FINDES - Integrating Design and Manufacturing*

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ABSTRACT: FINDES (Feature INtegrated DEsign System) was developed to assist the design and the manufacturing of prismatic parts supporting the integration of CAD/CAPP/CAM Systems through a Feature Based Part Model. The system can be divided in two main modules. The first module assists the design and was developed using the Design by Features methodology and a manufacturing features oriented library. It supports the design with a semantic based on manufacturing features, has functions to validate and to manipulate the instantiated manufacturing features, determines explicit interactions among the features automatically and assists the user by the definition of technological attributes (tolerances, implicit interactions not automatically determined, etc). The second module generates the NC process for a designed part with an attached process plan automatically.
KEY WORDS: Design by Feature, Manufacturing Feature, Feature Validation, Feature Interaction, Integration of CAD/CAPP/CAM Systems

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1. Introduction

The term "Computer Aided Design" has been used since the end of the 1950's when D.T. Ross initialized a project with this name at the MIT [GRA 92]. The first commercial CAD systems came out to the market only ten years later [CHA 81]. During the last 25 years the CAD systems as a shape modeller have been experienced a lot of significant developments like: 3D modelling, parametric design, improvements in the user interface, etc.

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Despite all those improvements basically related to the development of the geometric functionalites [KRA 89], the CAD systems offer a limited support to the designers when the whole design process is taken into consideration. They support the description of the product through shape modelling and routine activities like: dimensioning, generation of the list of parts, etc [GRA 92]. These limitations and purely geometry based design interfaces make the designer's work methodology exactly the same as that used working on the drawing board. The used tools were significantly improved increasing the productivity, but the designers are still working with low level geometrical elements like lines, points, arcs, etc. to describe their product. Some CAD systems on the market are now supporting the design with form features, but considering their solely geometric character they rather should be classified as a macro-geometry element [SCK 90].

Important developments were also realized in the areas of planning (CAPP) and manufacturing (CAM), but similarly to CAD systems these improvements brought solutions for local problems. A CAPP system can generate a process plan automatically, but only when the user provides a re-description based on manufacturing features of the designed part (Fig. 1). The same happens with the CAM system. In this case the system can at least use the same geometrical database resulting from the part design, but an user must provide all the output of the CAPP system.

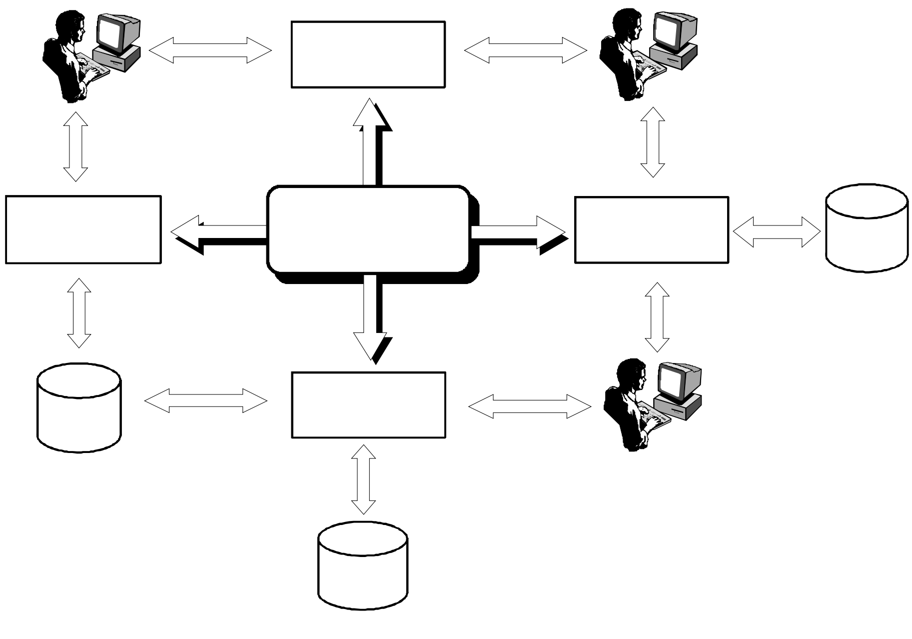

Figure 1. *CAD/CAPP/CAM information' flow*

The Figure 1 represents a clear picture of this situation were the CAD, CAPP and CAM systems represent isolated solutions for local problems, but the communication among them in direction to a global integration is limited and depends on the direct interference of the users. Each of the systems maintain their own model and there is no automatic information exchange among them except the purely geometric information exchange between the CAD and CAM systems. The global solution for this problem is only possible through a manufacturing feature based representation of the part, which can be understood by all the related system.

To obtain such part representation it is possible to use three different methodologies [CAS 93, PRA 91, SHA 91, SRE 92]:

- *feature identification*: the user selects interactively on the screen elements of an already defined geometric model and defines features.
- *feature recognition*: the already conventionally defined geometric model is processed by computer programs to automatically identify features.
- *design by features*: the part model is directly built with features already defined in the system.

Comparing these methodologies [CAS 93, SHA 91, CHM 93, CHN 88, SCL 92] and considering the support to the designers there are some advantages for design by features that have to be mentioned:

- the designers interact with a system that offers a semantic that represents design and manufacturing elements;
- the related geometry is defined at a higher level that avoids the interaction with low level geometry and reduces the possibility of errors;
- it supports designers to transfer to the database much more information that is available during the design process;
- the form feature-based workpiece model contain the geometrical and technological description of the part for the further integration with CAPP and CAM systems;
- standard libraries of features can be used to build parts proven to be manufacturable and cost effective;
- the designer's intents are kept in the part representation.

Considering the advantages of the Design by Feature methodology it was chosen for the implementation of the FINDES - Feature INtegrated DEsign System.

2. FINDES - The Feature INtegrated DEsign System

As mentioned FINDES was developed and implemented for the design of prismatic parts using the Design by Feature methodology. When designing a part or defining technological attributes the designers interact with a semantic based on form features. Considering that FINDES must not only support the design process but also simultaneously verify the manufacturability of the part and provide a part representation that can be used by the CAPP and CAM systems, the use of manufacturing features proved to be more efficient.

An overview of the architeture of FINDES is presented in the Figure 2. During the design process the users interact with a feature based user interface. This interface communicates with the Feature Modeller and the Geometric Modeller respectively. The activities developed by FINDES can be divided in two main modules: the *Design Module* and the *Manufacturing Module*.

The *Design Module* provides all the necessary functions for the feature based modelling, validation and manipulation of features, automatic identification of feature interactions, feature based definition of technological attributes like tolerancing and heat treatment, and also the management functions to maintain the feature based part model and geometrical database. During the execution of these activities FINDES utilizes the Feature Description Library, the Production Means Model, the Feature-based Tolerancing Knowledge and the Feature-based Manufacturing Knowledge. For the geometrical representation of the part and the graphic interface with the user during the design process FINDES interacts with the Geometric Modeller. The CAD/CAM system Euclid-IS which is also used for the manufacturing activities has been chosen for this implementation.

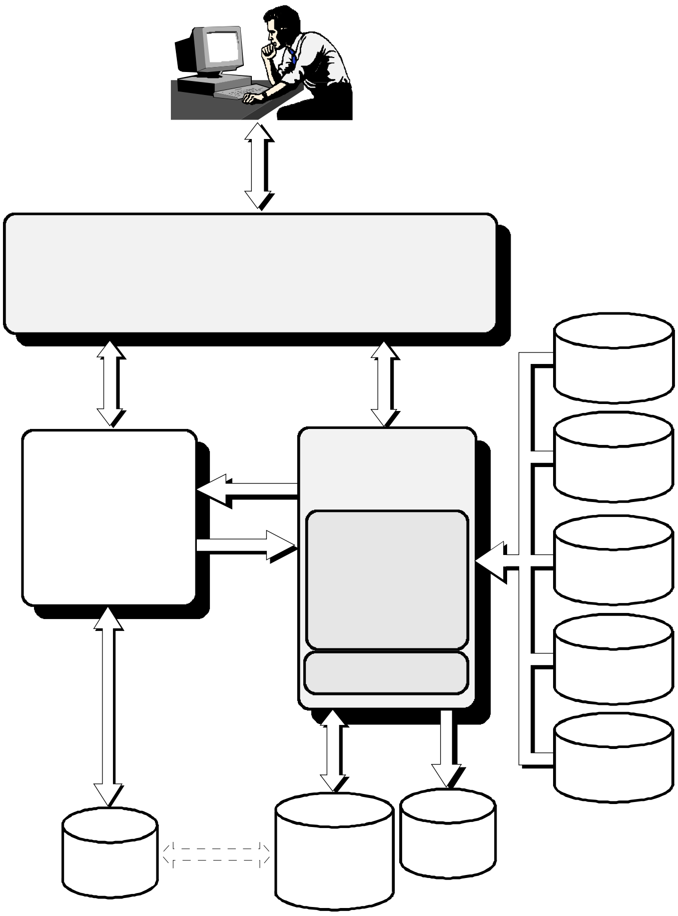

Figure 2. *Architeture overview of FINDES*

The result of the design process is the Feature Based Part Model which is used by the CAPP systems [SCL 93a]. This Model does not contain the geometrical representation of the part because it is not necessary for the process planning activities. It is generated by the Geometric Modeller and FINDES maintains the link and the consistency between both representation.

The *Manufacturing Module* will be used to automatically generate the NC process of a part already designed and processed by a CAPP system [SCL 93a]. In this case FINDES additionally needs the process plan of the part to be processed. The necessary knowledge with respect to the cutting strategies and parameters for each manufacturing feature was defined considering the severity, material, etc, and stored in the already mentioned Feature-based Manufacturing Knowledge.

The Figure 3 presents an overview of the system functions which will be described in the following topics.

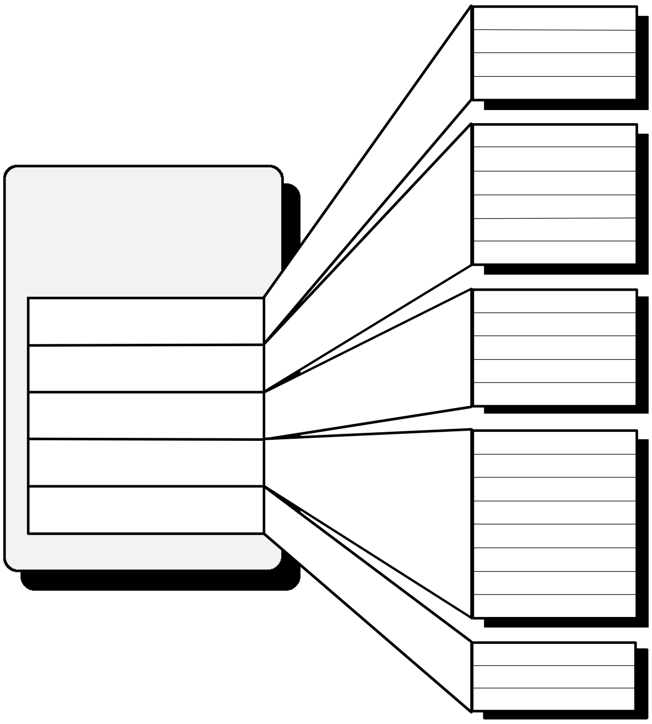

Figure 3. *FINDES's modules and functions*

2.1. *Design Module*

2.1.1. *Management Functions*

FINDES has a set of functions to manage a design session. These functions support the designers by the initialization of a new part, the modification of a existing part and can also support the variant design. By finishing the design activities of a valid part a file with the feature-based description of the part will be automatically generated to be used by the planning activites.

During the initialization of a new part or by the variant design the system aids the designer to specify the material of the part. He can initialize the choice of the material only by defining the material group and then, interacting with the system, to define the material to be used. In the case that the designer has already a defined material for the part, he can directly put it in to the system. In both cases FINDES consults the table with the standard materials of the company.

During the design process any information of the actual part can be retrieved. The avaible functions permits to get a list of the instantiated manufacturing features, the parameters and attributes of a chosen feature, a list of the existing feature interactions or the parameters and attributes of the blank used in the actual part.

2.1.2. *Manufacturing Feature Based Design*

The design functions are related to the definition of the blank that will be used in the part modelling and the instantiation of the manufacturing features. For the definition of the blank the current implementation FINDES covers two possibilities. The first possibility is using the the option *prismatic stock*, so the system generates a prismatic stock as the blank to be used to produce the part. In the second possibility, *retrieve blank*, the system supports the use of a non-cubic blank which was already designed by a CAD system. In this case it is possible to use a blank resulting from a casting or forging process for the further design of the part.

For the instantiation of the manufacturing features FINDES utilizes a Feature Description Library where the available features are encoded. The feature description comprises (see Fig. 4) the geometrical parameters necessary to produce the feature and the definition of material-surfaces and closure-surfaces. The material-surface represents a real surface that will be present in the final part, in opposite to the closure-surface that represents an imaginary surface whose perpendicular vector represents a possible tool approach direction.

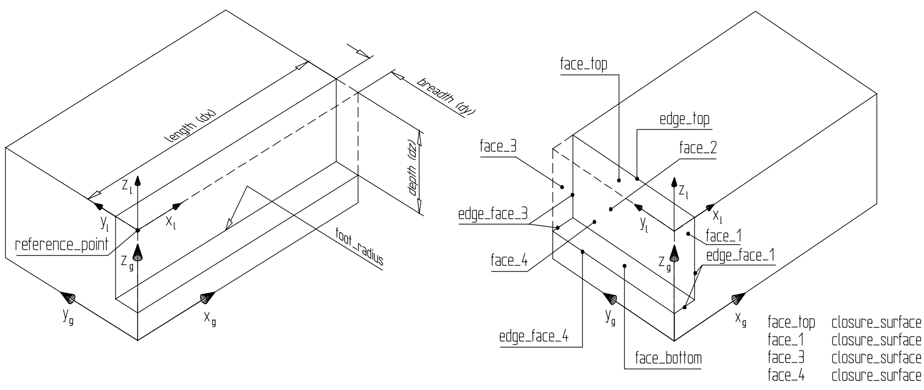

Figure 4. *Step with geometrial parameters and surfaces and edges description*

The system offers for the part's design the following types of features:

- *volume feature*: these are single volumetric features that can be protrusions like a circular boss, or depressions like pockets, holes, threads, etc;
- *pattern feature*: this type of feature results from a set of single volumetric features of the same type distributed in one face of the part. The possible distributions are:

circular, matrix or irregular. It is to note that all the single features in a pattern feature have the same parameters and attributes;

- *surface feature*: these are features whose utilisation in the part will result in a surface. Considering that FINDES is manufacturing feature oriented, these features also represent a removal volume, but they were separately classified considering, similar to the other types, the result of their application;
- *edge feature*: are features like roundness or chamfer that will be applied to an edge of a feature of the first three types or to an edge of the blank. For this type of feature FINDES does not produce an explicit graphical representation. They will be kept and managed in the Feature Based Part Model as an attribute to the related feature or blank.

Considering that the system can automatically identify feature relations it was irrelevant to offer compound features. The system, for example, can identify the relation between two holes as the case of a stepped-hole and stores this constraint in the Part Model, thus providing the necessary information for the process planner. Another reason for not implementing the compound feature is, that such an implementation would cause an artificial growing of the feature library, making the user interface worse. A system that can automatically identify such kind of relation is more efficient.

During the instantiation of a chosen manufacturing feature FINDES initializes the first validity control [SCL 93b], where it is verified if the feature is geometrically valid and the first manufacturability criterion is applied. The geometric validation means that all parameters are positive reals and the generated feature section is valid, for example, in the case of a closed rectangular pocket the corner radius must be smaller to the half of the length and to the half of the width.

The first manufacturability criterion is the verification if a tool exists in the Production Means Model to manufacture this feature. In the case of the mentioned rectangular pocket it will be verified if there is an endmill whose diameter is equal or smaller of the double of the pocket's corner radius.

If one of this critera fails the manufacturing feature will not be instantiated. The instantiated feature is not automatically an element of the part under construction. Only after its complete validation, a Boolean operation can be automatically applied.

2.1.3. *Manipulation Functions*

The manufacturing features are instantiated in relation to one of the attachment surfaces of the blank. In the case of a simple prismatic stock there are six main attachment surfaces availables which can be used to position the manufacturing features. A non cubic blank, for example a casting part, can have more than the six attachement surfaces which will be defined as auxiliary attachment surfaces. The information about the attachment surfaces are fundamental during the process planning for the definition of the setups [SCL 93a]. The function *part positionning* supports the designer to choose the appropriated attachement surface of the blank where the feature will be constructed.

As mentioned above, only after the complete validation of a manufacturing feature, it can become an element of the part. When the designer chooses a manufacturing feature to attach it to the workpiece under construction FINDES automatically applies the validity constraints [SCL 93b] and if all of them are correct the appropriate Boolean operation is applied, if not, the user has the opportunity to modify that feature. The validity constraints are the following:

- *feature surfaces validation*: as above mentioned, the manufacturing feature description comprises surfaces' definition. This criterion is considered true if the surfaces of an instantiated feature comply with the defined material and closure surfaces of the respective feature description.
- *manufacturability validation*: this is the second manufacturability verification. FINDES verifies if an instantiated manufacturing feature can be manufactured with at least one of the available tools. For this task the tool path is generated using the cutting strategie defined in the Feature Manufacturing Knowledge. The system verifies if there is any collision with the part shape. At this stage of the design process this validation criterion considers only the part shape and the tool, a complete verification considering tool-holder and fixture can be realized during or after the process planning when these information are made available.
- *feature interaction validation*: contrary to the above mentioned criteria it is not concerning the validation of a manufacturing feature itself, but it verifies the explicit relation among the chosen features and those that are already elements of the part. It is represented by the parent-child relation between the closure-surface of the chosen feature and the material-surface of a feature that belongs to the part or the blank itself. FINDES can automatically determine and maintain this constraint which is fundamental for the operation sequencing during the process planning task.

For the execution of these tasks FINDES maintains parallel to the volumetric representation of each manufacturing feature a surface representation with an attribute defining which are the material surfaces and the closure surfaces. Such information are necessary for the surface validation and the determination of the feature interaction. For example, the parent-child relationship can only be realised between a material surface (parent) and a closure surface (child), as showed in Figure 5 and 6.

A manufacturing feature which belongs to the part can be at any moment modified or deleted. In both cases FINDES identifies the related features for the necessary re-validation.

2.1.4. *Technological Attributes Definition*

The technological attributes supported by FINDES are: tolerance, heat treatment and implicit interactions. They can be applied only to the complete part or to a manufacturing feature that belongs to the part, therefore, the instantiated features that are not validated will be ignored during this task.

For the definition of attributes that are valid for the whole part the user selects the function global attributes, which supports the determination of global tolerances for dimensions, form, position and surface quality. The related standards are considered by the system to execute this task. Those defined attributes are, therefore valid for all manufacturing features allowing this type of attribute unless the attribute is locally assigned.

The function *dimensional tolerance* assists the definition of a tolerance:

- to a dimension of a manufacturing feature;
- to the dimension between two features;
- to the distance between a feature and one of the surfaces of the blank.

In the first case FINDES verifies which of the dimensions of the chosen feature can get a dimensional tolerance and asks the user to select one of them. This verification is done to avoid that a non-valid tolerance is defined like the tolerance to the depth of a through hole. In the last two cases the designer is requested to choose a feature surface of two manufacturing features or one blank surface and one feature surface. Before the system determines the dimension between both and asks the tolerance value, it is verified if they are valid to get a tolerance. In positive case the first element is considered the reference and the second the toleranced element.

For the definition of form and position tolerance the designer can either select one of the functions *form tolerance* or *position tolerance*. In both situations, after the choice of a manufacturing feature, FINDES consults the Feature Tolerancing Knowledge to determine the applied tolerances to the chosen feature. The system also gets all the necessary information defined in the tolerance standards to assist the user in this task.

The Feature Tolerancing Knowledge consists of the tolerance standards organized with respect to the manufacturing features in the Feature Description Library. It describes for each feature the valid tolerances, the valid feature elements, the valid feature reference and feature element reference in the case of positional tolerance, tolerance zone orientation, maximum material condition, etc. During the tolerancing tasks the system consults this knowledge base to assist the user and to control the choices done by him. The main advantage of this knowledge base is the ability to assure the correct tolerancing of a part. This knowledge can be modified considering the internal standards of a company.

The function *surface quality* supports the definition of roughness for the material-surfaces of a manufacturing feature. In this case the knowledge used in the system also includes the rugosity standards and the respective rugosity values.

The existing feature interactions can be classified in explicit und implicit interactions. The first type considers the relationships between manufacturing features that touch themselves, therefore building an explicit interaction. This is the case of the above mentioned parent-child relationship, or when two perpendicular slots intersect resulting in a manufacturing volume interaction. FINDES can automatically identify, classify and manage the explicit interactions.

The second type, implicit interaction, considers relationships between features that do not touch each other. But this still results in interactions that must be considered for design or planning reasons. This is the case of two slots positioned very near to each other producing a thin wall, or when to manufacture a feature the tool path must pass through another manufacturing feature which does not have any explicit relation to the first. FINDES can not automatically identify all the implicit interaction. Interactions like the second example will be indirectly identified through the interaction of the tool path, whereas such cases like the first one can not be automatically identified by the present version. For such cases the function *implicit interaction* assists the user to interactively identify the interaction, the further management is done by the system.

2.1.5. *Feature Based Part Model*

The Feature Based Part Model is the core module in FINDES and also the one for the integration with CAPP/CAM systems [BUT 85]. As already mentioned it does not comprise any geometrical representation of the part or the manufacturing features, however it contains all the geometrical parameters used to describe the features and the prismatic stock, it means that it is possible to rebuild geometrical representation if necessary.

It can be divided into two blocks, the first comprising the information applied to the whole part like: part code, part name, geometrical parameters or external dimensions of the blank depending on it is a prismatic stock or not, material description, global tolerances and heat treatment, etc. The second block contains the manufacturing feature oriented description of the part. Initially, it decribes the feature interactions whose relationships are not directly related to the surfaces of the involved features, this is the case for all implicit interactions and the manufacturing volume interaction. For the case where the interaction occurs through the contact of feature surfaces, this information is appended to the related manufacturing features and the respective surfaces.

The manufacturing feature description of the part model contains the following information:

- *feature identification*: the feature classification, the feature code and feature name resulting from the feature instantiation. This code is also used for the management of the geometrical representation;
- *feature parameters*: it comprises all the parameters necessary for the geometrical (see Fig. 4) and technological description of the feature. A parameter necessary for the technological description is for example the foot radius of a pocket. There is no geometrical representation necessary, however it will be one of the constraints to choose the tool;
- *surface and edge information*: it represents the decomposition of the manufacturing feature in its surfaces and edges as presented in the Feature Description Library. The attribute values of a feature surface are of surface type (material or closure) or an explicit interaction. For example, to the edge of a manufacturing feature an edge feature as mentioned above can be allocated;
- *technological attributes*: it comprises the descripition of all the technological attributes defined to the manufacturing feature like: dimensional tolerance, form tolerance, etc.

2.2. *Manufacturing - NC Process Generation*

The manufacturing functions are related to the second module of FINDES. They support the input of a process plan of an already designed part. This plan will be interpreted and the NC process can be automatically generated.

The first function, *tool limit*, will always be called when the design of a part is successfully finished. This function will determine for the process planner the maximum tool dimensions for each of the manufacturing features. For the reasons already explained by the manufacturability verification, FINDES considers only the tool dimensions. It will produce a file relating the indicated tool types and the maximum dimensions to each manufacturing feature. Executing this function the system consults the Production Means Model to obtain the list of available tools. During the process planning the planner has also the possibility to question FINDES to verify possible colisions of a chosen tool. In this case the planner can also inform the chosen tool holder which will be considered during the verification.

Afterwards a process plan can be read and interpreted. During this task the defined setups will be identified and the structure of the NC process automatically determined. In the present version of FINDES an interface for using the process plan produced by the planner tool FINPLAN [SCL 93a] has already been implemented. FINDES can automatically generate the NC process of the part using the function. The NC code will be generated for each setup at a NC machine defined in the process plan. For the execution of this task the system consults the Feature Manufacturing Knowledge to obtain the necessary information how to manufacture each feature. The manufacturing information like: approach and retract feedrates, cutting strategy, cutting type, cut overlap and lateral overlap factors, etc. are available in the knowledge base and related to the manufacturing feature, manufacturing severity and allowance. The obtained NC process can still be modified interactively by the user.

3. Industrial Validation and Example

At the present stage FINDES is intensively tested using real parts provided by Mares S.A. - Construcciones Mecanicas, Barcelona, specialist in molding tools and partner of our Institute in an European Project.

Using CAD System (Euclid - Matra Datavision) and FINDES the same parts are designed using both systems and comparing the time to generate the model of the part. The production of a final drawing of the parts is not included because the concept of FINDES considers this task as unnecessary since the integration of CAD/CAPP/CAM is implemented. The time to define the technological attributes (tolerances, heat-treatment, etc.) using FINDES is considered.

A final report with the detailed results will be soon published, but it is already possible to observe the significant advantage for FINDES for the design of parts like that presented in Figure 5 or with even a bigger number of features. For complex parts with more that 70 manufacturing features, the time necessary for the feature validation increases resulting in a design time longer compared to the CAD System, but it is necessary to consider that despite of this time increase the user gets a part model ready to input in the CAPP avoiding all other necessary input or re-definition of the part as it is the case of using a conventional CAD System.

The time necessary for the feature validation will be reduced with the implementation of more optimized algorithms in the next version.

Some tests with the manufacturing modul of FINDES and the process planner FINPLAN were already done. Example parts were designed with the first system, followed by the automatic process planning task and finally the generation of the NC-programm, which was sent to a 3 axis milling machine for the manufacture. A second study using real parts is planned to compare the manufacturing modul of FINDES for the automatic generation of the NC-programm and a CAM System.

A part designed by using FINDES can be seen in the Figure 5. It shows a part belonging to a molding tool of the company Mares. The design starts from a sheet metal stock with 1750X780X90 mm. All the instantiated manufacturing features have been proven to be manufacturable using the available resources in the Production Means. In the exploded view of the part (Fig. 5) some of the manufacturing features used can be observed, for example: hole-patterns, therad-patterns, slabs, steps, etc.

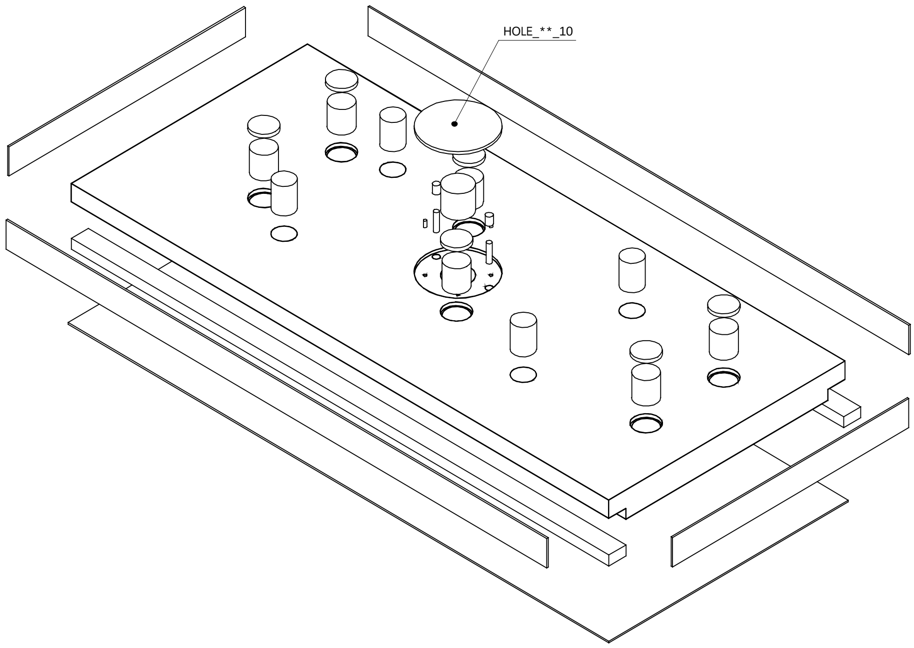

Figure 5. *Part of a molding tool designed by FINDES (Mares S.A. - Construcciones Mecanicas)*

The existing feature interactions were automatically identified by FINDES and Figure 6 shows the ASCII output of one of the used manufacturing features, the hole coded HOLE_**_10 which is positioned at the bottom face to the SLAB_**_11, which is no present in the Fig. 5 for visualization reasons. The mentioned feature interaction and the necessary technological attributes for the HOLE_**_10 (dimensional tolerance and surface quality) can be observed in the Figure 6.

4. Conclusions

FINDES was implemented using the design by feature methodology, its form features library being based on manufacturing features. This combination and all the additional design and manufacturing support provided by the system has been proved to be a tool that shows the possibilitity to improve the design methodology and a decisive step in the direction of the integration of CAD, CAPP and CAM systems.

FEATURE_IDENTIFICATION	
name_of_feature	HOLE
code_of_feature	HOLE_**_10
FEATURE_GEOMETRY	
type_of_feature	BLIND
reference_point_glob	870.000 385.000 5.000 GLOBAL
reference_point_face	870.000 385.000 -5.000 OZ-
diameter_hole	200.000
depth_hole	8.000
foot_radius	1.000
SURFACE_AND_EDGE_INFORMATION	
face_top	SLAB_**_11
face_botton	MATERIAL_SURFACE
face_cylinder	MATERIAL_SURFACE
edge_top	
QUALITY_SPECIFICATION	
quality_type	INTERNAL_DIMENSIONAL_TOLERANCE
reference_dimension	diameter_hole
nominal_dimension	200.000
upper_value	0.046
lower_value	0.000
QUALITY_SPECIFICATION	
quality_type	SURFACE_TOLERANCE
type_of_surface_tolerance	Ra
list_of_surfaces	face_cylinder
tolerance_value	6.300

Figure 6. *ASCII output of a manufactruing feature HOLE with geometrical parameters and technological attributes.*

The designer does not need to deal with low level geometry anymore. FINDES supports the design with a new semantic based on the elements used to produce a real part which are related to a high level geometry. The design modifications will also be realized through those elements resulting in the reduction of the design time. The definition of technological attributes will also be assisted by the system and the resulted part model based on a manufacturing feature description can be transferred to a CAPP system without any additional treatment.

The manufacturing module of FINDES proved to be able to retrieve a designed part and its process plan and automatically generates the NC process.

The tests that have been done with FINDES designing the same part using the system and using the standard tools of a CAD system resulted in a significant time reduction. Additionally, FINDES has the advantage that a part model with the geometrical and technological description is generated eliminating completely the necessity of feature recognition or further input of the technological attributes to the processs planner. Considering the whole integration - design/planning/

manufacturing - the time reduction provided by the system is still more significant. That encourages further developments of FINDES.

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- -precision cutting
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- -CIM components
- -Total Quality Management
- -consequences of CA-techniques on the organization

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1979 - 1981	Indústrias Romi S/A, Santa Bárbara D'Oeste, Brazil - Product Engineer
1979 - 1981	Methodist University of Piracicaba - Assistant Professor for Machine Elements (part time)
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Keypoints of reserach:
- -Computer Aided Design
- -Application of form features in design and manufacturing
- -Integration of CAx Systems