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ALGORITHMS FOR DESIGNING A GENERATIVE CAPP SYSTEM

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Abstract: The variants of process plan are difficult to obtain. In a computer aided environment there are two main possible alternatives to do that: Variant Process Planning and Generative Process Planning. First alternative is based on large databases storing the process plan variants for different groups of parts, developed in a previous stage. The second alternative, more difficult to design, define and develop, but much more flexible, is based on a method of defining the variants of process plan, in a generative way. In such a system, the input data are the assembly of geometrical information extracted from the solid model of the part, made with an integrated or external CAD system. Within the technological module, blocks with certain functionalities identify the groups of data assigned to the features, which define the external and internal shape of the part. The identified features are subsequently analysed, ordered and grouped so as to form complex features. Then, the combinations of complex features are generated, by observing certain technological rules.
After selecting or defining the technological parameters assigned to the machining phases, the variants of process plans are obtained. The paper presents some algorithms for designing an original generative CAPP system for revolution parts.
Key words: CAPP, revolution part, process plan, distinctive feature word

1. INTRODUCTION

The modern CAPP systems are generative ones. Such a system needs detailed information in order to complete its work and to generate variants of process plans [Allada 1996]. The four stages of the method developed to create a generative CAPP system are [Doicin 1999]:

(1) Define the initial data, necessary to generate the variants of process plans, by creating the solid model of the part and after that, by filling in the technological data;

(2) Define the constraints and preliminary establish the technical possible variants of process plans, by preliminary establish the raw stock dimensions and intermediate dimensions, the machining parameters and the time required for machining, and by preliminary generating the set of variants of process plans satisfying specific technical criteria;

(3) Establish the technical possible variants and select the optimum one;

(4) Design the jigs and fixtures used in the selected variant of process plan.

In the first stage, the 3D model of the part is defined, usually outside the CAPP system, using a CAD package. Then, by running some specific routines, geometrical data are extracted from the CAD model and transferred in a certain programming language. The extracted data are stored in a transfer file, [Doicin 2001].

Then, in the second stage, the parameters of the constructive description of the part (extracted from the CAD model) are completed with technological data, all the information being stored in the transfer file. Based on these data, some preliminary variants of process plans are generated.

After this, during the third stage, the final variants of process plans are generated. The algorithm which generates process plans uses a technological database containing information about part materials, machining parameters, cutting forces, tools, machine-tools etc.

Finally, in the fourth stage, the jigs and fixtures are designed.

In accordance with the previous mentioned method, a generative CAPP system was created. The system is composed from 3 modules, see Figure 1:

(1) The Module for Identifying the Parts' Shape - MGF (corresponding to the stage 1);

(2) The Module for Generating Variants of Process Plans - MGPT (stages 2 and 3);

(3) The Module for Designing the Jig and Fixtures - MGES (stage 4).

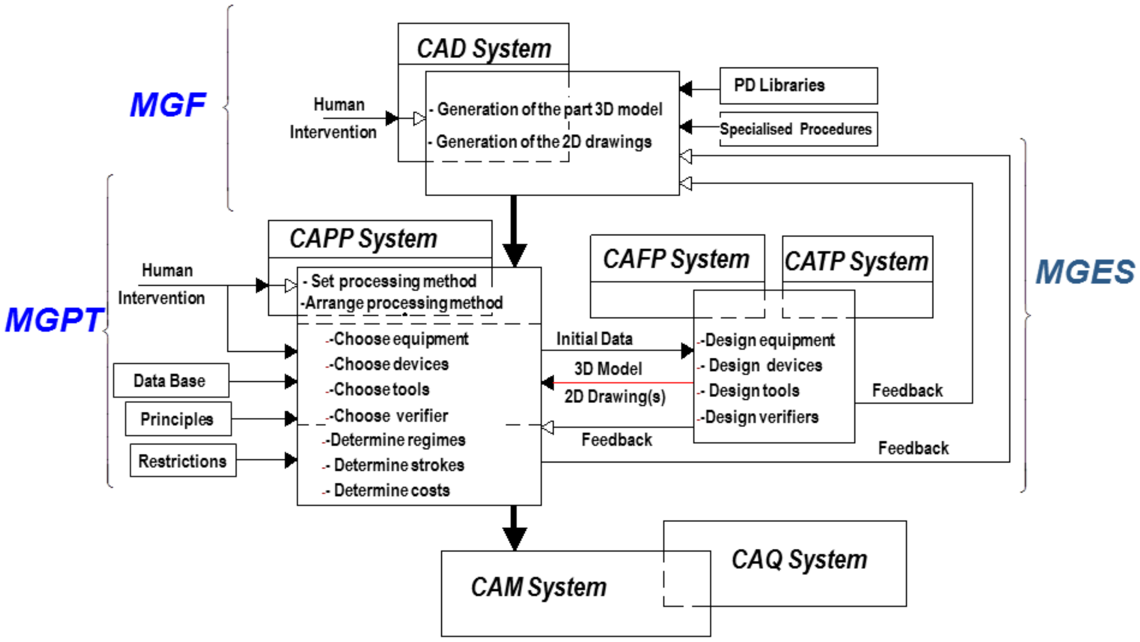

Fig. 1. The Modules of a standard generative CAPP system

2. TERMS AND CONCEPTS

In the process of developing the CAPP system we've used specific concepts (with some particular definitions given by the authors) to define the constructive-technological entities (components) describing the machined part. We've named these components Distinctive Features [Doicin & Tonoiu 2008].

Let's consider that a Simple Distinctive Feature (shortly, Distinctive Feature, abbreviated DF) is the simplest constructive piece of a part – made from a surface or a group of surfaces that can be machined together – in which a part can be divided (the atom of the part, from constructive point of view).

In connection to this definition, other two important concepts can be described [Doicin 2001]:

- Complex Distinctive Feature (CDF), defined as being a compound distinctive feature, composed from several neighbouring distinctive features (a group of adjacent DFs), connected by precedence relations and having a certain role in the activities of defining the process plans variants, and
- Dominant Distinctive Feature (DDF), as being the distinctive feature, component of a CDF, having the biggest dimensions comparing with its neighbours belonging to the same CDF, and giving to the CDF the main constructive characteristics.

We may also define some associated terms, as follows:

- Dependent Distinctive Feature (DeDF) – as being the Distinctive Feature which can be machined only after we machine another Distinctive Feature, usually adjacent one, named Independent Distinctive Feature;
- Generic Distinctive Feature (GDF) – as being the Distinctive feature which express, in an unitary way, the technological characteristics of a group of Geometric Distinctive Features;
- Finite Distinctive Feature (FDF) – as being the Distinctive Feature we may identify on the part surface;
- Raw Distinctive Feature (RDF) – as being the that Distinctive Feature we may identify on the raw stock surface;
- Outer Distinctive Feature (ODF) – as being the Distinctive Feature which contribute to define the outer shape of the part;
- Inner Distinctive Feature (IDF) – as being the Distinctive Feature which contribute to define the inner shape of the part;

Other terms describing the part from geometrical point of view will be defined in the following sections.

3. ROUTINES AND FUNCTIONS

The routines for generating the process drawings are written by the system in a specific file, having a structure defined by two types of functions: a) Generative functions, defined before the system starts to run, as the core of the graphical representation kernel of the system, which are able to draw standard graphical components of the drawings (points, lines, squares, rectangles etc.) and b) Transfer functions, which depend on the currently analysed variant of process plan, and contain the lists with 3D

point coordinates of the part, extracted from the database of the CAD model of the part.
The generative functions create the process drawings.
The transfer functions are automatically generated by the CAPP system for each variant of process plan. They have the role of transferring the data – calculated or extracted from the database [Doicin, 2001; Doicin & Tonoiu, 2008] – to the generative functions. The routines contain technological information about machine-tools, tooling etc. and also create the list with 3D point coordinates required in order to draw the part having machined surfaces corresponding to the current operation. In this way, the generative functions will use the 3D lists of points made by the transfer functions in order to generate the 2D drawing of the part, as main component of the process drawing.

4. THE MODULES OF THE CAPP SYSTEM

The proposed CAPP system is composed of three main modules, each of them having specific roles (see Figure 1).

The MGF Module
The MGF module contains two main blocks: The Modeller of Distinctive Features and the Analyser of Distinctive Features.
The main element of the MGF module is the Analyser/ Modeller of Distinctive Features (Figure 2).

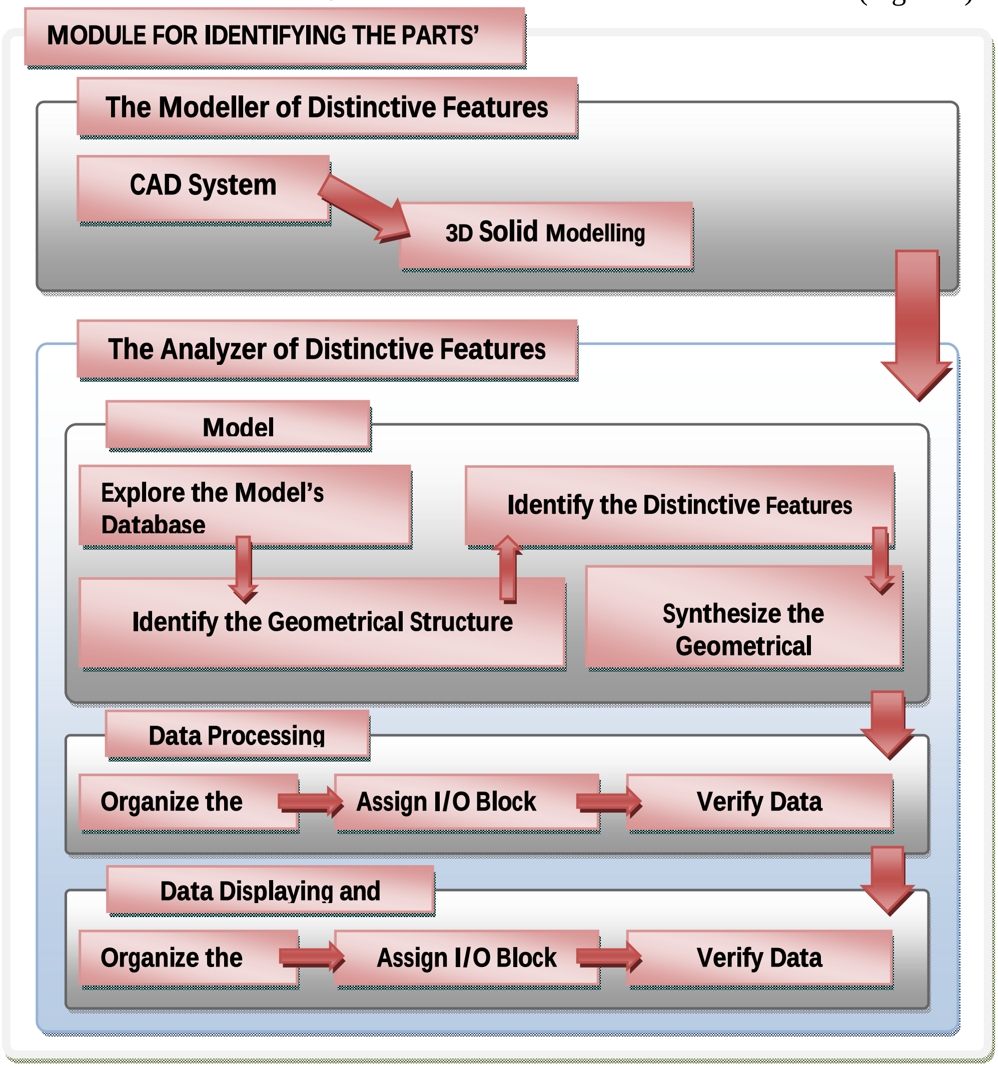

Fig. 2. The Analyser/ Modeller of Distinctive Features

The modeller is based on a CAD system able to generate the solid model of any rotational part, using Distinctive Features (DFs). The new generated model will become the prime data for the Analyser.
The data required by the Analyser is composed of the 3D model of the part and the 2D drawings.

The Analyser extracts the geometrical data from the 3D CAD model and interprets the technological information contained by the 2D drawings (or interactively delivered by the user). The 3D model will give the image of the spatial arrangement of the distinctive features on the part main axis, and the 2D drawings will allow completion of the list containing attributes attached to each DF (tolerances, roughness, heat treatment etc.).

The MGPT Module

Based on the data contained by the transfer file generated within the MGF module, the module for generating process plans variants (MGPT) identifies the machining phases aligned to each surface (group of surfaces). Then, the MGPT module groups the machining phases, calculates the dimensions of the raw stock part and the intermediate dimensions for each assigned machining phase and each process plan variant, calculates / selects the machining parameters and the time required to complete the machining of each phase and orders the variants depending the durations previously calculated.

The user has to have periodically interventions within these activities, in order to simplify the lists of technological parameters and the variants of process plans, automatically determined by the system.

After the final selection of the tools and machine tools – according to each group of machining phases that fulfil a certain set of technological criteria and specific constraints – the machining parameters and the machining time are re-calculated. The variants are ordered taking into consideration the new obtained values. Further on, the technological documentation (process plans) is generated, as the output data of the MGPT module.

The MGES Module

According to the designing requirements, the module for generating system elements (MGES) selects the adequate system elements from a technological database, or generates them interactively. Then, the module identifies the physical configuration of the system, in order to assure the machining of each surface, in conformity with the prescribed technical requirements.

Important – general and particular – elements regarding the MGPT module – emphasizing the way of generation of the process plans variants – taking into consideration general principles and criteria and, also, technological restrictions, are presented further on. The algorithm for generation of the process plans variants is accomplished following a certain algorithm. The algorithm consists of many successive phases, presented in the following sections.

5. THE PROCESS OF OBTAINING THE OPTIMAL PROCESS PLAN WITHIN A CAPP SYSTEM

The analyse of the distinctive features

Using specific rules, the Finite Distinctive Features (FDF) [Doicin, 2001] are extracted from the 3D solid model or are created starting from the 2D drawings (Figure 2). Further on, the Finite Distinctive Features are separated into two categories: outer (ODF-oj, where $j = \overline{1,n}$ and n = the number of total outer Finite Distinctive Features) and inner (IDF-ik, where $k = \overline{1,m}$ and m = the number of total inner Finite Distinctive Features).

Thus, the FDF-o set is defined as the multitude of the FDF-oj, which defines the outer shape of the part, and the FDF-i set is defined as the multitude of FDF-ik, which defines the inner shape of the part.

In accordance with the above description, the defining relations could be developed, as follows:

$$FDF - o = \{DF - o1, DF - o2, \dots, DF - on\} \quad (1)$$

or

$$FDF - o = \bigcup_{j=1}^{n} DF - oj \quad (2)$$

and

$$FDF - i = \{DF - i1, DF - i2, \dots, DF - in\} \quad (3)$$

or

$$FDF - i = \bigcup_{k=1}^{m} DF - ik \quad (4)$$

where: $j = \overline{1,n}$; $k = \overline{1,m}$; n = the total number of outer Finite Distinctive Features; m = the total number of inner Finite Distinctive Features.

Reading the transfer file

The communication between MGF and MGPT modules is realised through a transfer file, generated by the MGF. This file contains all the geometrical information extracted from the solid model, written in a specific format. The information stored in this file is used as initial data by the MGPT module.

Grouping the simple DFs and generating the complex DFs

The methodology for obtaining the process plans variants, by successive combining groups of surfaces, starts from the idea of part decomposition. Thus, any part will be decomposed in groups made of maximum 3 simple distinctive features (SDF). Such a group will be referred as a Complex Distinctive Feature (CDF).

At the limit, a Complex Distinctive Feature is compose of a single Simple DF. Thus, the basic simple DF which defines a CDF from constructive point of view is the geometrical 3D primitive of type cylinder. The absence of such a Distinctive feature leads to the impossibility of complete defining a Complex Distinctive Feature (Figure 3).

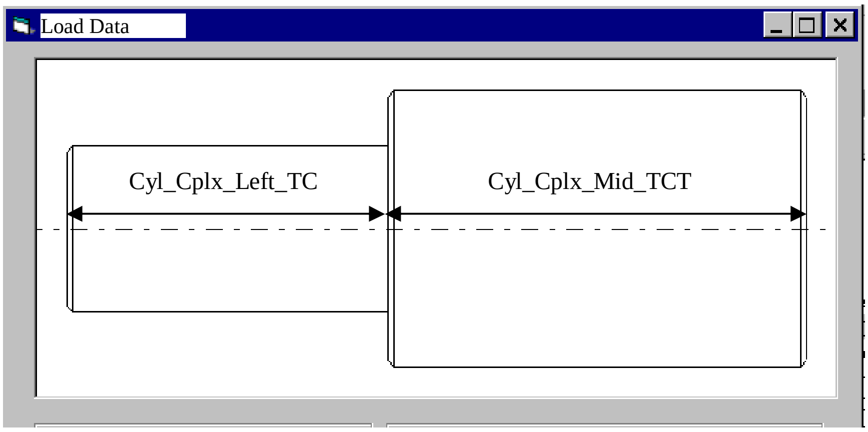

Fig. 3. Shaft having 2 Complex DFs and 5 Simple DFs

For this reason, this basic Distinctive Feature was named Main Distinctive Feature (MDF). Each Complex Distinctive Feature has to contain only one Main Distinctive Feature. Thus, for any shaft neck, the associated MDF is a Distinctive Feature of type Cylinder (DF-Cylinder), for a gear with 2 chamfers, the associated MDF is a Distinctive Feature of type Gear (DF-Gear) [Doicin 2001, Doicin 2004, Kunwoo 1999] etc.

Identifying the generic distinctive features

In order to generate the variants of successions of machining phases, each simple Distinctive feature (e.g., DF-Chamfer) has associated the same machining phases, no matter on which side (left or right) of the Main Distinctive feature of type cylinder belongs. Thus, for future processing of technological data – in order to find the optimum successions of machining phases – the system database stores a single Distinctive Feature, of type chamfer.

On the other hand, it is necessary to store the position of each Distinctive Feature, other than cylinder related to the Main Distinctive Feature of type cylinder, in order to know the moment when a re-clamping is necessary. This is accomplished by assigning a logical variable (left, right) to each simple Distinctive Feature.

The communication between MGF and MGPT is realised through a transfer file. This file contains all the geometrical information extracted from the solid model, written in a specific format. The geometrical data depends on the complexity of the geometrical primitives, which compose the part's shape.

Each geometrical primitive or set of geometrical primitives composing a distinctive feature is extracted from the solid model and stored in the transfer file.

The transformation / ordering of the distinctive features

After analysing the distinctive parts, some activities of transformation/ ordering of the identified distinctive parts will be realised, as outlined below.

The extraction of the geometrical information from the transfer file

The primary information used within the MGPT module is extracted from the transfer file, which contains only geometrical data. In order to complete this information with the values of the prescribed roughness, tolerances and heat treatment, there are two methods that can be followed: by extracting them from the 2D engineering drawings or by typing their values by the operator.

The completion of the geometrical information

For completing the geometrical information with the data necessary for elaboration of the process plans variants the second method was used. The generative CAPP system developed during the researches allows entering the technological data necessary for the further processing, through a specific interface.

The user (operator) can type or select the following data:

- general constraints useful for generating the technical possible combinations of variants of machining phases in order to obtain feasible process plans;
- the type of the machine tool used for machining the part;
- the general roughness of the part and the specific roughness prescribed to each surface;
- the deviations from the nominal values of the part dimensions.

Identifying the distinctive features which can be machined in the same clamping

Based on the data written in the transfer file and those added next by the user, the systems is able to establish which are those Distinctive Features which can be machined in the same clamping. No matter that some Distinctive Features could be independent – from geometrical point of view – it will be imposed that these groups of features to be machined in the same clamping, in order to fulfil the prescribed characteristics.

In order to simplify the algorithm of elaborating the feasible variants of process plan, the next data processing activities will take into account this group of features as a single Distinctive Feature.

Such a situation could be met at the outer circular grooving. Both Distinctive Features of type Cylinder, adjacent to such circular groove will be considered as a single Distinctive Feature.

Identifying the independent and dependent distinctive features

Based on certain rules and specific principles, a set of precedence constraints, referring the machining order of the Simple Distinctive Features which compose a Complex Distinctive Feature, can be established (for example, the chamfers has to be always machined after the carrying cylindrical surface was machined; the threads: after the carrying cylinder; the grooves: after the carrying cylinder; external and internal grooves: after the carrying cylinder). In this way, a first set of precedence relations within the DFs has been created.

On the other hand, the Simple or Complex Distinctive Features can be classified as independent and dependent ones. This order isn't affected by the previous classification (as simple and complex ones). Thus, it is possible as a dependent Distinctive Feature to be, in the same time, a Complex Distinctive Feature.

This hierarchy is useful in the process of grouping DFs for machining.

The analysis of the precedence constraints used for ordering the simple distinctive features for machining

Being given two Distinctive Features, several situations regarding the machining order may appear, depending on the set of precedence constraints used.

A detailed analysis of these constraints reveals the fact that some of them are essential. Thus, it is considered that the precedence constraints could be split in compulsory constraints and optional constraints.

The CAPP system generates variants of process plan by respecting two sets of precedence relation: one for ordering the simple Distinctive Feature within each Complex Distinctive Feature and the other for ordering the Complex Distinctive Features.

In the case of machining on the CNC machine-tools, appliance of the above-mentioned constraints leads to a machining order as follows:

- machining of the Distinctive feature of type cylinder, starting from an end of a shaft to another;
- machining of the Distinctive feature of type key;
- machining of the Distinctive feature of type groove;
- machining of the Distinctive feature of type gear

After the final selection of the tools and machine tools – according to each group of machining phases that fulfil a certain set of technological criteria and specific constraints – the machining parameters and the machining time are re-calculated.

The variants are ordered taking into consideration the new obtained values. Further on, the technological documentation (process plans) is generated, as the output data of the MGPT module.

Initialisation of the technological parameters

Within the CAPP system it's considered being technological parameters having influence in establishing the variants of process plans – the following: the machine-tools; the cutting tools; the material of the part / cutting tool; the jig and fixtures; the machining time.

Through a specific interface, the necessary values of the technological parameters can be settled, as initial data useful for the designing of the process plans variants.

The calculus of the dimensions of the raw-stock

It is admitted that the notion of raw-stock (SF) of the part (P) describe a solid body, from which is made the part by applying one or many transformations.

Depending on the geometrical and material characteristics prescribed for the part, and also by functional conditions, some variants of methods for obtaining the raw-stock are established. Corresponding to each method, a variant of main raw-stock is generated.

As a result, the 3D model of the main raw-stock and the associated engineering drawing are obtained.

Let's consider that can be identified k variants of raw-stock. For each variant an algorithm which is composed by three stages may be followed:

(1) the analysis of the raw Distinctive Features;

(2) the establish of the correlation between the Raw Distinctive features and the Finite Distinctive Features;

(3) the calculus of the dimensions of the raw stock (made in conformity with specific methodology [Vlase 1996]);

(4) the calculus of the dimensions of the part surfaces in different machining stages.

All the obtained information is stored in the system database.

Generating and ordering the combinations of complex and simple distinctive features

Let's consider that the part is completely described by a finite number of Complex Distinctive Features.

In order to generate the combinations of Complex and Simple Distinctive Features for machining, a specific algorithm has to be respected, as follows.

(1) axial ordering of the Complex Distinctive features, depending on the coordinate of the characteristic points;

(2) generation of all combinations of variants of successions of Complex Distinctive Features, ready for machining;

After these two steps, will be obtained m = n! variants of successions of Complex Distinctive Features – if no constraint is present, where n=no. of Simple DF.

(3) generation, for each Complex Distinctive Feature, of all the variants of successions of machining phases for the Simple Distinctive Features describing the entire part.

If each Complex Distinctive Feature is composed of maximum three Simple Distinctive Features (e.g., Chamfer-Cylinder-Chamfer) and it doesn't exist any precedence restrictions between the component Simple Distinctive Features, it will be obtained maximum 6 (3!) variants of combinations of Simple Distinctive Features.

After identification of all technically possible variants of complex PD combinations, the next step is the generation of simple PD combinations within each sequence of complex PD previously identified (Fig. 4, 5).

Identification of machining phases adequate for each PD

By extraction from the appropriately developed databases, variants of technically possible sequences of machining operations are established for each distinct part. The database retains the machining sequences associated to a given simple PD, whose associated list contains certain values of tolerance level and surface roughness.

Thus, assuming that the overall roughness associated to the work piece shown in Figure 6 is Ra = 6.3μm and that the prescribed deviations allow inclusion in the tolerance level 9 (for dominant PD – of type Cylinder – within each step), then the following algorithm will apply:

- Identify the tolerance level associated to the deviations prescribed for each dominant PD (CIL1 and CIL2);
- Associate to the chamfered edge adjacent to the dominant cylinder a tolerance level higher by 1 unit (meaning that, if a cylinder-type of PD is associated with the tolerance level 9, then the chamfer will be associated with the tolerance level 10 - a requirement imposed by the dimensional accuracy prescribed to any chamfer and by the need for a simpler organization in the database of the data related to associated machining operations;
- Associate to the adjacent connection the same tolerance level as to the dominant cylinder;
- Browse one by one each string of simple PDs in the combinations previously obtained and extract from the database maximum t strings of machining sequences associated to each and every distinctive part currently under examination;
- Store up in a tree-type structure, for each and every Simple PD, along with the list of associated attributes, the collection of those t series of machining processes;

For each simple (single) distinctive part, a maximum t sequences of technically possible machining variants are considered as identifiable (Figure 5).

Machining processes may be grouped by observing the two principles (Concentration and Differentiation) recognized by the literature. Thus, at one extreme, it has been considered that the maximum limit of differentiation occurs where each step is machined in one single operation, as result of grouping the machining processes without surpassing the boundary of the complex PD. At the other extreme, the maximum limit of concentration implies the machining in one single operation of all the ascending steps from one end of the shaft.

The CAPP system developed, applies alternatively the two criteria specified above, thus offering as possible solutions several PP variants. Some of them have a high degree of concentration of machining operations, while others, a high degree of differentiation. The system has an interface for four types of Machine-Tools: Classic, CNC, Multi-spindle and Copying Machine. The class of restrictions leading to determination of the PP variants has been implemented only for the first two categories, with the following to be developed within the future versions.

The restriction observed throughout the generation of these combinations was that, dealing with setting up, the sequence of the machining operations by their type, in the case of a given simple PD, will impose that rough cutting will always be performed before semi-finishing and semi-finishing before the finishing operation.

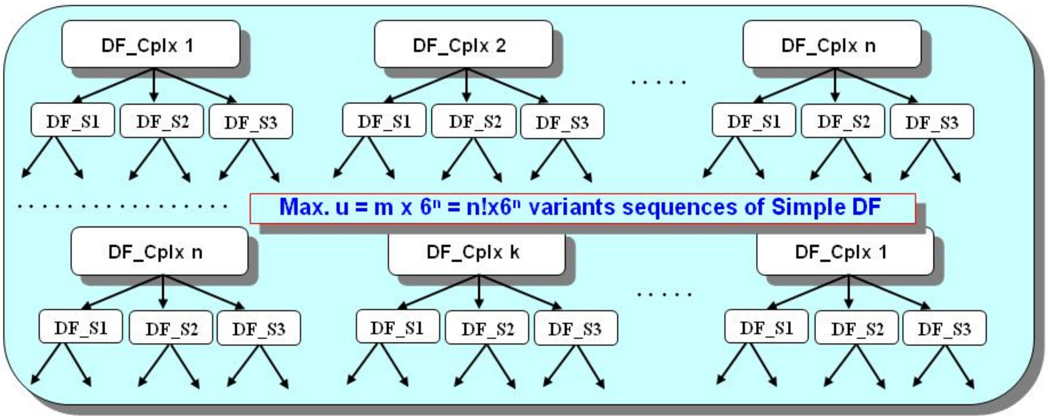

Fig. 4. Variants of successions of machining phases

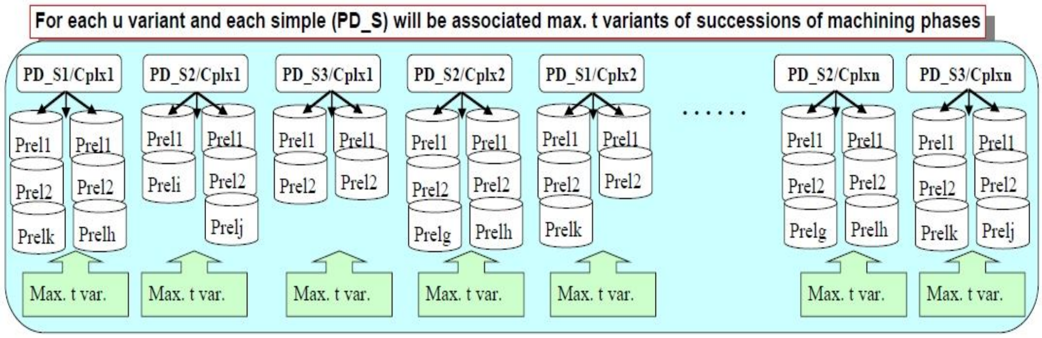

Fig. 5. The number of successions of machining phases for each PDs

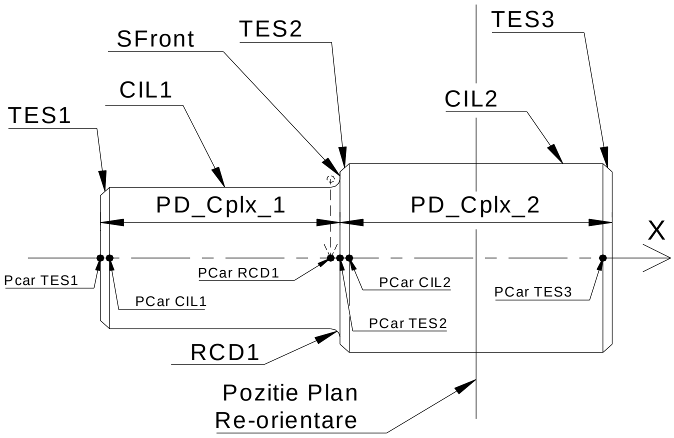

Fig. 6. Simple shaft

Grouping by operations is anticipated at this stage, as result of compliance – at the level of complexity of current stage – with the two principles of continuity and non-destroying the already machined surfaces.

For each of the m combinations of the Complex Distinctive Features, maximum 6n, where n= no. of Simple DF, variants of successions of Simple Distinctive Features will be identified (by considering all the combinations between 6 variants for each Complex Distinctive Feature).

Thus, for the all m variants, maximum u = m x 6n = n! x 6n variants of successions of Simple DFs (Generic DFs), for a part composed of n Complex DFs will be obtained (Figure 4).

Considering that we may assign, to each Simple Distinctive Feature, maximum t variants of successions of machining phases for each variant k of raw-stock material, maxim $v = u \times k \times t^{3n}$ variants of successions of machining phases for the Complex DFs describing the analysed part, will be generated (Figure 5).

It is considered that for one of the v machining sequence variants, there are maximum g possibilities for grouping them into operations. Under these circumstances, the total number of possibilities of grouping the machining into operations is $w = v \times g = n! \times 6n \times k \times t^{3n} \times g$.

By associating certain precedence restrictions between the simple PDs within the complex PDs, the number of variants decreases. Thus, restrictions have been imposed within the simple PDs in the composition of each PDC, as follows:

- chamfer machining follows the cylinder cutting;
- connection machining follows immediately after the cylinder cutting (and the adjacent front face);

If the complex work piece has the structure: Chamfer, Cylinder, chamfer (as in the case of maximum diameter step), then the requirements are as follows:

- machining should be conducted in the sequence: Bevel, Cylinder, Bevel (taking into account all combinations resulting from permutation - in terms of machining sequence – of the two chamfered edges);
- chamfered edges can be machined consecutively, subject only if it is included an auxiliary phase (understood by the system as a virtual machining) of the type "Work piece indexing and clamping".

One single category of restrictions applies to the generation of all these combinations: the cylindrical part and the adjacent connecting Simple PD should always be cut by the same type of machining operations. Thus, a sequence of the type: Cylinder Turning – Connection Milling cannot be a valid sequence.

Identifying the auxiliary phases

The moment for inserting an auxiliary phases (like "clamping/unclamping the part") is identified by specific routines through some geometrical constraints, based on the relative position between two characteristic points from part description. Thus, for example, if the X coordinate of the characteristic point of the DF being currently machined is greater than the coordinate X of the Reorientation Plane (DF_Current_X > Pr_X) and the coordinate X of the characteristic point of the DF previously machined is smaller (DF_Previous_X <Pr_X) or vice-versa (DF_Current_X < Pr_X and DF_Previous_X > Pr_X), then an auxiliary stage will have to be included between the DF_Previous and the DF_Current.

This rule is valid for all sequences that are involving no simple PD from within the PDC composition containing the maximum diameter dominant PD (maximum diameter step).

The characteristic point is geometrically defined for each Distinctive Feature, depending on the DF type.

For example, if the X coordinate of the characteristic point (a point having a certain position for each type of DF) of the current machined DF is greater than the X coordinate of the Reorientation plane (associated to the cylinder having the maximum diameter) and the X coordinate of the characteristic point from the previous machined DF is smaller than the X coordinate of the Reorientation plane (or vice versa), then we need an auxiliary phase between machining the two DFs. The rule is valid for all the successions without any Simple DF from the Complex DF which contain the Dominant DF of maximum diameter.

After this, the variants of PP are compared, based on an economic criteria, and the optimal PP is obtained (Figure 7).

6. CONCLUSIONS

The paper briefly describes the algorithms for designing and elaborating a generative CAPP system. The main stages and modules of such a system are presented, together with some algorithms, and the description of the main modules involved in the process. The system is able to generate valid process plans for revolution parts.

Efforts are being made in order to reduce at minimum the user intervention, and the system is continuously evolving. Thus, a friendlier interface it is planned for the system in the future.

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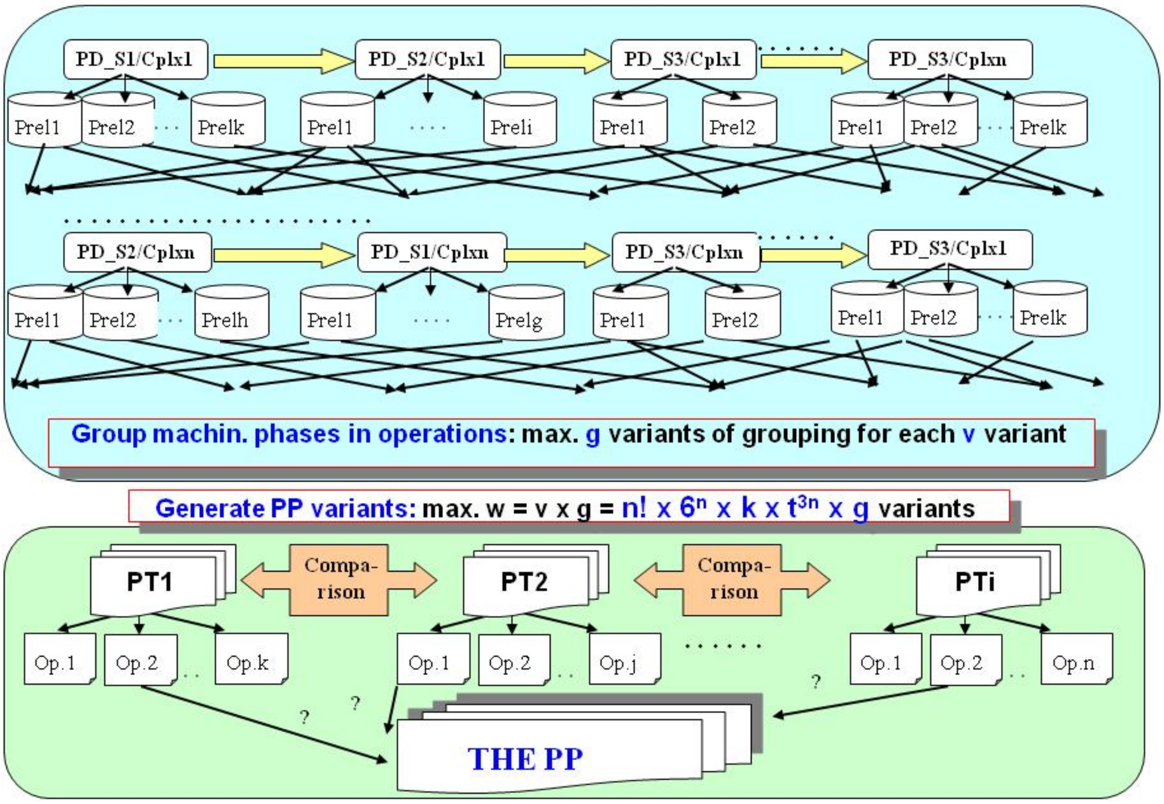

Fig. 7. Obtaining the optimum Process Plan

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