



KNOWLEDGE-BASED MANUFACTURING: A PROPOSAL TO MANAGE MANUFACTURING RULES

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Abstract

In manufacturing companies, technologists use CAD/CAM tools for NC programming. Feature based approaches enable to faster programming, but require advanced competences and a standardization too rigorous for real machining practices. It is necessary a data and manufacturing rules management environment, in which knowledge engineer can define the rules based on industrial best practice and CAM Experts can customize them for production requirements. A possible solution is to extend the FBM software module with an easy-to-use system that simplifies feature based rules management and deployment.

Keywords: features, computer aided design (CAD), computer aided manufacturing (CAM), digital manufacturing, knowledge based engineering (KBE)

1. Introduction

Nowadays, many of common challenges faced by manufacturing industries that adopt CNC machines can be minimized or eliminated by automating the NC programming. The loss of knowledge due to the staff turnover, the high costs associated with maintaining and updating corporate standards, the inability to effectively capture and reuse best practices and the inability to improve productivity, while reducing costs, are examples of business challenges that can be addressed using a CAM system and adopting modern programming automation technologies.

The advantages deriving from CNC programming automation are different both in engineering departments and in the shop floor. Companies have achieved quantifiable benefits, such as a reduction of the programming time, a reduction of programming errors, a reduction of machines set-up times, a better productivity and the ability to capture and reuse demonstrated processes in the form of best practices and standards.

The need for programming automation become clear in everyday activities of manufacturing engineering departments as well as in workshops. The NC programmers and operators, who face these challenges on a daily basis, can get significant benefits from the automation of CNC programming solving the mentioned problems. Specifically, referring to engineering departments, where CNC program are wrote, the common observed problems are redundant programming effort for similar types of parts and misinterpretation of 2D drawings and tables. At the same time in, the workshop, there are incorrect CNC Programs (missing features, wrong tool selection, etc.) and incorrect documentation, dependence on paper-based processes and standard machining processes / company standards that are not followed properly. For both engineering departments and workshops, there is also the problem of excessive training time of less experienced staff.

CNC programming automation can solve most of these problems; it significantly minimizes time-consuming manual programming effort and reduces repetitive tasks. This streamlines program development, reducing the number of actions needed to complete CNC program code and above all, it increases program accuracy minimizing the number of inputs and selection errors (Evans, 2016).

FBM (Feature Based Machining) approaches allow amplifying these benefits. They allow the geometric recognition of manufacturing features and the automatic generation, for each of them, of the best (or preferred) machining process.

However, FBM requires a standardization and the definition of rules too rigorous for real machining industrial practices. Due to the variety of CNC process parameters and the complexity of parameters setting, the path pattern and process parameters used may be different from one engineer to another, even with the same CNC parts programming, leading to different standards, which is likely to cause chaotic management (Wang et al., 2014).

Over last years, most of efforts have been done in investigating the use of knowledge-based methodologies in the field of production management, and particularly in the field of Material Resource Planning. Many existing studies analyses the automation of CNC programming and the critical issues of feature technology (i.e. feature recognition and feature-based machining.), but they do not address the management of data and rules; moreover the problems related to the industrial application are not adequately exploited.

Based on these premises, the paper aims to propose a knowledge-based methodology, supporting manufacturing processes, to improve the management of manufacturing data and rules for automating CNC programming. The proposed methodology has been applied for developing a IT system, able to capture the knowledge of the manufacturing engineers and experts in an analysed industrial context. Its main functionalities and fields of applications are described in the paper.

These results have been achieved during the Italian Research Project SPIA (Innovative Aeronautical Bearing Structures) by the researchers of the CORE Lab - University of Salento, by Enginsoft, a consulting firm in the field of Simulation Based Engineering Science (SBES), and by an Italian manufacturing company, operating in the aerospace industry. Project SPIA has aimed to improve dramatically production process performance through the design, development and testing of Smart Factory methods and technologies, such as the results treated in this paper.

The next section introduces the background of the research emerged in previous studies. A following section describes the research context in terms of research method and industrial setting. Then, a new procedure for manufacturing process design, based on KBE-FBM practices, and a tool supporting it, are described. A final section of conclusions ends the paper.

2. Background

Manufacturing engineers use CAD-CAM tool to program CNC machines. These systems were originally developed separately, with no apparent link between them (Groover and Zimmers, 1983). CAD is used during the design phase to create the part model, containing only geometric information, and this model is subsequently imported into the CAM environment and enriched with the technological information necessary for manufacturing. With the development and widespread use of CAD and CAM technologies in industry, their integration became increasingly important. The benefits of integrated CAD-CAM systems include decreased time to market, lower development and design costs and the ability of translating rapidly ideas into products (Hou and Faddis, 2006).

The demand of supporting and utilizing engineering knowledge beyond simple geometry has resulted in the introduction of the feature concept, that plays a key role in achieving CAD/CAM integration. A "feature" is a collection of topological and geometrical entities grouped together; engineers can link to them knowledge, in form of additional layers of information, useful for product design and for integrating it with downstream applications (Shah and Mäntylä, 1995) such as process planning. Different types of features can be classed into a matrix representation introduced by the FEature Modelling EXperts group "FEMEX" (Weber, 1996), that crosses the different stages of the product life-cycle with different classes of properties like requirements, geometry and tolerances and views of special features.

Despite two-decades of research on feature technology, researchers are still working on feature recognition, feature-based process reuse and on incorporating manufacturing knowledge, defining "Machining feature" as a combination of a feature and the manufacturing semantics (Li et al., 2012;

Borkar and Puri, 2015). A machining feature is typically defined as a collection of geometric elements which, as a whole, correspond to a particular machining method or process (Shah and Mäntylä, 1995). Features are also used for tolerancing (Weber et al., 1998) and Environmental Impact/Cost analysis attaching non-geometric data to the geometric model (Klette and Vajna, 2007; Gaha et al., 2015). Miao et al. (2002) instead demonstrated the use of features in automating process planning tasks, combining feature recognition and knowledge-based methods.

Typical machining features indicate machinable shapes, such as holes, slots and pockets (Hou, 2008). Regarding feature recognition, various approaches have been proposed in literature (e.g. Rahmani and Arezoo, 2006), however, the existing feature recognition technologies mainly focus on analyzing the geometric information of the mechanical part, ignoring the technological data (e.g. dimensional tolerance, geometrical tolerance, and roughness).

Huang et al. (2015), proposing a NC machining process reuse approach for similar subparts, have addressed the limit of current approaches. According to authors existing approach usually need the support of experts to construct the NC machining know-how database in advance, and the detailed process knowledge is always reused by manual editing and evaluating, which cause a lot of repetitive work and lower reuse efficiency. They concluded that there still exists no flexible and effective NC process reuse implementing approach to automatically evaluate and reuse the associated NC process of similar feature/subpart.

Some authors address the issue of CAD/CAM integration from the point of view of product data representation and knowledge exchange based on STEP standards, used as a transfer mechanism between different computer aided systems (Borkar and Puri, 2015; Danjou et al., 2016).

The scope of the Feature Based modules of modern CAM systems (e.g. Siemens NX CAM, Mastercam) is to make CNC programming even faster, easier, with a greater degree of standardization and of greater quality, because of few errors.

In CAx environment Knowledge Based Engineering (KBE) also plays a key role KBE is generally regarded as an umbrella term describing the application of knowledge to automate or assist the engineering tasks (Baxter et al., 2007). KBE is considered a valuable enabling technology for the next generation of design tools (La Rocca and van Tooren, 2012). The KBE systems (KBS) complement traditional CAD and CAM tools creating an efficient framework for capturing engineering knowledge and for integrating the entire design process in a single data model. Through KBE techniques, it is possible to organize data flows and architectures to implement effectively automated variant design solutions (Corallo et al., 2012).

(Wang et al., 2014) developed an intelligent CNC programming system proposing a method to establish standard process templates in which CNC machining process and process parameters were standardized by using this KBE system.

An interesting example of development of knowledge-based CAM system and methodologies is provided by the USQUICK project (Candlot et al., 2008; Harik et al., 2008). The project held in aerospace industry and based on Dassault Systemès CATIA V5 technological solution, aimed to translate, through methods and tools, the knowledge, expressed in the form of legacy specifications, for the development of CAM automations. The focus of the project was the knowledge capitalization process, i.e. the process of capturing and formalizing expertise before its implementation in an IT system. Manoharan et al. (2016) have instead shown how a manufacturing knowledge integration in CAD systems can support the planning and work preparation.

3. Research design

3.1. Research method

Starting from an exploration of the feature-based manufacturing issues in an Italian manufacturing company, in the paper is discussed the solution developed and applied to improve the whole manufacturing programming process. The main research questions that the authors want to address are: *How does a manufacturing company deal with the complexity of CAM programming automation? How can the complexity associated to the adoption of FBM technologies be decreased?*

These questions emerged as objective of an action research, conducted during the Italian Research Project SPIA, in which the University of Salento (CORE Lab) and Enginsoft were involved with a project industrial partner, operating in the aeronautical field. Action research is the act of making research for problem solving (Reason and Bradbury, 2001) and it is based on a learning by doing practices (O'Brien, 2001). In this study problems have been faced thanks to the collaboration among three teams (i.e. University researchers team, Enginsoft IT and mechanical engineers team, and the Manufacturing Company product and manufacturing process engineers and technologist team). During the study, there have been different moments of comparison among the team to collect experiences, evidences and feedbacks (Figure 1). The study is not aimed to build new theory but rather to discuss and share a real practice of particular relevance for the companies involved in the manufacturing field and develop an innovative solution for leading to optimized time and quality of new product development.

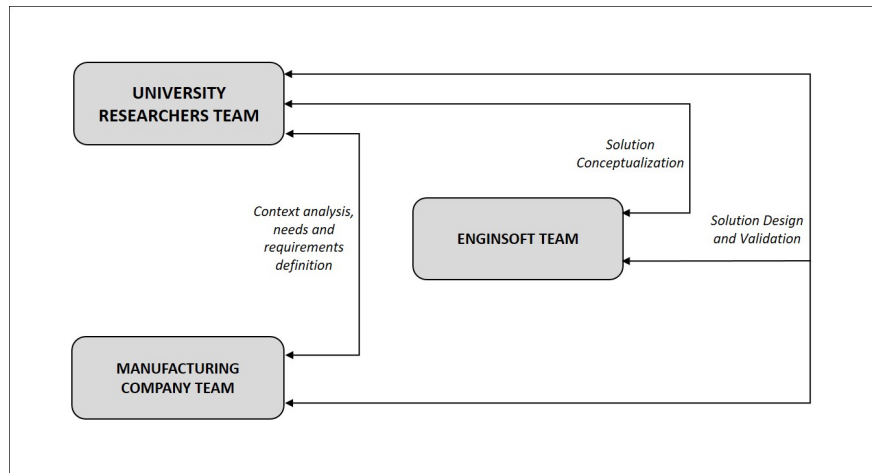


Figure 1. Action research phases of collaboration

A team of University researchers have analysed for several months the FBM activities in collaboration with the team of the industrial partner. These have included the study of the functionalities provided by NX FBM module (CAM tool used by the involved company), demonstrating the feasibility of using this technology in the manufacturing of one of the complex products designed by the company, and evaluating the limits of this solution. Key users from the engineering and the manufacturing departments were involved in the study and they identified the main problems and the desired requirements for a new tool. This preliminary exploration activities has led to analyse the CAM programming automation complexities and open issues in implementing FBM approaches and to define requirements for an easier and more effective implementation in the industrial scenario. The researchers team have later shared their experience with the Enginsoft team. This has lead to a new KBM methodology based on a software tool realized to overcome these limits that have been applied in an industrial case composed of features for milling and turning operations. For convenience to research context, the overall solution is named SPIA-KBM methodology and tool.

3.2. Industrial scenario

Engineering and manufacturing departments of the analysed company work in concurrency and use a PLM (Product Lifecycle Management) system to share data and information. Product engineering designs the product from the functional and the geometrical point of view, realizing the 3D model and the relative drafting. Manufacturing engineers, starting from the designed 3D model, develop and optimize machining cycles and cutting tools library and create the CNC part programs.

The company uses Siemens NX 10 as CAD-CAM system. Both manual and CAM programming methods are implemented for creating or editing part programs. The latter allows the following advantages: toolpath graphic check before real production, reduction of errors, possibility of adopting optimization criteria in the machining process, time reduction in the programming work, reduction of the machine tools downtime and simplification of part programs definition for geometrically complex products.

In traditional CAM programming, tool path are created manually step by step by the operator; after the first activity of workpiece definition, the engineer has to repeat some steps for each machining operation to be created: select geometry, select tool, specify cutting and non-cutting parameters, define feeds and speeds, add UDEs (User Defined elements), and finally generate the tool path. After creating the different operations, the manufacturing engineer simulate, verify and post process the tool path to obtain the NC-code.

The research activities, discussed in this study, focus on turning and milling operations. For both processes, the part CAD model, only containing geometric information, imported into the CAM and enriched with the technological information (e.g. Tolerances) needed to obtain the workpiece dimensions and the expected surface quality of the final product.

4. Results

4.1. The preliminary analysis of FBM context

The research project analyzed the potential of FBM approaches, demonstrating how they can significantly reduce the time needed to create NC programs, improving productivity, reducing the amount of mistakes and supporting the standardization of cutting tools and processes by automating tool paths generation thanks to geometric features recognition and best practices rules application.

Figure 2 represents an example of features and their parameters.

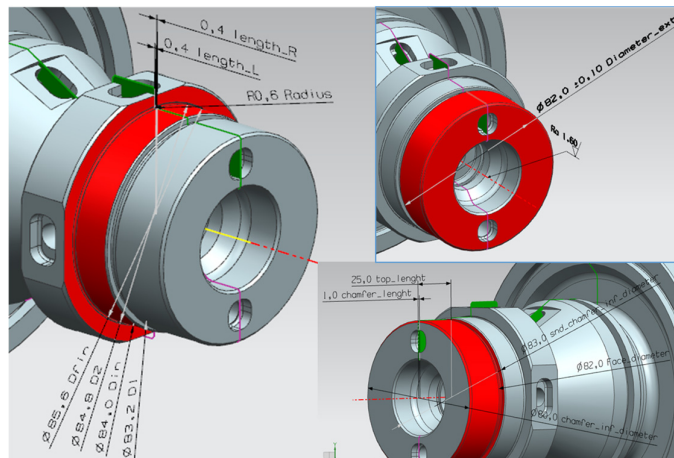


Figure 2. Features examples

The firm defined the requirements of the solution to be developed and the rules for machining processes creation. Thirty requirements have been defined on turning and milling facing, roughing and finishing operations, regarding: tolerances and roughness, tools choices, materials, machine parameters, etc. A simplified version of two requirements is reported in Table 1.

Table 1. Example of industrial requirements

<p>Requirement 1: Finishing tool selection For finishing operations, a tool with nose angle of 55° and nose radius ≤ 0.8 mm (selected according to the minimum radius on the cut region) must be used.</p>
<p>Requirement 2: Part material The system has to allow the operator to choose the part material. On the basis of part material, the part will be work differently in terms of cutting speed, feed rate and depth of cut.</p> <ul style="list-style-type: none"> For IRON: Cutting speed 150 SFM; Feed rate roughing 0,3 mmpr; Feed rate finishing 0,1 mmpr; Cut depth 2,5 mm; Cut depth finishing “all” For INCONEL: Cutting speed 35 SFM; Feed rate roughing 0,2 mmpr; Feed rate finishing 0,1 mmpr; Cut depth 1,5 mm; Cut depth finishing “all”

Among the thirty requirements faced during the study, the need to define rules easily customizable by the technologists was treated in an ad-hoc requirement.

Therefore, based on the elicited requirements, manufacturing rules have been defined in the Machining Knowledge Editor (MKE). It is an NX stand-alone application used by expert manufacturing engineers, with proper licensure and administrative rights:

- create and edit machining rules libraries;
- define in-process features;
- define the alternative processes to be used if the tool required for the preferred process is not available.

Nevertheless, using MKE (both to define and edit rules) requires computer and programming skills that, as emerged in the industrial scenario, a technologist might not have. Moreover, in their daily working practice, there is a need to easily customize the set of parameters within the rules (e.g. feed cut, spindle maximum RPM, etc.). The standardization required by MKE is perhaps too rigorous for real industrial machining practices, in which the expertise of the manufacturing engineers is the determiner of tool path quality and needs more flexibility of adaptation to the context.

The current FBM approaches require the definition of machining rules developed by CAM programmers. For different reasons, these rules often require to be modified according to operational needs. It was therefore necessary a data and manufacturing rules management environment, in which knowledge engineers can define the rules, on the basis of industrial best practices, and CAM technologists can customize them for production requirements.

4.2. The SPIA KBM methodology

Considering the preliminary analysis described in the previous section, for simplify and structure this process, it has been formulated and proposed the "SPIA - *Knowledge-based Manufacturing methodology*" (SPIA - KBM), supported by a new tool (KBM tool) for data and manufacturing rules management.

Before to define the KBM methodology, a classification of manufacturing process participants according to their competences and according to their role in the process has been realized. Three categories are therefore defined:

- **Manufacturing Knowledge Engineer:** Super-user (i.e. characterized by a deep expertise in the product manufacturing processes) that can modify machining rules and develop new ones based on company best practice, using NX-MKE. Adding specific comments to the MKE code, he also defines which rules parameters are editable by CAM Experts (i.e. exposed parameters). Even if, editing machining and mapping rules does not require knowledge or skills in specific languages (e.g. C or C++), he must have programming skills.
- **CAM Experts:** Technologists that, for temporary needs related to specific operations, can edit the defined rules entering custom values for the exposed parameters (i.e. speeds, feed rate, tool, starting point of the tool, etc). In the developed KBM tool, different professional experience levels are also defined: senior technologists (level 5) can edit all the exposed parameters while other users, with a lower level, can edit only a subset of parameters (level 1 correspond to a new hire).
- **CAM Operators:** They use the customized rules to generate toolpath in NX-CAM.

In Figure 3 the new SPIA-KBM Methodology is represented. It is composed by three main phases.

- **PHASE 1 - Defining standard rules.** The Machining Knowledge Engineer defines machining standard rules, by means of NX-MKE, and the relevant editable parameters (exposed parameters).
- **PHASE 2 - Customizing standard rules.** The CAM Expert, in order to fit operational needs, customizes machining standard rules editing only the values of the exposed parameters, by mean of the KBM tool.
- **PHASE 3 - Using customized rules.** The CAM Operator uses the custom rules to generate, by mean of NX-CAM, the tool path and subsequently the NC-program.

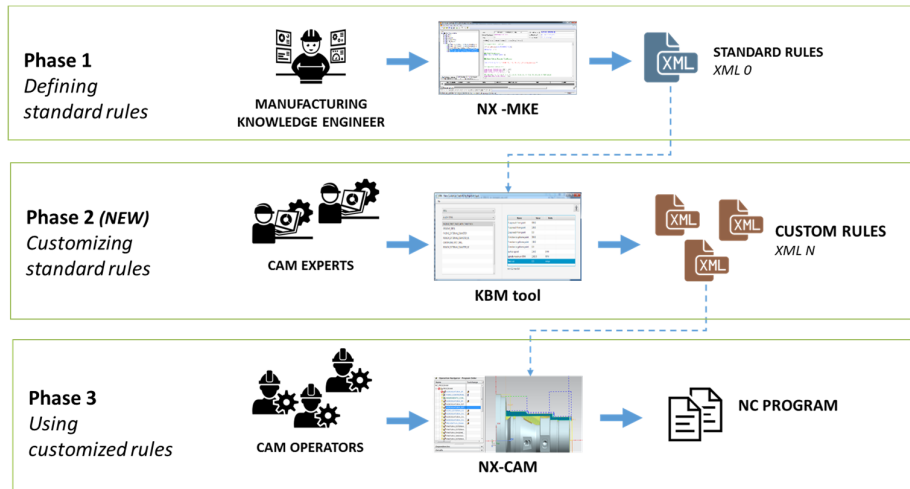


Figure 3. Phases of SPIA-KBM methodology

The standard rules defined by the Manufacturing Knowledge Engineer are saved in an XML file managed by NX and MKE. Any change made by CAM Experts to this file, using the developed KBM tool, generates new XML files, whose owners are the CAM Experts; they are finally used by CAM operators for NC machines programming.

The standard FBM process made available with the out-of-the-box CAM software results not applicable in the real industrial scenario, because standard rules do not permit to manage exceptions (e.g. unavailability of a specific cutting tool or of a specific CNC machine). These considerations have guided the design of the proposed methodology and the addition of PHASE 2 to the FBM process; it facilitates the customisation of rules when specific production needs arise (very frequently in real industrial environments).

4.3. The proposed tool

As described in the methodology, the CAM Experts have to change the values of the rules exposed parameters in order to adapt them to the specific operating conditions and needs. This task has to be extremely easy to use and able to show, to technologists, only the strictly necessary information (editable parameters). For supporting, the methodology implementation, a tool has been realized that allows CAM experts to easily customize the rules defined by the Manufacturing Knowledge Engineer by mean of the NX MKE. The tool is very easy to use and install, and has been developed to communicate, in input, with NX-MKE, in order to read the defined rules, and in output with NX-CAM, in order to send customized rules, defined by technologist. It allows the management of the customized rules as well as of user profiles. Furthermore, to implement the KBM methodology, in the tool a method to characterize editable parameters has been defined: by mean of a specific syntax, the XML files can be enriched with zero or more exposed parameters and each of them can be associated to a minimum CAM expert level required to access and edit it.

In NX-MKE, each rule is written, by the Manufacturing Knowledge Engineer, through a specific programming language. A new syntax, that uses NX-MKE comment lines (identified by prefix keyword "REM") has been used to add information before the editable parameter. These lines are recognized and interpreted by the KBM tool.

Each comment line is composed by the following elements:

1. *Nicename*: unique self-explanatory name of the parameter;
2. *User level*: minimum user professional level necessary to fix custom parameter value;
3. *Comment*: comment string containing useful information for the CAM Experts (optional);
4. *Bounds*: boundary values accepted for the parameter (optional);
5. *Unit*: unit of measurement (optional);
6. *Value*: the standard value of the parameter that can be edited by the CAM Expert.

```
REM VAR <USER_ACCESS_LEVEL: Int> <NICE_NAME: String> <COMMENT: String>  
<UNIT_OF_MEASUREMENT: String>
```

For instance, the Figure 4 shows the annotated NX MKE code developed for a turning operation: finishing external diameter with undercut. It can be noticed that this code is compliant with requirements of Table 1, regarding respectively the selection of the tool and the definition of the cutting parameters according to the part material.

```

1. REM tool criteria
2.   tool.'(A) Nose Angle'=55
3.   tool.'(OA) Orient. Angle'=32
4. REM VAR 1 "tool radius" "according to minimum radius on cut region" "mm"
5.   tool.'(R) Nose Radius' <= 0.8
6. REM Less Worked Feature Criteria
7.   lwf.MACHINING_RULE = "FINISH_EXTERNAL_DIAMETER_WITH_UNDERCUT"
8. REM Operation Attributes
9.   oper.Spindle_Mode = "SFM"
10. REM VAR 1 "surface speed" "min 120 max 200" "SFM"
11.   oper.Surface_Speed = 150.0
12. REM VAR 1 "spindle maximum RPM" "selection based on machine type" "RPM"
13.   oper.Spindle_maximum_RPM = 1500.0
14. REM VAR 1 "feed cut" "min 0.2 max 0.4" "mmpr"
15.   oper.Feed_Cut = 0.2

```

Figure 4. Annotated NX MKE code (example)

Once editable parameters have been defined by the Manufacturing Knowledge Engineer, by means of comment lines (in green), and are recognized by the tool, they are exposed to the CAM Expert through the KBM tool user interface represented in Figure 5.

The CAM Expert must login using the system (section 1 in Figure 5). Then he selects the XML file to edit (section 2) and, through drop down menus, the rules sub-set (section 3) and the part material (section 4). All the rules, defined for that material, are shown (section 5). Selecting a specific rule, the parameters editable, filtered according to CAM Expert professional experience level, are exposed (section 6). For each parameter, if previously defined by the Manufacturing Knowledge Engineer, a comment is visible in the lower part of the window (section 7). It is important to notice that the XML file, that can be chosen (section 2), is the standard one or an already customized version of it.

The tool has been developed and tested collaborating with company engineers and technologists. The test in the industrial scenario has shown quantitative benefits in terms of time and cost savings, that can be maximize upon completion of the rules database, but also qualitative, in terms of the degree of standardisation obtainable and codification of the tacit knowledge of experienced engineers. The proposed methodology is considered very suitable for the type of processes and products that characterize the company involved in the project.

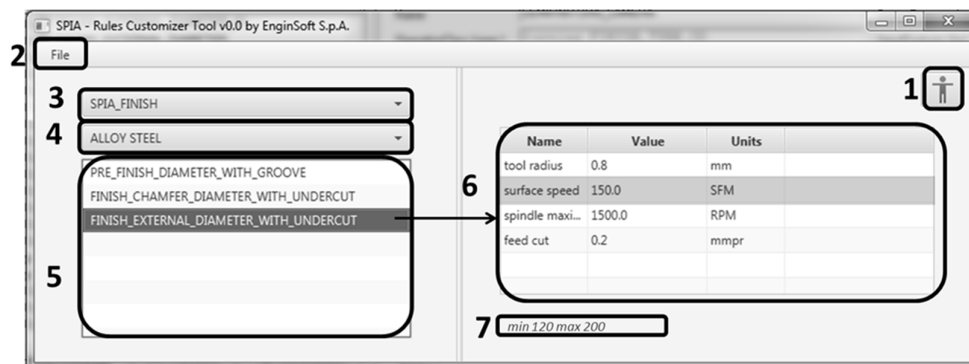


Figure 5. SPIA-KBM tool user interface

5. Conclusions

The aim of the research activity has been to define, implement and test a Knowledge Based Manufacturing methodology, and a supporting tool, that could improve the management and customization of machining rules. Following an action research approach, the industrial practices has been at the centre of the study and the collaboration among the different teams has been very intensive

with different and continuous feedbacks. The whole study has been lead by the concrete need to develop a solution for a concrete industrial problem.

The results do not propose an amendment of the company modus operandi, but they offer a new procedure and a tool that supports engineers and technologists, facilitating and speeding up their daily work. The different industrial roles involved, who contribute to the definition of the rules, their customization and their current use in manufacturing activities, and the proposed new operating process, are compatible with professionals and procedures of the industrial partner.

The main benefits achieved by the research are the reduction of complexity in adopting FBM tools, and the overcoming of some of their limitations. In particular, referring to the industrial company involved, the ability to customize machining rules parameters, not implemented in the out-of-the-box adopted software (Siemens NX), fostered the industrial use of Feature Based Manufacturing approaches.

Even if results have been developed in a NX-centered scenario, the proposed methodology is general for each manufacturing industry where FBM problems are faced and its implementation could be performed in every company adopting a CAD-CAM-CNC tools chain eventually using also standards for product data exchange.

The generalization of the SPIA-KBM methodology will be also further investigated in future researches in order to propose a complete set of procedure platform independent and detailed for each possible case of application. About the tool, in the next research, it will also be exploited a function to check the customized parameters.

Currently, SPIA-KBM solution composed by the methodology and tool is still at a prototype stage, but the industrial company is evaluating to adopt it in a real working operative contexts.

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References

- Baxter, D., Gao, J., Case, K., Harding, J., Young, B. et al. (2007), "An engineering design knowledge reuse methodology using process modelling", *Research in Engineering Design*, Vol. 18 No. 1, pp. 37-48. <https://doi.org/10.1007/s00163-007-0028-8>
- Borkar, B.R. and Puri, Y.M. (2015), "Automatic extraction of machining features from prismatic parts using STEP for downstream applications", *Journal of The Institution of Engineers (India): Series C*, Vol. 96 No. 3, pp. 231-243. <https://doi.org/10.1007/s40032-015-0171-3>
- Candlot, A., Perry, N., Bernard, A. and Ammar-Khodja, S. (2008), "Case study, usiquick project: Methods to capitalise and reuse knowledge in process planning", In: Bernard, A. and Tichklewitch, S. (Eds.), *Methods and tools for effective knowledge life-cycle-management*, Springer, Berlin, Heidelberg, pp. 487-506. https://doi.org/10.1007/978-3-540-78431-9_28
- Corallo, A., Margherita, A., Pascali, G. and Turrise, G. (2011), "Optimising the design of gearshafts with Knowledge-Based Engineering (KBE): an application to aircraft engines", *International Journal of Product Development*, Vol. 13 No. 3, pp. 185-203. <https://doi.org/10.1504/IJPD.2011.040266>
- Danjou, C., Le Duigou, J. and Eynard, B. (2016), "Manufacturing knowledge management based on STEP-NC standard: a Closed-Loop Manufacturing approach", *International Journal of Computer Integrated Manufacturing*, Vol. 30 No. 9, pp. 995-1009. <https://doi.org/10.1080/0951192x.2016.1268718>
- Evans, K. (2016), *Programming of CNC Machines*, Industrial Press, New York.
- Gaha, R., Benamara, A. and Yannou, B. (2015), "An environmental impact/cost model for evaluating multiple feature-based machining methods", *Proceedings of CMSM'2015 / the 6th Conference on Design and Modeling of Mechanical Systems, Hammamet, Tunisia, March 23-25, 2015*, Springer, Cham, pp. 21-27. https://doi.org/10.1007/978-3-319-17527-0_3
- Groover, M. and Zimmers, E. (1983), *CAD/CAM: computer-aided design and manufacturing*, PTR Prentice Hall, Upper Saddle River, New Jersey.
- Harik, R.F., Derigent, W.J. and Ris, G. (2008), "Computer aided process planning in aircraft manufacturing", *Computer-Aided Design and Applications*, Vol. 5 No. 6, pp. 953-962. <https://doi.org/10.3722/cadaps.2008.953-962>
- Hou, M. and Faddis, T.N. (2006), "Automatic tool path generation of a feature-based CAD/CAPP/CAM integrated system", *International Journal of Computer Integrated Manufacturing*, Vol. 19 No. 4, pp. 350-358. <https://doi.org/10.1080/09511920500504354>

- Huang, R., Zhang, S., Xu, C., Zhang, X. and Zhang, C. (2015), "A flexible and effective NC machining process reuse approach for similar subparts", *Computer-Aided Design*, Vol. 62, pp. 64-77. <https://doi.org/10.1016/j.cad.2014.10.004>
- Klette, G. and Vajna, S. (2007), "A knowledge based framework to estimate manufacturing complexity of machined parts based on early design concepts in CAD systems", *Proceedings of ICED'07 / the 16th International Conference on Engineering Design, Paris, France, August 28-31, 2007*, The Design Society, Glasgow.
- La Rocca, G. and van Tooren, M. (2012), "Knowledge based engineering to support complex product design", *Advanced Engineering Informatics*, Vol. 26 No. 2, pp. 157-158. <https://doi.org/10.1016/j.aei.2012.02.008>
- Li, P., Hu, T.L. and Zhang, C.R. (2012), "Development of an ontology-based and STEP-compliant intelligent CNC system", *Applied Mechanics and Materials*, Vol. 141, pp. 251-257 <https://doi.org/10.4028/www.scientific.net/AMM.141.251>
- Manoharan, T., Humpa, M., Martha, A. and Koehler, P. (2016), "Knowledge integration in CAD-CAM process chain", *Computer-Aided Design and Applications*, Vol. 13 No. 5, pp. 729-736. <https://doi.org/10.1080/16864360.2016.1150720>
- Miao, H., Sridharan, N. and Shah, J. (2002), "CAD-CAM integration using machining features", *International Journal of Computer Integrated Manufacturing*, Vol. 15 No. 4, pp. 296-318. <https://doi.org/10.1080/09511920110077502>
- O'Brien, R. (2001), *An overview of the methodological approach of action research*. [online] Rory O'Brien. Available at: <http://www.web.ca/~robrien/papers/arfinal.html>
- Rahmani, K. and Arezoo, B. (2006), "Boundary analysis and geometric completion for recognition of interacting machining features", *Computer-Aided Design*, Vol. 38 No. 8, pp. 845-856. <https://doi.org/10.1016/j.cad.2006.04.015>
- Reason, P. and Bradbury, H. (2001), *Handbook of action research: Participative inquiry and practice*, Sage, London.
- Shah, J.J. and Mäntylä, M. (1995), *Parametric and feature-based CAD/CAM: concepts, techniques, and applications*, John Wiley & Sons, New York.
- Wang, L.Y., Huang, H.H., West, R.W. and Wang, D.Z. (2014), "Intelligent manufacturing system of impeller for computer numerical control (CNC) programming based on KBE", *Journal of Central South University*, Vol. 21 No. 12, pp. 4577-4584. <https://doi.org/10.1007/s11771-014-2463-9>
- Weber, C. (1996), "What is a feature and what is its use?-Results of FEMEX Working Group I", *Proceedings of ISATA 96 / the 29th International Symposium on Automotive Technology and Automation, Florence, Italy, June 3-6, 1996*, Automotive Automation Limited, Croydon, UK, pp. 287-296.
- Weber, C., Thome, O. and Britten, W. (1998), "Improving Computer Aided Tolerancing by using Feature Technology", *Proceedings of DESIGN 1998 /the 5th International Design Conference, Dubrovnik, Croatia, May 19-22, 1998*, pp. 117 – 122. <https://doi.org/10.22028/D291-22459>

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