TOWARDS AN EXPERT SYSTEM FOR THE MANUFACTURING SYSTEM PLANNING OF PRODUCTS WITH GRADED PROPERTIES

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Abstract: Ontologies open new ways for representing, sharing and reusing knowledge. This paper is based on the investigations within the Collaborative Research Centre (CRC) Transregio 30. In the CRC, thermo-mechanically coupled processes are developed and analyzed. They provide the possibility to produce functional graded components. Functional gradation is the targeted and reproducible adaptation of a material microstructure with the intention of establishing the macroscopic properties of the component. The objective is the steady progress of the microstructure´s variation through at least one spatial dimension. To support the manufacturing system's planning of products with graded properties, we develop an expert system. An expert system is a software which emulates the reasoning of an expert. One of the components of our intended expert system is an ontology. It assists researchers with the use and reuse of the acquired knowledge of the CRC, as well as with communication between the different projects within the CRC. In this paper we explain the architecture of the intended expert system as well as its elements, placing special emphasis on the ontology. Then we explain the ontology´s development based on knowledge extraction and representation.

1 INTRODUCTION

Ontologies open new ways for representing, sharing and reusing knowledge. The Collaborative Research Centre (CRC) Transregio 30 investigates structures with a functional gradation and their manufacturing processes. *"Functional gradation is the targeted and reproducible adaptation of a material microstructure with the intention to establish the macroscopic properties of the component. The objective is the steady progress of the microstructure´s variation through at least one spatial dimension" (Reyes-Perez et. al., 2009).*

Graded components require a sophisticated manufacturing process design which considers the interaction between the manufacturing processes, the sequences of the manufacturing steps and the attributes of the part, the appliances to be used, the suitable tools, the simulations and all the peripheral activities that are involved within the process. Due to the complexity of these types of components, collaboration between experts of different domains is required.

The CRC consists of research groups from engineering, material sciences, applied mathematics, production and manufacturing technologies as well as information technology. It is comprised of diverse faculties of three Universities: Technische Universitaet Dortmund, Universitaet Kassel and Universitaet Paderborn, in Germany.

The research is divided into the project groups A,B,C and D. Each project group is divided in several projects and each project deals with issues of functional gradation. Nevertheless, each field has a different topic and approach. Consequently the relations between each field are implicit, rather than explicit.

Typical difficulties within such collaborative works are the communication, the integration of the generated information and dilemmas caused by semantic and terminology obstacles. The challenge of these types of projects increases when not only the research fields are different, but also the collaboration is geographically distributed.

We decided to create an ontology with different goals in mind. In the short-term:

- To surmount the communication problems;

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- For the integration of the information acquired in the CRC;
- For modelling the domain knowledge of the project acquired in the CRC;

In the long-term:

- As part of an intended expert system which will help the developers with the manufacturing planning of products with graded properties. An expert system is a software which emulates the reasoning of an expert.

The structure of the paper is as follows: First, we explain some definitions and basic concepts used for the development of the work. Then we discuss our ontology and the structure of the intended expert system. After that, we give details about the ontology development. Finally we describe our future work.

2 DEFINITIONS

Here we review some definitions and basic concepts used in the development of the work presented here.

2.1 Manufacturing System Planning

There are different approaches and methods used for manufacturing system planning. Some of them focus on the creation and evaluation of technology chains (Brecher et al., 2005) or provide product-process or even product-process-resource models in combination with methods to use them (Feldmann et al., 2008). Nevertheless, existing approaches do not provide a solution for the manufacturing system planning of products with graded properties.

At the Heinz Nixdorf Institute we are currently developing a specification technique for the conceptual design of the product (Gausemeier et al., 2008) and the production system. In this work, we made an adaptation of these specifications in order to support the conceptual design of a manufacturing system for products with graded properties.

A product can be considered using two approaches, the product design approach (functionality, what is made for) and the manufacturing system design (embodiment, what is made from). The manufacturing system development starts with a conceptual design phase (Gausemeier et al., 2006). The result of this phase is the principle solution of the manufacturing system. The description of the principle solution of the manufacturing system is divided into aspects. They form a coherent system and are mapped on the computer by partial models (Figure 1).

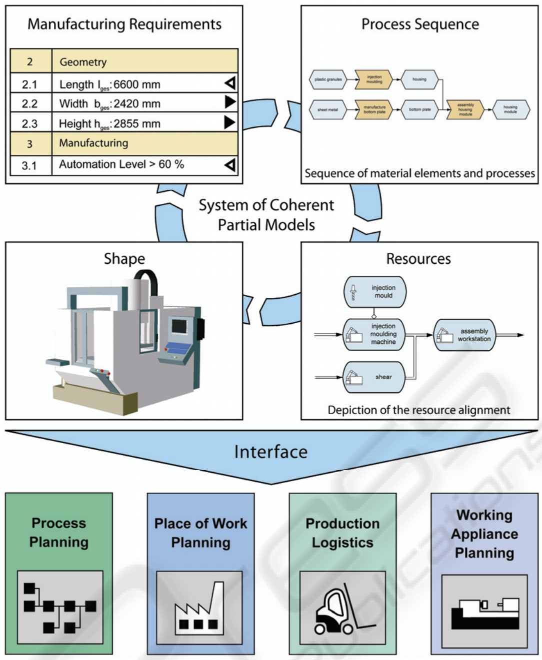

Figure 1: Partial models for the domain-spanning description of the principle solution of manufacturing systems.

Thus, the principle solution consists of a coherent system of partial models:

- **Manufacturing Requirements:** These are the requirements posed to the production system (e.g. the dimensions of the working spaces, speed of operation). These requirements are derived from the requirements stated on the principle solution of the product (e.g. tolerances, production volume);
- **Process Sequence:** The description of the manufacturing operations as a chain of processes. Each process is characterised by a manufacturing function and additional attributes;
- **Resources:** These are all the equipment, tools and personnel that are required for the execution of processes (DIN69902, 1987). At least one resource is allocated to each process of the partial model “process sequence”. Nevertheless, it is possible that one resource realises more than one process;
- **Shape:** We refer to the shape as workspace, the required floor space of machines or the ac-tive areas of handling appliances;

These aspects are made of elements like:

- **Product Properties:** For example weight, structure, surfaces of the product. They are used to derive requirements on the applied manufacturing equipment (e.g. tolerances, surface finish, production volume);

- **Process:** These are all the activities that are made within a production system. For example: Manufacturing processes, logistic processes and assembly processes;
- **Manufacturing Processes:** These are the processes required to obtain a first shape or state from the formless original state to change the material properties. They are taken from the standard DIN 8580 (DIN8580, 1974);
- **Logistic Processes:** These processes deal with the procurement, distribution, maintenance, and replacement of material and personnel. For example "transport" or "storage";
- **Assembly Processes:** These are the processes that are used to add parts to a product in a sequential manner. For example "mounting";
- **Parameters:** Parameters are used to describe processes and resources. *Process parameters* are specific values required by a process. *Resources parameters* state the range of values that the resources are capable to perform;
- **Material Elements:** Include all raw materials, auxiliary materials, parts from suppliers and trade goods, as well as raw, unfinished and finished goods (Gienke & Kämpf, 2006);
- **Material:** The material from which the product is made, e.g. Steel;
- **Products:** This class contains the analysed products within the CRC, e.g. crashbox, a flanged steel shaft and a door interior trim;
- **Project Groups:** There are four main groups within the CRC:
  - **Project A:** Process Design
  - **Project B:** Material modelling / identification of parameters / experimental validation
  - **Project C:** Numerical Treatment
  - **Project D:** Product Optimization Process
- **Projects:** Each project produces, measures or simulates different attributes of the demonstrators. The activities and the attributes that they handle are classified. The relationships and interdependencies between the projects were also considered;
- **Shape of the Product**: The geometry of the product;

2.2 Expert System

An expert system is a computer program that has encoded knowledge and information about a particular field. This knowledge is represented in a machine readable format. An expert system emulates the decision making and problem solving capabilities of a human expert (Nikolopoulos, 1997).

According to Negnevitsky (Negnevitsky, 2005) a rule-based expert system has 5 components:

- Input/output interface: Is the communication interface between user and system (input/out-put of the information);
- Inference engine: Is a software that tries to derive answers from a knowledge base. It manipulates the knowledge in order to solve problems;
- Knowledge base: Stores the domain knowledge. The knowledge is represented as a set of rules;
- Data base: Stores the facts used to match against the rules;
- Explanation facilities: Enables the user to ask the software how a particular conclusion is reached.

2.3 Ontology

In the field of informatics, Sure defined: *"An ontology is an explicit, formal specification of a shared conceptualization of a domain of interest"* (Sure, 2003). 'Formal' refers to the fact that the ontology should be machine readable. 'Shared' means that it is a common characterization of an application area. 'Domain of interest' indicates that a specific area is modelled. In other words, ontologies are used as a form of knowledge representation about a domain. If the knowledge is categorized and formalized it is possible to store it within an ontology.

An ontology has 2 types of relationships: hierarchical relationships and semantic relationships. With the first ones, the elements within the ontology form tree structures, or hierarchies. With the latter ones, it is possible to link elements from different hierarchies. Semantic relationships could be any expression. Because of this, an ontology represents any relationship between concepts (Tudorache, 2004). For example "Element A *measures* Element B" or "Element A *defines* Element B". In this way an ontology produces a clear domain model of the applied terminology. If correctly specified, no ambiguities will occur (Lewis et al., 2001).

Ontologies offer many applications. They solve the problems caused by semantic obstacles, such as those related to the definitions and approaches of the experts of different fields. They also deal with the management of the knowledge. Ontologies are a way to represent the knowledge in a machine-readable format. This representation allows us to use the knowledge with different reasoning mechanisms and problem-solving methods to generate more knowledge. In our case, we use the knowledge that we have of the manufacture of products with graded properties in combination with the procedural knowledge of a developer to generate a process chain to manufacture a product with graded properties.

2.3.1 Ontologies for Manufacturing Systems

Currently, there are different approaches and methods for using ontologies in the manufacturing domain. Lemaignan (Lemaignan et al., 2006) presents a proposal for a manufacturing upper ontology that aims to draft a common semantic net in manufacturing domain. Catalano presents the Product Design Ontology (Catalano et al., 2008), an ontology for product design. Other ontologies focus on development of reconfigurable modular production systems, for example, the work of (Lohse et al., 2004), a web-enabled design of modular assembly systems.

Nevertheless, existing approaches do not provide a solution for the manufacturing system planning of products with graded properties. Because of this, we developed OntoMaDa, which is described in section 3.

2.4 Protégé

Protégé is a free, open source ontology editor and knowledgebase framework. It lets the user create any ontology with a graphical user interface.

Protégé represents knowledge in the form of classes, slots, forms, instances, queries and graphical tools. The classes are the concepts of our system. The slots are the properties and characteristics of the concepts. The slots have a value type (e.g. string, integer), a cardinality (e.g. multiple) and a domain. Finally the instances are the values of the attributes.

JessTab (Eriksson, 2006) is a plug-in for Protégé that allows the use of Jess and Protégé together. Jess (Java Expert System Shell) is a rule engine. With Jess (Freidman-Hill, 1995) it is possible to build Java software that has "reasoning" capacity. Jess uses the supplied knowledge in the form of declarative rules. JessTab enables development of programs that manage Protégé knowledge bases directly. Protégé, JessTab and Jess are the core of our expert system structure.

3 ONTOLOGY OF MANUFACTURING DATA

In our sub-project we developed an ontology which aims to help with the design of the manufacturing system planning of products with graded properties. Its name is "OntoMaDa" (Ontology of Manufacturing Data).

It was constructed with basic elements which allow themselves to be used as construction blocks for the generation of other solutions if the corresponding rules are followed. It integrates experimental data, conceptual knowledge, empirical models and concepts in such a way that the developers can generate new results. Please refer to (Reyes-Perez et al., 2009) for more information about this ontology.

Based on this ontology, two enhancements were made. First, information about the peripheral activities of the manufacturing process and information about the sub-projects research and interaction was included. The ontology facilitates the data exchange between the different domain researchers. The items within the ontology have links between them. Each link is a relationship (hierarchical or semantic). These links allow researchers to follow a path in which the relationships explain how the items are connected. The researcher can start in any item and then follow the different paths and "navigate" through the Transregio project. The projects and sub-projects within Transregio as well as their work, are explicitly defined within the ontology.

The second enhancement was in the structure of the ontology. It was changed to facilitate the manufacturing system planning conception. In the following paragraphs we explain the concept.

We can see the manufacturing system design as a "chain of decisions" which starts with the requirements of the product. Each link between the different items of the ontology, offers different possibilities. Because of this, the selection of the next link must be carefully taken. For example, one product requirement could be the material (e.g. polypropylene, steel). Each possible material implies a different manufacturing process. A specific example: a thermo-mechanical process can achieve a tailored graded hardness in the case of a monomaterial, whereas a chemical process could be used for a composite material.

This chain of decisions, which we can see as a "linear and sequential design", is what we want to depict in the ontology. But an ontology allows us to create relations between the items and as a consequence we create a net with these relations. These relations could be dependencies, sequences, restrictions or any type of relation. Commonly, the manufacturing process design has a sequence and starts with the definition of the product requirements. Nevertheless, the ontology doesn´t follow a particular sequence. It is a net of intertwined hierarchies and items. Each item was carefully classified in order to allow an intuitive use of the ontology. This allows the developers to start a new design based on previous information and, what is more important: the process design is not "linear" any more. It could start not only with the requirements. It could start with restrictions, for example: use only the available machines and processes. In other words, the intention is to enable the user to start his or her search from any item of a manufacturing system. Then he or she can navigate through this net, either forwards or backwards. In this way, the user can see other possibilities for manufacturing a product.

4 STRUCTURE OF THE SYSTEM

The structure of the expert system is shown in Figure 2. Its components are:

- *Data bank (Information)*: Here is where the information about the manufacturing pro-cesses, resources (e.g. machines) and the pro-ject is saved. Among other things are pictures, mathematical models, etc.;
- *Rules module:* It is used to define the rules used to represent the procedural knowledge. The rules have the format:
  If (condition), Then (conclusion)
- *Ontology:* Here are all the elements and relationships used to model the domain knowledge;
- *User and developer interfaces:* We are building a user interface and a developer interface within Protégé. The first one is where the user states his or her queries to the system. The latter one is where the developers control and modify the contents of the system;
- *Inference engine:* We will use the Jess inference engine as the inference engine of the expert system;
- *Explanation facilities:* Enables the user to ask the software how a particular conclusion is reached. It is made in Protégé.

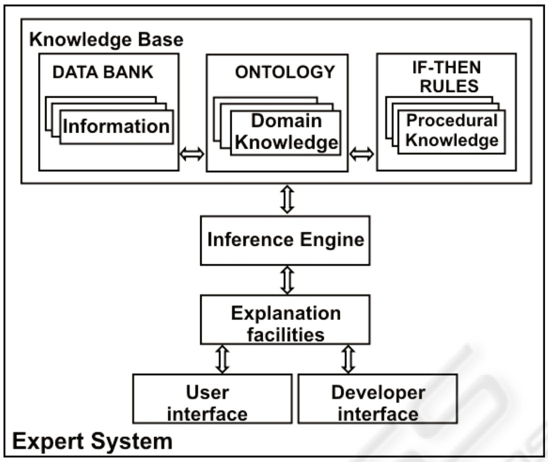

Figure 2: Structure of our system.

The knowledge base is the core of the system. It stores the knowledge of the CRC (factual and heuristic). Its three components are: Data bank, rules module and the ontology.

The user interface is the input interface of the system. First, the user writes his or her query. Then, the interface will invoke the inference engine to activate the decision rules, and the procedural knowledge will be activated. If the system finds a possible solution to the query, the solution will be shown in the user interface.

The expert system is developed in Java. For the communication between Jess and Protégé we use the JessTab plug-in of Protégé.

5 ONTOLOGY DEVELOPMENT

To develop the ontology it was necessary to collect the necessary knowledge of the domain (*knowledge extraction*) and then make the formalization for its further use (*knowledge representation*). The formalized knowledge was saved in Protégé.

5.1 Knowledge Extraction

Knowledge extraction is the process of collecting the necessary knowledge for problem solving in the specific domain. Here is where the knowledge is gathered and structured or classified in a conceptual model.

Our intended expert system has 2 types of knowledge: domain knowledge and procedural knowledge. The first captures knowledge in a specific area or domain, in this case, all the elements that form part of the manufacturing system planning and relationships between these elements. The latter captures the manufacturing system planner's procedure for planning new manufacturing systems.

The domain knowledge was classified in terms of a manufacturing system, according to the classification described in the section 2.1. On the other hand, procedural knowledge is extracted in form of steps.

5.2 Knowledge Representation

Knowledge representation is the formalization of the extracted and classified knowledge, to make it machine-readable (Nikolopoulos, 1997).

We used an ontology to model the domain knowledge and it is planned to translate the steps of the procedural knowledge into rules and save the rules in Jess.

5.3 Structure of the Ontology

We use the ontology to model the knowledge that we have of the manufacture of products with graded properties. Figure 3 shows some of the hierarchies contained within the ontology.

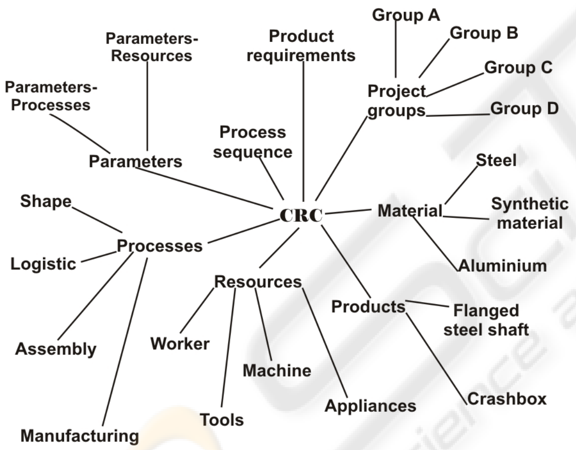

Figure 3: Part of the ontology.

We can see that different elements of the ontology are matched with lines. Each line represents a hierarchical relation. This hierarchical relation, intrinsically, provides the basis for a logical inference within the knowledge base. Multiple inheritances is one kind of inference explicitly represented in the ontology (Lewis et al., 2001). A relation represents the dependency between classes in a domain. We used this characteristic in the development of the query system of our ontology. One element can have one or more relations. Some of the relations that we made in our ontology are:
ProjectGroup_A4-"measures"-Specific_temperature
ProjectGroup_D3-"measures"-Internal_friction

There are different ways to structure the information. But the challenge is to do it in a useful way. The generation of the knowledge depends on the relations. If the relations are excessively abstract there could be loss of information. If the relations are excessively concrete the complexity will increase significantly and confusion might be expected. Up to now, the information retrieval is made in two ways:

- Query tab in Protégé;
- Visualization of the ontology with SHriMP Simple Hierarchical Multi-Perspective (Jambalaya Widget, software within Protégé) and OntoViz;

6 CONCLUSIONS AND FUTURE WORK

The focus of this project is to help the developer with manufacturing planning of products with graded properties, regarding the interaction between product and production system. To achieve this goal, we develop an instrumentarium, which, among other things, includes an expert system. A key element of this expert system is the ontology explained here.

Future work includes finishing the user interface and the developers interface. Another task is to translate the steps of the procedural knowledge into rules and save the rules in Jess. Once the rules are saved we are going to join Jess and the ontology by means of JessTab.

Up to this point, the expert system will be able to suggest possible manufacturing processes for the required products, but to know the exact values of the machine parameters, the user needs to open the empirical models on Matlab. We are working on an interface between Matlab and Protégé. The idea is that the user receives the optimal machine parameters to manufacture his or her product, without opening Matlab.

At the moment a prototype of the software tool for the description of functional graded components is developed and programmed. The tool uses the exported CAD model of the component and transforms this model into a voxel model (a voxel is the three-dimensional equivalent of a pixel), where the user can save the desired properties values to manufacture. We are working on an interface between this program and Protégé. This interface will be the final user interface of our expert system.

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