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An Integrated Intelligent CAD/CAPP Platform: Part I-Product Design Based on Elementary Machining Features

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Abstract: We present a platform for integrated CAD/CAPP part design based on Elementary Machining Features (EMF) and intelligent approach for setup planning and operation sequencing based on a genetic algorithm through two papers. In this paper, as Part I of this platform, CAD design is executed by destructive method using objects in the form of EMF. We developed this platform based on EMF in the form of extension of the SolidWorks program system, based on Application Programming Interface (API). Also, completely new informational structure of the EMF`s, database and management of the database of the EMF`s were developed. During design phase, child EMF (generated via parent EMF from database) was enriched with a wide range of technological information. Production rules, based on the existing (geometrical) and additional (technological) information generated from the EMF, were developed and further used to generate a list of elementary machining operations (EMO) for each EMF. All previously mentioned pieces of information were necessary in the later phase of the proposed platform which was described in Part II of this paper. In this paper we present a case study applied to one new industrial example-body of the hydraulic cylinder, confirming a high level of usability of this part of integrated intelligent platform.

Keywords: computer aided process planning, elementary machining features, production rules

1 INTRODUCTION

The modern business environment and the global market today are based on digital technologies. The implementation of digital technologies during the realization of all product life-cycle activities, starting from product development and design, through process planning design, production, assembly and sale of products, can provide the competitiveness of manufacturing enterprises. It can be said that the digitization of all product life-cycle activities within a manufacturing enterprise belongs to the concept of overall CIM (CIM-Computer Integrated Manufacturing).

It is known that the main bottleneck in the implementation of CIM concept is an activity of computer aided process planning design (CAPP-ComputerAided Process Planning). For the last few decades, scientific and practical achievements in the field of CAPP are not still giving right directions for practical implementation of these achievements and complete removal of CIM concept bottlenecks. Accordingly, further scientific and practical research in this field is the imperative.

This paper presents a model for integrated CAD/CAPP part design based on EMF (EMF- Elementary Machining Features). The main characteristic of this model is establishing a link between design phase and process planning phase. CAD/CAPP integration is based on the using of the information related to enriched Elementary Machining Features in the part design phase, as well as production rules and genetic algorithms during determining operation sequencing, as one of the key activities of overall CAPP systems. The EMFs were used as design objects during the implementation of a destructive method in the part design phase. Production rules, based on the existing and additional information generated from the EMF and design phase, are used to generate a list of elementary machining operations for each EMF. In this manner, the list of elementary machining operations represents the input into the process of determining the operation sequencing for the whole part. Detailed description of the elementary machining features is shown in the section 3 of this paper. The process of integrated CAD/CAPP design is described in section 4. Verification of the proposed model for integrated CAD/CAPP design of a part based on the EMF is carried out using a body of the hydraulic cylinder for a hydraulic press brake (section 5). At the end conclusions are given in section 6.

2 LITERATURE REVIEW

For many years, CAD/CAPP integration represents a researchers focus all over the world. Techniques and methods for CAD/CAPP integration include: feature-based techniques, STEP standard, objected-oriented programming languages, artificial intelligence, agent-based technology and a combination of the aforementioned techniques (hybrid technologies). Therefore, an overview of the previous research in these areas is given below.

A large number of standalone Feature Based Design Systems (FBDS), integrated into existing CAD systems or integrated with a system for process planning design, is developed for the purpose of CAD CAPP integration [1]. Based on the available literature, some of these systems are described below. An EFMS (EFMS - Expert Feature Modelling Shell) represents a modelling shell based on manufacturing features [2]. The EMFS system was intended for the design, documentation and evaluation of parts. The EMFS consists of three models; each of models supports one type of manufacturing features, namely: form features, precise features and material features. A QTC (QTC - Quick Turnaround Cell) an integrated CAD/CAM system in which a feature-based design model was used to perform process planning activities [3]. The QTC uses a destructive method for part design based on the volume of manufacturing features with B-rep solid modeler. A B-rep solid modeler can generate an annotated boundary model. Feature recognition was applied to this model in order to generate a model which contains manufacturing features. Wang et al. has developed a framework for a system for distributed process planning based on manufacturing features [4]. This system uses IGES data format for part model description. A part model was based on standard manufacturing features. An FDG (FDG - Feature

Dependency Graph) was developed by Lin and Sheu [5]. The dependency graph of form features represents a relationship between form features in the part model. Operators for positioning of the features within the graph act as bridge between dependent features in FDG. Each form feature consists of a B-rep model to represent its volume. EXPO represents an object-oriented system for part design based on the primitive features that supports simultaneous product design and process planning [6]. A set of primitive features was installed in the EXPO library based on AutoCAD12 Advanced Modelling Extension. The final shape of a part was obtained by subtracting standard machining features from the blank. In [7], the authors developed a system which feature-based models generate from the solid model of the part by using feature recognition approach. The system generates multiple machining features. This requires an evaluation of the machining features in order to design feasible process planning. A system for modelling of products, namely ZD MCADII [8] was a parametric oriented modelling system based on features and it was integrated with the CAPP/CAM system. In order to facilitate the process of product design, ZD-MCADII provides product modelling using standard machining features and user-defined machining features. FEB-DAPP was a system for the design of products and process planning activities based on features, developed by [9]. It was a hybrid system incorporating design by feature and feature recognition approaches. By including the benefits of both approaches, the system provides the designer with more flexibility in the process of part modelling and process planning activities. In [10], the authors introduce a database and knowledge base presentation schemes based on the machining features which were used for modelling of distributed databases and knowledge bases. The process of reasoning was carried out by the production rules contained in the knowledge base. The content of the machining features was associated with a number of production rules. Zimmermann et al. [11] introduced ULEO - Universal Linking of Engineering Objects in the field of product development based on machining features. The aim of the ULEO approach was to provide high-quality data flow of information between applications, as well as generating a product model based on machining features. Patil and Pande [12] developed a system for intelligent process planning design based on machining features (IFPP-Feature based Intelligent Process Planning). The IFPP system performs the synthesis of part model and process planning design for prismatic parts which were machined at CNC machining centres. Rosado and Gonzalez [13] have developed a prototype CAPP system (GF-CAPP - General Flexible Computer Aided Process Planning), whose purpose was to achieve the concept of generalization and standardization in the CAPP system at the level of processes and machines. The methodology used in GF-CAPP system was based on the observation of machining features as atoms of the part, for which it was necessary to design a process plan. The aim of the GF-CAPP system was to make the selection and assignment of processes, operations and machines to every single machining feature. Y. S. Kim et al. [14] proposed a methodology for process planning design for turning and milling operations. Design features were converted to machining volumes suitable for turning and milling operations. Machining volumes were then associated with the respective classes of the machining processes. Based on this classification, machining operation sequencing was determined.

3 ELEMENTARY MACHINING FEATURES

Research activities in the field of features date back to the 1970s, and since then in the literature a wide range of approaches and applications of these technologies can be found. The concept of features is not a new idea, as the earliest research in this area dates back to 1976, when Grayer [15] first mentioned features in his PhD thesis. In the context of the features, it is necessary to clearly distinguish between design and machining features. Modelling of parts from the perspective of the designer is reflected primarily in meeting the constructional demands of the desired part, whereas modelling from the perspective of a process planner is reflected primarily in manufacturability of the desired part [16].

The result of the development of information technology has led to the emergence of two techniques for part modelling based on machining features. The partition was based on whether the machining features were extracted from existing geometry (FfG - Feature from Geometry) or the geometry is formed based on machining features (GfF - Geometry from Features) [17]. In this paper we applied the technique of geometry forming based on machining features (GfF).

3.1 The Concept of Elementary Machining Features

In this paper we introduce machining features as generic Elementary Machining Features (EMF). Generic EMF represent a solid model with unique geometry that makes a functional unit in the sense of the process planning design.

Within the framework of this paper, the EMF can be defined as an elementary generic form with which process planners associate certain attributes and knowledge that can be used in the process of part design and process planning design (Fig. 1).

Thus defined the concept of the EMF, during its machining, anticipates action of one or more cutting tools according to a previously defined operation sequence.

Each solid model of the EMF consists of geometric, manufacturing and general information which was used in the stage of determining the elementary machining operations which will be discussed later. The concept of the part design by pre-defined features, including developed elementary machining features, was based on the principle of subtraction of features volume in relation to the blank (raw material) volume.

The procedure of volume subtraction was implemented by applying the Boolean operation of subtraction. Compound elementary machining features which cannot be found in the library of the generic EMF can be generated using a combination of one or more existing EMF (Fig. 2).

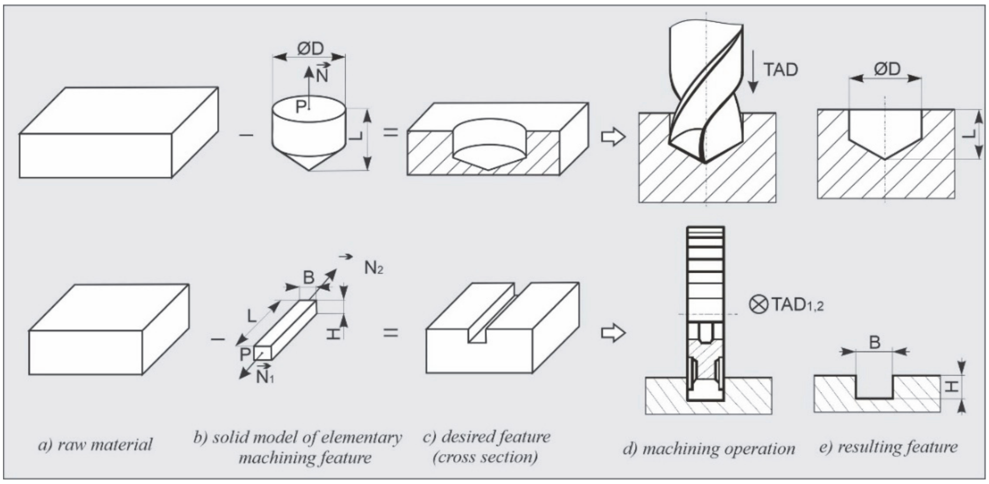

Figure 1 Concept of the elementary machining features (EMF)

This principle of detailed part design, with limited purpose and the number of elementary machining features, allows for the possibility to design complex part models. The complex part model, in this case, contains complex geometrical and manufacturing requirements, expressed through elementary machining features.

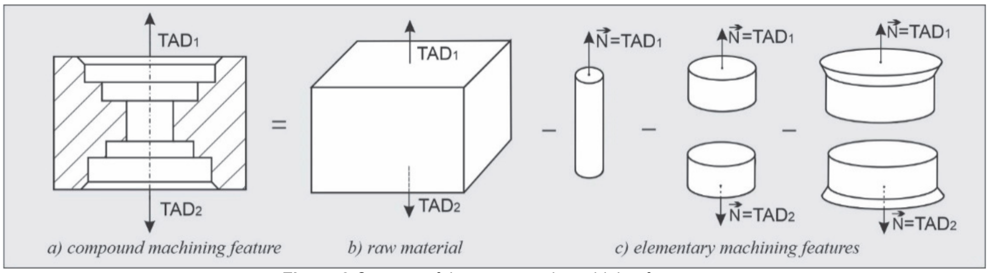

Figure 2 Concept of the compound machining features

3.2 Data Structure of Elementary Machining Features

During developing of the structure of the elementary machining features, the possibility of machining from the standpoint of manufacturability was analysed. As previously mentioned, elementary machining features which were located in a developed EMF database were associated with the action of one or more cutting tools according to a defined operation sequence. The defined operation sequence, whose realization enables to create the observed EMF, we called the list of elementary machining operations EMO. The list of elementary machining operations consists of one or more elementary machining operations.

The elementary machining operation was executed with one tool, one machine setup and one or more tool passes. The idea of the concept for part design using EMF, which was developed in this paper, was based on the possibility that the developed EMFs were intelligent carriers of manufacturing information.

The realization of this concept was done by introducing and defining the two groups of attributes within the structure of elementary machining features (Fig. 3). The first group of attributes refers to an existing geometric parameter of the EMF. Geometric parameters were related to the geometric shape of the EMF. Geometric parameters were already contained within the standard structure of the EMF. By gaining access to geometrical parameters, the process planner changes and adjusts the geometry of the EMF according to the design requirements. The geometric parameters include dimensions and parameters of the relationship, which was located within the sketch of the solid model of the EMF. The second group of attributes in the structure of EMF refers to the new parameters. New parameters of the EMF were defined through standard attributes of EMF and can be divided into two groups of attributes:

- Manufacturing parameters and
- General parameters.

Manufacturing parameters were parameters which directly refer to the machining process, as surface roughness, geometric tolerances of form of the faces from the EMF solid model and similar. These attributes were associated with geometric elements of faces of the EMF. General parameters were usually related to the purpose of EMF in the context of parts, special kinds of machining and notes.

The process planner can define type and content of general parameters of the EMF according to design requirements. The structure of EMF knowledge representation which was used to define the list of elementary machining operations was defined through the production rules.

A production rule was a condition-action pair of information used to define a single chunk of problem solving. The condition part of the rule was used to determine when the rule may be applied, while the action part defines the associated problem-solving step.

In our approach, production rules consist of a set of predefined geometric, manufacturing and general attributes as the condition part of the rule, as well as of lists of elementary machining operations as the action part of the rule. Knowledge in the form of production rules serves for the purpose of analysis of the defined geometrical, manufacturing and general parameters of the EMF. The results of the analysis of the defined parameters via production rules present an appropriate list of elementary machining operations for the observed EMF.

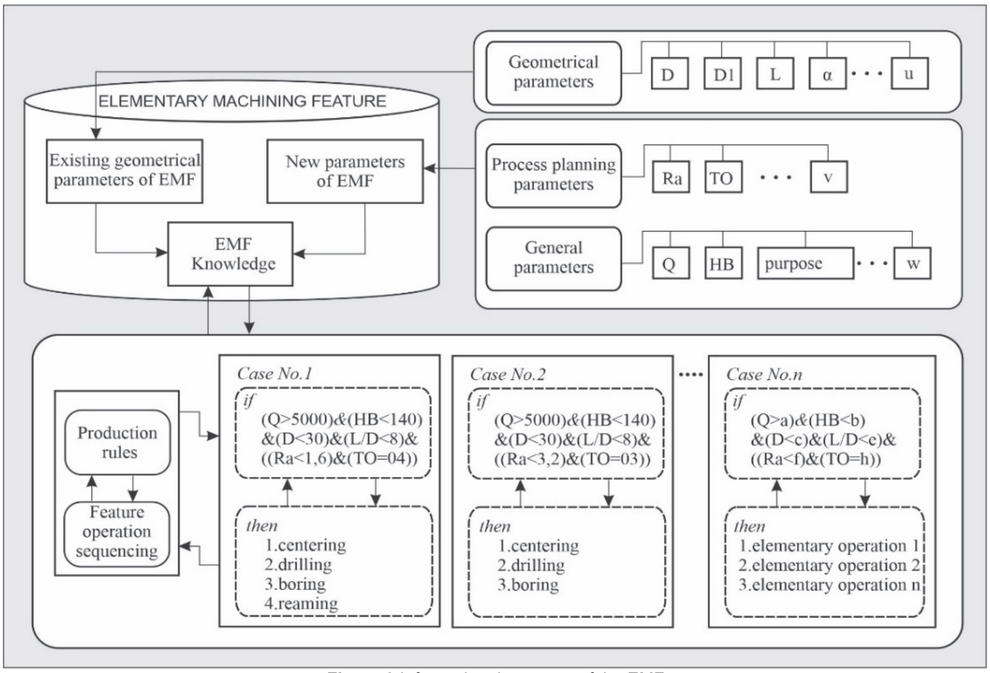

Figure 3 Informational structure of the EMF

3.3 Classification of Elementary Machining Features

In this paper the generic EMFs were classified according to the manufacturability characteristics in the two groups (Fig. 4):

- EMF`s for drilling and related operations,
- EMF`s for milling and related operations.

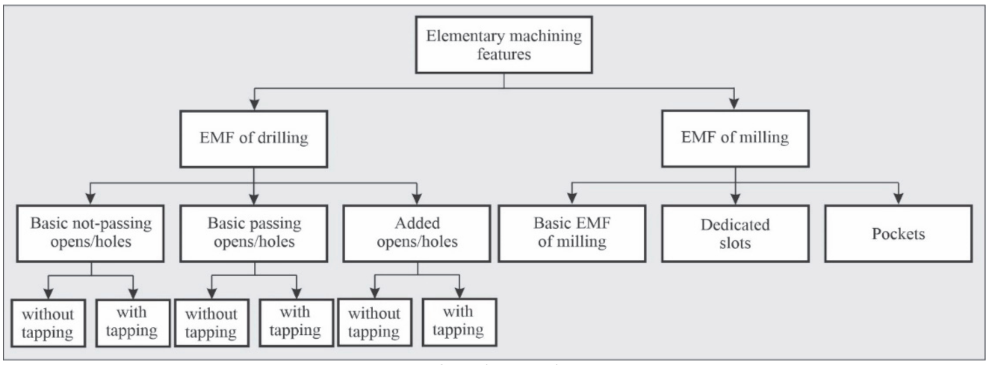

Figure 4 Classification of the EMF

EMFs for drilling and related operations refer to the features whose geometry directly corresponds to the outside geometry of cutting tools (drill, reamer, counter sink, etc). During defining the concept of EMF of drilling, the authors did not set restrictions concerning the type of machines (drilling and milling machines) or other tools needed for machining the observed EMF. Elementary machining features for drilling operations were related to basic non-passing and passing openings/holes, with or without tap, with or without additional structural elements in the form of countersink, chamfering or rounding. Added openings/holes, with or without tap, define the features that represent an expansion of existing openings, with or without additional structural elements in the form of countersink, chamfering or rounding.

An elementary machining feature for milling operations refers to the features whose geometry corresponds as a result of multi-axial movement of the tool/part. When defining the concept of EMF of milling, the authors did not set restrictions concerning the type of machines (types of milling machines, machine centres, planer machines) or tools needed for machining the observed EMF. Elementary machining features for milling operations were divided as follows: basic milling EMF (face milling, step milling, plane milling), slot EMF (T-slot, V-slot, round slot, rectangular slot, etc.) and pockets EMF (open/closed pockets, rectangular pocket, round pockets, as well as pockets for the wedge, etc.).

4 PART DESIGN BASED ON ELEMENTARY MACHINING FEATURES

The structure of the developed platform for integrated intelligent CAD/CAPP design based on EMF and GA is shown in Fig. 5. The developed platform is integrated in the environment of the SolidWorks program system.

The integration of the developed platform was conducted through developing dedicated program functions and using existing program tools based on API (Application Programming Interface).

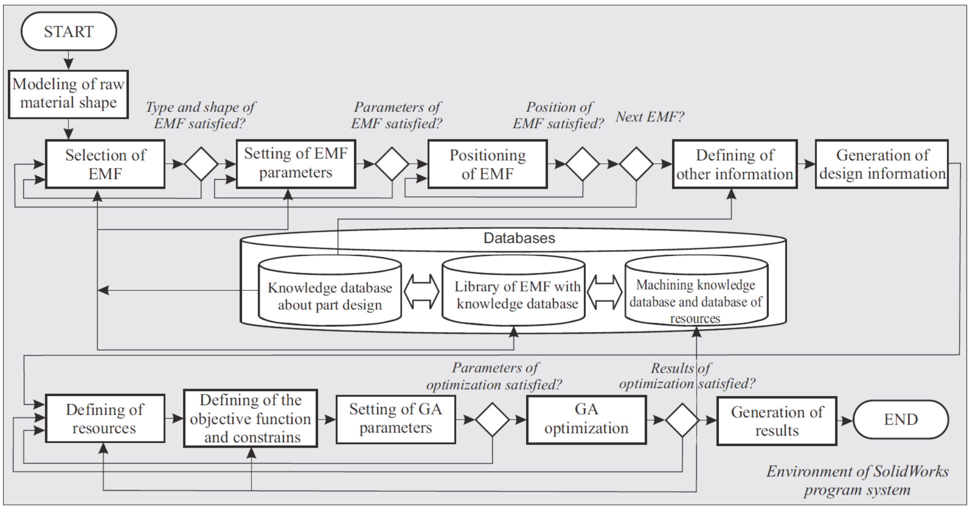

Figure 5 Structure of the integrated intelligent CAD/CAPP platform based on EMF and GE

The initial activity within the structure of the developed platform is solid modelling of blank/raw material of the part, from the standpoint of the process planner. Then, the process planner/system user selects single EMFs, one by one, from EMF library, based on the requirements of the part geometry. The process planner also has available knowledge in the form of guidelines for the design for manufacturability (DfM), located in the knowledge base of the developed platform. The process planner, in the next step, performs setting of the geometric, manufacturing and general parameters of each EMF. After parameter setting, the next step is positioning and subtracting of the EMF solid model from the solid model of raw material. Positioning of the EMF solid model was done using the program tool for the space limitations of solids (Mates), while the subtraction of the EMF solid model from the solid model of raw material was done by the Combine program tool. Standard program tools Mates and Combine were automated into a developed platform through API functions. The procedure of including a new EMF solid model was repeated according to the above-described procedure. It is important to emphasize that it is possible to make corrections at all stages of the design for previously defined parameters. After generating valid geometry of the part, the process planner defines additional information. Additional information refers to the definition of the geometric tolerance of orientation and location, namely: perpendicularity, position, concentricity, etc. All pre-defined information about all EMFs and their positions, orientations relative to the coordinate system of the solid model of the raw material, as well as additional information, were registered in the internal database of the developed platform. The numerical record of EMFs for the observed part was generated from the above-mentioned database, as one of the results of the design process. The numerical record of EMFs for the observed part has the structure of information shown in Fig. 6 and comprises:

- the list of used EMFs (name and code),
- geometrical parameters for each EMF (labels and parameter values),
- manufacturing parameters for each EMF (surface quality, tolerances, etc.),
- general parameters for each EMF (purpose, special types of machining, notes, etc.),
- list of Elementary Machining Operations (code and list of operations for each EMF),
- part material (defined by the material hardness expressed in Brinell scale HB),
- the quantity of parts (Q).

Finally, the results of the part design based on the EMF include the solid model of desired part and the numerical record of EMF. The next activity within the structure of the developed platform of integrated intelligent CAD/CAPP design is to define the resources required for the machining of previously generated Elementary Machining Operations. Required resources were defined in the form of a list of available machines and tools. All of this information was intended as input information for determining the potentially optimal operation sequence, which was described in detail in the second part of this paper.

4.1 The Mechanism for Managing the EMF

The developed platform for integrated intelligent CAD/CAPP design based on EMF was associated with the EMF library and manufacturing knowledge base. The EMF library contains predefined or generic (parent) EMFs. During the part design, generic EMFs can be used numerous times with the same or different parameters.

Manufacturing knowledge base consists of production rules. Production rules were integrated within the EMF data structure and their purpose was to define the list of Elementary Machining Operations (EMO). Accordingly, the manufacturing knowledge base can be observed as part of an EMF library.

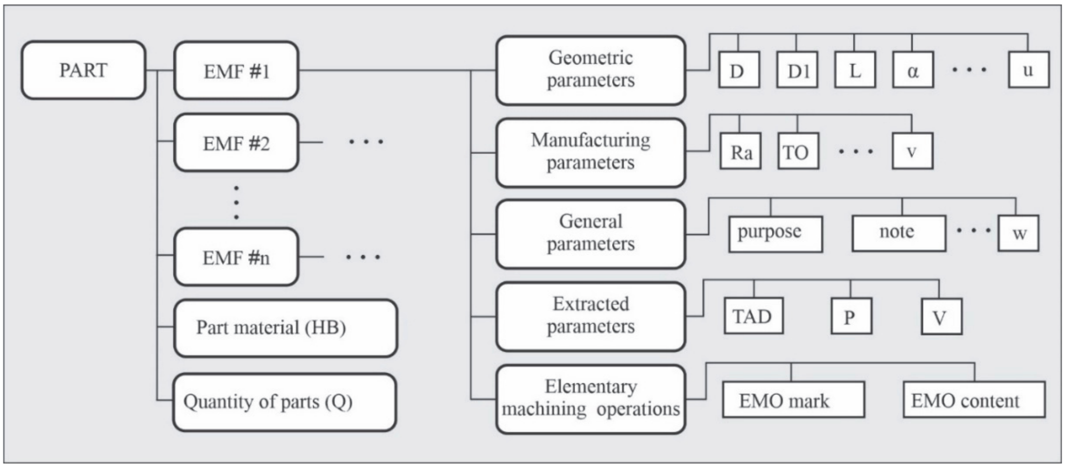

Figure 6 Numerical representation of EMFs of a part

The mechanism for managing of the EMF library was developed in order to provide flexibility and expendability of the developed platform for integrated intelligent CAD/CAPP design (Fig. 7). The mechanism for managing of the EMF provides an update of generic elementary machining features and manufacturing knowledge base. The update of the generic EMF was carried out in order to define a new generic EMF and to expand the existing EMF library. The update of the EMF library begins with classic solid modelling of the new (generic) EMF in the context of the SolidWorks program system. Then, the solid model of new EMF was loaded by the control mechanism of the EMF library. The next step is identification and connection of the existing geometric attributes of the generic EMF with the new attributes, as well as assigning of manufacturing and general attributes for the new EMF. A new generic elementary machining feature, together with its attributes, then became a part of the EMF library. Updating the manufacturing knowledge base was carried out in the framework of the mechanism for managing of the EMF library. The first step in the process of manufacturing knowledge base update is a selection of the generic EMF from the EMF library. The knowledge in the form of production rules was assigned to the selected generic EMF. Production rules were condition-action pairs used to define a single chunk of problem solving in the form of "If <Condition> Then <Action>". This causal connection was defined by using the attributes of the generic EMF.

The attributes of a condition define the causal part of production rules, while the attributes of effect define an action part of production rules. The conditional part of production rules was applied to a combination of geometrical, manufacturing and general parameters of EMF. The action part of production rules refers to the list of elementary machining features for observed combination of mentioned EMF parameters. After the assigning of production rules to the EMF, connection and storage of production rules was conducted for the selected EMF.

This way of a continuous updating and extending of the EMF library enables the reusability of the identified forms which were further used for design of various classes of the parts.

5 VERIFICATION OF THE DEVELOPED CAD/CAPP PLATFORM BY DESIGN BASED ON EMF

Verification of the developed platform for integrated intelligent CAD/CAPP design based on EMFs and GA was conducted on the industrial example of the body of hydraulic cylinder for a hydraulic press brake. Design of the body of the hydraulic cylinder was made in compliance with the developed structure of the platform, shown in Fig. 3.

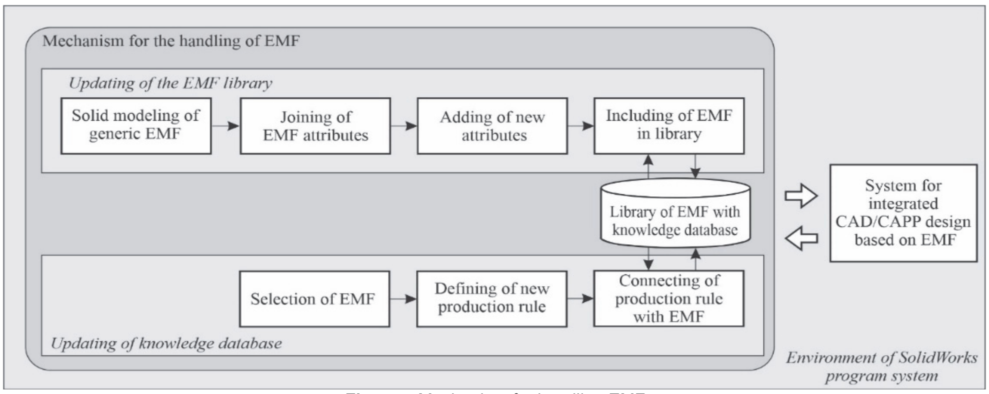

Figure 7 Mechanism for handling EMF

The verification procedure was conducted within the SolidWorks program system using new program tools which were introduced in this research and classic technique of solid modelling. These new program tools were developed based on API, which was a common approach used for extending the SolidWorks environment. The process of verification of the developed platform consists of the following activities: The solid model of raw material (blank) of the body of the hydraulic cylinder was modelled based on design requirements. Continuation of part design was conducted based on a previously designed blank and by application of a destructive method based on EMFs. Part design procedure based on EMFs begins with the selection of an appropriate generic (parent) EMF from the library of EMF. Then, setting of the geometrical, technological and general parameters for the selected generic ETF was done. The solid model of the child EMF with appropriate parameters was generated as a result of previously conducted actions by developed program tools. The solid model of the child EMF was generated into working environment of the model of the SolidWorks program system. The procedure of selection, setting and generation of the child EMF was done using the developed program interface, shown in Fig. 8. The next step of the design process is the positioning and subtracting of the solid model of the child EMF in relation to the solid model of a blank.

The process of positioning and subtracting of the solid model was carried out using a standard Locate Part programming tool. In order to improve and accelerate the process of part design, some functions of Locate Part program tool were upgraded and automated using API functions.

After positioning and subtraction of the solid models, the developed platform stores relevant information about generated child EMF (Tool Approach Direction-TAD, geometrical and manufacturing data, etc.) in the internal database. The procedure of selection, positioning and subtracting of the solid model of the child EMF, related to the solid model of the blank, continues until the process planner was completely satisfied with the design results.

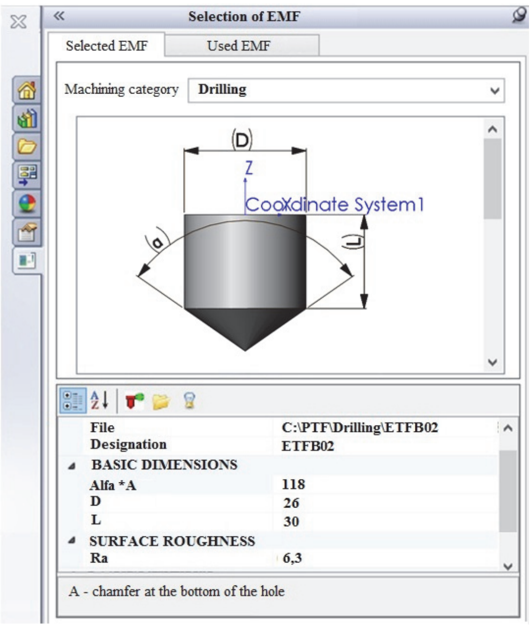

Figure 8 Interface for selection, setup and generating of the EMF

The final solid model of the body of the hydraulic cylinder, as a result of the above-described design method, was shown in Fig. 9. The solid model of the body of the hydraulic cylinder consists of 52 child EMFs. From 52 child EMFs, 39 child EMFs for drilling operations and 13 child EMFs for milling operations were used. In general, from these numbers 3 generic EMFs for drilling operations and 7 generic EMFs for milling operations were used to design the solid model of the body of a hydraulic cylinder. After the process of design of the solid model of the body of a hydraulic cylinder was finished, the next step was to generate output information. The generation of the output information was done for the purpose of operation sequencing and preliminary cost determining using GA, which were described in detail in the second part of this paper.

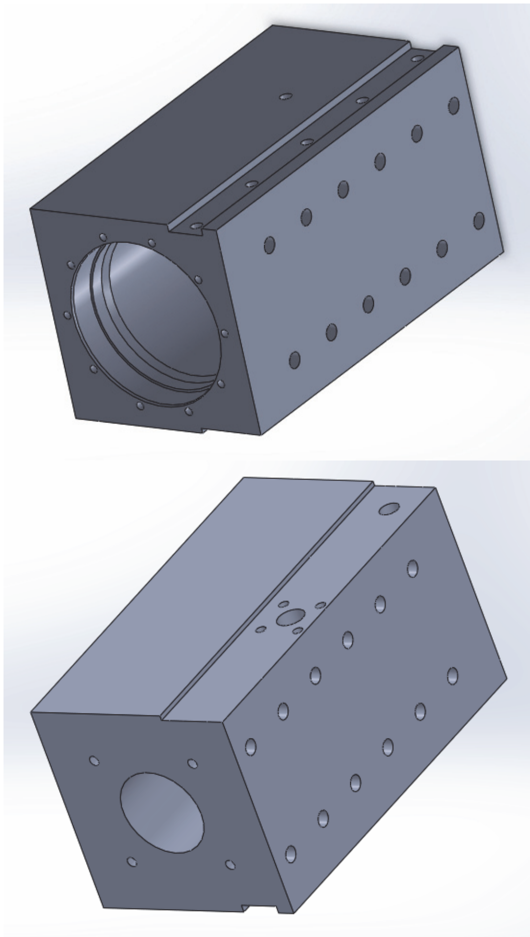

Figure 9 3D model of the body of hydraulic cylinder

The structure of the output information from the design phase includes the following information: codes and geometrical parameters of the EMFs, position coordinates and TADs of EMFs related to the coordinate system of the body of a hydraulic cylinder, and a list of elementary machining operations (EMO) for each EMF. Codes, geometrical parameters, position coordinates and TADs of EMFs were generated based on developed platform functions for data collection. The list of elementary machining operations for each EMF was generated based on the developed production rules that were contained in each of the generic definitions of the EMF. A segment of output information with data related to some EMFs used for the design of the body of the hydraulic cylinder is shown in Fig. 10, while the overall structure of output information was provided on the website of the first author, accessible by the link https://mf.unibl.org/Stevo/.

This information represents a segment of data that were required for the process of optimization of the operation sequencing using the GA. Other data that were necessary for the realization of the operation sequencing using the GA were: available number and designation of machines and tools, total machines and tools utilization costs, total machine change, tool change, and setup change costs, as well as the matrix of constraints for performing of the elementary machining operations. Description of this information is done in the second part of this paper.

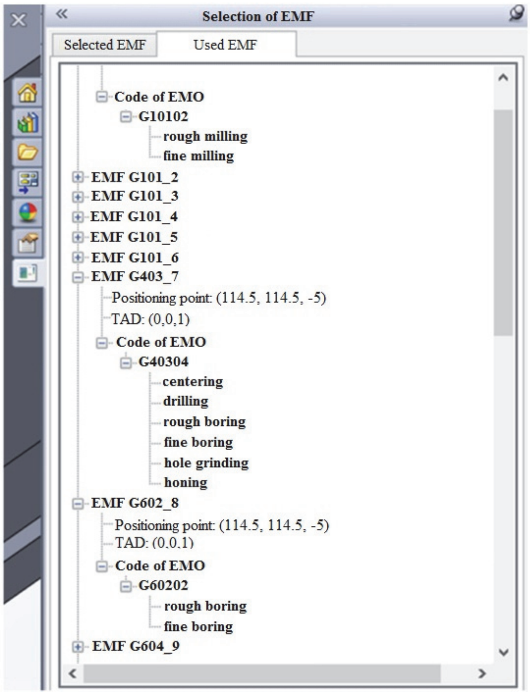

Figure 10 A segment of the information of the used EMF`s for the body of hydraulic cylinder

6 CONCLUSIONS

In this paper we introduced an integrated intelligent CAD/CAPP platform based on the elementary machining features and the genetic algorithm. In this first paper we proposed a new methodology for the CAD based on Elementary Machining Features. Main advantage of our new approach is to make usable and intelligent EMF. In other words, in the design phase we add a critical information to the EMF (enriched EMF), which we later used in the process of the operation sequencing. In this way we can establish a link between part design phase and process planning phase. In the part design phase, enriched EMFs as design objects were used by the destructive method.

Production rules, based on existing and additional information generated from EMFs during the design phase, were used for determining the list of elementary machining operations for each EMF, which was a novel approach to automatic identification of the set of information needed for the process planning phase.

In a comprehensive case study, the proposed approach is verified on an industrial example of the body of hydraulic cylinder for hydraulic press brake. Obtained results indicate a high level of usability of the proposed integrated platform.

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