting from the difference between their sizes before assembly is called a *fit*. Depending on the actual limits of hole or shaft, the fit maybe a *clearance fit*, or a *transition fit*, or an *interference fit*. Different standards specify precisely the types of fits to be considered. Some of the well known standards include, the American National Standard and the International Tolerance standard.

Allowance is the intentional difference between the hole dimension and shaft dimension for any type of fit.

All dimensions are subjected to a tolerance unless specified as *reference* or *basic tolerances*. References tolerances convey the intended sizes only, and are not used for manufacturing purposes.

There are three types of dimensioning techniques

1. Chain dimensioning

2. Datum dimensioning

3. Direct dimensioning

Of the above three techniques, only *datum dimensioning* is of relevance to datum dependency. Chain dimensions are used when the dimensions between adjacent features is more important than the overall tolerance accumulation. Datum dimensioning is used to fix the dimensions of features with respect to a common reference surface. Direct dimensioning is applied to control specific feature locations.

A.1.3 Geometric Tolerances

Geometric tolerances state the maximum allowable deviation of a form or a position from a perfect geometry implied by the a drawing. There are five types of geometric tolerances. In this section definitions from Foster [1986] are listed.

1. Form

a. Straightness

b. Flatness

c. Circularity/ Roundness

d. Cylindricity

2. Orientation

a. Perpendicularity

b. Parallelism

c. Angularity

3. Location

a. Position

b. Concentricity

4. Runout

a. Radial runout

b. Total runout

5. Profile

a. Profile of a line

b. Profile of a surface

Datum surfaces are always used while assigning tolerances of *orientation*, *location*, and *runout*. Datum surfaces may be used while assigning tolerances of *profile*. Datum surfaces are never used while assigning tolerances of *form*. The geometric tolerances for which datum surfaces are always used in prismatic machined components are:

1. Perpendicularity tolerance

Perpendicularity is the condition of a surface, median plane, or axis which is at exactly 90 to a datum plane. A perpendicularity tolerance specifies:

1. A tolerance zone defined by two parallel planes perpendicular to a datum plane within which:

    a) The surface of a feature must lie

    b) The median of a feature must lie

2. A tolerance zone defined by two parallel planes perpendicular to a datum axis within which the axis of a feature must lie.

3. A cylindrical tolerance zone perpendicular to a datum plane within which the axis of a feature must lie.

4. A tolerance zone defined by two parallel, straight lines perpendicular to a datum plane or datum axis within which an element of the surface must lie (e.g. radial perpendicularity).

In terms of "holes" and "pockets" this means that a perpendicularity tolerance can be defined between:

1. A plane surface (datum) and another plane surface, i.e. one pocket is the datum feature for another pocket.

2. A plane surface (datum) and the axis of a cylindrical surface, i.e. a pocket is the datum feature for a hole.

3. An axis of a cylindrical feature (datum) and a plane surface, i.e. a hole is the datum feature for a pocket.

4. The axis of a cylindrical feature (datum) and the axis of another cylindrical feature, i.e. a hole is the datum feature for another hole.

2. Angularity tolerance

Angularity is the condition of a surface, axis or median plane which is at the specified angle (other than 90) from a datum plane or axis.

Angularity tolerance is the distance between two parallel planes, inclined at the specified angle to a datum plane or axis, within which the tolerances surfaces, axis, or median plane must lie.

3. Parallelism tolerance

Parallelism is the condition of a surface or axis which is equidistant at all points from a datum plane or axis. A parallelism tolerance specifies:

A tolerance zone defined by two planes or lines parallel to a datum plane (or axis) within which the considered feature (axis or surface) must lie.

A cylindrical tolerance zone parallel to a datum axis within which the axis of the feature under consideration must lie.

In terms of "holes" and "pockets" this means that a parallelism tolerance can be defined between:

1. A plane surface (datum) and another plane surface, i.e. one pocket is the datum feature for another pocket.
2. A plane surface (datum) and the axis of a cylindrical surface, i.e. a pocket is the datum feature for a hole.

3. An axis of a cylindrical feature (datum) and a plane surface, i.e. a hole is the datum feature for a pocket.

4. The axis of a cylindrical feature (datum) and the axis of another cylindrical feature, i.e. a hole is the datum feature for another hole.

4. Position tolerance

Position is a term used to describe the perfect (exact) location of a point, line, or plane of a feature in relationship with a datum or other feature.

A position tolerance is the total permissible variation in the location of a feature about its exact true position. For the cylindrical features (holes and bosses) the position tolerance is the diameter (cylinder) of the tolerance zone within which the axis of the feature must lie, the center of the tolerance zone being at the exact true position.

For other features (slots, tabs, etc.) the position tolerance is the total width of the tolerance zone within which the center plane of the feature must lie, the center plane of the zone being at the exact true position. Position tolerance is the appropriate tolerance, if the need is to control the total cylindrical or profile surface and its axis in composite location relative to the datum axis on a Maximum Material Condition (MMC) basis, e.g. on mating parts to assure interchangeability or assemblability.

In terms of “holes” and “pockets” this means that a position tolerance can be defined between:

1. A plane surface (datum) and another plane surface, i.e. one pocket is the datum feature for another pocket

2. A plane surface (datum) and the axis of a cylindrical surface, i.e. a pocket is the datum feature for a hole.

3. An axis of a cylindrical feature (datum) and a plane surface, i.e. a hole is the datum feature for a pocket

4. The axis of a cylindrical feature (datum) and the axis of another cylindrical feature, i.e. a hole is the datum feature for another hole.

The tolerances that do not result in a datum dependency for prismatic machined components, although they may result in datum dependency for other machined components are:

1. Runout Tolerance

Runout is the composite deviation from the desired form and orientation of a part surface of revolution during full rotation (360) of the part on a datum axis. Runout tolerance are applicable to rotating parts (cylindrical surfaces).

2. Concentricity

Concentricity is the condition where the axes of all cross-sectional elements of a feature's surface are common to the axis of a datum feature.

Concentricity is not the appropriate tolerance if the need is to control the total cylindrical or profile surface and its axis in composite location relative to the datum axis on an MMC basis, e.g. on mating parts to assure interchangeability or assemblability. The recommended tolerance for such a purpose is the position tolerance. The concentricity tolerance is used to control the axis of one or more features in composite relative to a datum axis, Regardless of Feature Size (RFS). e.g., to control balance of a rotating part.

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