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Abstract. The paper discusses the feature-based process planning in a digital manufacturing concept, for prismatic parts manufacturing. STEP standard as an enabler of feature-based manufacturing is presented in detail, along with belonging application protocols. The case study on the feature-based CAPP/CAM model in Serbian SME is shown to depict the advantages, followed by the research recommendations for the improvement of the presented concept.

Keywords: Digital manufacturing, Feature-based manufacturing, CAPP, STEP.

1 INTRODUCTION

Digital manufacturing, within digital factory, has become the main manufacturing concept in the twenty-first century and highly important for companies to enhance their competitiveness. One of the research priorities in Strategic Research Roadmap 2010-2013 of European public-private partnership for Factories of Future (PPP FoF), is ICT-enabled intelligent manufacturing [1]. It was stressed here that ICT is a key enabler for improving manufacturing systems at three levels: smart factories, virtual factories and digital factories. In this context, digital factories are defined with the ultimate goal to improve design productivity using software for the digital representation and test of products and processes prior to their manufacture and use. This also implies better understanding and design of production and manufacturing systems for better product life cycle management involving simulation, modelling and knowledge management from the product conception to manufacturing, maintenance and disassembly/recycling. The major sub-topics are: knowledge and analysis; enhanced, interoperable models for products and processes; design environments; and lifecycle management [2].

Digital manufacturing is considered a part of a digital factory. From the industrial application aspect, digital manufacturing implies IT support for planning and engineering processes and 3D computer visualization. The digital manufacturing could be defined as a methodology that uses deeper and extensive knowledge and IT. In general, there are three main elements that define the digital manufacturing: (i) IT system and its application; (ii) theoretical model of a digital manufacturing – the knowledge

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level used as a methodology for digital manufacturing: and (iii) usage of specific advanced methods and techniques, such as e.g. web-based multi-agents systems. From the informational point of view, the fundamental characteristics of information/data in digital manufacturing are: digital presentation/format; multiple usage; and, independence with respect to the distance, time and place of utilization [3].

IT integrated with traditional manufacturing technologies improved automation and digitization of the planning, design, production, inspection, management, and other related activities. Hence, the overall digital output presents a mirror of the actual manufacturing using limited amount of data. The digital presentation of a product is the very essence of the digital manufacturing in terms of numerous activities performed in the factory. The digital model of a product could be used to simulate and analyse the related production activities flow or to verify different production planning, machining/tool path, inspection and resource utilization scenarios.

It could be summarised that the main features of digital manufacturing are [4]:

- Ambiguity of any knowledge must be eliminated, and knowledge must be presented in forms that can be processes/analysed/utilised by various IT tools and transformed into digital data. This is a basis for factory-wide knowledge integration in terms of widespread application of Computer Aided Design (CAD)/Computer Aided Process Planning (CAPP)/Computer Aided Manufacturing (CAM)/Computer Aided Inspection (CAI)/CAx, and for the cooperation: factory system – process - numerical control machining. Therefore, one of the main problems is a synthesis of different formal presentations of different aspects/elements of digital manufacturing system.
- Simulation and prediction of product development is of essential importance, since it allows analysis and evaluation of manufacturability, product’s performance, and other related characteristics.
- All manufacturing-related activities supposed to be independent of distance, time and location (i.e. in a networked environment).

Enabling technologies for digital manufacturing could be divided into following groups [4]:

- for product design/development and simulation: CAD, VM (Virtual Manufacturing), CAPP, CAE (Computer Aided Engineering), CAM, etc.;
- for material processing (machining) and material flow control, such as NC (Numerical Control), CNC (Computer Numerical Control), DNC (Direct Numerical Control), FMS (Flexible Manufacturing System), control systems for material flow, etc.;
- for production management: IGES (Initial Graphics Exchange Specification), STEP (Standard for the exchange of product data), ERP (Enterprise Resource Planning), MES (Manufacturing Execution System), PDM (Product Data Management), database, Internet, Intranet, ...;
- for collaboration among enterprises: networked manufacturing, client relation management and supply chain management, etc.

The objective of this research is to analyse process planning for prismatic parts in a digital manufacturing concept. After the introduction, the second section presents the process planning model based on product features for prismatic parts. As an example, the existing feature based CAPP/CAM model for prismatic parts used in Serbian SME IVA-28 is discussed in the third section. Finally, concluding remarks are given with respect to the advantages and limitations of the feature based process planning model in a digital manufacturing, as well as recommendations for our future research.

2 FEATURE BASED PROCESS PLANNING

The objective of process planning in a manufacturing enterprise is to generate the optimal sequence of necessary manufacturing processes in order to produce the observed part in the technologically feasible and economically effective way. Today, this is performed by using computer-aided process planning (CAPP) systems. Process planning is based on the relevant data of a part design model, such as geometrical features, material, tolerances (accuracy), surface roughness, etc. The set of all these data could be considered as manufacturing features, which present a link between computer-aided design (CAD) and computer-aided manufacturing (CAM). The main issue here is how to translate the manufacturing features (derived from a part design model) into the manufacturing operations sequence [5]. Beside the integration with CAD and CAM, it is very important to design CAPP systems at such a way to provide a real-time link with the other existing IT systems in the enterprise such as ERP, MES, etc.

Probably the most important advantage of the feature technology is the ability to associate not only geometric and topological information, but also form features, tolerances, material properties and other information which may be used during the process planning. Today, Standard for Exchange of Product Model (STEP) is used for the implementation of feature technology. STEP provides the neutral, interoperable, computer interpretable file format of product data, that is independent of any particular system and suitable for transfer, processing and communication between different systems such as CAD and CAM. STEP file applies object oriented database method to model the relationship within the file data, and uses a formal specification language EXPRESS to define product data (entities, attributes and relationships). Therefore, STEP has been accepted as an international standard for feature based technologies. The official designation of STEP standard is ISO10303: Industrial automation systems and integration - Product data representation and exchange. STEP covers a wide range of applications. To specify the part data representation for a specific application, STEP uses Application Protocols (AP).

Application Protocol 224 (AP224) gives manufacturing feature definitions based on prismatic and turning parts. AP224 is defined in the part ISO 10303-224: Application protocol: Mechanical product definition for process planning using machining features. The latest version of this standard was issued in 2006. The standards includes the application protocol for the representation and exchange of information for manufacturing mechanical parts and shape representation of machining features, addressing manufacturing part properties, process control documentation, manufacturing specifications, administration data, and requisitions [6].

The extension of STEP standard is STEP-NC standard, that defines independent tool paths and volume removal features based on geometric features (constructs), and adds geometric dimension and tolerance data for inspection. Basically, it combines and interconnects STEP (ISO10303) standard with ISO 14649: Data model for computerized numerical controllers that defines the requirements for machining. This is formally defined in Application Protocol 238 (AP238) of ISO 10303 standard. The main idea behind it was to replace ISO 6983 G code standard with a modern format that connects the CAD part design data used to determine the machining requirements with the CAM process data that solves those requirements (CNC process data).

It is also important to mention AP203: Application Protocol for Configuration Controlled Design, that is used to exchange design data (geometry, product structure, tolerances, configuration management) among different CAD systems [6].

For feature based CAPP, AP240 is of essential importance (AP240: Application Protocol For Process Plans For Machined Products). It defines the information for macro process planning, and provides process plans, machine tool resources (i.e. fixtures, cutting tools), process planning activities and their sequencing, setups, materials, properties, process requirement documents, and part shape with features and tolerances [6].

According to the above, integration of feature-based product knowledge directly in CNC programs in STEP-NC manufacturing is presented in Figure 1.

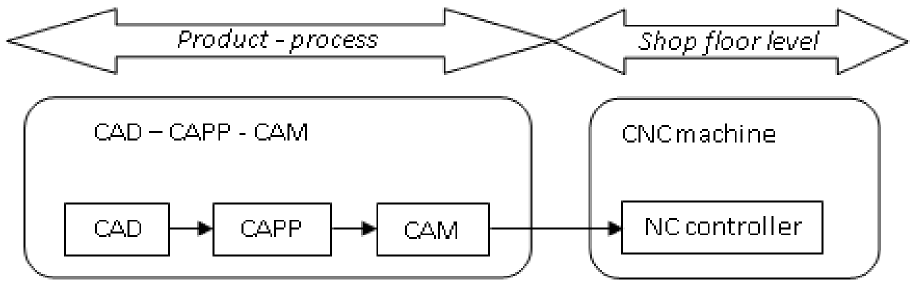


Fig. 1. STEP-NC manufacturing concept

The above commonly accepted standards and protocols enable further advances in feature based CAD/CAM/CNC collaborative systems. Several recent researches used different approaches to solve problems in feature based process planning. Yongtao and Jingying [5] constructed a feature based process planning model for the hole's machining that consists of three parts: the features framework, the semantic precedence-relations-net and the sequencing mathematical model. Ming and Mak [7] used the combination of neural networks (NNs) to solve setup planning problem in CAPP, in an intelligent manufacturing environment. Capponi et al. [8] presented feature based CAPP developed for the aircraft industry, characterised by complex geometries of parts. Deja and Siemiatkowski [9] presented the CAPP approach which focuses on the identification of process alternatives and sequencing adequate working steps, based on part design data in terms of machining features. Álvares and Ferreira [10] developed a system for web-machining, aiming at integrating CAD/CAPP/CAM for the remote manufacturing of cylindrical parts, adherent to STEP-NC. Xu and He [11] analyse a total integration of CAD, CAPP, CAM and CNC based on STEP-NC. Campos and Miguez [12] developed the collaborative STEP-based CAD/CAM/CNC chain, that integrates both types of information - process data and standard machining (STEP-NC) program, enabling full monitoring and traceability of activities in the system.

There are few recent papers from a literature that discuss feature based process planning for prismatic parts in an integrated CAD/CAPP/CAM system. Sharma and Gao [13] presented a feature based CAPP for prismatic parts using STEP AP224, where process plans and related documentation is automatically generated from AP224 files. The decision logic is stored in an external database, making the system compatible with various manufacturing applications. Amaitik and Kilic [14] developed an intelligent CAPP system for prismatic parts using STEP features, which generates process plan (including operations selection, tool selection, machining parameters determination, machine tools selection and setup planning) and corresponding STEP-NC file. In this system, the inference engine uses hybrid approach consisted of NNs, fuzzy logic and rule-based system. Collazos and Álvares [15] proposed a methodology for the integration of CAD/CAPP/CAM for prismatic parts, in accordance to STEP-NC standard. It starts with a product design using DSG (Destructive Solid Geometry) where the features of machining are associated to machining operations (it can incorporate also the elements related to the process planning, such as selecting the type and diameter / length of a tool for removing material in a cavity). The output from the CAD module is in conformance with AP203 and AP224, and it presents an input for CAPP module. The CAPP module uses AP224 and STEP-NC to define the machining features of the part to be machined. This research considers the extended CAPP or an integrated CAPP/CAM system, hence one of the process planning outputs is the NC program in the format STEP-NC ARM ISO 14649 that contains information of machining features, cutting parameters, cutting tools, fixturing, working steps, workplans, among others. This further generates the tool path for each working step described in a NC program in the G and M codes (RS274) format to be used in traditional CNC machines without support for STEP-NC. In this approach, the data generated at each interface of the modules are stored in a database in XML format. Nassehi et al. [16] applied collaborative multi-agent systems in designing an STEP-NC compliant, object-oriented CAPP for prismatic parts. It is highlighted here that the data model, i.e. the ability to store complex geometries and multi-level class hierarchies, plays an essential role in CAPP. STEP-NC environment provides potentials for the above data model, due to clear entity definitions and expandable architecture, and also due to the fact that STEP-NC architecture stores full information about a product. Hou [17] presented a research on CAD/CAM integration, mainly focusing on the connection of CAPP and CAM utilising machining features for prismatic parts. In this approach, the existing CAPP system is integrated with the commercial CAD/CAM system by implementing the prototype integration layer. This provides the whole set of data available as an input for CAM system: product geometric features, process plan information together with machining features. Hence, the tool paths can be automatically generated from solid models and process plans. Sun et al. [18] proposed an integrated setup/fixture planning approach for prismatic parts machining, that consists of four steps: definition of the requirements and constraints for setup/fixture planning; description of the precedence constraints between setups; selection of the suitable location surfaces; evaluation of the candidate setup/fixture plans.

It is important to clarify how STEP-NC and the related APs impact process planning systems, considering a fact that process planning occurs between design and manufacturing. AP203 presents an interface for design, and AP238 - an interface for manufacturing. Hence, the popularity of AP238 will contribute to popularity of CAPP systems, where enterprises will define their inputs and outputs according to STEP APs. To facilitate this, AP224 (part features) and AP240 (process planning) were defined. In the long term it is expected that CAD system will write AP203 edition 2 or AP224; CAPP system will read AP224 and write AP240; CAM system will read AP-240 and write AP238; and, finally, CNC system will read AP238 to manufacture a part [19].

Figure 2 presents the primary data flow in STEP-NC manufacturing concept based on design features and using STEP APs, enabling a direct exchange and a better data flow between CAD-CAPP-CAM-CNC systems (for prismatic parts). The steps could be described as follows [12, 19]:

1. In the part design phase (CAD), the part is defined using the AP-203 (edition 2) that includes geometric and tolerance data, and other basic data about the part (i.e. product structure, configuration management, etc.). Hence, is suitable for CAD data exchange, but it does not include the feature information needed for macro process planning (CAPP) and for CAM.
2. Based on AP203 data detailed part design is performed including features modelling (CAD-f), and gives AP224 data. AP224 data contains AP-203 geometric information and new information - features to be machined and their tolerances.
3. Based on AP224 data CAPP system extract design features and performs macro process planning implying information about facilities, available CNCs, and the distribution of work. This also includes definition of fixtures and setups, process selection and operations definition, machining tools selection and machining parameters definition. All these data are added to AP224 to generate AP240 output.
4. CAM system generates data for CNC controllers programming using AP240 data. These data are added to AP240 to create AP238 output for feature based machining.
5. Based on the received AP238 data, CNC system performed manufacturing operations.

As presented at Figure 3, the basic architecture of CAPP system is based on the interaction with databases that contains information about features, as well as information about CNC machines, cutting tools, fixtures, types of material, etc. [15]. Data from these databases are needed for the optimization of processes/machines sequence and for CNC and cutting tools selection, to generate AP240 file that can be used by CAM system that create AP238 file. This file contains data about part design, manufacturing feature, setup and fixture requirements, and sequences of processes, setups and cutting tools, and can be directly used by CNC controllers to perform machining processes.

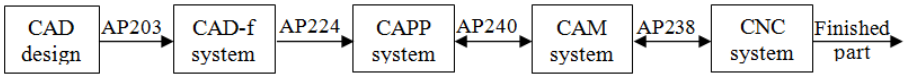


Fig. 2. The simplified scheme of CAD/CAM/CAPP/CNC integration enabled by STEP-NC for prismatic parts

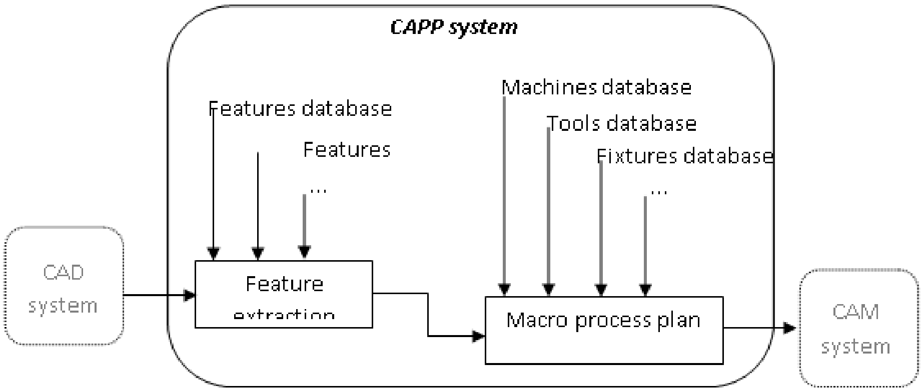


Fig. 3. The basic architecture of CAPP system in STEP-NC manufacturing concept

In the above STEP-NC manufacturing concept, CAPP system that performs macro process planning is supposed to carry out the following activities:

- features extraction and translation of design features into manufacturing features;
- selection of the machining processes based on manufacturing features, considering constraints related to dimensions, tolerances, material, etc.;
- selection of the machining sequence with alternatives and setups for fixture;
- selection of the cutting tools, considering the machine tool, material of the part, toll characteristics (material, dimensions, geometry, tool life, etc.);
- calculation of the time – cost model;
- creation of the process plan documents including alternative plans and time - cost estimates.

Besides the above activities, in some instances (e.g. [10]) the extended CAPP system or the integrated CAPP/CAM system performs also the following:

- selection of the strategies for tools paths creation based on STEP-NC;
- determination of the technological conditions of optimized machining;
- generation of the NC program (AP238), etc.

The AP224 of STEP standard specifies a set of features for use in process planning. Figure 4 presents a part of the feature classes defined in STEP AP224, for prismatic parts. A manufacturing feature identifies the types of features necessary to manufacture a machined part. In general, manufacturing form features are divided into three categories: (i) machining feature presents volume that should be removed by machining to obtain the final part geometry (e.g. hole, pocket, slot, step); (ii) transition feature presents an area between two surfaces, which include chamfer, edge round and fillet.; (iii) replicate feature is the arrangement of identical copies of the base shape, or a pattern of features, where the same features in terms of size and sort are arranged on the final product in circular, rectangular or general pattern [17, 19, 20]. The above features definition according to STEP AP224 is shown in Table 1.

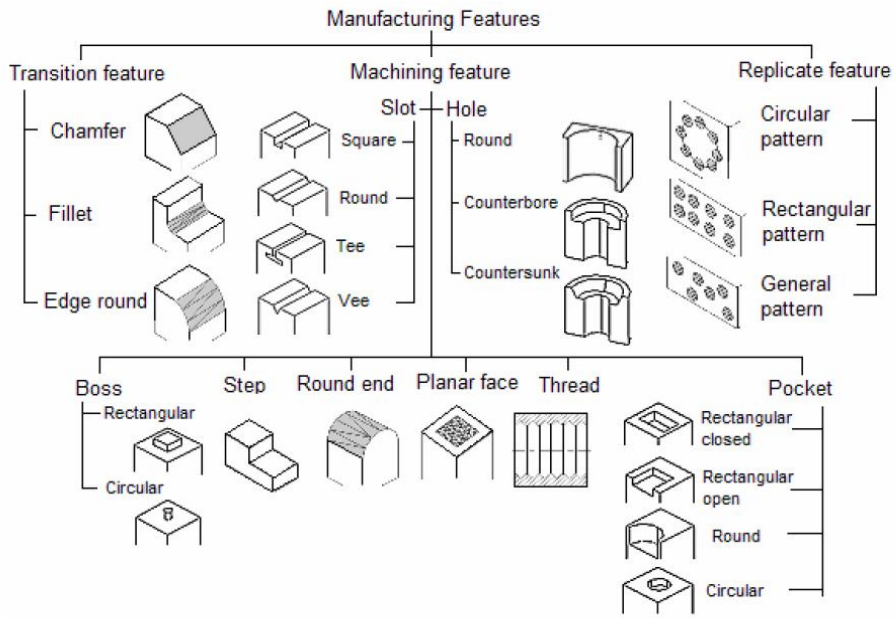


Fig. 4. A part of form feature categorisation in STEP AP224 for prismatic parts [20]

Feature	**Definition/explanation**
Hole	A type of multi-axis feature that is the removal of a cylindrical volume from a part (a counterbore, countersunk, or a round hole).
Pocket	A type of multi-axis feature that is a volume with a specific shape, removed from the part; the sides of a pocket may be parallel to the pocket's orientation vector coming out of the pocket or the sides may be tapered (a general, rectangular closed, or a rectangular open pocket).
Slot	A type of multi-axis feature that is a channel or depression with continuous direction of travel (a square, round, tee, or a vee slot).
Boss	A type of multi-axis feature that is a closed shape that protrudes from the surface of the part; the intersection of the boss and the base surface may have a radius shaped blend between them (a circular boss or a rectangular boss).

Step	A type of multi-axis feature that is a linear sweep of a shape; the shape shall be specified by two lines that connect at a point and extend infinitely; the enclosed angle shall be smaller than 180 degrees; the intersection of the two lines need not be blended with a radius.
Thread	A type of machining feature that is a ridge of uniform section on the form of a helix on the external or internal surface of a cylinder.
Planar face	A type of multi-axis feature that is an unbounded planar cut of a part; the Planar face shall have an orientation that the Z-axis is the direction away from the part.
Marking	A type of machining feature that is one or more text characters on a surface of a part.
Rounded end	A type of multi-axis feature that is partially circular shape passed along a linear path.
Chamfer	A type of transition feature that is a transition between corresponding edges of surfaces, having a flat cross section.
Fillet	A type of transition feature that is a concave circular arc transition between two intersecting surfaces; the blend surface may be tangent to both of the adjacent surface edges.
Edge round	A type of transition feature that is a convex circular arc transition between two intersecting surfaces; the blend surface is tangent to both of the adjacent surface edges.

Table 1. STEP AP224 feature definitions for prismatic parts [19, 20]

3 FEATURE BASED CAPP/CAM FOR PRISMATIC PARTS IN SME "IVA-28"

This section presents a feature based production setup, or the integrated CAD/CAPP/CAM concept in Serbian SME "IVA-28" that produces precise, mainly prismatic parts for machine building industry. The STEP-based production scenario is as follows:

- The product specification is received from the customer in a form of 3D CAD model or STEP file. In case of 3D CAD model, the corresponding STEP file is generated from the CAD model.
- CAM technology is prepared base on the product design, including the following steps:
  - the product geometry is divided into the predefined feature;
  - all known features are imported from the features knowledge database in order to connect the product geometry with the existing features from the database;
  - if there are no existing features in the database that correspond the product geometry, new features are generated using pre-prepared tools and added to the database.
- Then the program post-processing is performed for different machine controllers included in the macro process planning, in order to generate the corresponding NC codes. The generated NC codes are stores on the server.

- Machines access the corresponding NC codes store on the server and perform machining operations.
- After machining, the automatic measurement is performed on the 3D measuring machine using the above STEP file.

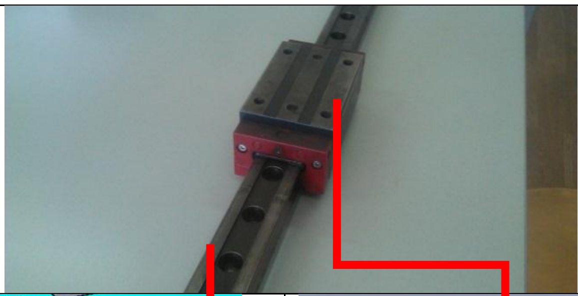
The approach used in "IVA-28" is the features recognition where the part geometry/topology is examined and matched with the predefined feature from the knowledge base, in contrast to the design by feature approach where the part is formed from the predefined features with their attributes.

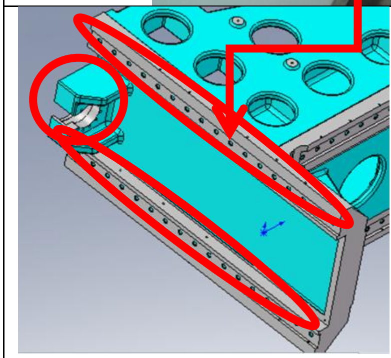
It could be notice that the whole system is organized as a direct numerical control (DNC), where CNC machines are networked and their operations are controlled from the central computer. Each machine has its own IP address which allows them to behave as a computer. Some of the direct benefits of this STEP-based manufacturing concept in "IVA-28" are: company-developed standards for machining particular forms/ features; independence off CNC machines; proven strategies for machining the most important features, assuring high quality of final products; very fast and risk free setup of new products in case of known features and known materials; price, cost and capacity predictability.

Figure 5 presents the feature based CAD model of a typical product – a slide used for various kind of machine tools (for x, y and z axis kinematics). The features base is organized as a knowledge base, with systemized groups of elements and corresponding solutions. The set of geometric features (shapes) forms one functional whole. The corresponding group of machining operations is applied over the observed set of geometric features, and this presents an independent part of a program. For each set of geometric features and product material, there is a predefined sequence of machining operations together with the optimal machining parameter values, corresponding tool geometry and material, etc.

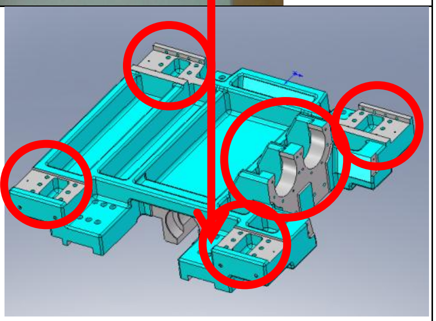
The above shown product (slider) consists of two groups of features designated as Feature A and Feature B, which are stored in features knowledge based together with other features. The corresponding CAM technology is generated first by loading the set Feature B and set Feature A from the knowledge base, and then connecting Feature B and Feature A with the product geometry. The set Feature B contains machining operations sequence, process parameters, tool data and other machining-related information. The same applies for the set Feature A. Figures 6.a) and 6.b) show generation of CAPP/CAM program for the set Feature B and set Feature A, respectively.

For the existing program it is possible to change or reselect the machine, tool library (e.g. select the library for some other material of a product), or machining operations. Each machine is presented by its postprocessor. The machining operations library contains systematized group of products, where each group could contain almost infinite number of functional group of operations that correspond to the functional wholes of a product. Figure 7-left presents the selection of machine group properties, namely the selection of a postprocessor/machine and related tool and operation libraries. The selection of tool-related parameters is presented in Figure 7- right, with two options: to load tools from the library into the program with the pre-defined regime parameters, or to automatically re-calculated the tool-related parameters with respect to the selected material of a part.





Feature A
A set of features: Feature A = 2 x slide with special sinked M12 holes + main axis spindle with bearing housing 115J6/10 with 8xM10 in the middle.



Feature B
A set of features: Feature B = 4 x slide connector with 6 x D13 holes + simple spindle or double spindle with M8 treads and without bearing housing, with side pressure threads on a guided side.

Fig. 5. A real product (slide) – top, and CAD model with typical features - down

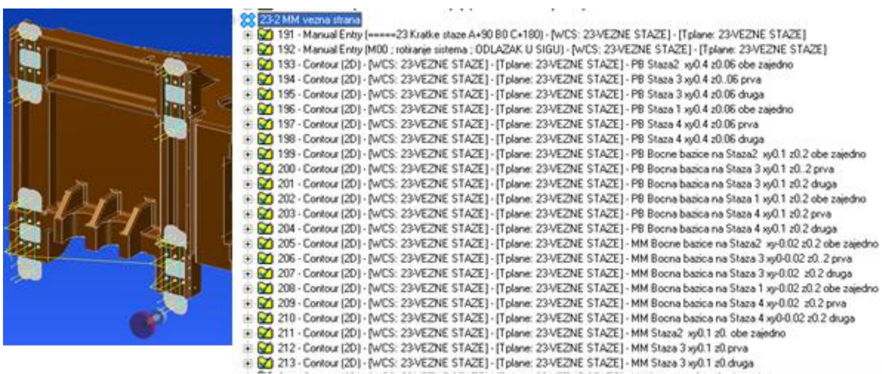


Fig. 6. a) Generation of CAPP/CAM program for the set Feature B

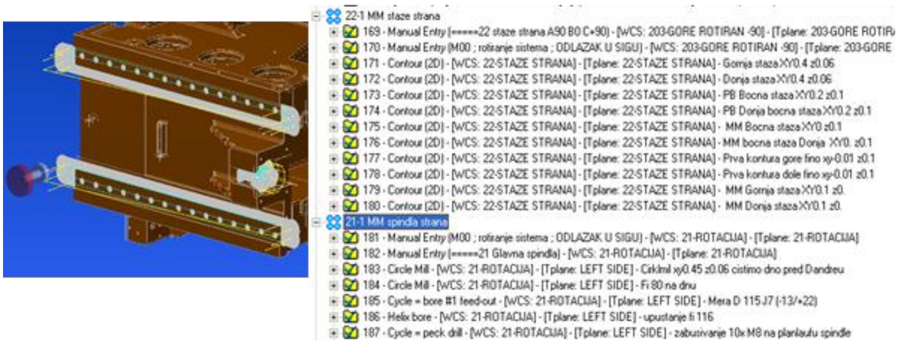


Fig. 6. b) Generation of CAPP/CAM program for the set Feature A

Hence, in case of a new material of a part, all regime parameters must be re-calculated according to the material selection. Prior to this, it is necessary to define how to calculate the regime parameters for each material. This is performed according to the table for material definition (Figure 8).

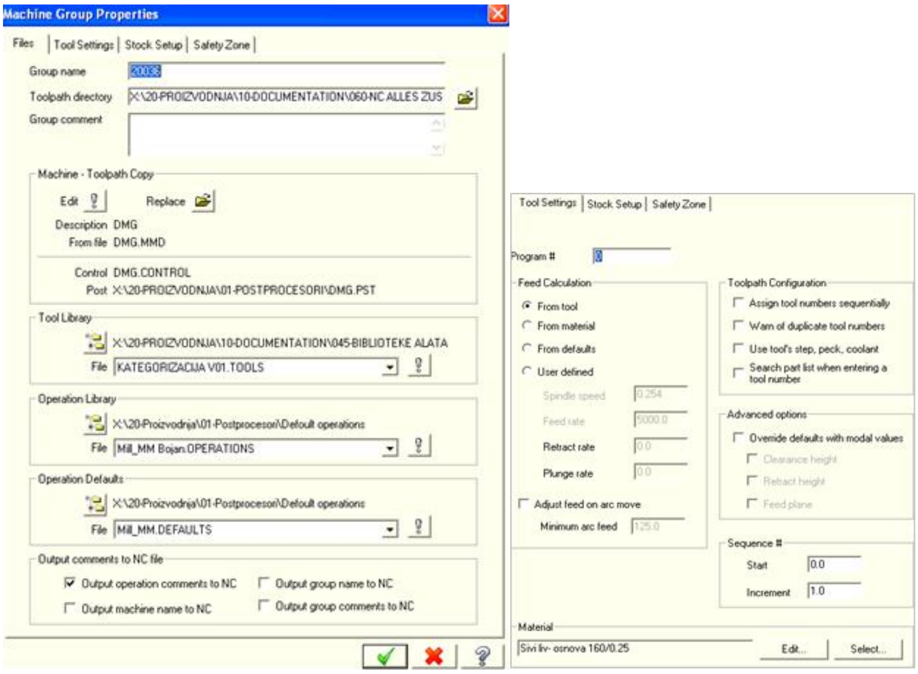


Fig. 7. The selection of machine group properties (machines, tools, and operations) – left, and tool settings – right

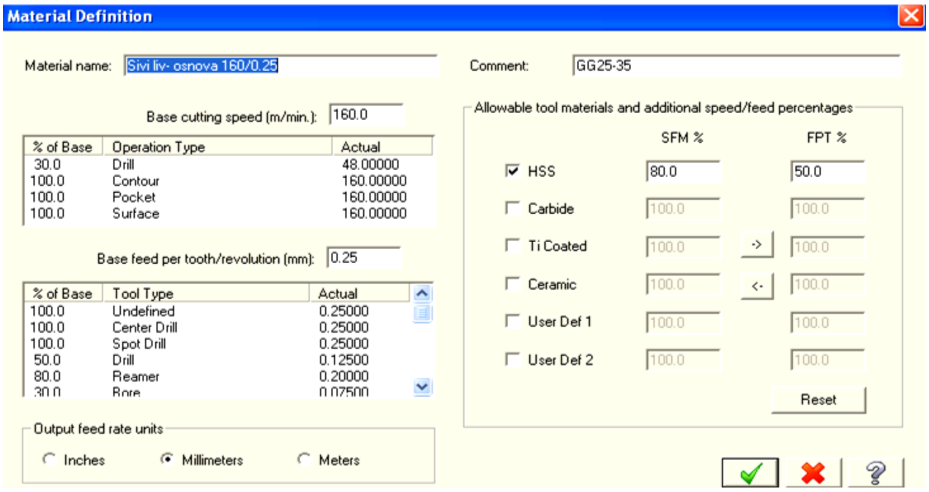


Fig. 8. The material definition: the adjustment coefficients for regime parameters (with respect to the operation and tool type) for the selected material of a part

The above process planning concept is partly integrated with IT infrastructure for manufacturing management: MES and ERP along with Bill of Material (BOM) module, where planning process considers products with the belonging elements and resources (e.g. machines with belonging elements).

4 CONCLUDING REMARKS

Feature based model is assumed as a main contributor to the efficient integration of CAx technologies. STEP-NC standard allows for more effective, bi-directional data exchange between CAx systems and NC controllers. STEP-NC enables that all CAD, CAPP, CAM and NC data could be stored in a single database, to which each CAx system or NC controller can have access for information retrieval or alteration [11]. This is of essential importance for full realisation of a digital manufacturing concept.

Dynamic conditions in a global supply chain, as well as in an enterprise itself, lay down complex requirements in front of CAPP systems in a digital, STEP - based manufacturing. In such dynamicity, the main tasks that CAPP should simultaneously respond to are: identification of the most efficient and effective machining sequence (including selection of machining operations, machines, tools, fixtures, and other relevant data) and alternatives, considering all possible constrains in the actual production; automated and timely generation of a process plan based on design features of a part/product (from CAD system); generation of the optimal process plan based on the time-cost criteria. The output of such CAPP system is a STEP-NC process plan, that could be directly used by CAM system to control the CNC system and perform the actual production operations. One of the main challenges is also the complexity of today's products, so future activities should include the enrichment of a feature database.

The future research direction for the improvement of the existing IVA-28 digital manufacturing concept implies the following: (i) the unambiguous definition and further development of STEP manufacturing features, and their full implementation in the practice; (ii) the design of a feature recognition model, the selection of machines, tolls, machining operations and optimal machining parameters, and the generation of process plans using artificial intelligence techniques.

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