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DECOMPOSITION OF KNOWLEDGE FOR AUTOMATIC PROGRAMMING OF CNC MACHINES

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ABSTRACT
In the era of Industry 4.0, the automation of processes in the life cycle of a product seems to be a necessity. Although programming CNC machines with CAM systems make it possible, it is necessary to effectively acquire knowledge about the programming process and technological requirements for effective automation. The paper presents a method for decomposition of knowledge about the CNC machine programming process based on acquiring knowledge from various sources, both from technologists as well as on the basis of analysis of archival CNC control programs. To decompose the programming process, it is proposed to apply the knowledge model described by various attributes. Verification of the method is shown in the process of knowledge decomposition for manufacturing special production tooling.

KEYWORDS
Computer Aided Manufacturing, CNC programming, knowledge-based engineering, acquisition of knowledge.

Introduction

Complete and proper implementation of modern, integrated CAD/CAM programs is of particular importance for the enterprises dealing with mass production of products, that are similar but are of diverse characteristics at the same time. An example of such a process can be the production of automotive parts, where very similar components, having the same purpose, may differ from each other due to different variants of the vehicle [1]. It is similar in many other industries, such as household appliances, sanitary or consumer electronics, where many companies can be examples of implementing the strategy of mass customization in practice [2, 3]. In order to increase efficiency in the field of design and manufacturing processes, intelligent IT solutions are implemented. They allow to flexibly respond to customer requirements on the one hand and to maximize the standardization of technical solutions on the other [4]. Possibility to produce products in many different variants has a significant impact on the de-

sign and production process not only of individual product components but also dedicated tooling for production [5, 6].

Tooling for production is various technical tools that complement the equipment of production machines necessary to manufacture specific products or perform a given operation. According to their purpose, universal (general-purpose) and special (dedicated to specific machines, processes, products) can be distinguished. The process of manufacturing special tooling is most often an example of MTO (*Make to Order*) production, and more precisely one of its types – ETO (*Engineering to Order*) [7], which is a custom process, where the design of the tooling is based on digital or real product model, delivered by the ordering. In the context of the mass customization (many variants of the product), the design and manufacture of special tooling for production can be optimized through the use of advanced IT solutions developed in an integrated CAD/CAM system [8–10]. However, without a proper approach to the management process of specialist engineering

knowledge, such solutions are developed ad hoc and become not as effective as they should be.

The purpose of this work is to present the use of decomposition method for acquisition and arrangement of specialist engineering knowledge in the field of CNC machine programming with the aim of developing an automated solution in an integrated CAD/CAM environment in the future.

CNC programming in a CAM system

The process of programming CNC machine in the CAM program is carried out with a view to starting it on a specific CNC machine, where the selected part will be manufactured [11,12]. Basic settings for the program are related to machine parameters, such as the number of controlled axes, the size of the working space, shifts in individual axes, etc., which will be very important for correct launch program on the machine. Regardless of the type of CAM software, the process of program preparation can be divided into tasks related to (Fig. 1):

1) definition of the shape of the workpiece,
2) determining the next machining operations,
3) simulation and verification of the machining program.

In the beginning, general geometric features are defined, i.e. the shape of the design part and the shape of the stock, from which part will be made. The user of the CAM program must define the co-ordinate system for the machining process with zero point for proper orientation the workpiece in the working space of the CNC machine (Fig. 1 I-II).

The main tasks of the programming process are related to the detailed course of subsequent machining operations, depending on the complexity of the object and its size. In individual machining operations the engineer specifies (Fig. 1 IV):

- specific geometric elements of the CAD model for machining (planes, edges, points),
- type and features of the machining tool,
- machining strategy that determines the path of the machining tool,
- detailed values of the operation parameters (speed, paths of input/output of the machining tool in relation to the workpiece).

The above activities require preliminary verification and evaluation in the CAM program (in order to detect possible errors in operations definition). Then, in the structure of the machining program, the tool path for a particular operation is generated and saved. This process is repeated for each operation separately, taking into account the geometric changes resulting from the previously generated operations. Finally, a simulation of the entire process is carried out (Fig. 1 V), and if the program requires corrections, the necessary changes are introduced in the selected operations. After verification, using a special translator (postprocessor code) creates an NC code that will be implemented in a particular CNC machine (Fig. 1 VI).
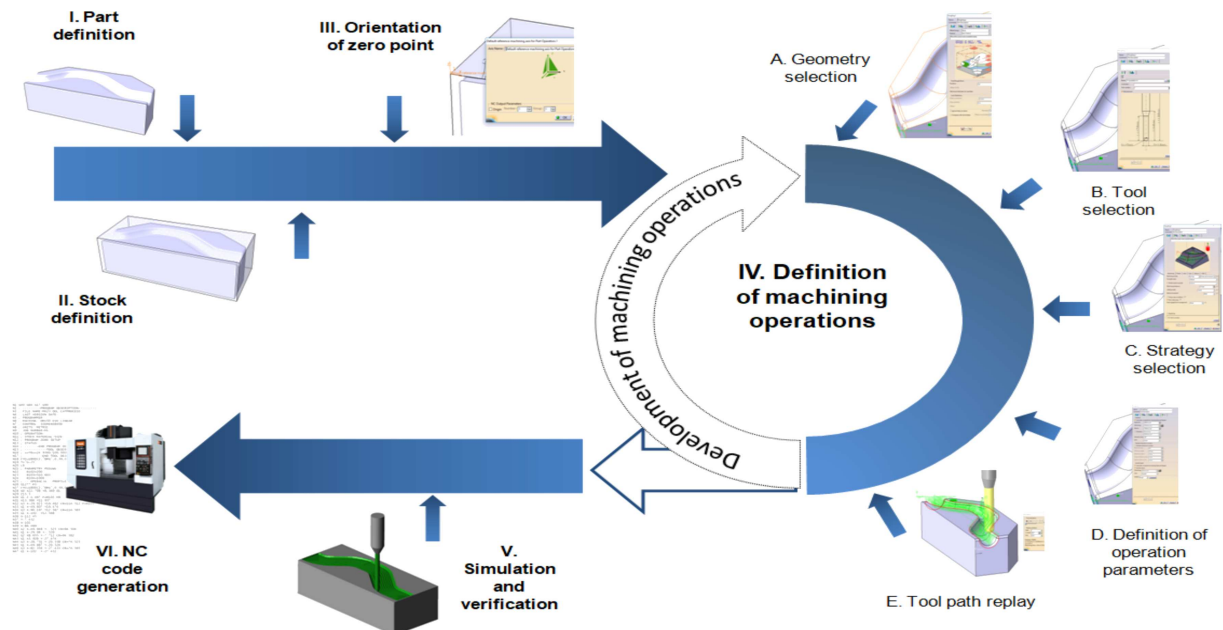

Fig. 1. Preparation of manufacturing program for CNC machine in CAM system.

Programming of CNC machines for manufacturing special production tooling in most cases requires programming in CAM systems. This is related to the level of complexity of the shape of the machined surfaces, which are closely related to the shape of the final products, manufactured by them. For example – nowadays, only CAM programs allow programming of CNC machines operating in many axes.

Special production tooling dedicated to specific product groups are characterized (like these products) by their variability. This means that, despite significant differences in their structure, they are also similar to each other to a large extent. Due to the fact that the machine programming process in CAM systems is a time-consuming and expensive process (requires highly qualified personnel), in the Industry 4.0 era automation of this process becomes one of the main aims [13–16]. Integrated CAD/CAM systems offer some predefined solutions that enable automation of CNC programming based on searching for specific geometrical features of the object. After recognizing them, the CAM program, according to of the previously saved logical rules, selects the appropriate type of operation, strategy and tool for processing the recognized feature [17–19].

Unfortunately, methods of automation of such type are limited only to 2.5D machining, which in industrial practice does not allow automating the process of generating the entire program, but only its fragments. In addition for the development and recording of all rules (logical expressions, mathematical relations), which form the foundation of automation, the appropriate, general and specialized knowledge is necessary (including the process, the product, and machines). Issues related to the acquisition and processing of knowledge for the needs of engineering work are discussed in the context of the construction of solutions known as Knowledge Based Engineering [20–22]. However, there are no methods supporting specifically the process of acquisition and implementation of knowledge about the technological process for effectively support the automation of programming CNC machines in the CAM system.

Knowledge Based Engineering methods

The most important reason for the construction of the KBE system is primarily the opportunity to rationalize the design process. It is estimated that about 80% of the design time concerns routine tasks [23, 24], which acceleration can significantly affect the optimization of the entire life cycle of the product. Therefore, the basic advantage of using KBE

solutions is the ability to automate repetitive design work [6], while at the same time increasing the ability to implement creative works [25].

Despite the fact that the KBE solutions are widely used in practice, about 80% of them are prepared in an ad hoc manner [5]. They are built to solve a specific problem and are unsuitable for reuse. It happens, despite existing standards, aimed at organizing the knowledge processing processes. In addition, based on the literature analysis, it can be stated that in the field of building KBE solutions more attention is devoted to the development of the product and not the technology of its production. There are no methodical models supporting processes such as CNC machine programming. There are some methodologies of KBE system, aimed at supporting the engineering design process for that. Two of them are presented below:

- MOKA (*Methodology and software tools Oriented to Knowledge based engineering Applications*),
- MDAVP (*Methodology of Design Automation of Variant Products*).

The MOKA methodology was developed in order to support the construction of engineering KBE systems focusing on design-construction process [23]. The authors have singled out six stages in the creation of this application although the proper application of this methodology encompasses only two of them: knowledge acquisition and knowledge formalization [26]. Knowledge structuralization is carried out on two prepared models: informal and formal. The former is based on special ICARE forms (Illustration, Constraints, Activities, Rules, Entities) and is used to gain and decompose knowledge into basic components. The latter is designed to build knowledge bases and assumes the application of MML language (*Moka Modelling Language*) to prepare a formal description of the product and the process for the application that is being built.

MOKA methodology is recognized as a standard in the process of collecting and recording knowledge for the needs of building KBE systems for industrial applications. However, it is not orientated to cooperate with any CAx systems. Its most valuable advantage is the concept of ICARE forms which enable the organization of technical knowledge in a user-friendly way. The fact that it is excessively product-orientated and much less to the process itself [25, 27], and that it supports solely the work performed by knowledge engineers, disregarding future system users, are seen as its disadvantages.

The MDAVP methodology was based on the MOKA methodology guidelines and is a certain extension of it. The objective of MDAVP methodology is

to support designers and builders of IT systems to enable the users (constructors and manufacturer's clients) to configure a product variant followed by automated, i.e. without resorting to direct CAD operation, development of design documentation [28].

The development of the methodology had the following assumptions:

- it is dedicated to product variant design in situations when each new variant must be accompanied by design documentation,
- configuration of product variant may involve its user,
- methodology should be recorded in the form of a procedure,
- methodology should offer tools indispensable for acquisition of knowledge about design process,
- construction of automated design process requires qualifications in CAD operation (building generative CAD model), in programming (preparation of service interface) as well as in construction of database (building knowledge base).

In MDAVP methodology the following phases of building a KBE system can be identified:

- identification,
- knowledge acquisition,
- project of a system,
- building system components,
- implementation.

Knowledge acquisition is carried out separately for each product variant that is selected for analysis by means of re-creation and recording (in forms for each stage, task, parameter, and parameter and relation) of a detailed course of its design (CAD modeling). To that end, information about individual tasks carried out at each, previously identified stage of that process is recognized. This is followed by description of each task by indicating the parameters applied and the relations between them. Knowledge base built in this way will enable re-creation of the topology of the analyzed CAD models and verification of the collected data.

The methodologies quoted above are not focused on the automation of the process of CNC machine programming and for this reason building such solutions force specialists to take for ad hoc solutions, what are usually not effective. The automation tasks in CAM programs use various tools (program functions) that require gathering more or less complex knowledge. The essence of this record must be characterized by both - universality (meaning the possibility of applying to all variants) as well as detail knowledge (include descriptions of exceptions, case studies, etc.) [29, 30]. According to that effective work on automation requires to efficiently acquire of knowledge about the CNC machine programming process (detailed data and information) for a given organization, and then organize and evaluate it. For this purpose, it is proposed to use the method of decomposition of knowledge.

Decomposition of CNC programming knowledge

The method of gathering knowledge proposed in this work consists in gathering specialist knowledge and general knowledge in the field of CNC machine programming, assuming the context of a specific company and a specific technological process. The accumulation of knowledge takes place through the decomposition of the programming process (its division into components). It is assumed that the knowledge base developed in this way will be translated into a language comprehensible to the CAM program in the further stages of the development of automation.

The method of decomposing knowledge about the CNC machine programming process is based on acquiring knowledge from various sources, both from technologists as well as on the basis of analysis of archival CNC control programs (based on code analysis). To decompose the programming process, it is proposed to apply the knowledge model described by the following attributes:

A. **Area of process input data**

1) CNC machine
    - number of machine axes,
    - the size of the workspace,
    - shifts in individual axes,
    - type of control;
2) Definition of the workpiece
    - workpiece geometry;
3) Definition of the stock
    - stock geometry,
    - position of the stock in relation to the workpiece;
4) Definition of the position of the worpiece in the machine workspace
    - position of the workpiece coordinate system (X, Z axes);
5) Definition of fixing the stock in the machine workspace
    - fixing geometry;
6) Definition of a safety plane.

B. **Area of technological operation data**

1) The type of machining operation;

2) Selection of machining strategy (tool movement, machining direction);

3) Selection of geometry;

4) Selection of the machining tool (type, holder, dimensions);

5) Definition of cutting parameters (depth, width, speed, feed);

6) Generating the tool path.

C. **Area of simulation and verification data**

1) Simulation of the machining process;

2) Verification of the machining process;

3) Implementation of changes and necessary corrections.

D. **Area of the NC code generation data**

1) Selection of the postprocessor;

2) Determination of postprocessor parameters;

3) Creating the NC code.

Case study – tooling for manufacturing plastic pipes

The family of products was selected for the verification of method of decomposition process – special tooling for the production of plastic pipes, in particular – for fixing dedicated connectors. The product family consists of several dozens of such matrices. Examples of matrix variants are shown in Fig. 2.
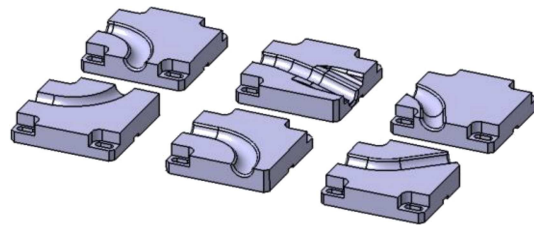

Fig. 2. Examples of variants of the matrix.

Table 1
Collected and ordered knowledge of the area of technological operations for a selected tooling family.

B. Area of technological operation data			
No	Machining operation	Attributes	Description
4	Tube mounting surface (roughing)	The type of machining operation	Roughing
		The strategy of the tool	Helical
		Milling direction	Climb
		Geometry selection	According to 3D model
		Machining tool	End mill 10 mm, torus KOMET F154D 78921011331000
		Holder type	Hydraulic holder Eroglu 403.65.10.80
		Dimension of the tool	Based on the producer's data
		Depth of cut	0.5 mm
		Cutting width	10 mm
		Cutting speed	80 m/min
		Feed speed	0.06 mm/tooth
		Generating the tool path	According to CAM
5	Tube mounting surface (finishing)	The type of machining operation	Finishing profile contouring
		The strategy of the tool	Back and forth
		Milling direction	Unlimited
		Geometry selection	According to 3D model
		Machining tool	End mill ball-end 6 mm KOMET F344D 78954010020600
		Holder type	Hydraulic holder Eroglu 403.65.10.80
		Dimension of the tool	Based on the producer's data
		Depth of cut	According to assumed offset
		Cutting width	0.15 mm
		Cutting speed	120 m/min
		Feed speed	0.06 mm/tooth
		Generating the tool path	According to CAM

Despite the similarity in the scope of functions and dimensions, the variants of the presented tooling differ in a quite significant range – the geometry of the die seat. This is related to the shape of the pipes for which they are prepared and the characteristics of the technological process of assembling the connectors. Matrices are produced in the milling process on CNC machines and from the point of view of this process, the NC code for each variant must be prepared by a specialist separately. In practice, the machine programming process is carried out in the CAM program. The repeatability of the programming tasks is, however, high and therefore the automation of these activities is possible. It is assumed that intelligent CAM solution with aided of knowledge base will bring significant time savings, which is very important in the case of a time-consuming programming process.

Following the methodology of MOKA and MDAVP, special forms were prepared to acquire knowledge about the technological process for the presented tooling. Forms were prepared based on the attributes presented in the knowledge decomposition method. The result is a knowledge base, a fragment of which is shown in Table 1.

The obtained knowledge in a comprehensive and unambiguous way describes the machining process of these parts and will allow to prepare a template for the machining process of the dies. Such template will be implemented in automatic CAM system to create NC machining programs.

Conclusions

In the era of Industry 4.0, the automation of processes in the life cycle of a product seems to be a necessity. Although programming CNC machines with CAM systems make it possible, it is necessary to effectively acquire knowledge about the programming process and technological requirements for effective automation. The method presented in the article makes it possible to acquire specialized, often hidden knowledge, its unification and verification. The developed knowledge base is also a guarantee of securing the know-how developed in the company.

The results of the described works (knowledge base) will be implemented in special templates of machining processes in the CAM program (the equivalent of generative CAD models). It is assumed that CAM process templates will significantly reduce the time needed to prepare machining programs, automating repetitive activities in the technologist's work. Shortening the programming time will therefore reduce the costs of implementing the CNC machine programming process. It is also assumed that the implementation of verified knowledge will contribute to the minimization of errors made at the stage of machining programming.

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