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Original article

Knee Prosthesis Biomaterial Selection by Using MCDM Solver

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ABSTRACT

Biomaterials are a special class of contemporary materials used to make prostheses, parts of organs or to replace entire organs. They are used to replace soft and hard tissues. Metal biomaterials are mostly used to replace hard bone tissues and joints. There is no ideal substitution for natural biological material, but each of the biomaterials has a number of advantages and disadvantages. The problem of choosing the most favorable biomaterial is a complex process of multi-criteria decision-making, which requires a lot of knowledge and experience. In order to help decision makers in solving this complex task, a decision support system named MCDM Solver is proposed. MCDM Solver is used in decision-making process to rank the biomaterials with respect to several criteria. In this paper, MCDM Solver was used to select knee prosthesis material.

Key words: *biomaterial selection, multi-criteria decision making (MCDM), MCDM Solver, decision support system, knee prosthesis;*

1. INTRODUCTION

Material selection process is a complex task which needs knowledge of materials engineering, technologies, operational research and design. To select the suitable material for an application necessitates the simultaneous consideration of many conflicting and diverse criteria.

Biomaterials are commonly characterized as materials used to construct artificial organs, rehabilitation devices, or implants to replace natural body tissues [1]. Selection of an appropriate material for a given biomedical application is important from more points of view – medical, technological, and economic. Nowadays, there is a large number of biomedical materials and manufacturing processes, each having its own properties, applications, advantages and limitations. Therefore, many difficult decisions need to be made while selecting a material for a specific biomedical implant.

In order to select the most suitable biomedical material, the decision maker should have a complete understanding of the functional requirements of the product and a detailed knowledge of the considered criteria for a specific biomedical application [2]. Unsuitable choice of a biomedical material may lead to a premature failure of the product, a need for repeated surgery, a cell death, chronic inflammation or other impairment of tissue functions as well as an extension of healing period and overall increasing of the costs [3].

Only with a systematic and structured mathematical approach the best alternative for a specific engineering product can be selected. The material selection problems with multiple non - commensurable and conflicting criteria can be efficiently solved using multi - criteria decision making (MCDM) methods. The MCDM methods have the capabilities to generate decision rules while considering relative significance of considered criteria upon which the complete ranking of alternatives is determined [4].

Decision support system (DSS) is a special class of information system oriented to the decisionmaking process and aims to support, mainly business decision - doing processes. DSS is a symbiosis of information systems, application of functional knowledge and ongoing decision making process [5]. Their main goal, as the goal of other information systems, is to improve the efficiency and effectiveness of an organization.

This paper is focused on the application of developed DSS named MCDM Solver for solving biomaterial selection problem. The most suitable biomaterial for femoral component of knee - joint replacement was selected by applying MCDM Solver.

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2. MCDM SOLVER

MCDM Solver is an "on - line" DSS, which was developed within the doctoral dissertation of Dušan Petković. The developed DSS is located on the "Virtuode" web site (https://virtuodeportalapp.azurewebsites.net/) and it is available to everyone who registers by creating an account (Fig. 1). This DSS offers the possibility of working with maximization, minimization and target criteria [6].
The input data for MCDM Solver:

- Initial matrix of decision - making with target value of criteria (Step 1);
- η - Confidence level of decision maker in significance of the selected criteria (where η =1 corresponds to 100% confidence level, while η=0 corresponds to a confidence level of 0);
- Pairwise significance evaluation of the selected criteria.

Based on the input data, MCDM Solver can determine the values of the criteria weights (Step 2) and ranking alternatives (Step 3) with the corresponding values by means of Extended TOPSIS [7], Comprehensive VIKOR [8] and Comprehensive WASPAS [6, 9] methods.
Developed DSS architecture is flexible and easy to upgrade, so it enables the inclusion of new models that will come in the future. MCDM Solver has a user - friendly interface, which enables a simple and efficient way of entering the necessary data [10]. Its use simplifies the solution of the MCDM problems, especially material selection problems, because it does not require expert knowledge from the decision making theory from the user.

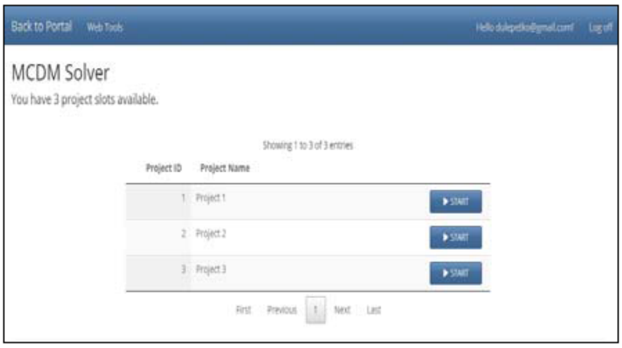

Fig. 1 *MCDM Solver – initial layout*

3. BIOMATERIAL SELECTION FOR TOTAL KNEE REPLACEMENT

Knee prostheses are implanted in the human body to relief pain and restore form and function. A total knee replacement is shown in Fig.2. In order to match the performance of a natural knee, the materials of prosthesis are required to have several specific properties with values approaching those of natural biological materials (bone and tissue).
In this study, 15 metallic biomaterials (biologically comparative materials) that are currently used and could be used for the femoral component of knee-joint implants are considered as candidate materials [4, 11, 12]. Biomaterials which considered as alternatives include stainless steels (SS), Co - Cr alloys, titanium and titanium alloys as listed in Table 1 [6, 13]. It shows commercial names, state and standards which define quality of these materials.
For any knee implant to be successful it needs to have high strength, biocompatibility, wear and corrosion resistance, durability, and machinability. In addition, elastic modulus and density should be near to the bone values in order to minimize stress - shielding effect. Finally, material cost is criterion of the smallest, but not negligible significance for knee replacement biomaterial selection.

Table 1 List of potential biomaterials for knee replacement

Material	*Commercial name*	*State*
M1	BioDur® 316LS Stainless	Annealed
M2	Carpenter 22Cr-13Ni-5Mn	Annealed
M3	BioDur® 108 Alloy	Annealed
M4	BioDur® 734 Stainless	Annealed
M5	BioDur® Carpenter CCM® Alloy	Annealed
M6	BioDur® CCM Plus® Alloy	Annealed at 1093 ^{0}C/1 h
M7	Micro-Melt® BioDur® Carpenter CCM® alloy	Annealed at 1093 ^{0}C/30 minutes
M8	Carpenter MP35N Alloy	35 % deformed and aged at 538 ^{0}C/4 h
M9	Carpenter L-605 Alloy	Annealed at 1204^{0}C
M10	CP Titanium Grade 4	Annealed
M11	Titanium Alloy Ti 6Al-4V ELI	Recrystallized Annealed
M12	Protasul 100, (Ti-6Al-7Nb)	Annealed 700 ^{0}C/1 h
M13	Ti-5Al-2.5Fe	Centrifugal casted
M14	ATI Allvac® Titanium alloy	Annealed na 704 ^{0}C
M15	Ti-15Mo-5Zr	Quenched

The considered material property criteria are:

- Yield strength (C1);
- Tensile strength (C2);
- Elongation (C3);
- Elastic modulus (C4);
- Density (C5);
- Corrosion resistance (C6);
- Biocompatibility (C7);
- Machinability (C8);

- Hardness (C9);
- Cost (C10).

The criteria such as corrosion resistance, biocompatibility and machinability initially are defined by using linguistic terms. An 11-point scale is used for better understanding and representation of the qualitative attributes and converting linguistic terms into corresponding dimensionless numbers [6], as shown in Table 2.

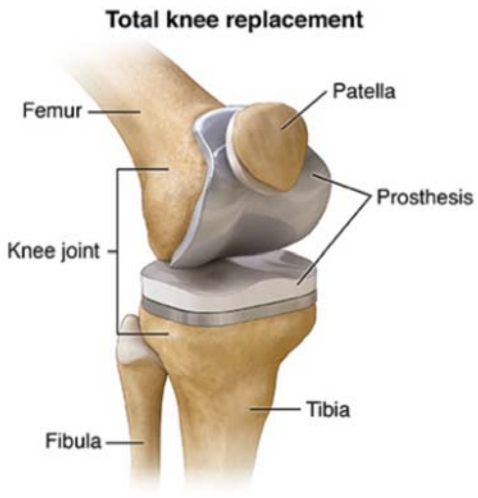

Fig. 2 *Main components of a total knee replacement*

Table 2 Qualitative criteria and conversion values in format of 11 - point scale

Qualitative measure of material selection factor assigned	*Value*
Exceptionally low	0.045
Extremely low	0.135
Very low	0.255
Low	0.335
Below average	0.410
Average	0.500
Above average	0.590
High	0.665
Very high	0.745
Extremely high	0.865
Exceptionally high	0.955

4. RESULTS AND DISCUSSION

Based on the input data, i.e. initial decision matrix, confidence level η=1 and pairwise significance evaluation of the criteria, weights of the criteria are determined (shown in Fig 3).

MCDM Solver calculation of the subjective weights (confidence level η=1) of criteria were carried out based on modified digital logic (MDL) method [14]. This is a pair-wise comparison method, where participants/criteria are presented with a worksheet and asked to compare the importance of two criteria at a time (Fig.3). Thereby hardness (C9) biocompatibility (C7) and corrosion resistance (C6), are considered as the most influential criteria with weights of 0.144, 0.139 and 0.133, respectively (Table 3). Criteria such as elongation (C3), elastic modulus (C4) and density (C5) are equally influential with weights of 0.094. The cost and machinability are the least influential criteria with weights of 0.055 and 0.061, respectively.

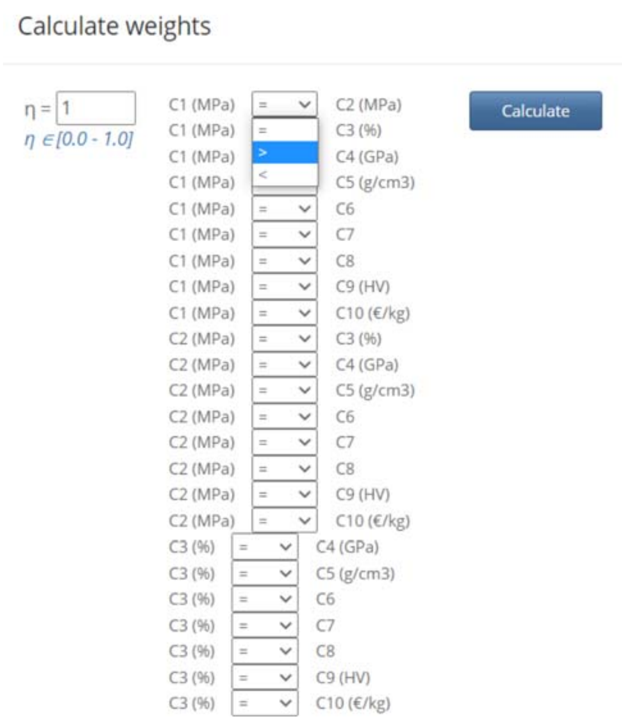

Fig. 3 *Pairwise significance evaluation of the criteria*

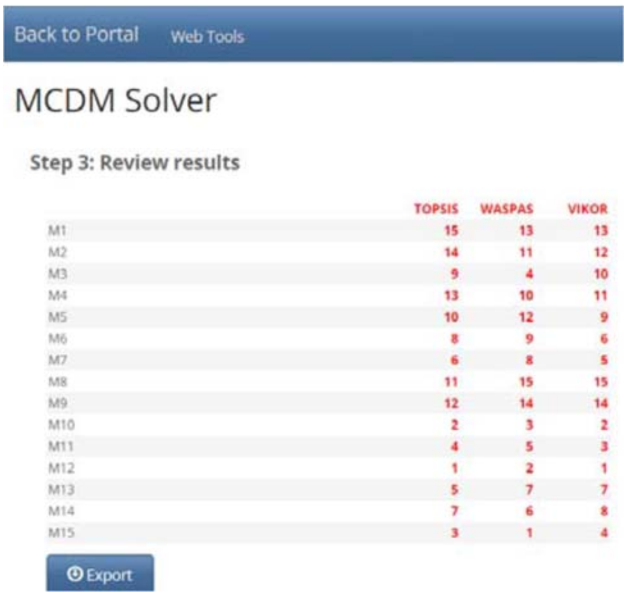

Fig. 4. *Ranking results*

Table 3. Initial decision matrix for knee replacement biomaterial selection

Biomaterial	C1 (MPa)	C2 (MPa)	C3 (%)	C4 (GPa)	C5 (g/cm³)	C6	C7	C8	C9 (HV)	C10 (€/kg)
M1	250	585	57	193	7.95	0.41	0.59	0.865	174	3.8
M2	450	825	45	193	7.86	0.5	0.59	0.865	225	5
M3	580	930	52	200	7.64	0.5	0.745	0.865	304	1.6
M4	450	840	39	195	7.75	0.5	0.59	0.865	270	4.2
M5	585	1.035	25	241	8.28	0.745	0.745	0.335	304	35
M6	880	1.35	22	241	8.28	0.745	0.745	0.41	410	37
M7	1.115	1.42	28	241	8.29	0.745	0.745	0.335	455	140
M8	1.34	1.4	21	235	8.43	0.665	0.59	0.255	425	60
M9	415	1.035	60	243	9.22	0.665	0.665	0.335	155	58
M10	550	670	22	103	4.51	0.955	0.955	0.5	280	21
M11	710	880	12	105	4.43	0.865	0.865	0.41	304	29
M12	850	950	12	105	4.52	0.955	0.955	0.41	318	25
M13	820	900	6	112	4.45	0.865	0.955	0.41	260	26
M14	570	690	15	103	4.48	0.865	0.865	0.5	278	26.5
M15	920	960	25	78	5.06	0.865	0.865	0.41	280	31
Target value	**1340**	**1420**	**60**	**16**	**1.3**	**0.955**	**0.955**	**0.865**	**455**	**1.6**
Criteria weights	**0.1**	**0.089**	**0.094**	**0.094**	**0.094**	**0.133**	**0.139**	**0.061**	**0.144**	**0.055**

Table 4. Ranking results obtained by using MCDM Solver

Biomaterial	Class	TOPSIS	WASPAS	VIKOR
M1	SS	15	13	13
M2	SS	14	11	12
M3	SS	9	4	10
M4	SS	13	10	11
M5	Co-Cr alloys	10	12	9
M6	Co-Cr alloys	8	9	6
M7	Co-Cr alloys	6	8	5
M8	Co-Cr alloys	11	15	15
M9	Co-Cr alloys	12	14	14
M10	Ti	2	3	2
M11	Ti-alloy	4	5	3
M12	Ti-alloy	**1**	**2**	**1**
M13	Ti-alloy	5	7	7
M14	Ti-alloy	7	6	8
M15	Ti-alloy	3	1	4

The Step 3 is the ranking of the biomaterials by means of MCDM Solver. Ranking orders of biomaterials for femoral component of the hip prosthesis using different MCDM methods (TOPSIS, WASPAS and VIKOR) are shown in Fig.4. In order to make ranking results clearer and more readable, they are also shown in Table 4. As could be seen, the best ranked biomaterial is M12, while the M10 is the second ranked biomaterial.

The ranking results also show that Ti-alloys are the most suitable materials for this biomedical application, while stainless steels and Co-Cr Alloys are less preferable alternative.
Ranked results indicate unambiguously that Ti-6Al-7Nb (Commercial name Protasul 100) is the most preferable material for the total knee replacement. The second ranked biomaterial is pure Ti which seems to be excellent biomaterial, but not to be suitable for this application due to its poor tribological properties.
It is also interesting that there is total matching of the TOPSIS and VIKOR results for the first and second ranked biomaterials (M12 and M10). On the other hand, WASPAS and VIKOR the last three ranking results are totally matched (M1, M9 and M8).

4. CONCLUSIONS

In this paper, the application of developed DSS named MCDM Solver for solving biomaterial selection problem is considered. Thanks to MCDM Solver, the material selection process is carried out much faster and easier, because it comes down to selection of potential materials and pairwise significance evaluation of the selected criteria. Hence a complex mathematical apparatus is avoided and ranking process is faster, comfortable to work and reliable. Ranked results showed that Ti-6Al-7Nb alloy is the most preferable biomaterials for the femoral component of knee prosthesis. The results also proved that stainless steels and Co- Cr alloys are not good biomaterial selection for knee prosthesis.

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NOTE

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