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IMPLANT MATERIAL SELECTION USING EXPERT SYSTEM

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Abstract. *Most certainly, in the field of medicine there is a great contribution of new techniques and technologies, which is reflected in an entire system of health care services. Customized implants are both fully geometrically and topologically adjusted so as to meet the needs of individual patients, thus making each implant unique. Their production requires joint efforts of a multidisciplinary team of different profile experts who combine their knowledge in the Implant knowledge model. Thus, we develop an expert system which should help or replace humans in the process of Implant material selection. This paper gives an overview of the expert system concept for the given problem. Its task is to carry out a selection of biomaterial (or class of material) for a customized implant. The model significantly improves the efficiency of preoperative planning in orthopaedics.*

Key Words: *Customized Implant, Biomaterial Selection, Expert System*

1. INTRODUCTION

Technological development influences all spheres of the society, especially the field of information technologies, economy, as well as the user's needs. With constant innovation and invention, thousands of computer applications are being created every day, on various topics, available worldwide, whose functionality meets the customer needs and market demands.

Using the information integration capabilities of the computer integrated manufacturing system, which shortens product lead-time, improves its quality and reduces its cost, has led to the formation of multidisciplinary teams of different area experts [1]. Moreover, the knowledge based technologies have provided the integration of different areas of knowledge into a single software environment. Such systems are usually based on the application of

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methodologies from the domain of artificial intelligence [2]. The most commonly used are expert systems, genetic algorithms and neural networks. Their application in biomedicine is significant, both in the data monitoring systems, and in the advanced decision-making systems.

In comparison to the personalization in industry, personalization in medicine has just recently begun to gain importance. Personalized medicine derives from the belief that the same illnesses afflicting different patients cannot be treated in the same manner [3].

An implant is a medical device manufactured to replace a missing biological structure, support a damaged biological structure, or fix an existing biological structure [4 – 7]. Implants must respond to the specific demands in patient treatment. As such, they are used in almost all the areas and fields of medicine.

Unlike standard orthopaedic implants, which have predetermined geometry and topology, customized implants are completely adjusted to match anatomy and morphology of the selected bone of the specific patient [8]. In this way they fully meet the needs of the patient, thus shortening a post-operative treatment period and significantly reducing adverse reactions to the acceptance of implants or possible pain. The patient-specific implant concept has been evidenced since 1996 as research of hip replacement implants for the sake of implant adaptation and customization [9]; then, since 1998, the first cases of patient-specific implants for the skull have been developed [10]. These kinds of implants are custom devices based on patient-specific requirements [11].

Material selection is one of the most important steps in implant design and manufacturing. The selection and use of implant materials involve important prospective decisions [12]. Each material has specific combinations and ranges of chemical, mechanical, electrical, thermal, and biologic performance characteristics. Design requirements dictate material selection; however, once the material selection is made, they strongly affect the design process in both positive and negative ways [12]. The material used for implant manufacturing should, beside mechanical characteristics, be similar to the host bone with sufficient mechanical strength; it should have adequate porosity because it reduces mechanical properties such as compressive strength and resistance to corrosion [13]. The material should be reproducibly processable into a three-dimensional structure and it must tolerate sterilization according to the required international standards for clinical use [14]. Moreover, the manufacturing costs of these materials should be reasonable and their implantation relatively simple, precise, and reproducible [15].

The selection of the most appropriate material, or combination of materials, is an important process in view of a large number of materials and their associated materials processes, necessitating the simultaneous consideration of many conflicting criteria [16].

The chart method, computer-aided materials selection and knowledge-based systems are common techniques in material screening. The material selection system developed by Ashby [17] concentrates on the data modeling aspect of the problem by presenting the data in a chart format. Cambridge Engineering Selector (CES) is a powerful selection and analysis tool that is based on the Ashby's materials selection methodology [18].

ELECTRE (ELimination and Choice Expressing REality), TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution), and AHP (analytic hierarchy process) are utilized for material selection. Fuzzy techniques have been employed either independently or with other techniques such as genetic algorithm, neural networks, KBS (Knowledge-based system), and MCDM (multicriteria decision making) techniques [19].

Dargie et al. [20] presented a computer-aided design system for suggesting candidate manufacturing process and material combinations. Lai and Wilson [21] suggested interactive computer program and artificial intelligence techniques to select candidate material and primary process combinations for a part, during the early stage of design.

Bamkin and Piearcey [22] justified the development of a 'Design Assistant' program for the selection of materials according to knowledge-based system.

Sapuan et al. [23] demonstrated application of knowledge-based system in material selection of ceramic matrix composites for engine components. Moreover, Zha [24] described the work of selecting suitable manufacturing processes and materials in concurrent design according to a fuzzy knowledge based decision support method.

In this paper, the knowledge based system for implant material selection by the production rules has been developed. In order to make reasoning closer to human nature, the system allows work with some uncertainties due to fuzzy logic.

The Implant material selection using expert system can be made by rankings properties such as strength, formability, corrosion resistance, biocompatibility and low implant price [19]. The application of quantitative decision-making methods for the purpose of biomaterial selection in orthopedic surgery is presented in the paper [25]. A decision support system based on the use of multi-criteria decision making (MCDM) methods, named MCDM Solver, is developed in order to facilitate the selection process of biomedical materials selection and increase confidence and objectivity [26]. Based on these research results, we propose an expert system.

Bearing in mind that the implants are complex geometric forms, the most commonly used method for their design is reverse engineering [27].

This paper presents an example of the expert system which is a decision support system used for the selection of materials, applied to the orthopaedic implants design. Therefore, in the definition of the implant model, the implant knowledge is additionally inserted in the form of facts, which actually define a knowledge model about the implant. This knowledge, connected by appropriate relations to the rule databases for the material selection (or the material class selection), provides the prerequisites for the start of the customized implant material selection process.

2. Expert System for Implant Material Selection

Expert systems are meant to solve real complex problems by reasoning about knowledge which would normally require a specialized human expert (such as a doctor, e.g. orthopaedic surgeon). The typical structure of an expert system consists of: a knowledge base, an inference engine and an interface.

Since in the expert system the decision making process and the knowledge base are separated, parts of knowledge within the knowledge base can be easily supplemented or modified. The knowledge base contains rules, which describe the knowledge and work logic of a particular field expert. The task of the expert system presented in this paper is to recommend a suitable material to meet the requirements of a customized implant, and then to decide on the selection of the manufacturing technological process.

This expert system is actually a rule-based application implemented by the Jess rule engine [28].

3. Implant Knowledge Model

For the needs of a missing bone part, a geometrically precise and anatomically conforming 3D model of a customized implant is designed. Such model requires 3D bone model reconstruction, for which the implant is intended, most commonly on the basis of an incomplete bone image [29]. Fig. 1 [30] presents the model of a tibia bone where the upper selvage is lacking. The upper selvage is designed to replace the missing part of a bone in the form of a volumetric bone implant.

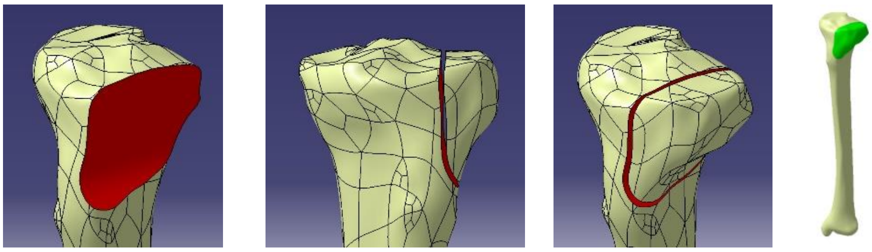


Fig. 1 The model of proximal tibia and the missing customized bone implant [30]

The presented model contains geometrical data which can be easily transferred from the model tree into the knowledge implant model, and, when necessary, be used in the work of a material selection system. In order for the expert system to begin its work, it is necessary for the implant model knowledge to be designed.

The basic building block of every expert system is knowledge. Knowledge in expert system consists of facts and heuristics. While heuristics is made of rules of judgment based on experience or intuition (tacit knowledge domain), the facts are widely distributed and publicly available information that are agreed upon at the expert level in subject areas (explicit knowledge domain). For a successful work of our expert system it is necessary to ensure an adequate knowledge transfer (Fig. 2) from the field expert to the knowledge engineer, so that the engineer could insert accumulated knowledge in the knowledge base.

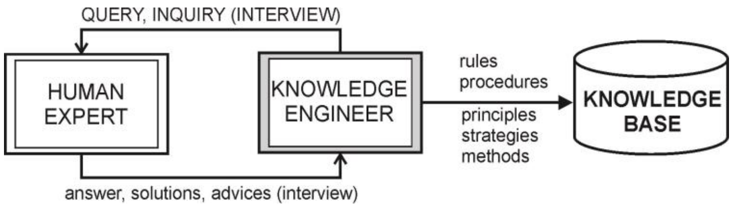
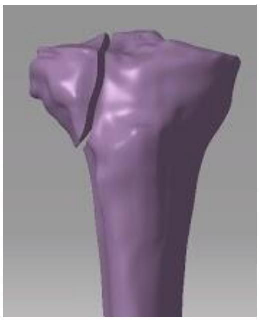


Fig. 2 Knowledge transfer from an expert to an expert system knowledge base

In order for a resulting database of expert knowledge to have its function, it needs to be connected, on one side, with the specific problem database (in our case it is the knowledge model about customized implant), and on the other, with reasoning mechanisms (which is a part of the expert shell). The following table gives a part of the knowledge base about customized implants. This knowledge base is adequately fulfilled by orthopaedist and engineers who have designed and manufactured the implant. Since these parameters are essential, it is important to present a knowledge model about the customized implant with the facts, characteristics, as well as with the description of the facts or the definition of certain parameters values.

Table 1 Query on the volume implant

<table>
<tr><td rowspan="8"></td><td>Patient gender:</td><td>Male</td></tr>
<tr><td>Age:</td><td>56</td></tr>
<tr><td>Cause:</td><td>Bone damage</td></tr>
<tr><td>Patient weight:</td><td>84 kg</td></tr>
<tr><td>Type of injury:</td><td>Disease</td></tr>
<tr><td>Cause of injury:</td><td>Cancer</td></tr>
<tr><td>Bone:</td><td>Tibia</td></tr>
<tr><td>Part of the bone:</td><td>Lateral Proximal Tibia</td></tr>
<tr><td colspan="2">Should implant be inserted by internal or external fixation?</td><td>Internal fixation</td></tr>
<tr><td colspan="2">Is implant permanent or temporary?</td><td>Permanent</td></tr>
<tr><td colspan="2">Implant volume</td><td>10-15 cm^3</td></tr>
<tr><td colspan="2">In what way will the implant be fixed?</td><td>With screws</td></tr>
<tr><td colspan="2">With how many screws and which type of screws?</td><td>2 or 3, Depending on the patient age</td></tr>
<tr><td colspan="2">What is the connection of the implant and the adjacent tissue?</td><td>Towards bone (trabecular bone)</td></tr>
<tr><td colspan="2">Should the implant have the same surface quality towards adjacent tissue or is it different in the area where it faces the bone, in the part where it is connected to cartilage/muscles…?</td><td>Cavities should be 500-900μm
Soft tissues do not ingrown
(lower roughness, polished surface)</td></tr>
<tr><td colspan="2">How much load should the implant endure during lifetime?</td><td>High</td></tr>
<tr><td colspan="2">Biocompatibility</td><td>Very high</td></tr>
<tr><td colspan="2">Sterilizability</td><td>Very high</td></tr>
</table>

The Query shown in the Table 1 was used for data acquisition from experts in this field. Based on this knowledge, the rules were formed and written.

For execution of the rules, we used the expert shell JESS, a rule engine and scripting environment written entirely in the Java language.

The query can be sent to doctors, engineers and other experts so that they can give their suggestions and examples. The data collected this way can later be integrated into the system and also used for further development and improvement of the system. The system will, depending on the input values, show these suggestions as well as explanations why some material is selected.

4. Biomaterial Class Knowledge Base and Example of Decision–Making Process

As there is no universal or optimal material, whose characteristics fit each implant model, it is necessary to choose from a large number of available biomaterials the one that, according to certain specific requirements, fully corresponds to the model.

On the other hand, a wide range of materials ensures that the materials belonging to different classes of biomaterials will have certain properties. In order to decide upon the selection of a concrete material, it is often necessary to predict such a conflict resolution that will clearly define the procedure for determining priorities; thus, the process of material selection will be fully defined.

The structure of the described expert system consists of 3 modules: a module for material class selection, a module for material type selection, and a module for customized implant manufacturing technology selection. The first module for biomaterial class selection is shown in Fig. 3.

Based on the recognized class of materials, we can further narrow our search by selecting the specific material for implant manufacturing. In the module for customized implant manufacturing technology selection of the designed expert system, the manufacturing technology is determined according to available resources, restrictions and applicable technologies.

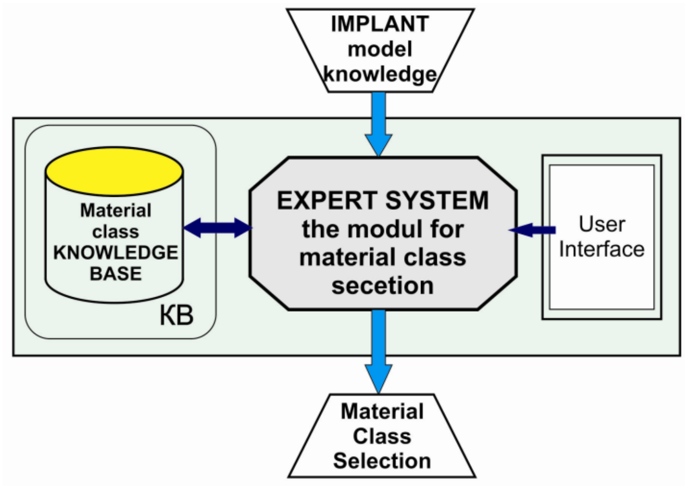


Fig. 3 Model of an expert system module for material class selection

In Table 2 the rules for material class selection are given [31]. For defined parameters in the form of facts, there are three classes of biomaterials presented and their comparison is in a certain value range.

After integrating the knowledge about the model, and the biomaterial classes and other necessary knowledge models, in the expert system, the user of such a proposed system, e.g. a doctor, can select material (or material class) for the customized implants.

Table 2 Rule base on material classes (extract) [31]

	Tensile modulus	Yield strength	Ultimate tensile strength	Strain to failure	Ductility	Toughness	Resistance to *in vivo* attack	Local host response (bulk)	Manufacturing location
Metals	M	H	H	M	M	H	L	H	O
Ceramics	H	/	M	L	L	M	H	L	I/O
Polymers	L	L	L	H	H	L	M	M	O
Explanations									
L – Low; M – Intermediate; H – High;					O – Out I – In I/O – In and Out				

By inserting this knowledge in Jess a code is in the following form:

```
(defrule choose_M
   (and
         (or (not (Feature_has_value (feature TM))) (Feature_has_value (feature TM) (value M)))
         (or (not (Feature_has_value (feature YS))) (Feature_has_value (feature YS) (value H)))
         (or (not (Feature_has_value (feature US))) (Feature_has_value (feature US) (value H)))
         (or (not (Feature_has_value (feature SF))) (Feature_has_value (feature SF) (value M)))
         (or (not (Feature_has_value (feature E))) (Feature_has_value (feature E) (value H)))
         (or (not (Feature_has_value (feature DT))) (Feature_has_value (feature DT) (value M)))
         (or (not (Feature_has_value (feature UT))) (Feature_has_value (feature UT) (value H)))
         (or (not (Feature_has_value (feature HRC))) (Feature_has_value (feature HRC) (value M)))
         (or (not (Feature_has_value (feature D))) (Feature_has_value (feature D) (value H)))
         (or (not (Feature_has_value (feature R))) (Feature_has_value (feature R) (value L)))
         (or (not (Feature_has_value (feature LHR))) (Feature_has_value (feature LHR) (value H)))
         (or (not (Feature_has_value (feature M))) (Feature_has_value (feature M) (value H)))
         (or (not (Feature_has_value (feature PP))) (Feature_has_value (feature PP) (value P)))
)
   => (printout t "Choose Metal" crlf)
      (assert (MaterialClass (name Metal)))
   )
```

As a result Jess has, based on the criteria given by the user and the defined rule base, selected the biomaterial class [30]. In this scenario the suggested solution is the metallic biomaterial (Fig. 5).

```
<terminated> primer_3.clp [Jess Application] C:\Program Files\Java\jre1.8.0_60\bin\javaw.exe (Dec 29, 2015, 6:11:28 PM)

Jess, the Rule Engine for the Java Platform
Copyright (C) 2008 Sandia Corporation
Jess Version 7.1p2 11/5/2008

This copy of Jess will expire in 1613 day(s).

Recommended materials are:
Material class: Metal
```

Fig. 5 Material class recommended by Jess [30]

Biomaterial class recommended by Jess (Fig. 5) is further presented to the user through the user interface.

5. Implant Material Selection

Module for material class selection has shown a shortcoming as it cannot work with uncertain values. The proposed material class is, for the given criteria, better than the other classes, but there is no solution ranking capability which would indicate the extent to which the given solution is more acceptable. This is the reason why the material selection module was designed. This module also introduces the principles of a fuzzy expert system.

When defining certain values, the experts use linguistic expressions more often than numerical values. Thus, the statements become more general and imprecise, but are, as such, more understandable to the interlocutor.

For example, for a doctor or an engineer who needs to describe the characteristics of the material it is much easier to quantify their values by using the linguistic expressions such as "the price of materials is *low* and tensile strength is *extremely high*," than to quantify his/her evaluation "the price is 3.7 € / kg, a tensile strength 1200 MPa."

The fuzzy approach, in addition to relaxation, is characterized by softness, gradual transition from one to the other extreme, for example, from small, medium to large biocompatibility of materials. In the fuzzy logic, the statement is true to some degree. The fuzzy logic allows linguistic statements to be computer processed and, therefore, the technologies that use a fuzzy approach (fuzzy technologies), are considered human oriented.

For each material, in addition to standard data such as name, group, chemical composition, status etc., the values of material characteristics, such as modulus of elasticity, ultimate elasticity, fatigue, tensile strength, density, biocompatibility, and other characteristics presented in appropriate units, are defined. In order to facilitate the insertion and updates, a module has been designed that inserts the values of the fuzzy variables from Excel files. This enables people without any programming skills to change and add new materials in the Excel file. New values and materials will be automatically read when the system restarts or runs again.

Each characteristic of the material has its defined minimum and maximum value as well as a fuzzy set of values that it uses for the proper linguistic value. In addition, each fuzzy value is defined by its membership function (triangle, rectangle, trapezoid or other) and the domain over which is defined. Other functions such as sigmoid or Gaussian curve can be used depending on the needs of the application. The example of fuzzy values is given in the Fig. 6.

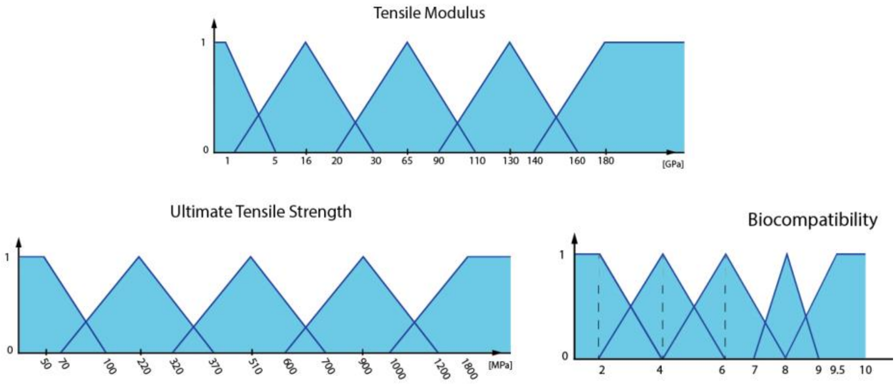


Fig. 6 The fuzzy values of material characteristics

All the information about material and Fuzzy values of the characteristics (features) are added to the Jess file.

```
          rete.batch(clpFile);
          rete.reset();
          rete.add(miv);
          rete.eval("(facts)");
          rete.getGlobalContext().setVariable("lMsg", new Value(lMsg));
          for (Material m:lMaterials) {
            rete.add(m);

          for (Feature f:lFeatures)
               rete.add(mf.fv);
```

Afterwards we call the execution of the appropriate Jess file which in this case is modul3.clp.

```
    rete.run();
```

Jess attributes enable us to add and change rules in Jess scripts without the need to change or compile the entire application. An example of a rule is:

```
 (defrule implant_volume_ex_low
    (MaterialInputValues (implant_volume "ex_low" ))
    => (call ?lMsg add "Consider the possibility of non-implementation of
bone implant and consider the possibility of implementation of a scafold")
```

This rule will be activated if the linguistic value of the implant volume is low. A message will be added in the list of messages informing the user that it is necessary to reconsider the implementation of bone implant and suggest the implementation of a scaffold.

Appropriate weight factor is assigned to each material characteristic. Default value for each weight factor is assigned by the knowledge engineer and can be further modified by writing the Jess rules for a specific case. The resulting score function for material quality then multiplies each of the obtained values for material features by weight factor and sums up these values.

$$f_{score} = \sum_{i=1}^{n} f_i \cdot w_i \quad (1)$$

By activating the rules, the system has performed material base search and then ranked the materials. An overview of the application results is presented in the Fig. 7.

Using the resulting score function (equation 1) where f_i is the truthfulness of fact for a specified characteristic, and w_i is the weighting factor of that characteristic, a material candidate list is obtained, which is presented in a descending order starting form from the best solution (with the highest score function) downwards. By applying additional rules for displaying only materials in a certain range, only those materials that meet a desired range of values can be presented.

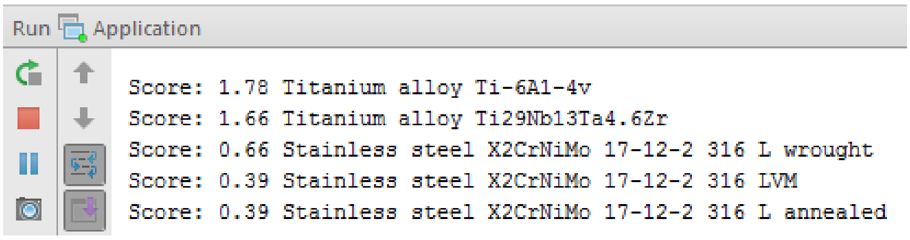


Fig. 7 Recommended implant material by expert system

Presented results show that the optimal solution for customized implant material is Ti6A14V alloy. Second suggested solution is Ti29Nb13Ta4.6Zr alloy that has slightly better biomechanical characteristics, but, on the other hand, also a higher price which negatively influences the final score for the second material.

6. CONCLUSION

This paper presents the concept of the expert system applied to the decision making process for an appropriate selection of the material for customized implants. In order to choose a suitable material from a group of candidate materials, the system for material selection based on the expert system technology was developed. Due to the rule based system and fuzzy logic a framework for fuzzy expert system for implant material selection development was created.

The user interacts with the system through the user interface and defines certain parameters.

Thus he communicates with Interface engine which, on one hand, reads the facts from a database or excel file into the working memory, and on the other, uses if-then rules that represent accumulated knowledge. By activating these rules and procedures, the expert system actually makes set of steps that ultimately provide a decision.

At the moment the system considers 27 possible materials, and provides possibility for new material insertion by simply editing Excel file. The rule base consists of 24 simple rules that illustrate possibilities of this system. New rules can be added, which makes this system adaptable.

The system is designed as an open one for upgrading the knowledge base and the rule base; it gives a good basis for development of quality and applicable system for practical use.

The presented system was successfully tested on a customized volumetric bone implant model. For the developed implant knowledge model, the expert system suggested a list of materials. This list of materials reflects the clinical practice experience data, and thus the expert system work results are verified.

Further development can secure the creation of software tool that can be used for educational purposes as the system can provide suggestions and explanations that normal human expert cannot. On the other hand, the system can be used to help, support, optimize and improve a complex decision making process for choosing customized implant material and manufacture technology.

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