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KNOWLEDGE BASED ENGINEERING AS A CONDITION OF EFFECTIVE MASS PRODUCTION OF CONFIGURABLE PRODUCTS BY DESIGN AUTOMATION

The paper presents possibilities of improving design and manufacturing preparation processes of configurable (variant) products in scope of realization of mass customization strategy. Knowledge based engineering tools are presented as a base for building systems for automation of design and manufacturing preparation. Methodologies of building KBE systems are presented and described, authors' own methodology is presented along with selected cases of its use. It is proven that reduction of time needed for design and manufacturing preparation can be vast, justifying use of KBE systems as a way of manufacturing optimization of configurable products.

1. INTRODUCTION

Production companies use various strategies while competing for a strong position in the market. One of them is readiness to fulfill individual needs of clients. This strategy is known as the mass customization (MC) [1]. The mass customization idea was described as early as at the end of 70s and the beginning of the 80s of the 20th century, but it is still up-to-date, especially in context of a developing concept of fourth industrial revolution, known widely as the Industry 4.0 [2]. One of the first technical solutions, based on mass customization assumptions was presented by the Dell company. Dell started to supply its clients with personal computers configured individually in the beginning of the 90s [3]. Nowadays, similar forms of cooperation are known in almost each branch, starting from promotional gadgets, through clothing design, interior equipment and decoration, to automotive products. Such an approach can significantly improve competitiveness of a company [4],[5]. In literature, examples of implementation of the MC strategy can be found among branches such as the food industry [6], electronics [7], engineering [8] or cellular telephony [9]. Fogliatto and co-authors [10] claim, that development of the mass customization strategy in the last decade was heavily influenced by simultaneous

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development of the Rapid Manufacturing technologies and growing popularity of web-based product configurators. Such configurators allow the recipients themselves to shape a particular product variant.

Variant possibilities	Production capabilities: low	Production capabilities: high
high	*Piece production (on order)*	*Mass customization*
low	*Small series production*	*Mass production*

Fig. 1. Place of mass customization among traditional production types

Mass customization combines advantages of piece and mass production (Fig. 1). Its implementation is very attractive from the recipient's viewpoint, but it is very difficult for a production company and has a certain risk of failure, especially as a result of increasing costs of design and manufacturing. As opposed to mass production, which means manufacturing repeatable (and usually identical) products in high amount, the mass customization allows to fulfill expectations of each client as regards a given product, known as a configurable or variant product. It does so by adjusting the product to his individual needs. The "mass" aspect is therefore considered as a potential to fulfill a certain need, not real fulfillment (Fig. 2). The mass production and the mass customization have a common trait – a need for presence of appropriate production capabilities in a company.

The mass customization is a competitive strategy as long as a company is able to quickly react to clients' expectations and requirements. In other words, a company must expand the mass customization with another strategy, known as the Quick Response. Such a connection is perfectly possible, if the company has a flexible manufacturing system and a possibility of rapid design (in terms of duration) and implementation of products and their manufacturing processes.

A measure of flexibility of a manufacturing system is its capability of performing various tasks, as well as time at which it can be prepared for a new task (the shorter the better). Rapid design of a product means automated (or partially automated) design, while rapid implementation is connected to the notion of Rapid Manufacturing (RM). A scheme in the Fig. 2 shows, that if these factors – flexibility or automation – are not developed enough, it is difficult to realize the Quick Response aim. In case when flexibility of a manufacturing system is low, while automation design level is high, rapidly designed products have to wait for their turn to be produced. If, on the other hand, the design automation level is low, high flexibility of a manufacturing system will make it not fully loaded. In both cases, time of a customer waiting for the product (the Customer Lead Time) is prolonged and may be unacceptable.

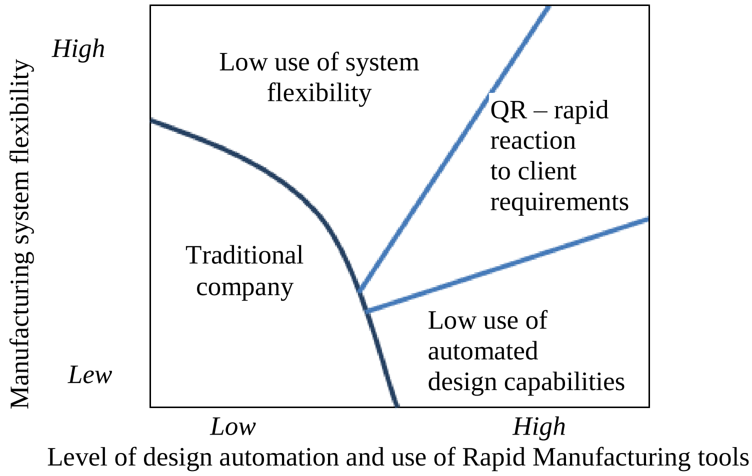

Fig. 2. Quick Response strategy

Integration of advantages of piece and mass production requires changes in scope of organization of the whole manufacturing system, including the design process. It is necessary to develop dedicated solutions, for improvement and coordination of design of the configurable products in a way to shorten this process and ensure its sufficient quality [11],[12],[13]. Modern systems belonging to the CAx class (Computer Aided Technologies) can be used for this purpose, as they allow to enrich geometrical CAD (Computer Aided Design) models with a formal description of engineering knowledge. Digital, intelligent models of products created in such a way are a basis of so-called Knowledge Based Engineering systems (KBE).

In the KBE systems, expert knowledge about what, when and how it needs to be done is identified, gathered and then processed by computer systems, allowing its easier use in new projects. A formal description of rules followed by the design engineers helps standardization of the design process and allows to shorten it [14],[15],[16],[17].

The paper presents different approaches at gathering knowledge related to design processes, especially regarding design of variant products. It also shows literature examples of various methodologies of defining functional requirements and planning of systems automating the engineering activities related to design and planning of manufacturing of product families in accordance with the MC strategy. The authors propose their own methodology, partially based on known solutions, and show its validation on several examples of systems for automated design and manufacturing process preparation, developed and implemented in cooperation with specific production companies.

2. DESIGN OF CUSTOMIZABLE VARIANT PRODUCTS

Considering the creativity level required from a design engineer, the design process can be classified by distinguishing the following types of design:

- routine – preparation of design on the basis of existing, verified solutions,
- innovative – preparation of design with partial application of new solutions,

- creative – development of an entirely new design.

The creative design is a complex and lengthy process, currently impossible to realize without human participation. That is why topics covered in this paper are related mostly to routine design and, to a lesser extent, innovative design. These design types are both based on adaptation of existing solutions.

Design of a variant product is a specific example of design process, as course of realized tasks has a routine character and is often repeated while developing a new variant. The variant product (also known as configurable product) is a type of a product, in which there is a possibility to adjust values of certain features (e.g. structure, functions, visual features) to individual expectations of a recipient [18]. These features are known as options and a process of their adjustment is known as the configuration, which results in a specific variant of a product. From the viewpoint of a manufacturing company, the variant product is often a product family, meaning a part of assortment of a given company with common design and manufacturing processes [19],[20].

As regards the basic assumptions of the MC strategy, the scope of configuration of a variant product – meaning what and how it can be changed – should be dependent on planned influence of product recipient on the final shape of the product [21]. Nowadays, the recipients can configure their variant of a product by themselves by using special software applications, known as the product configurators. The configurators are used in many branches, in the automotive, clothing, furniture or house building among others. They help the sales process and improve communication between producer and recipient. Dynamical development of web-based applications in recent years made the companies to share variant product configurators in the Internet with their customers [22],[23],[24]. In the configuration process, there are two possible approaches – selection among a limited set of variable options, or a freedom of definition of options, which increases level of customization. Number of possible to obtain product variants will be then theoretically unlimited, which increases attractiveness of the company's offer on the one hand, but is a huge organizational challenge on the other hand.

Development of applications for configuration often goes beyond the sales, allowing automation of flow of information inside a manufacturing company. An example of such a flow can be the design process. Recent trend in development of design processes is striving at achievement of automatic (no human participation) preparation of technical documentation for a new variant of a product. For this purpose, the CAx systems are used, as they allow expansion of simple CAD models with formal knowledge description, thus forming a base for building the Knowledge Based Engineering systems.

3. KNOWLEDGE BASED ENGINEERING

3.1. KNOWLEDGE BASED DESIGN

Knowledge Engineering (KE) is a discipline which deals with problems of acquisition, representation and application of knowledge in computer systems. It is a discipline focusing on creation of knowledge bases and use of semantic technologies to process knowledge in the computer systems. It comprises of:

- identification of knowledge sources,
- acquisition (obtaining) of knowledge,
- representation of knowledge,
- analysis of identified knowledge,
- creation of bases and repositories of knowledge,
- searching, accessing and sharing knowledge.

Efficient use of knowledge in the industrial design process requires its appropriate acquisition and proper recording in the knowledge base. Methods of knowledge gathering are also dependent on its sources, which can be of variable number and form. The most important knowledge sources are:

- personal notes of design engineers,
- design documentation (part and assembly drawings),
- technical documentation (operation drawings, manuals etc.),
- previous projects information,
- study results (e.g. from simulation or operation studies),
- libraries of documents, books, papers,
- industrial standards and catalogues,
- remarks from research centers and patent offices,
- remarks from customers and suppliers.

Representation of knowledge is understood as its formal recording. A selected method of representation should be as simple, complete, comprehensible and unequivocal as possible, not only for persons dealing with its description – knowledge engineers – but most of all for those, who will be using it in the future. For creation of an ontology – description of concepts and relations characteristic for a given knowledge branch – specific notations and languages are used (e.g. UML – Unified Modelling Language).

Problems of knowledge management in the design process were a subject of numerous studies as early as in the 90s. As for today, many solutions of various level of generalization were created, based on repositories, databases or artificial intelligence [25]. The most effective ones are based on structural forms of knowledge representation, as it allows relatively simple processing [26]. There are many patterns for building systems based on general knowledge, known as the KBS (Knowledge Base Systems), as well as patterns specifically for the engineering design process – the KBE systems. The KBE connects object-oriented programming, artificial intelligence techniques and CAD systems, bringing benefits in automation of tasks in the design process [27].

Development of design using the KBE approach is distinctly related to CAx systems, which allow more and more effective knowledge management. Obtaining, formalization and application of knowledge for its repeated use in the CAx environment is a base of problems related to engineering systems based on knowledge [28]. Experience of experts – their know-how about the design – can be gathered and recorded virtually on every stage of product development. Gathered information is used repeatedly, aiding the decision making process and accelerating tasks which are routine and repeatable. A base is usually formed by a group of software tools, enabling knowledge representation (an example of such a tool is the Knowledgeware module of the CATIA v5 CAx system). Its implementation is done through appropriate description of facts (values of features), relations between them and procedures, which contain information about resulting activities. It allows, for example, to build parametric models of virtual prototypes using CAD tools [28]. Their characteristic feature is high automation capability, through realization of algorithms written in their structure.

Building a KBE system can be a way of realization of the mass customization strategy [14],[29],[30]. Numerous benefits of building solutions of such type can be observed. Among these benefits, possibility of shortening the duration of the design process should be mentioned as the most important one (see Table 1), along with reduction of the product lifecycle costs (known as PDP – Product Development Process), influence on development of creative work or possibility to access and re-use the recorded knowledge [14],[15],[16],[17].

Table 1. Reduction of design time by use of KBE systems on the basis of [31]

Reference	Focus area	Achievement
Kulon [32]	Design of manufacturing tools	Reduction from weeks to hours
Brewer [33]	Automotive – body design	Reduction of time by 73%
Chapman & Pinfold [28]	Automotive – body design	Reduction from 15 person-weeks to minutes
Cooper [34]	Design of windscreen wiper mechanism	Reduction from weeks to minutes
Stokes [17]	Design of car bonnet	Reduction from 8 weeks to 20 minutes
Stokes [17]	Aeronautical industry – design of wing elements	Reduction of time from 8000 hours to 10 hours
Lin [35]	Automotive industry – design of manufacturing tools	Reduction of time from 10 days to 1 hour

Tiwarii, Jain and Tandon [36] present an example of a solution of a KBE class, aiding design process of a pin joint. The application prepared by them allows automatic preparation of a CAD model on the basis of the input data – requirements which need to be fulfilled by a designed joint. Thanks to this, necessity of checking all limitations and relations between joint elements in each project was eliminated. The authors developed a KBE system, distinguishing the following steps of its building:

- identification of components, their functions and behaviors,
- conversion of functions and behaviors in scope of valid rules and relations (identification of knowledge),
- management of rules and relations (knowledge management),
- access to the knowledge base through a program and user interface,

However, in their work, the authors focused only on description of operation of their solution, not showing a method of knowledge processing.

Lin and Hsu [35] developed a solution aiding engineers in design of manufacturing tooling – dies used for production of car equipment elements (Fig. 3). They developed a user interface and connected it to a CAD model template of a die, to make it easier for the design engineers to enter parameters of a tool. Moreover, one of the system's components is an appropriately prepared knowledge base, which contains guidelines necessary in preparation of a tooling variant.

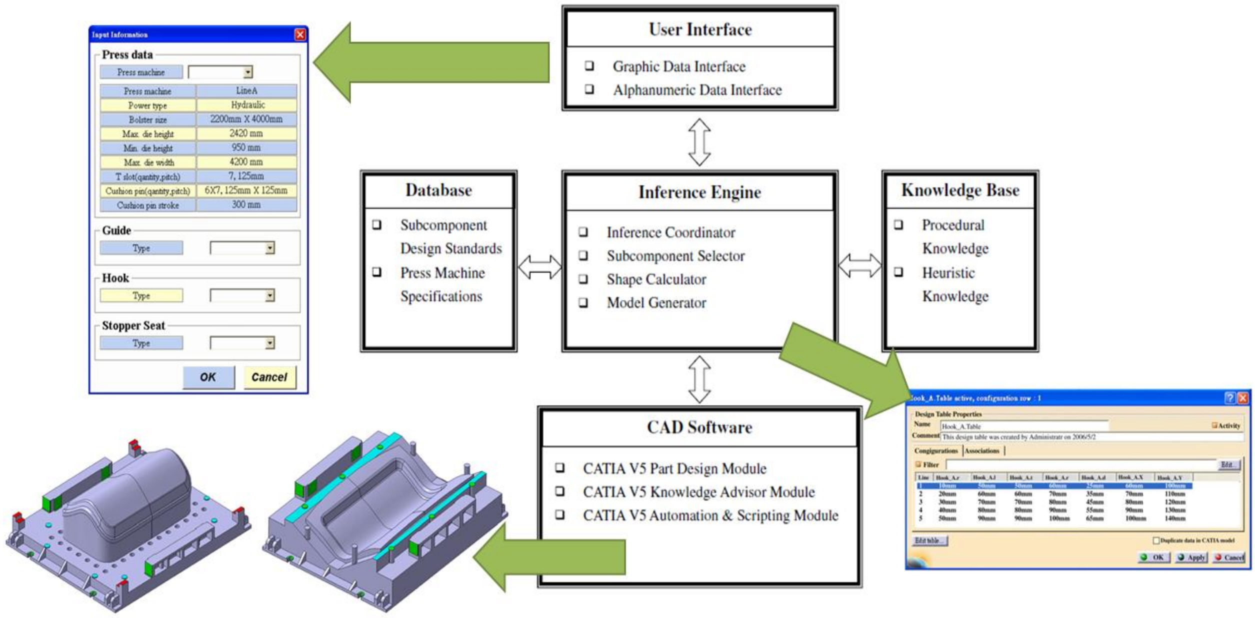

Fig. 3 Architecture of a system for automatic die design, on the basis of [35]

In recent years, there was a distinct development of knowledge based systems oriented at aiding of design work. As Verhagen and co-authors notice [14], most solutions of this type (more than 80%) are built in an immediate manner, not considering possibilities of a methodological and systematic approach, aiding creation of a system based on knowledge.

3.2. METHODOLOGIES OF BUILDING KBE SYSTEMS

A basic problem while building knowledge based systems is a problem of ordering the knowledge. Realization of tasks related to this problem, because of their similarity in various disciplines, contexts and applications, was attempted to be simplified by development of various methodologies, focused on supporting of building systems based on knowledge. During the last two decades, many solutions appeared, aiding the development of knowledge-based systems of general purpose, such as the CommonKADS methodology (Common Knowledge Acquisition and Documentation Structuring) [37]. However, a general model of knowledge has become insufficient for the more demanding design processes, which was a reason for preparation of new standards in processing of engineering knowledge. In the further part of the paper, in the context of the presented work, the following methodologies will be presented in greater detail:

- MOKA – Methodology and software tools Oriented to Knowledge based engineering Applications,
- KNOMAD – Knowledge Capture & Identification of Knowledge Change, Normalization, Organization, Modelling & Implementation, Analysis and Delivery,
- KADM – Knowledge Aided Design Methodology.

The MOKA methodology, being a result of interdisciplinary work of scientific teams and representatives of aeronautical and automotive industry was prepared to achieve the following main goals [38]:

- reduction of risk, time and cost of development of KBE applications by 20-25%,
- ensuring development and maintenance of KBE applications,
- preparation of tools supporting application of the method,
- introduction of an international KBE standard.

Creators of the MOKA methodology divided work on building a KBE system into the following stages:

- identification – determination of purpose and range of building of the KBE system,
- justification – approximation of resources, costs and business risk,
- acquisition – gathering the knowledge from selected sources,
- formalization – formal recording of the gathered knowledge,
- application – implementation of knowledge in a computer software,
- implementation – launching of the KBE system.

In the beginning, aim of building the system needs to be determined, available resources must be estimated, plan of the project should be prepared and a need of its building must be justified. Then, the knowledge must be extracted out of the indicated sources and recorded in a way to ensure possibility of its implementation in a chosen software. Stages related to identification and justification apply to organizational and economical aspects of building a KBE system and in reality are omitted in the MOKA methodology [39], just as the two last stages – application and implementation – which concern development of an application, its installation, use and testing. The MOKA focuses on stages of acquisition and formalization, which apply to methods of collecting and converting knowledge into language understandable for a computer application (Fig. 4).

The MOKA methodology assumes structural division of knowledge for its representation and storing. For this purpose, two types of knowledge models were prepared – the informal model and the formal model. In the first one, the knowledge representation is realized through application of special ICARE forms:

- Illustration – used for representation of all types of general knowledge – figures, descriptions, comments,
- Constraints – used for modelling relations between entities,
- Activities – used for description of various actions in the design process,

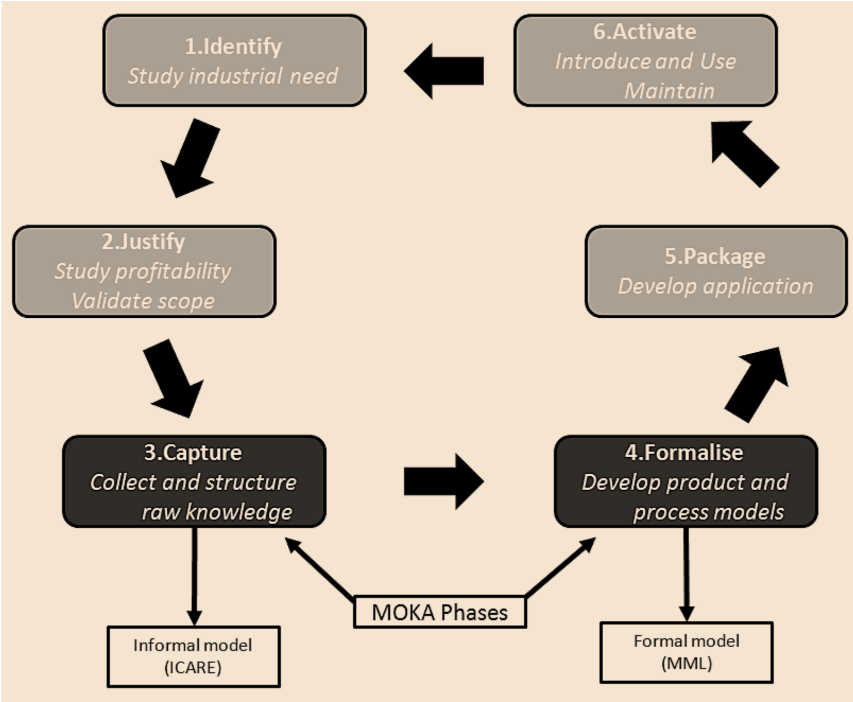

Fig. 4. Stages of KBE system lifecycle with consideration of MOKA scope [14]

- Rules – used for description of rules related with activities in the design process,
- Entity – used for description of object class (structure, functions, behaviors).

The ICARE forms in the informal MOKA model can be related to each other, ensuring possibility of rich knowledge representation, in form of a relation network. Application of the informal model is user friendly and relatively easy. The entity form is used for obtaining knowledge about product structure. Entities such as Assembly, Part and Feature are distinguished here. The Activities form is responsible for representation of the product structure. Both forms can be connected. The informal model additionally assumes connections on the level of entity with constraints and activity with rule. Through an additional illustration form, extra information can be added to each of the previous forms. The whole model forms a multilayered network, allowing collecting knowledge mostly from experts, but also from other sources.

The formal model should be used directly for building the knowledge base, as it assumes higher formalism of its representation than the informal model. For the knowledge description, a dedicated language (MOKA Modelling Language, MML) is used – it is a profile of the UML language. The formal model should have a neutral format, where knowledge representation is comprehensible for human, while it should still be possible for processing by a computer system. The knowledge base itself is built with use of the formal model, with knowledge which is identified and preliminarily structured by the informal model and the ICARE forms.

The MOKA methodology is considered a standard in scope of gathering and recording the knowledge for the needs of a KBE system. The developed knowledge models (formal and informal) and tools – ICARE forms – allow ordering of the relevant technical knowledge. In the MOKA, the lifecycle of such a system is presented, although as observed in literature, MOKA only focuses support of work realized by a knowledge engineer, not including tasks of preparation of application and its maintenance [40],[31].

On the basis of the MOKA methodology, many other solutions emerged expanding its concept. One of them is the KNOMAD methodology [41], focusing on the knowledge management process, considering a necessity of verification of the obtained knowledge and possibility of introducing changes in its description [42]. The following stages of KBE system building are considered in the KNOMAD methodology (Fig. 5):

- knowledge acquisition – identification of range, purpose and assumptions of KBE implementation, identification of knowledge sources and its recording using various tools,
- knowledge normalization – process of analysis and control of obtained knowledge, for application in further stages of building the KBE system,
- knowledge organization – appropriate structuring of knowledge, enabling its implementation in various areas of the design process interaction, through building of an ontology,
- modelling – developing models of products and design processes,
- analysis – tasks related to development of models of processes of analyses and reports, e.g. production costs, planning, manufacturing, logistics etc.,
- implementation – supplying and evaluation of a developed solution.

The MOKA and KNOMAD methodologies present general guidelines and do not operate in a sufficient range of applications of a CAx system to build a KBE system. This is, however, a distinct feature of the KADM methodology [43]. Using this approach, formalization of knowledge concerns a process of building a generative (automatically built) model in a specific CAD system. The KADM methodology comprises the knowledge processing in three stages (Fig. 6):

- acquisition,
- formalization,
- implementation.

The process of knowledge acquisition assumes collecting open, procedural and declarative knowledge from experts. For this purpose, techniques of structuring and creating diagrams and forms are used. For the knowledge description, formal and informal models are used, separately for a product and a process, using the UML.

The informal model is based upon the MOKA methodology and assumes using properly adjusted ICARE forms. The models were divided, taking the content criterion (product and design process) and level of specificity (model and metamodel) into consideration. The last division criterion is formality of used knowledge representation (formal and informal). The knowledge formalization stage is related to building a generative model in CAD software, while the The process of knowledge acquisition assumes collecting open, procedural and declarative knowledge from experts. For this purpose, techniques of structuring and creating diagrams and forms are used. For the knowledge description, formal and informal models are used, separately for a product and a process, using the UML.

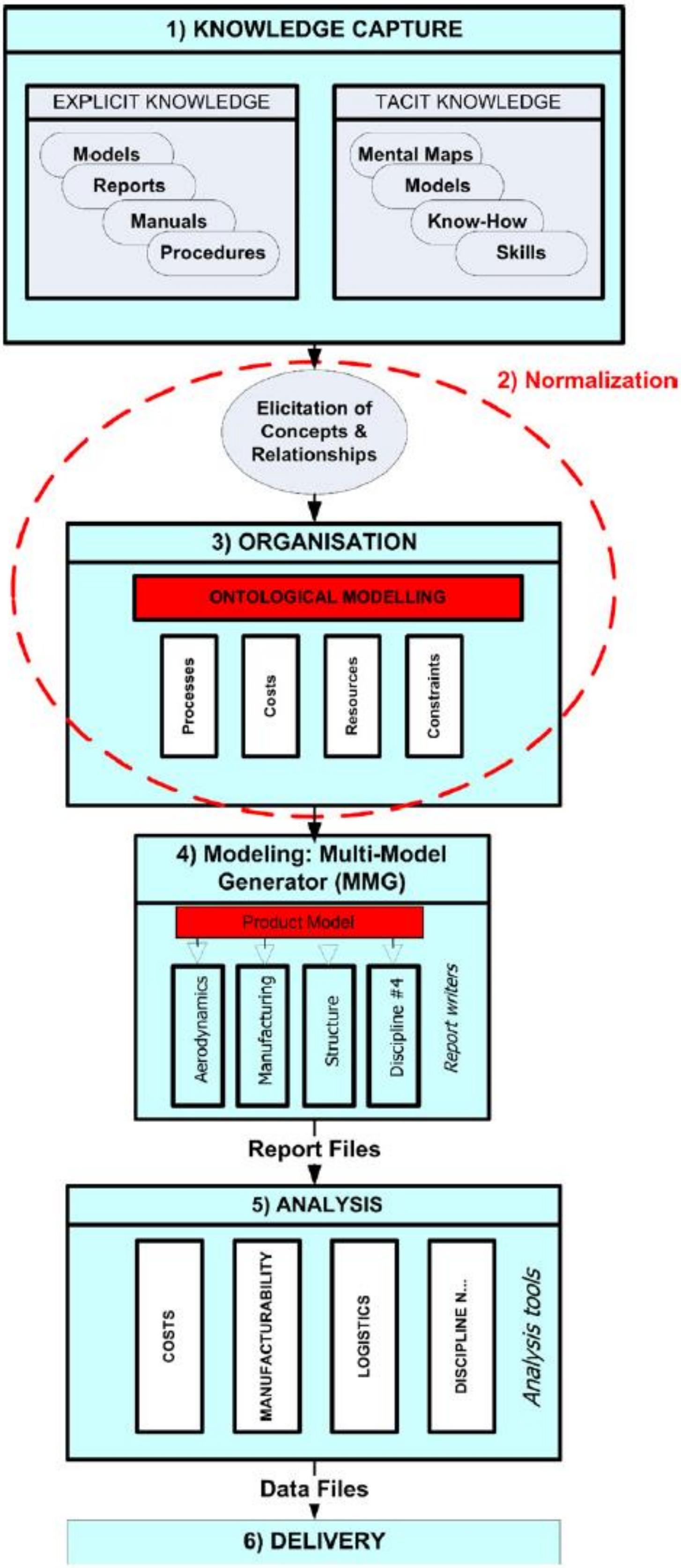

Fig. 5. Stages of KNOMAD methodology [41]

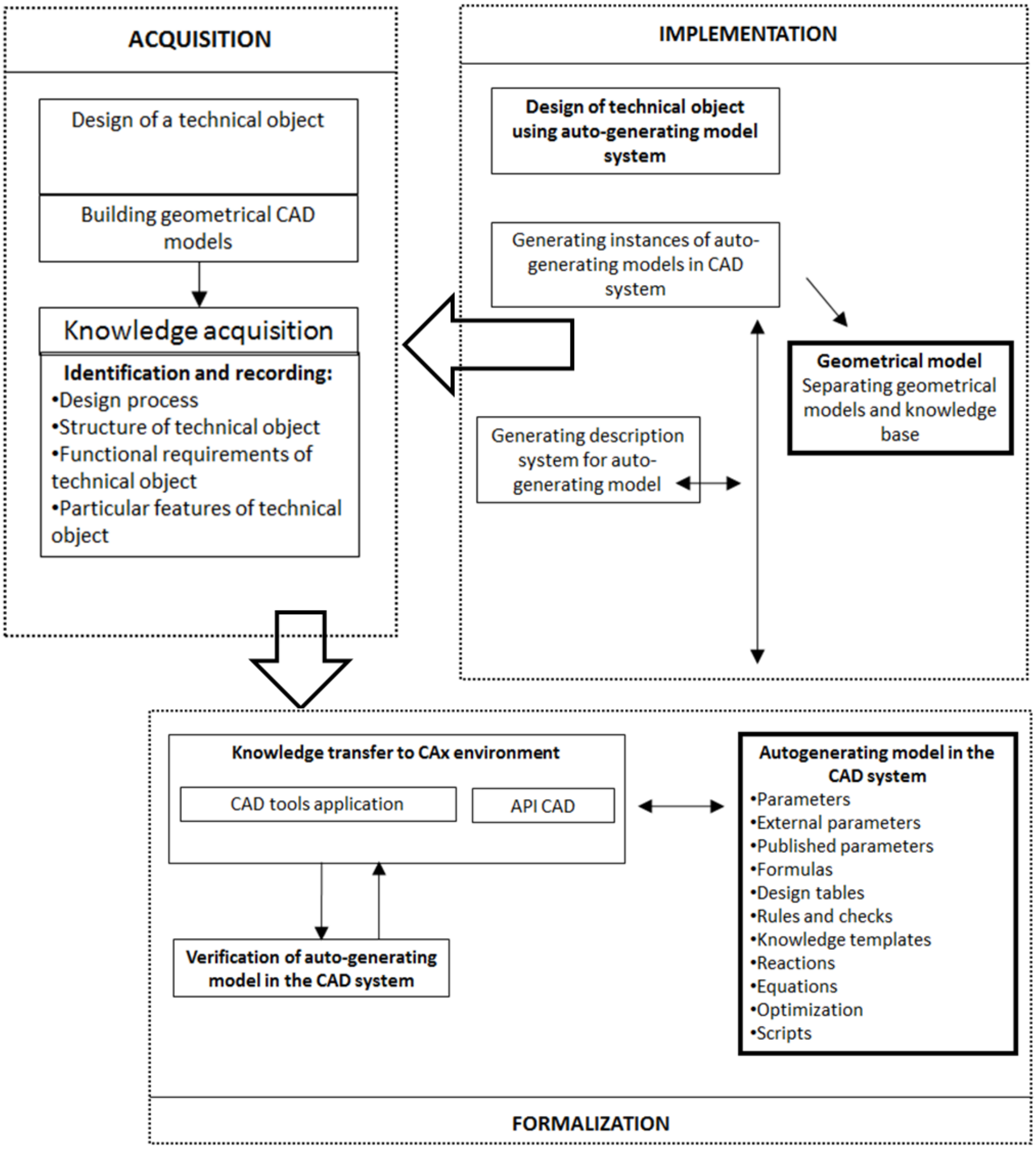

Fig. 6. Stages of KADM methodology [43]

The informal model is based upon the MOKA methodology and assumes using properly adjusted ICARE forms. The models were divided, taking the content criterion (product and design process) and level of specificity (model and metamodel) into consideration. The last division criterion is formality of used knowledge representation (formal and informal). The knowledge formalization stage is related to building a generative model in CAD software, while the implementation stage comprises of its practical application, result management and development.

3.3. KBE – SUMMARY

Development of a system of the KBE class is a difficult and time-consuming endeavor. Most of such solutions are built in an incidental manner, with immediate solutions of given problems. Units or persons implementing the KBE systems rarely refer to the methodological models, as they are usually too general for specific cases or access to specific tools is limited, which directly translates into their small usage in practice [14].

The examples of KBE systems presented in literature are based on development of intelligent (generative) CAD models, which can be, among other things, used for preparation of new variants of designed products, thanks to appropriately recorded knowledge. For the knowledge acquisition, the ICARE forms developed in scope of the MOKA methodology are useful, as they ensure possibility of detection of product structure and relations between its components. For representation of the gathered knowledge, the UML language is used the most frequently – it facilitates modelling of the knowledge base. The knowledge implementation, which is development of an intelligent CAD model, is realized in a specific CAD system, using available, built-in tools for knowledge management and programming.

4. METHODOLOGY OF DESIGN AUTOMATION OF VARIANT PRODUCTS - MDAVP

4.1. ASSUMPTIONS OF THE METHODOLOGY

The authors of this paper propose an original methodology of automation of variant (configurable) product design, on the basis of their own experience and literature analysis. Its application is aimed at supporting the building process of a computer system, which will allow its users (among others, the product recipients) to configure a new product variant by themselves and automated preparation of technical documentation of this variant.

While developing the methodology, the following assumptions were made:

- in the design process, there is a need to prepare technical documentation for each new product variant,
- configuration of a product variant is a process, which can engage a recipient of this product,
- the methodology should be written in form of a procedure, to support the work of a team engaged in building of a system,
- the methodology should offer tools necessary for conducting the process of acquisition of knowledge about the design process.

The methodology is named MDAVP – Methodology of Design Automation of Variant Products. The system which is built using the methodology is known as the SAVPD (System for Automatic Variant Product Design).

The methodology consists of the following stages (Fig. 7):

I. Identification
II. Acquisition of knowledge
III. Project of a system
IV. Building system's components
V. Implementation

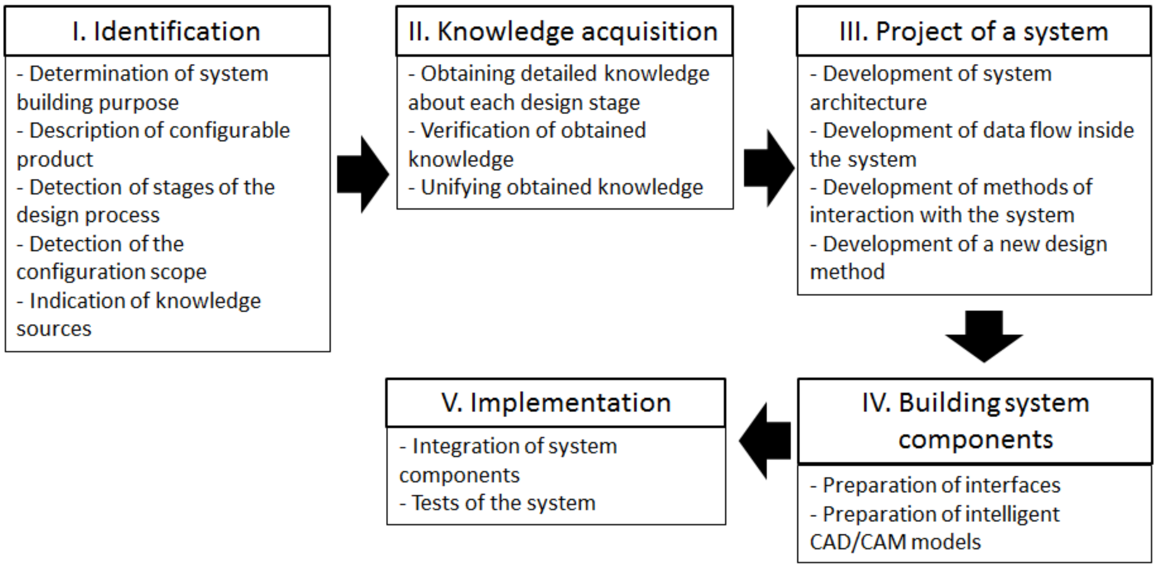

Fig. 7. Stages of MDAVP methodology

The identification is conducted to find out about possible options of variant product configuration and stages of its design. Aim of building the system is determined and sources of knowledge which should be used on the acquisition stage are shown. The second stage of the MDAVP methodology is the knowledge acquisition. The knowledge is about methods of designing of the product variants, used beforehand. The acquisition also consists of verification and unification of gathered data and information. The third stage of the MDAVP methodology assumes development of project of the built SAVPD system. The project consists of architecture and formal description of knowledge needed to build the system's components. The fourth stage is realization of practical work, related to building of components of the SAVPD system. The last stage assumes launching the system and conducting tests on it.

For the need of realization of stages of identification and knowledge acquisition, special forms were decided to be used. The forms were created on the basis of concept of the ICARE forms of the MOKA methodology. They were modified and adjusted to needs of the variant products design process. The MDAVP consists of 5 forms:

- process,
- stage,
- task,
- parameter,
- relation.

4.2. KNOWLEDGE IDENTIFICATION

The identification is realized through an interview study, which is aimed at gathering and recording the basic information, consisting of:

- description of a variant product,
- scope of configuration of a variant product,
- detection of stages of the design process,
- indication of knowledge sources,
- aim of building the system.

The information gathered on the stage of identification is recorded in the process form. The product description should ensure unequivocal identification of the product. It consists in gathering information about product destination, applied manufacturing processes, naming, notations etc. Scope of configuration is a set of information about what and how can be changed by the product recipient in the configuration process. Indication of the design stages is aimed at detection of a cycle, which is repeated for each variant of the product (the more detailed information about particular tasks, parameters and rules will be collected in the II stage of the methodology). In the beginning, it is also necessary to indicate the knowledge sources, which are intended to be used in the further stages of methodology. The possible sources include:

- expert knowledge (design and process engineers) and personal notes,
- industrial standards and catalogues,
- documentation of already produced variants – selection of specific product variants for further analysis.

Determination of purpose of the system translates into determination of expectations of a company.

4.3. KNOWLEDGE ACQUISITION

The knowledge acquisition process is a key one, as omitting or wrong recording of data and information may result in improper implementation of knowledge in the SAVPD system. In industrial practice, process of preparation of CAD models of even very similar products may be realized on many different ways. Preparation of automation required identification of all these ways, verification of gathered data and unifying them. That is why proper re-creation of the design process structure gains importance, with special consideration of order of realized tasks, applied parameters, their values and relations between them.

For the needs of realization of the knowledge acquisition stage, an approach was proposed in which the design process is divided into consecutive stages, which end in certain results. Each stage is divided into tasks, for which applied parameters and relations are identified. For each detected element, the knowledge acquisition process must be conducted, by filling appropriate forms (Fig. 8). The acquisition process should be conducted for each variant of the product selected for the analysis.

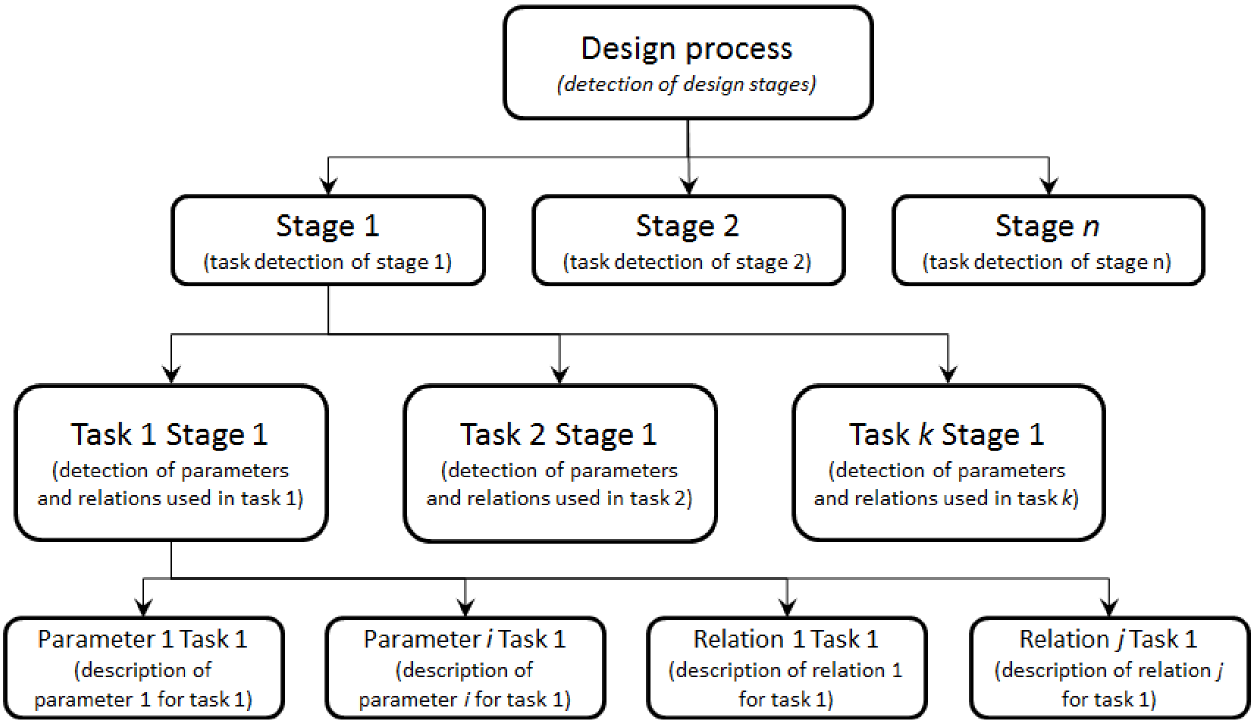

Fig. 8. Structure of knowledge acquisition

Afterwards, structure of the collected data must be compared. Verification of knowledge is conducted to detect differences regarding tasks, parameters and relations for each stage of the design process. The divergence evaluation is necessary to eliminate errors and avoid redundancy of data. After the verification, it is necessary to describe the unified design procedure.

4.4. PROJECT OF AN AUTOMATED DESIGN SYSTEM

After gathering knowledge about the design process, with consideration of purpose of the system, it becomes possible to develop an architecture of a new solution. The work is concentrated on determination of the system's function and its components, as well as methods of data exchange between them. Method of interaction with the system should also be developed, in form of user interface project. Preparation of design automation requires preparation of structure for the new, generative CAD model, on the basis of the unified procedure of design of the variant product, prepared on an earlier stage.

Description of the new stages of interaction with the system and automatic design procedure is prepared using forms. They allow recording concept of the system operation in a data base. Representation of this data is realized with use of an activity diagram of the UML language, which is a universal way of communication between persons engaged in building the system (knowledge engineer, design engineer, programmer, among others). An example of such a diagram is shown in the Fig. 9.

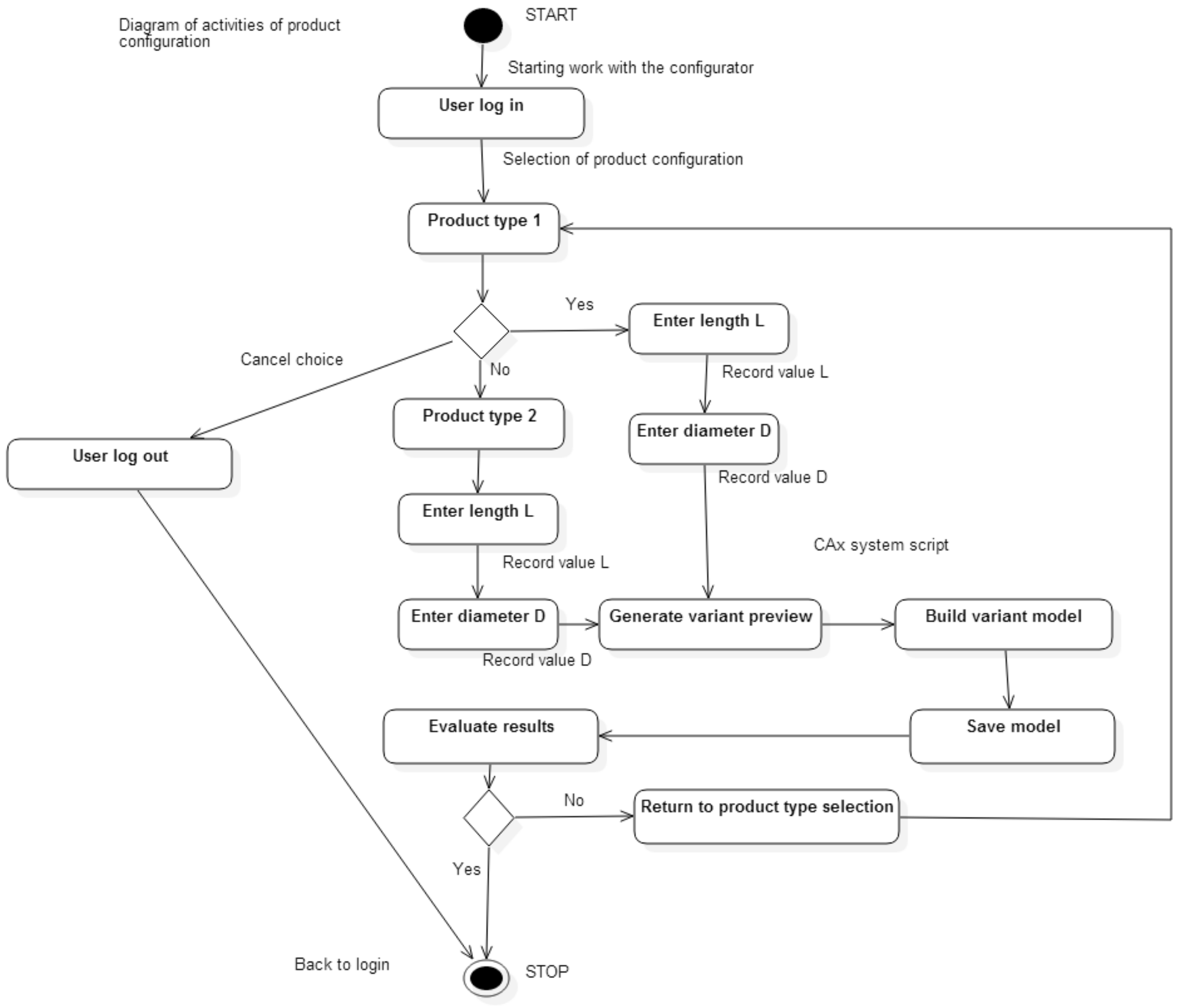

Fig. 9. Diagram of configuration of a product variant

4.5. BUILDING COMPONENTS OF AN AUTOMATED DESIGN SYSTEM

Formalization of knowledge consists in building components of the system (such as CAD/CAM templates, generative models, user interface), which is a reference to the KADM methodology. The knowledge contained inside the database as a result of the previous stages, also recorded in form of UML diagrams, becomes translated to a language understandable for tools used to build the system, including:

- software used by the company in the design process – mostly CAx software,
- programming environments used to build interfaces for interaction with the system, usually compatible with web technologies such as HTML or PHP.

Most of the CAx systems are ready to implement advanced parametric solutions. It allows indication of particular functions of a given software, which need to be used while describing parameters and relations. Information stored in the database using forms of tasks, parameters and relations should be therefore implemented in the CAx system.

4.6. SYSTEM IMPLEMENTATION

The launching stage consists in integration of the system components and carrying out tests of its operation. It is related to realization of programming work in scope of:

- preparation and configuration of a server,
- preparation of structure of data exchange between user interface and CAx software,
- preparation of macros automating task realization on the server side,
- preparation of application for managing the system.

During the implementation stage, work is conducted iteratively, by checking correctness of operation of particular modules of the system, responsible for realization of assumed functionalities. After the system is successfully launched, it needs to be incorporated in daily work of the company, replacing human work in scope of routine activities related to preparation of variants of considered products.

The authors have successfully built and implemented several KBE systems using the MDAVP methodology, for different products in different companies. Some examples are presented in the further part of this paper.

5. MDAVP CASE STUDIES

5.1. SYSTEM FOR DESIGN AND PROCESS PLANNING FOR FORGED COUPLINGS

The system was built in accordance with the guidelines of the MDAVP methodology. For servicing of the knowledge processing, a database application was prepared in the MS Access software, where appropriate forms were created.

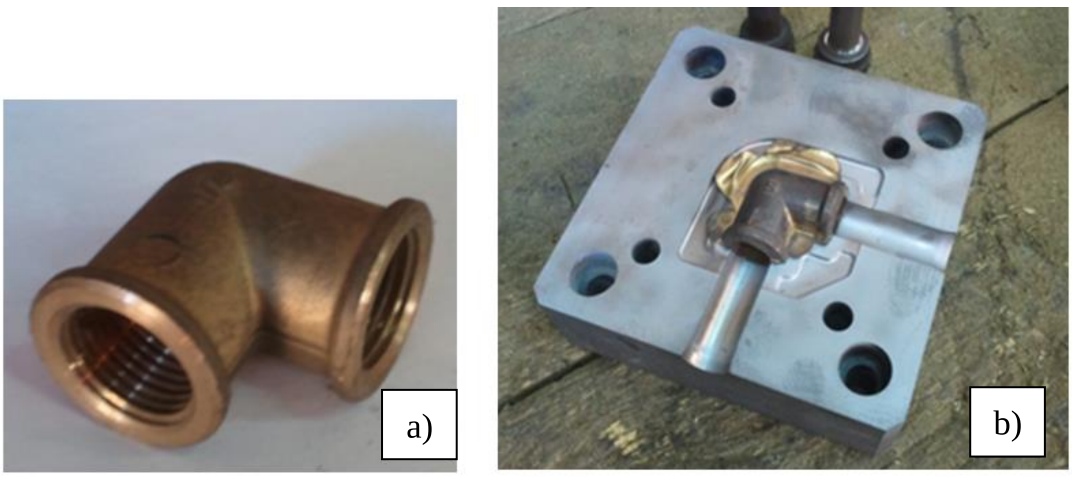

Fig. 10. Example of coupling and production tools, a) – product, b) – die, forging and punches

The identification stage allowed gathering basic information about the variant product and process of its design. A basic aim for development of a new system was automation of tasks related to preparation of 3D models for new configurations of products and production tools, needed for the manufacturing process (Fig. 10). Design of a single coupling consisted of preparation of models of the product, the forging, the die and the punch (Fig. 11) – a new modelling standard was intended to be prepared for these elements. The SAVPD system was also intended for realization of tasks related to preparation of CNC program of die machining. A standard design process (including CAD modelling) lasted between few to even more than a dozen working hours. After the design was accepted, another several hours of work in a CAM software were needed to prepare the machining program.

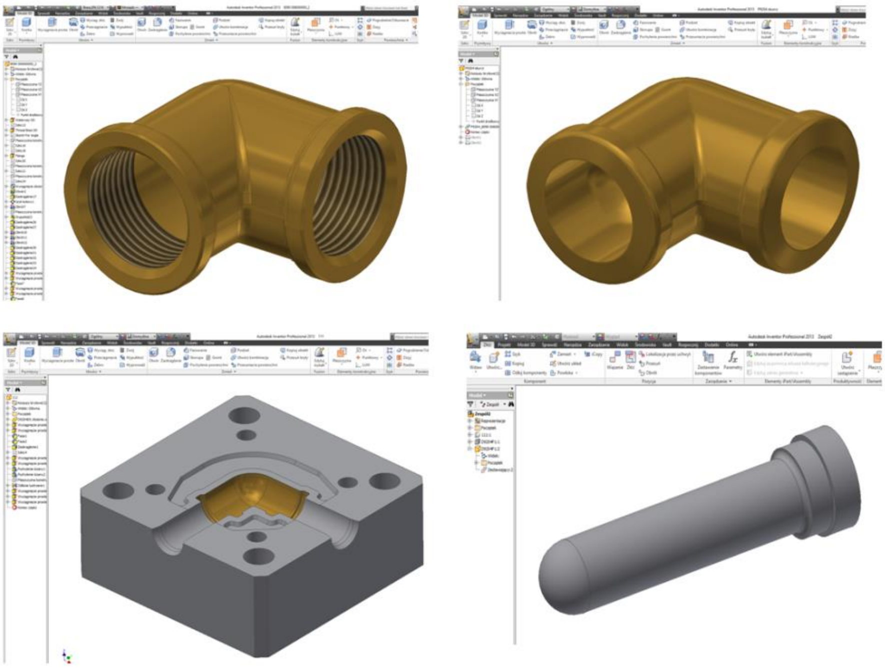

Fig. 11. CAD models of coupling and tools

The knowledge acquisition was conducted for the selected variants of the product (examples of variants are presented in Fig. 12), collecting information about design and manufacturing preparation methods.

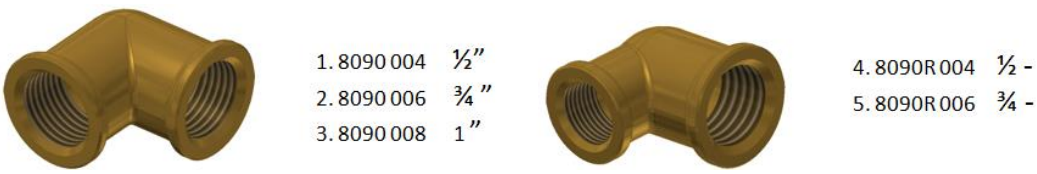

Fig. 12 Example of different variants of forged copper couplings

Each stage of the design process was described in an appropriate form, where chronological sequence of realized tasks was recorded. Finally, knowledge about structure of each selected product variant was gathered, creating unified, common design procedure.

Subsequent stages of building the SAVPD system consisted in preparation of project of the system and preparation of its components. Network architecture of the system was planned, consisting of the following components:

- user interface,
- generative CAD models,
- CAM template for machining planning,
- administrative application.

The concept of the system assumes that the user interface remotely connects to the CAD system, through integration of configuration data and certain parameters in the CAD model of the product. On this basis, the system automatically builds appropriate models of forging and tooling. After acceptation of the user, the CAM software generates a machining program for the die automatically.

On the basis of the unified design procedure, description of process of building of the generative model for the CATIA v5 system was prepared (Fig. 13a). To build the generative models, equations and rules were used for more advanced logical conditions. Special files for data exchange (design tables) were prepared. They were linked with parameters prepared in the CAD system, which allowed automatic use of values entered into the tables for generation of features in the 3D model. In parallel, the user interface was prepared, using PHP technology. That makes it possible to operate the system through the WWW site (Fig. 13b). To manage the system, dedicated software was prepared, integrated with the user interface, enabling system administrator to manage the order of processes and user permissions.

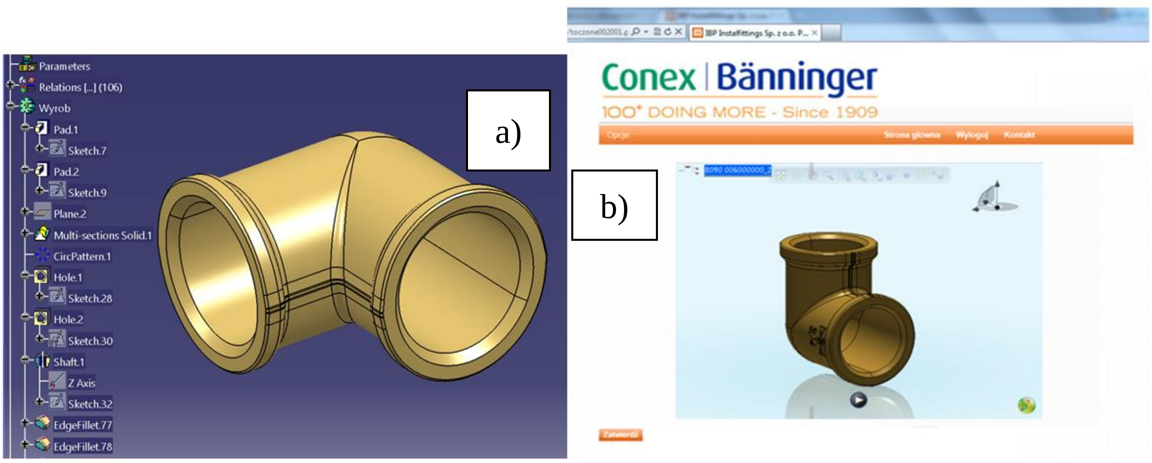

Fig. 13. a) – the product variant in the CATIA v5 system, b) – user interface – preview of variant on the WWW site

Stage of launching the system consisted of integration of components and carrying out tests of its operation. The server application was prepared and configured, along with macros for automation of data exchange. As a result, accepting configuration of variant on the level of WWW interface causes a recording of values of parameters directly in the design tables, stored on the server. A new, generated variant of the product is automatically saved on the server and simultaneously displayed on the WWW site. Confirmation of results launches a procedure of building models of the forging, the die and the punches for the new product shape, along with a machining program for CNC machines (Fig. 14). The models and the program are automatically saved on the server.

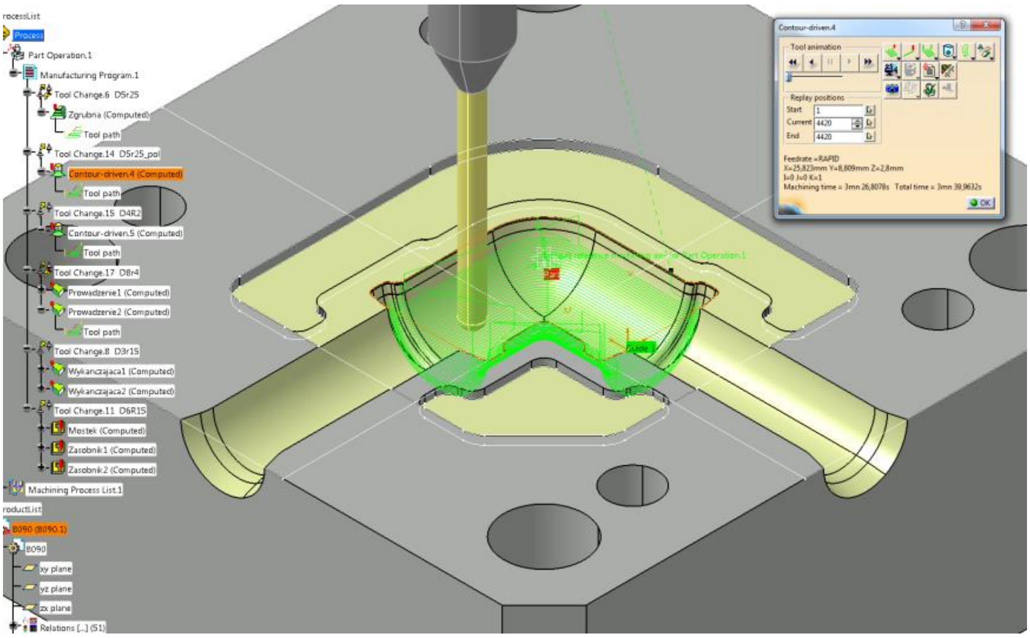

Fig. 14. Preview of machining simulation of a die socket, based on automatically generated model

The system allowed significant time reduction of both design and manufacturing preparation. Comparison of process durations before and after system implementation is presented in the Table 2.

Table 2. Comparison of traditional design versus automated design using KBE system

Traditional design method		*Design in an automatic system*	
Task	*Avg. time [min]*	*Task*	*Avg. time [min]*
Preparation of CAD models of product and forging	300	Product configuration	7
Preparation of CAD models of tooling	360	Preparation of CAD documentation	3
Generating of NC program	540	Generating of NC program	320
Sum	1200		330

5.2. SYSTEM OF DESIGN OF CITY BUSES WITH CLIENT PARTICIPATION

Another example of a system supporting design of a variant product is a city bus configurator, developed by the authors, in cooperation with a large vehicle manufacturer [44]. Aim of the work was to build a multimodal system for configuration of a city bus, intended to be used in work with the clients, to effectively select visual and technical features, avoiding mistakes and changes made directly before receiving a ready product, which happened frequently before implementation. The system consists of several subsystems, using various Virtual Reality tools to facilitate and accelerate selection of an optimal, user-centered variant of the product and preliminary preparation of the product documentation for the design, production planning and purchase departments. The system was implemented by the company and is used with clients during sales negotiations. The system is also partially integrated with CAD and PLM solutions currently used in the company. It works on the basis of specific knowledge related to design process of a city bus, including possible structure of a product along with logical relations. Therefore, it can be treated as a KBE system.

The system consists of self-contained modules, which interact with each other and use appropriate data sets, contained within the system knowledge base (known as the library). The most important module of the system is the visualization module, which displays three-dimensional, dynamical visualization of a city bus in a specific environment. The other modules are, among others, graphical user interface for changing configuration options (which can be observed and checked in real time) and data export module, which is used to send the configuration data to a PLM system used in the company, through PLMXML export mechanism. The whole system (settings, products, library contents and configuration logic) is managed by a special application, known as the VDS Admin Panel.

Proper contents of the visualization module and user interface is each time composed using the library data and information (3D and 2D models along with logical data about the bus structure and relations), on the basis of so-called Virtual BOM of a given vehicle. Presented contents are therefore dependent on structured knowledge about how the components in a bus are arranged, what material are they built from and what logical dependencies occur between them (defined by so-called exclusions and enforcements).

The system allows configuration of the most important visual features of a city bus. During knowledge identification and acquisition, approximately 100 configuration options were selected out of 400 available customization possibilities. They were classified in basic groups and divided into types (e.g. component change, material change, color change). During the stage of knowledge formalization, logical relations were defined between them using a special notation prepared by the authors and links between options and particular components and component properties were defined.

The adjusted bus configuration can be exported to a binary file for re-opening. The binary file can be converted and loaded into the PLM system used in the company, to build basic documentation facilitating and accelerating the further design process. The PLM data exchange works both ways, so product data can be prepared by the designers in the PLM system and visualized in the VDS system.

The system was partially built using the MDAVP methodology. The following tasks were realized during its creation:

1. Definition of configuration possibilities (options and values);
2. Identification of relations between different configuration options (limitations, enforcements, exclusions);
3. Development of system architecture (project);
4. Analysis of design process of a city bus;
5. Building the system's components, including user interfaces, VR applications, data exchange module;
6. Integration of system's components and tests.

In the first stage, the knowledge was gathered from the design engineers and designers and tasks of the system were defined. Then, formalization of knowledge was conducted – logical relations were recorded in a structured form to make it possible to configure the product on-line and visualize the configuration, along with passing the configuration data to design systems in the company.

Automation of the design process of the whole bus was not an aim of this project. It was oriented on improvement of quality of cooperation between client and producer. However, improvement of work of design engineers is one of the indirect results of the project. Studies conducted in this area were oriented at confirmation of using configuration data generated by a client in a CAD system. The bus design process is a complex one, engaging several dozens of engineers internally and, additionally, external design offices. Part of the tasks realized with each city bus variant is a creative work, which cannot be automated. However, some routine operations were distinguished, such as preparation of seat arrangement or internal button arrangement. As an additional module of a system, auto-generating CAD models were prepared, allowing quick design of these arrangements.

Implementation of the VDS system significantly improved the configuration (design) process in cooperation with clients, partially improving work organization inside the company and accelerating generation of documentation of consecutive variants of city buses.

6. CONCLUSIONS AND SUMMARY

A major number of design offices dealing with design of configurable products do not fully utilize potential of knowledge-based solutions, or even use them at all. One of reasons of such a state is surely a fact, that application of the KBE tools available in the CAx systems is not easy, as it requires engineers not only to have a significant experience in the design itself (along with process planning), but also in programming as well. That is why work on building or updating the knowledge based systems often requires engagement of a team consisting of engineers and programmers. For a company, it is often related to an investment, while constant changes in range of offered products are an additional hindrance. Another limitation in building such systems is labor consumption of the development process. It is possible that during work focused on gathering and implementation of knowledge, the product will completely change its characteristics, or even its production will be suspended.

Still, it needs to be stated, that in case of striving at fulfilling assumptions of the mass customization strategy – supplying each or almost each client with individualized products – application of automated design and process planning systems, based on knowledge, is often necessary, as it significantly reduces time of repeatable, routine actions taken by the design engineer and (to a lower extent) the process engineer. In case of the standard products, where design and process planning is a fraction of percent of the total manufacturing time, such an approach is not recommended. However, when there are several dozens or several hundred of new product variants each year in the company – as it was a case in the described application examples – the design and process planning of a product can take relatively long time, even up to 50% of the whole time of manufacturing of a complete series of products (if the products are manufactured in small series, as it usually happens in the MC strategy). In such cases it can be stated, that optimization (shortening) of the design process is a direct method and a basic condition of optimization of the manufacturing itself.

The authors think that further development of the KBE systems for design automation should focus on studies on preparation of tools for analysis of capability and potential of automation of a given variant product, referring to current market needs and necessary labor investments (the KBE system creation must be economically justified). If configuration assumptions for a variant product are too narrow, capabilities of the created system can be exploited soon after its implementation. On the other hand, excessive expansion of configuration possibilities will translate into increase of work consumption and lengthening of the building time. Without appropriate analysis, building of such a system may not bring expected benefits, its lifecycle will be short and the design engineers will return to traditional design methods after certain time.

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