

Article

Development of a Decision Support System for Biomaterial Selection Based on MCDM Methods [†]

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Abstract

The material selection process can be viewed as a multi-criteria decision-making (MCDM) problem with multiple objectives, which are often conflicting and of different importance. The selection of the most suitable biomaterial is considered as a very complex, important, and responsible task that is influenced by many factors. In this paper, a procedure for biomaterial selection based on MCDM is proposed by using a developed decision support system (DSS) named MCDM Solver. Within the framework of the developed DSS, the complete procedure for selecting the criteria weights was developed. Also, in addition to the adapted standard MCDM methods such as TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) and VIKOR (VIšekriterijumsko KOmpromisno Rangiranje), an extended WASPAS (Weighted Aggregated Sum Product Assessment) method was developed, enabling its application for considering target-based criteria in solving biomaterial selection problems. The proposed MCDM Solver enables a structured decision-making process helping decision-makers rank biomaterials with respect to multiple conflicting criteria and make rational and justifiable decisions. For the validation of the developed DSS, two case studies, i.e., the selection of a plate for internal bone fixation and a hip prosthesis, were presented. Finally, lists of potential biomaterials (alternatives) in the considered case studies were ranked based on the selected criteria, where the best-ranked one presents the most suitable choice for the specific biomedical application.

Keywords: biomaterial selection; decision support system (DSS); multi-criteria decision making (MCDM); MCDM Solver; plate for bone fixation; hip prosthesis; biomaterial ranking



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1. Introduction

The selection of the most appropriate material involves the study of many factors, such as mechanical, chemical, corrosion and wear resistance, physical properties, as well as the cost of materials [1]. Biomaterials are biocompatible materials used to build artificial organs, rehabilitation devices, or implants to replace natural body tissues [2]. Developing advanced biomedical implants is a complex design problem, and in conjunction with demanding technological constraints, the selection of the most appropriate materials remains a challenge. Nowadays, there are a certain number of biomedical materials and manufacturing processes, each with its own properties, applications, advantages, and limitations.

Therefore, decision-makers must consider multiple issues that affect the quality, safety, performance, and longevity of biomedical implants to the greatest extent [3].

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 criteria considered for a specific biomedical application. An inappropriate selection of a biomedical material may result in premature biomedical implant failure, the need for repeated surgery, cell death, chronic inflammation, prolongation of the healing period, and an increase in overall healthcare costs [4].

Various approaches have already been proposed by previous researchers to solve the problem of material selection. Among them, one should emphasize the Ashby approach, which is based on the presentation of the materials' data in a chart form. It is particularly helpful for the initial screening of materials, while detailed selection and ranking of the listed alternative materials can be carried out by using other selection methods [5].

In the material selection process, the criteria are of different significance, and often contradictory, which necessitates making certain trade-offs between alternative attribute values with respect to the considered criteria. Therefore, only by using a systematic and structured mathematical approach can one select the best alternative for a specific engineering product. The material selection problems with multiple non-commensurable and conflicting criteria can be efficiently solved using multi-criteria decision-making (MCDM) methods, which provide decision rules for the complete ranking of alternatives based on the provided set of criteria and their relative significance [6–8].

Over time, several MCDM methods for materials evaluation have been developed, and new ideas are constantly being proposed to supplement and improve existing ones. Consequently, there was a need for the development of a reliable, systematic, and not too complex mathematically based approach, which would support decision-making for the evaluation and selection of materials. For this reason, this stage in the materials selection has recently been divided into two sub-stages. The division is based on the classification of the performance requirements (criteria for selection) of materials into absolute—"strict"—and conditional (preferred)—"fine". Thus, "strict" requirements (type: passed–failed) are used for initial-rough selection, i.e., material screening, which eliminates materials whose one or more attributes are outside the limits defined by the restrictions.

For example, in the selection of biomaterials, biocompatibility is a strict criterion, which eliminates all materials that are not biocompatible. The second sub-phase involves comparing and ranking the alternatives based on "fine" criteria to further narrow down the list of potential materials. Hence, MCDM methods are increasingly being used for the assessment and selection of materials. Their application provides better results for material selection, especially if the problem being analyzed is quite complex or the purpose of the product for which the materials are chosen is of particular importance. In addition, with the help of the mentioned methods, it is possible to better evaluate the available potential materials (alternatives), and based on the evaluation, choose the best among them. In other words, material screening identifies materials that can perform a function, while ranking identifies materials that can best perform a defined function [9].

Some of the commonly used MCDM methods for solving material selection problems include the following: TOPSIS [10], ELECTREE [11], VIKOR [12], COPRAS [13], ANP [14], and UTA [15]. Recently, the fuzzy COMET method has been introduced for composite material selection [16]. A relatively unexplored MCDM method in the context of material selection, i.e., Reference Ideal Method (RIM), was applied by Sofuoğlu for solving hip prosthesis material and femur component material selection problems [17].

Rijwani et al. [18] proposed combining the entropy weighting method with the TOPSIS, MOORA, EDAS, and GRA methods for selecting the most suitable material for manufac-

turing prosthetic sockets. A hybrid MCDM framework for selecting the most appropriate material for the femoral component in total knee replacement, based on the use of degree of membership approach and multiple MCDM methods, was proposed by Kumar et al. [19]. To address the problem of rankings inconsistency obtained by different MCDM methods, Yang et al. [20] introduced a novel methodology based on an integrated comprehensive evaluation index (ICEI) for MCDM methods so as to enable a more robust and reliable framework for material selection, i.e., titanium alloys. Recently, Kumar and Rajak [21] applied the SWARA and WASPAS methods for criteria weights determination, ranking, and selecting the most appropriate material for the bio-implant applications that can be fabricated by metal additive manufacturing.

However, almost all methods can only work with beneficial and non-beneficial criteria. On the other hand, biomaterial selection also has target-based criteria, which are necessary for certain material properties to best mimic the properties of the biological material they are replacing.

Analyzing the suitability of MCDM methods, it was found that the TOPSIS method has the most frequent application in material selection [22,23]. In addition, it was adapted by Jahan et al. [24] to use target-based criteria and, as such, can be successfully applied for biomaterial selection. The VIKOR method [23] is the second most frequently used for material selection, immediately after the TOPSIS method. It is especially suitable for decision-making problems where quantitative attributes prevail [25]. Later, the comprehensive VIKOR method was developed, which has an innovative normalization method, so that target-based criteria can also be taken into consideration [26]. The WASPAS method was considered as a third potentially applicable method for solving material selection problems. The WASPAS method was developed by Zavadskas et al. in 2012 [27]. Basically, this method is a combination of two well-known methods, i.e., the WSM method and the WPM method. This method has been successfully used for technology selection [28,29]. However, its main drawback is the inability to work with target-based criteria, and therefore it is unusable for biomaterial selection. In this regard, the authors of this paper adapted the original WASPAS method and enabled it to work with target-based criteria [30,31]. This method was called the extended WASPAS method.

Since there is no absolutely reliable method for the selection of materials, and that due to the uniqueness of each method, the ranking results may vary [32,33], the problem should properly be solved by using several MCDM methods—in this case, by using TOPSIS, WASPAS, and VIKOR. To make the application of these MCDM methods simpler, faster, and devoid of any mathematical operations, a decision support system (DSS) called MCDM Solver (MCSI) was developed. Its primary purpose is the selection of biomaterials with all the specificities, but conceptually its application is universal. In this paper, the application of MCSI was focused on metallic biomaterials for orthopedic devices (plate for bone fixation) and prosthesis (body of hip replacement) applications. Namely, two case studies were solved by using MCSI with complete biomaterials ranking obtained. Moreover, the ranking results are compared, analyzed, and the best solutions are proposed.

2. Development of DSS for Biomaterial Selection

2.1. DSS

DSSs are a special class of information systems oriented towards the decision-making process. They present a symbiosis of information systems, the application of a range of functional knowledge, and the ongoing decision-making process [34]. This means DSSs should be an aid to decision-makers in terms of increasing their capabilities, not a substitute for their judgments. They do not make decisions automatically but only provide the analysis and necessary support for more specific decision-making. In other words, a DSS

contains algorithms of logical and rational processes through which it classifies, compares, and forms information necessary for the decision-making process [35,36]. By enabling multiple features, advantages, and benefits [37], there are at least three main reasons for the development of these systems:

- A large amount of data to be processed in the decision-making process;
- Time to decide is often limited, i.e., there is a period in which a decision should be made;
- There is a need for a decision-maker to make a correct and objective decision.

Each DSS consists of three subsystems (constituent elements), which are graphically illustrated in Figure 1:

1. Database subsystem—a DSS component where input and output data are stored.
2. Model base subsystem—a DSS component consisting of a decision model. This subsystem, based on the input data and the decision-making model, generates output data.
3. User interface subsystem—a component that enables communication between the DSS and the user. Since decision-makers are not always specialists for a particular model, this subsystem is very important.

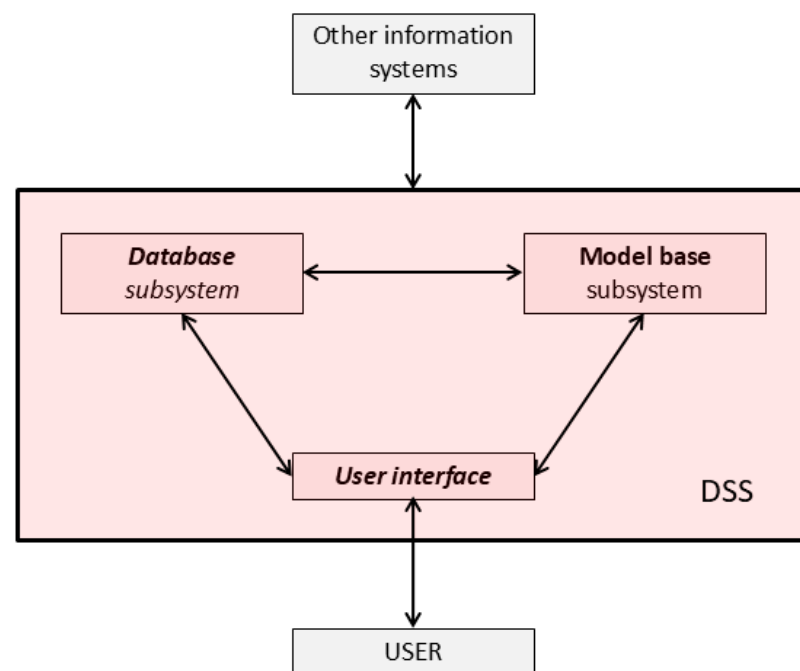


Figure 1. DSS structure.

The main drawback of DSSs is reflected in the problem of selecting methods and using suitable models from the model database. The decision-maker often faces the following questions: Which model to choose? How to use the selected model? How to combine multiple models? An additional problem with the model database arises when a new problem arises, for which there is no model in the model database.

2.2. MCDM Solver (MCSI)

This chapter presents an “on-line” DSS, called MCSI, which was developed as part of Dušan Petković’s PhD dissertation. The developed DSS is available on the “VIRTUODE” website (<https://virtuodeportalapp.azurewebsites.net/WebTools/Home>, accessed on 11 August 2025) to anyone who registers by creating an account. The appearance of the front page is shown in Figure A1. The developed DSS, in addition to solving the MCDM problems with beneficial and non-beneficial criteria, can also be successfully applied to

solving the MCDM problems with target-based criteria. MCSI has a universal purpose—its application is not limited to material selection but can be used for all MCDM problems too.

- Input data for MCSI are as follows:
- Initial decision matrix with target-based criteria;
- η —confidence level of decision-maker in terms of significance of the selected criteria (where $\eta = 1$ corresponds to 100% confidence level, while $\eta = 0$ corresponds to a confidence level of 0);
- Pairwise significance evaluation of the selected criteria or directly entering the criteria weights.

Based on the input data, MCSI can determine the criteria weights and ranking lists of alternatives with the corresponding values, based on which the ranking was performed, by using the TOPSIS, VIKOR, and WASPAS methods. The working principle of the developed DSS is based on the application of MCDM methods for the evaluation and ranking of alternatives and the methodology for evaluating the criteria weights. The architecture of the developed DSS is flexible and easily upgradable, so it allows the inclusion of new models that will be developed in the future. MCSI has a user-friendly user interface, which enables a simple and efficient way of entering the necessary data. Its use simplifies solving MCDM problems because it does not require expert knowledge in decision theory from the user. In addition, as an online DSS, it allows access and its use by users all over the world.

2.3. General Algorithm

The general algorithm of the developed DSS is shown in Figure 2. *ASP.NET MVC* (Front-end → HTML, JavaScript, jQuery, Back-end → C#) was used as the programming environment for the development of MCSI.

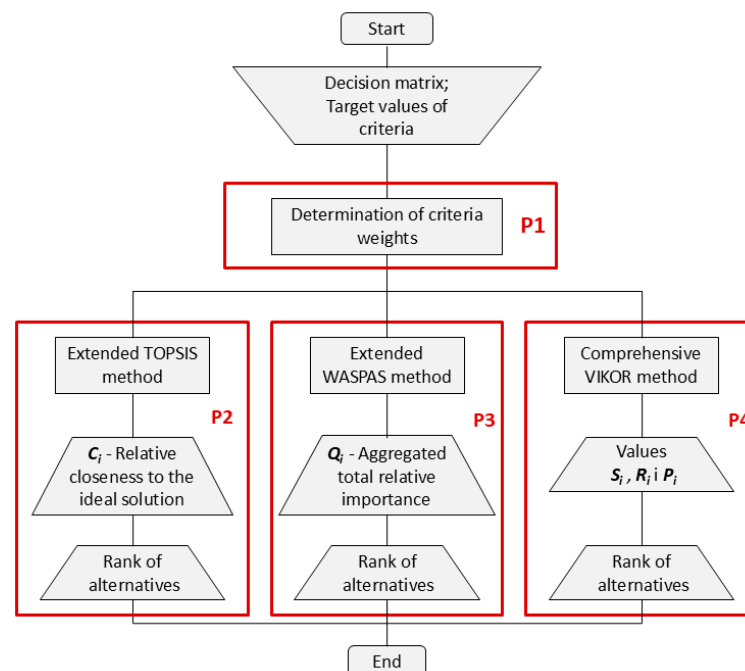


Figure 2. General algorithm of MCSI.

Input data in the developed DSS are the decision matrix and the target-based criteria. As an output, three ranking lists of alternatives with characteristic values are obtained, based on which the ranking is performed. In addition, if the criteria weights are not known in advance, they can be read within the output window.

MCSI is composed of four basic subroutines:

1. P1—program for determining criteria weights;
2. P2—program for solving MCDM problems using the extended TOPSIS method;
3. P3—program for solving MCDM problems using the extended WASPAS method;
4. P4—program for solving MCDM problems using the comprehensive VIKOR method.

After entering the input data, program P1 is executed first, while programs P2, P3, and P4 are executed in parallel, providing three ranking lists of alternatives, based on which the decision-maker can select the best one or the best ones.

The architecture of the software prototype was created to satisfy the following requirements:

- To implement the algorithm presented in Figure 2;
- To solve all MCDM problems in a simple way;
- To have upgradable and modular architecture;
- Software models located on the server;
- User-friendly interface, eliminating the need for expert knowledge. Based on the general algorithm, the MCSI is designed in such a way that the database is entered by the user, where the number of criteria and alternatives is not limited. The data must be in Excel format (.xlsx), organized as given in Figure A2.

2.4. Algorithm of P1—Determination of Criteria Weights

Determining the criteria weights is a very significant and influential part of the entire selection process based on the use of MCDM methodology [38,39]. The criteria weights may be determined based on data over which the decision-maker has no influence, and this is an objective method for criteria weighting. Very often, the criteria weights, which are defined based on objective methods, are not in accordance with the subjective evaluations of the decision-maker. On the other hand, the opinion of decision-makers depends on their knowledge and experience, and errors in subjective assessments are almost inevitable. Therefore, neither of these two approaches is perfect, so a combined method is often considered the most suitable for determining the criteria weights.

The combined method is particularly important in the problem of biomaterial selection with numerous alternatives, while the criteria are not completely independent of each other [40]. Within the P1 program, a combined method to determine the criteria weights was developed, as a linear combination of subjective (MDL-based) [25,30,41] and objective (standard deviation method-based) [4,25,30] for each criterion (Equation (1)).

$$w_j = \eta \cdot w_j^S + (1 - \eta) \cdot w_j^O, \quad j = 1, \dots, n$$

Confidence level of decision maker, $0 \leq \eta \leq 1$ (1)

Confidence level of decision-maker (η) was introduced to represent a measure of the decision-maker's confidence for the assumed criteria significance. If the problem is fully known, it is clear which of the criteria is the most significant and which one is the least significant; then, it can be assumed that the confidence level of the decision-maker is $\eta = 1$. In this way, the combined weighting coefficients of the criteria are reduced to subjective ones only. Otherwise, when the material selection problem is completely new and unknown, it is assumed that $\eta = 0$. In this way, the combined weights of the criteria are reduced to objective ones only. In practice, it is most often the case that the decision-maker is never completely confident which criteria are the most significant, so it is necessary to calculate the combined criteria weights, with the mathematical limitations and assumed value of η . An initial value of the confidence level is 0.5 while the operative value depends on the subjective decision-maker assessment of the assumed criteria significance.

Additionally, MCSI also offers the possibility of type criteria weights (in boxes), which provides an unlimited possibility to vary and try different combinations of criteria weights.

Initially, the criteria weights are equal; then, they can be calculated or entered by typing into the boxes (Figure 3).

Calculate weights

$\eta = 0.5$
 $\eta \in [0.0 - 1.0]$

Calculate

	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Criterion 1	=	=	=	=
Criterion 2	=	=	=	=
Criterion 3	=	=	=	=
Criterion 4	=	=	=	=

Weights

	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Weights	0.25000	0.25000	0.25000	0.25000

Confirm

Figure 3. Initial dialog panel for criteria weights calculation in MCSl.

2.5. Criteria Assessment

After uploading the data into MCSl, a dialog window appears in which the weighting coefficients of the criteria should be defined or the value of the confidence level (η) of the decision-maker in the significance of the criteria should be entered. If $\eta > 0$ the significance of the criteria should be pairwise assessed by assigning the following algebraic signs from the drop-down menu (Figure A3):

- “=”—equal importance of both criteria that are assessed;
- “>”—if the criterion on the left is more significant than the criterion on the right;
- “<”—if the criterion on the right is more significant than the criterion on the left.

When the weighting coefficients of the criteria are determined, MCSl performs calculations defined by the algorithm, based on which the alternatives/materials are ranked. Firstly, the ranking lists of alternatives/materials according to all three MCDM methods are displayed, based on which the best or several best should be chosen. In situations where disagreement about the best alternative arises, the three tables below should be analyzed, which show the values (metrics) based on which the ranking was made (Figure A4). Also, the tables show the calculated values of the weighting coefficients, according to algorithm P1. The results can be exported as an Excel file and thus saved.

2.6. Algorithm of P2 (Extended TOPSIS Method)

The TOPSIS method is based on the principle that the optimal point should have the shortest distance from the positive ideal solution and the farthest from the negative ideal solution. Hence, this method is suitable for risk avoidance designers, because the designers might like to have a decision that not only makes as much profit as possible but also avoids as much risk as possible [9]. The extended TOPSIS method [24] is based on the target values of the criteria. The steps of this method are as follows:

Step 1. Convert the raw values from initial matrix x_{ij} into the standardized measures r_{ij} , according to the proposed normalization technique in Equation (2).

$$r_{ij} = 1 - \frac{|x_{ij} - T_j|}{\text{Max}\{x_{ij}^{\text{max}}, T_j\} - \text{Min}\{x_{ij}^{\text{min}}, T_j\}} \quad (2)$$

where T_j is either the most favorable element x_{ij} or the target value in criteria j .

Step 2. Develop a set of weightings w_j for criteria, where $\sum_{j=1}^n w_j = 1$.

Step 3. Multiply the columns of the normalized decision matrix by the associated weightings (Equation (3)).

$$V_{ij} = w_j \cdot r_{ij} \quad (3)$$

Step 4. Identify the positive ideal solution (Equation (4)).

$$V_j^+ = \left\{ \text{Max}_i V_{ij}, \text{ for } i = 1, \dots, m \right\} \quad (4)$$

Step 5. Identify the negative ideal solution (Equation (5)).

$$V_j^- = \left\{ \text{Min}_i V_{ij}, \text{ for } i = 1, \dots, m \right\} \quad (5)$$

Step 6. Develop a distance measure for each alternative to both the positive ideal solution (D_i^+) and negative ideal solution (D_i^-) using Equations (6) and (7).

$$D_i^+ = \sqrt{\sum_{j=1}^n (V_{ij} - V_j^+)^2} \quad (6)$$

$$D_i^- = \sqrt{\sum_{j=1}^n (V_{ij} - V_j^-)^2} \quad (7)$$

Step 7. Calculate the relative closeness to the ideal solution according to Equation (8).

$$C_i = \frac{D_i^-}{D_i^- + D_i^+}, \text{ where } 0 \leq C_i \leq 1 \quad (8)$$

Step 8. Rank alternatives by maximizing the ratio in Step 7. The larger the index value, the better the performance of the alternative.

2.7. Algorithm of P3 (Extended WASPAS Method)

The WASPAS method is basically a combination of two well-known methods: the WSM and the WPM method. However, its main drawback is the impossibility of working with target-based criteria, so it is unusable for the selection of biomaterials. In order to use this method for the selection of biomaterials, an extension was necessary, so that the target criteria could also be considered. In this sense, the original WASPAS method was adapted and its application to the targeted criteria was enabled [31]. This extended method is called the extended WASPAS method and will be explained in detail below. The steps of the method are as follows:

Step 1. Determine the most favorable values for all criteria.

$$T = \{T_1, T_2, T_3, \dots, T_j, \dots, T_n\} = \{\text{Most desirable element } x_{ij} \text{ or target value for criteria } j\}$$

where x_{ij} ($i = 1, 2, \dots, m$ and $j = 1, 2, \dots, n$) are elements of the initial decision matrix (alternative i respect to criteria j).

Step 2. Linear normalization is used for transforming different criteria into a compatible measurement, i.e., numbers ranged from 0 to 1. Normalization of the alternative performances is carried out by using Equations (9)–(13).

$$r_{ij} = \frac{x_{ij}}{\max_i x_{ij}}, \text{ for beneficial criteria} \quad (9)$$

$$r_{ij} = \frac{\min_i x_{ij}}{x_{ij}}, \text{ for non-beneficial criteria} \quad (10)$$

$$\text{If } T_j < \min_i x_{ij} \Rightarrow r_{ij} = 1 - \frac{x_{ij} - T_j}{\max_i x_{ij}} \quad (11)$$

$$\text{If } T_j > \max_i x_{ij} \Rightarrow r_{ij} = 1 - \frac{T_j - x_{ij}}{T_j} \quad (12)$$

$$\text{If } \min_i x_{ij} < T_j < \max_i x_{ij} \Rightarrow r_{ij} = 1 - \frac{|x_{ij} - T_j|}{\max_i x_{ij} - \min_i x_{ij}} \quad (13)$$

where T_j is a target value for j -th criterion, $j = 1, 2, \dots, n$.

Step 3. Develop a set of weightings w_j for criteria, where $\sum_{j=1}^n w_j = 1$.

Step 4. Determine the two criteria of optimality based on the WSP and the WPM methods using Equations (14) and (15), respectively.

$$Q_i^{(1)} = \sum_{j=1}^n r_{ij} w_j \quad (14)$$

$$Q_i^{(2)} = \prod_{j=1}^n r_{ij}^{w_j} \quad (15)$$

Step 5. Calculate the aggregated total relative importance of the i -th alternative as shown in Equation (16).

$$Q_i = \lambda \cdot Q_i^{(1)} + (1 - \lambda) \cdot Q_i^{(2)} = \lambda \cdot \sum_{j=1}^n r_{ij} w_j + (1 - \lambda) \cdot \prod_{j=1}^n r_{ij}^{w_j} \quad (16)$$

$$\lambda = 0, 0.1, 0.2, \dots, 1$$

Parameter λ can be varied, but most frequently $\lambda = 0.5$ (in MCDI). The candidate alternatives/materials are ranked based on the aggregated total relative importance (Q values), i.e., the best alternative has the highest Q value and vice versa.

2.8. Algorithm of P4 (Comprehensive VIKOR Method)

The VIKOR method was developed for multi-criteria optimization in complex systems [12] and enjoys wide acceptance. The focus of this method is on ranking alternatives with conflicting criteria of different units of measurement. It is particularly suitable for decision problems where quantitative attributes predominate. A compromise solution is a possible solution that is closest to the ideal, based on the adopted measure of separation. The comprehensive VIKOR method is an adapted VIKOR using a novel normalization technique. The comprehensive VIKOR method [26] covers all types of criteria and overcomes the main error of the traditional VIKOR by using a simpler approach. A detailed algorithm of the comprehensive VIKOR method is illustrated step by step as follows:

Step 1. Determine the most favorable values for all criteria.

$$T = \{T_1, T_2, T_3, \dots, T_j, \dots, T_n\} = \{\text{Most desirable element } x_{ij} \text{ or target value for criteria } j\}$$

where x_{ij} ($i = 1, 2, \dots, m$ and $j = 1, 2, \dots, n$) are elements of the initial decision matrix (alternative i respect to criteria j)

Step 2. Develop a set of weightings w_j for criteria, where $\sum_{j=1}^n w_j = 1$.

Step 3. Compute the values S_i and R_i by the Equations (17) and (18).

$$S_i = \sum_{j=1}^n w_j (1 - e^{\frac{|x_{ij} - T_j|}{-A_j}}) \quad (17)$$

$$R_i = \max_j [w_j (1 - e^{\frac{|x_{ij} - T_j|}{-A_j}})] \quad (18)$$

where $A_j = \begin{cases} 1 & \text{For normalized values} \\ \max\{x_j^{\max}, T_j\} - \min\{x_j^{\min}, T_j\} & \text{Otherwise} \end{cases}$.
 $x_j^{\max}$ and $x_j^{\min}$ are the maximum and minimum elements in criteria j , respectively, and w_j represents the weightings of criteria j .

Step 4. Compute the index values P_i according to Equation (19). These index values are defined as follows:

$$P_i = \begin{cases} \left[\frac{R_i - R^-}{R^+ - R^-} \right] & \text{if } S^+ = S^- \\ \left[\frac{S_i - S^-}{S^+ - S^-} \right] & \text{if } R^+ = R^- \\ \left[\frac{S_i - S^-}{S^+ - S^-} \right] \nu + \left[\frac{R_i - R^-}{R^+ - R^-} \right] (1 - \nu) & \text{Otherwise} \end{cases} \quad (19)$$

where $S^- = \min S_i$, $S^+ = \max S_i$, $R^- = \min R_i$, $R^+ = \max R_i$, and ν is introduced as a weighting for the strategy of “the majority of criteria” (or “the maximum group utility”), whereas $(1 - \nu)$ is the weight of the individual regret. The value of ν lies in the range of [0–1] and these strategies can be compromised by $\nu = 0.5$ (in MCDI).

Step 5. Perform three ranking lists based on the values of S_i , R_i , and P_i . The best alternative, ranked according to the trade-off ranking, is the one with the lowest P_i value.

Step 6. Propose as a compromise solution the alternative $A^{(1)}$, which is the best-ranked by the metric/measure P (minimum) if the following two conditions are satisfied:

C1. Acceptable advantage

$$P(A^{(2)}) - P(A^{(1)}) \geq \frac{1}{m-1} \quad (20)$$

where $A^{(2)}$ is the alternative with second place in the ranking list by P_i ;

C2. Acceptable stability in decision-making

The alternative $A^{(1)}$ should also be the best-ranked by S or/and R .

A set of compromise solutions is proposed as follows, if one of the conditions is not satisfied.

- Alternatives $A^{(1)}$ and $A^{(2)}$ if only the C2 is not satisfied, or;
- Alternatives $A^{(1)}$, $A^{(2)}$, ..., $A^{(k)}$ if the C1 is not satisfied; $A^{(k)}$ is determined by the relation $P(A^{(k)}) - P(A^{(1)}) < \frac{1}{m-1}$ for maximum k .

3. Biomaterial Selection

Modern medical treatment procedures have significantly contributed to a better and longer life span, creating new challenges in the healthcare of the increasing elderly population [42]. According to estimates, by 2050, the USA will have 20% of the population over 65, Europe close to 30%, while in Japan, it could be almost 40% [43]. Because of this, it is reasonable to expect an increasing need for various medical interventions and the use of biomedical implants.

Biomaterials represent a special class of materials, which are used in medicine and stomatology to replace the structural components of the human body, to compensate for

damage caused by aging, disease, or accidents. The most significant factor that distinguishes biomaterials from any other material is their ability to be persistently in contact with the tissues of the human body without causing an unacceptable degree of reaction/damage to the body, i.e., biomaterials must be biocompatible [44].

Most implants successfully serve their wearers the purpose for which they are intended, for a certain period. However, some implants and extracorporeal devices inevitably create complications, either because of inflammation, infection, interactions in the form of unwanted (allergic or toxic) reactions, or due to device failure. Complications are most often the result of biomaterial–tissue interactions, which occur at the place of installation of each material, although they can also have a systematic or general character. The effects of the implant on the host tissue and the living tissue on the implant are equally important, both to avoid possible complications and to prevent malfunction or failure of the device. The most important properties of biomaterials are physical, chemical, mechanical, and biological, which are observed in relation to the surface or the entire volume of the biomaterial [45]. Biological properties indicate the behavior of materials in a biological environment, and these properties are crucial for the selection of biomaterials. They also represent limitations for many materials with superior mechanical and/or physical–chemical properties.

The selection of the most suitable biomaterial is a complex process, which must consider the wishes, needs, possibilities, and limitations of the available materials. It depends on many factors, such as the requirements regarding mechanical loads, chemical and biological properties, etc. Requirements regarding the biological properties must be met for each application, and the biomaterial should also meet most other requirements to avoid unexpected and unwanted failure.

For implants to adequately and safely perform their assigned function, they must possess the following essential properties (the list can be further expanded) [3,46]:

- Exceptional biocompatibility with the surrounding tissue.
- Non-toxicity of biomaterials or their degradation products.
- Adequate mechanical properties (mechanical continuity with the surrounding bone tissue).
- High corrosion resistance.
- High wear resistance.
- Osteo-integration (in the case of orthopedic and dental implants).

The aforementioned requirements, as well as specific additional requirements and limitations, should be taken into account when designing prostheses and implants.

Metallic Biomaterials

Metallic biomaterials account for between 70% and 80% of all materials used for the implant's fabrication, constituting one of the most important classes of biomaterials [47]. The basic mechanical properties of metallic biomaterials are the modulus of elasticity, yield stress, dynamic strength, and toughness. Among metallic biomaterial alloys such as stainless steels and Co-Cr alloys, titanium and its alloys show the best biocompatibility. In addition, titanium and its alloys are the most promising due to their excellent corrosion resistance and lower stiffness (which promises the best transmission of mechanical stresses from their implants to the bone), while TiO₂ on the surface shows certain bioactive properties and induces new bone growth.

4. Results and Discussion

4.1. Case Study 1: Plate for Internal Bone Fixation—Selection of Biomaterial

4.1.1. Plate for Internal Bone Fixation

Fracture treatment of the musculoskeletal system represents about 70% of the total activity in orthopedic surgery. The goals of treating bone fractures are to achieve rapid

growth, restore function, and preserve aesthetic appearance, without general or local complications. Surgical treatment can be external or internal fixation. From the aspect of biomaterials, treatment with internal fixation is more significant, where fragments of fractured bones are fixed using implants (wires, screws, plates, and/or intramedullary nails) [48].

All internal fixation devices must meet certain requirements for biomaterials, including biocompatibility, sufficient strength without dimensional restrictions, and corrosion resistance. In addition, the fixation device should provide suitable mechanical conditions for fracture healing. Their main function is to stabilize bone fragments, and they are most often made of titanium or stainless steel. There are numerous manufacturers and implant design concepts. The plates differ in size and adaptation to specific anatomical regions [49].

Internal fixation of bones implies the temporary or permanent incorporation of some foreign material into the human body, i.e., implants. Fractures in the hip area are most common in older people and more often in women (due to osteoporosis at that age). In approximately half of the injured, it is a fracture of the neck of the femur, and in the other half, a fracture in the trochanter region. These fractures comprise about 30% of the bed capacity of all orthopedic and traumatological institutions in the world [50].

Internal fixation plates (Figure 4) are usually used for the fixation of parts of bones (mostly long ones). They are made in very different shapes and sizes. Plates and screws for bone fixation can be very rigid, if they are intended for primary bone healing, but also relatively flexible, if the goal is to ease the physiological load on the bone. The stiffness and strength of the plate when bending depend on the shape of the cross-section and the material from which it is made [51].



Figure 4. Plates for internal bone fixation.

The most common causes of plate–screw fixation failure are loose screws and a weak (inappropriate) plate. Fracture of the plate occurs most often due to mechanical overload, fatigue at the place of the screw hole (where the stresses are highest), and/or corrosion at places with cracks [52,53].

Considering all the facts mentioned so far, it is completely clear that the selection of the biomaterial to produce plates for internal fixation has a very important and responsible role in the process of treating bone fractures. Therefore, in the following section, the selection of biomaterials to produce these plates using MCSI will be analyzed.

4.1.2. Criteria for Plate Biomaterial Selection

The basic aim of this study is a detailed analysis of the requirements and function of plates for the internal fixation and application of MCDM methodology for the selection of the most suitable biomaterial. In this sense, the selection of criteria is first performed, based on which the material candidates will be ranked. Taking into account the function of the bone and the environment in which the implanted plate is located, and based on all of the above, the criteria for the selection of biomaterial plates for internal bone fixation are as follows:

1. Yield stress in MPa (C1);
2. Tensile strength in MPa (C2);
3. Elongation in % (C3);
4. Elasticity modulus in GPa (C4);
5. Density in kg/m³ (C5);
6. Relative toughness (C6);
7. Corrosion resistance (C7);
8. Biocompatibility (C8);
9. Machinability (C9);
10. Relative biomaterial cost (C10).

Yield stress is a very important measure of material mechanical behavior since it shows at which stress permanent deformations begin, or conditionally speaking, when the elastic deformation curve ends. Therefore, it is desirable that the biomaterial for the plate has the highest possible yield stress.

Tensile strength is a commonly used measure of material strength. Regarding the design of bone fixation plates, the highest possible strength of the biomaterial is desirable, and therefore the highest possible tensile strength values.

Elongation of the material is a measure of its deformability due to tensile loading. For the plate biomaterial, high ductility is preferred, so that there is no sudden and unwanted premature breakage of the plate.

The modulus of elasticity is a measure of the stiffness of a material, i.e., a measure of resistance to elastic deformation due to loading. Regarding the requirements for the plates, it is desirable that the modulus of elasticity of the implant be as close as possible to the modulus of elasticity of the cortical bone, so that the load is evenly transferred from the bone to the plate and vice versa from the plate to the bone. Unfortunately, metal biomaterials have a much higher stiffness than bone, which in many cases can lead to a series of unwanted consequences [54].

It is known that metals have a much higher density than biological tissues, which is also one of their main disadvantages for biomedical applications. In this regard, biomaterials with a density close to cortical bone (titanium alloys) are most preferred.

Fracture toughness or critical value of the stress intensity factor (K_{Ic}) is a term from fracture mechanics that indicates the material's sensitivity to stress concentration, i.e., to the propagation of a crack in a mechanically loaded element. Fracture toughness can be defined as the ability of a part with a crack or defect to withstand a load without failure. Fracture toughness is the minimum resistance of a material to crack growth and is determined according to the standard procedure [55,56]. Based on the available data from the literature and comparative evaluations of material classes according to this criterion, a qualitative evaluation was performed according to an 11-point fuzzy scale [57].

Corrosion resistance is very important when considering the design requirements of a bone fixation plate. The reason for this is its environment with body fluids, which are aqueous solutions of salts and accompanying enzymes and proteins, which are very aggressive to the plate biomaterial. The evaluations of the performance of candidate materials in terms of corrosion resistance are given according to the phase scale, based on numerous research results, presented through articles and textbooks [58,59].

Biocompatibility is the most important property of biomaterials [58–61]. Roughly speaking, the greater the tolerance of the organism to the biomaterial, the greater the biocompatibility. From the aspect of biocompatibility, technically pure titanium is the best, while some elements, such as nickel, vanadium, chromium, cobalt, and aluminum, are marked as undesirable. A fuzzy scale was used to assess biocompatibility performance. Since the tiles are installed for a certain period, until the process of healing and the creation

of a stable callus are completed (up to several months), this criterion is not as emphasized as when making permanent implants. In any case, as much biocompatibility as possible is desirable.

The machinability of the biomaterial was introduced as a criterion that indicates the technical possibilities for shaping and processing products from the material considered. Indirectly, this criterion can be considered to include the costs that must be taken into account when designing and manufacturing the plate. Since it is not possible to numerically evaluate the machinability of a material, performance evaluations according to this criterion are based on a phase scale. At the same time, better machinability of the biomaterial was chosen as preferable.

Biomaterial cost is an important criterion for choosing any material. However, when making temporary implants, it is the least significant, but not negligible. In the initial decision-making matrix, approximate relative costs of materials are given, because they constantly vary on the market. In addition, the prices of biomaterials depend on the dimensions, quantity, method of production, and surface finishing. Hence, the relative costs of biomaterials are listed here as the ratio between the prices of each material in relation to the cheapest (M3—nickel-free austenitic stainless steel X4CrNiMoN23-21-1, Carpenter Technology (Europe) S.A., Mont-Saint-Guibert, Belgium).

4.1.3. List of Potential Biomaterials for the Plate

The next step (screening phase) in the selection of materials includes the collection of data on candidate materials that meet the criteria of biocompatibility and mechanical properties. This is also one of the most responsible phases of the work, because the accuracy and validity of the final ranking results depend on the accuracy and truthfulness of the initial data. Although it is obvious, it should be noted that MCDM methods cannot improve the quality of the optimal solution (the best-ranked material) above the quality of the data that make up the mathematical model (the initial decision matrix). It is also important to note that the list of candidate materials is also limited by the level of available data on their quantitative properties. When this is not possible (due to the unavailability of data (fracture toughness) or the very nature of the properties (corrosion resistance, biocompatibility, and machinability)), the material properties are expressed qualitatively using an 11-point fuzzy scale [57].

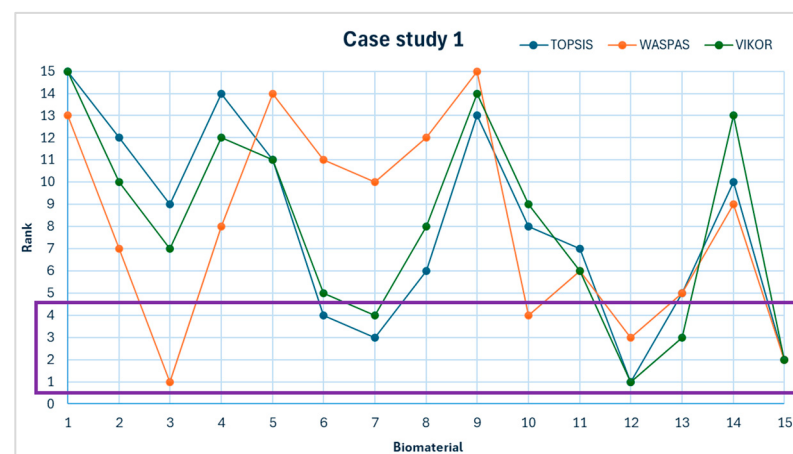
The list of potential biomaterials includes a total of 15 metallic biomaterials, of which 4 are stainless steels, 5 are from the class of Co-Cr superalloys, and 6 from the class of titanium alloys [54,61–66]. A list of potential biomaterials with elementary data is shown in Table A1. The initial decision matrix for plate biomaterial selection is shown in Table A2. The procedure for the determination of the criteria weights as well as computed values is shown in Appendix A.

4.1.4. Case Study 1—Ranking Results

Based on the ranking results obtained by the TOPSIS and the VIKOR methods (shown in Table 1 and Figure 5), it can be stated that the best metallic biomaterial for the manufacture of plates for internal bone fixation is M12 (Ti-6Al-7Nb). On the other hand, the WASPAS method proposed M3 (BioDur[®] 108 Alloy (Carpenter Technology (Europe) S.A., Mont-Saint-Guibert, Belgium)—wrought nitrogen-strengthened low-nickel stainless steel) as the best choice for this application. In addition, without any doubt, the second-ranked material is M15 (Ti-15Mo-5Zr), also from the titanium alloy class.

Table 1. Ranking results—case study 1 (determined by using MCSI for $\eta = 1$; the first three best ranked materials are highlighted).

No.	TOPSIS		WASPAS		VIKOR	
	C(i)	Rank	Q(i)	Rank	P(i)	Rank
M1	0.36091	15	0.47867	13	0.96259	15
M2	0.43561	12	0.54989	7	0.53136	10
M3	0.51072	9	0.6405	1	0.34875	7
M4	0.41394	14	0.5391	8	0.61966	12
M5	0.46863	11	0.46466	14	0.53465	11
M6	0.56775	4	0.51537	11	0.28385	5
M7	0.57665	3	0.51996	10	0.25942	4
M8	0.54337	6	0.5081	12	0.36803	8
M9	0.42652	13	0.44765	15	0.73832	14
M10	0.52587	8	0.56698	4	0.50918	9
M11	0.52614	7	0.55239	6	0.33352	6
M12	0.58704	1	0.59301	3	0.00151	1
M13	0.55505	5	0.55713	5	0.20215	3
M14	0.48953	10	0.53661	9	0.65273	13
M15	0.57799	2	0.60526	2	0.08705	2

**Figure 5.** Ranking results—case study 1 (determined by using MCSI for $\eta = 1$; purple rectangle—the first four best ranked biomaterials).

In order to check the rank stability of the proposed biomaterials as well as to determine the sensitivity of the applied MCDM methods to variation in the criteria weights, the biomaterials are ranked by using four values for confidence level η , i.e., 0.7, 0.8, 0.9, and 1 (shown in Table 2). Values of the criteria weights for the four considered confidence levels are shown in Table A2 with the initial decision matrix. Table A2 shows the variation in the criteria weights in the range of up to 20%, which is enough for the sensitivity of the methods being tested. Based on the sensitivity analysis, it can first be concluded that the WASPAS method has shown the highest robustness to the change in the criterion weights and absolute stability of the first-, second-, third-, as well as the last-ranked (14th and 15th) biomaterials. Also, M15 was unambiguously proposed as the second-ranked biomaterial for all considered methods and confidence levels (total match). The total match of TOPSIS and VIKOR is evident for the first, second, and the last rank. Each of the methods has shown a stable first and second rank as well as the last rank. The third-ranked biomaterials are different in the TOPSIS and VIKOR methods and there was not a stable ranking within the methods. Namely, only for $\eta = 0.7$ did both of them propose M3 as the third-ranked

while the increase in η moved the third rank to M7 and M13 by using the TOPSIS and the VIKOR methods, respectively.

Table 2. Ranking results—case study 1 for $\eta = 0.7, 0.8, 0.9$, and 1.0.

MCDM Method	TOPSIS				WASPAS				VIKOR			
η	0.7	0.8	0.9	1	0.7	0.8	0.9	1	0.7	0.8	0.9	1
M1	15	15	15	15	10	12	13	13	15	15	15	15
M2	11	11	12	12	4	4	5	7	6	9	9	10
M3	3	6	8	9	1	1	1	1	3	4	5	7
M4	12	13	14	14	6	6	8	8	11	11	12	12
M5	13	12	11	11	14	14	14	14	13	12	11	11
M6	4	3	4	4	11	11	11	11	8	8	7	5
M7	5	4	3	3	12	10	10	10	9	7	6	4
M8	8	7	6	6	13	13	12	12	7	6	8	8
M9	14	14	13	13	15	15	15	15	14	14	14	14
M10	7	8	7	8	5	5	4	4	10	10	10	9
M11	9	9	9	7	7	8	7	6	5	5	4	6
M12	1	1	1	1	3	3	3	3	1	1	1	1
M13	6	5	5	5	8	7	6	5	4	3	3	3
M14	10	10	10	10	9	9	9	9	12	13	13	13
M15	2	2	2	2	2	2	2	2	2	2	2	2

On the other hand, the metrics $C(i)$ based on which the TOPSIS ranking was performed differentiate between the first- (M12) and the second-ranked material (M15) as well as between the second- (M15) and the third-ranked (M7), which were 0.00905 and 0.00134, respectively ($C(12) - C(15) = 0.58704 - 0.57799 = 0.00905$ —less than 2% and $C(15) - C(7) = 0.00134$ —less than 1%). Within the WASPAS method, the difference is a bit larger: $Q(3) - Q(15) = 0.03524$, and $Q(15) - Q(12) = 0.01225$. Within the VIKOR method, the metric differences are nominally and percentually higher in relation to the other two methods ($P(12) - P(15) = \text{abs}(0.00151 - 0.08705) = 0.08554$; between the second- and the third-ranked one, it is $P(15) - P(13) = \text{abs}(0.08705 - 0.20215) = 0.1151$).

Taking into account the best-ranked biomaterials, one can notice that TOPSIS and VIKOR proposed M12 while WASPAS proposed M3. The second-ranked biomaterial for all methods is M15. The reason for this deviation and why WASPAS favored M3 lies in both the normalization method of the initial matrix and the part related to criterion C10, where this biomaterial (M3) received a many times higher value compared to the others (according to the values in the matrix). In other words, the proposed extension of the WASPAS method represents the linear normalization of the target-based criteria (see Section 2.7), where value zero (0) is not allowed due to further computing, which must continue without the loss of the criterion influence. This is why M3 is much more favored by the WASPAS method, regardless of the relatively low weight of the C10 criterion.

Based on the ranking results, one can conclude that for this orthopedic application, there is not much sense in using metallic biomaterials from the Co-Cr alloy groups. Additionally, as the best material for the plate production, MCSI proposed M12 (Ti-6Al-7Nb) and M3 (BioDur® 108 stainless steel), followed by M15 (Ti-15Mo-5Zr), which is consistent with the data from the literature. Wang et al. [67] reported the attractiveness of Ti-6Al-7Nb for orthopedic applications, such as fracture fixation plates, total hip replacement systems, etc. Moreover, many studies verify Ti-6Al-7Nb as one of the best Ti alloys for orthopedic devices and permanent implants [53,54,57–59,62].

Additionally, surgeons sometimes prefer more resistant stainless steel over titanium for trauma devices such as screws, plates, and intramedullary nails, which are subjected to intense solicitations [53]. Unlike most components used in arthroplasty, trauma devices are

often removed after the healing process has been completed and a perfectly osseointegrated titanium device would prove difficult to remove without damaging the surrounding tissue [49,68,69].

Ti-15Mo-5Zr has received a considerable amount of attention in the past few decades due to excellent biocompatibility and mechanical properties, especially for the modulus of elasticity [65]. However, the main lack of this alloy is a metastable structure, which may transform uncontrolled under certain conditions, potentially affecting the mechanical properties and biocompatibility [70]. For better development and application in the future, many studies have been conducted to investigate it. Although Ti-15Mo-5Zr has been used as a biomedical material, further investigations are still recommended to increase its reliability and bioactivity in the human body in long-term service [58].

4.2. Case Study 2: Femoral Component of the Hip Prosthesis—Selection of Biomaterial

4.2.1. Joint Replacement and Hip Prosthesis

The possibility of replacing damaged joints with prosthetic implants has brought relief to millions of patients, who would be severely limited in their most basic activities and condemned to living with pain. Joint degeneration is the final stage of joint cartilage destruction, which leads to severe pain, loss of mobility, and sometimes to angular deformation of the limb. Unlike bone, cartilage has a very limited ability to regenerate. Therefore, when it is exposed to severe mechanical, chemical, or metabolic injury, the damage is permanent and most often progressive. The hip joint is the most frequently replaced natural joint with an artificial implant in the world. The most common indication for hip replacement is a chronic degenerative disease, such as coxarthrosis. Among the other indications, the most common are rheumatoid arthritis, femoral neck fractures in relatively elderly people, aseptic necrosis of the femoral head, and other secondary arthrosis [54,71].

The hip joint prosthesis has the task of enabling the user to live and work normally (Figure 6). Under normal conditions, the hip joint prosthesis should function flawlessly from installation to revision for a period of 15 years, that is, it should withstand a minimum of 12 million cycles. From this fact, it follows that the dynamic strength, corrosion resistance, biocompatibility, and wear of the hip joint replacement affect its service life [72].

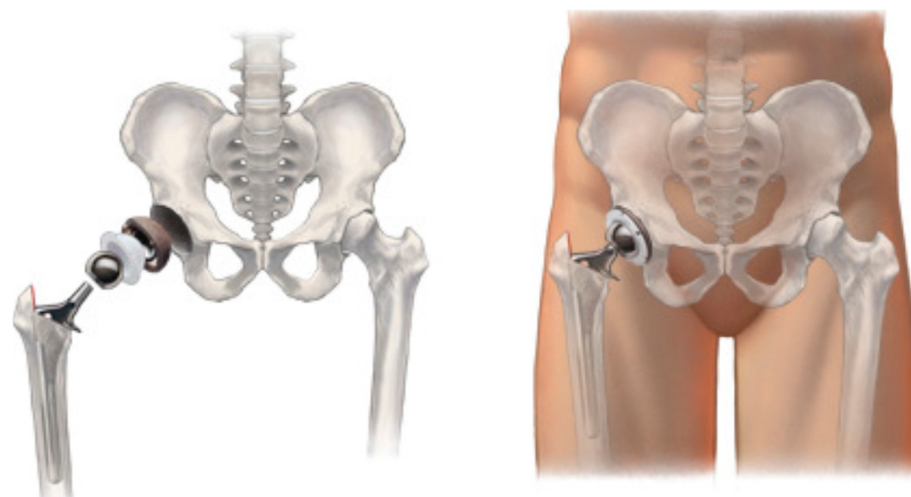


Figure 6. Hip replacement by prosthesis [30].

A hip prosthesis comprises three main components, as shown in Figure 7: (1) femoral component—commonly called stem or pin, (2) acetabular cup, and (3) acetabular interface—ball with neck [46].

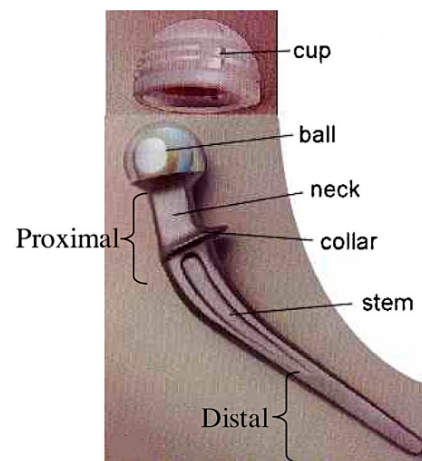


Figure 7. Hip prosthesis elements.

The femoral component is a rigid metal pin that is manufactured by precision forging in a cobalt chrome or titanium alloy, but previously also in stainless steel, with either an integral polished head or a separately attached ceramic ball head. This component is implanted into the hollowed-out shaft of the femur, replacing the natural femoral head [57]. The hip socket (acetabulum) is inserted with an acetabular cup; a soft polymer molding (a variety of materials were used in the past, but now it is predominantly made from polypropylene), which is fixed to the ilium [59].

The acetabular interface is placed between the femoral component and the acetabular cup and comes in a variety of material combinations (metal on polypropylene, ceramic on ceramic, and metal on metal) to reduce wear debris generated by friction [26,59].

MCSI was applied to select the most suitable material for the femoral component of the hip prosthesis. Before that, it is necessary to create a short list of alternative materials (preselection), which is given in Table 1. Additionally, determining the most favorable values in all criteria (target values— T_j) should be performed.

The compressive strength of compact bone is about 140 MPa and the elastic modulus is about 14 GPa in the longitudinal direction and about 1/3 of that in the radial direction. These values of strength and modulus for bone are modest compared to most engineering materials. However, a healthy bone is self-healing and has a great resistance to fatigue loading [54,59,73].

4.2.2. Criteria for the Hip Prosthesis Material Selection

It is necessary to have a good knowledge of the bone structure and its properties for the correct selection of the biomaterial for the hip endoprosthesis. The mechanical properties of bones are much worse than some metals and composite materials. However, it should be emphasized that bone heals and regenerates itself and has excellent resistance to the action of alternating dynamic loads. Therefore, the material for the prosthesis should be mechanically much stronger, since it does not have the possibility of regeneration and has limited durability. The list of potential biomaterials is the same as in the previously discussed case study of biomaterial selection, because this list was made by screening, with the most tolerant selection conditions (for a wider range of metallic biomaterials applications). A list of potential biomaterials with elementary data is shown in Table A1.

The selection criteria are mostly the same as in case study 1, while the difference is in an additional criterion—dynamic strength—and the absence of the relative biomaterial cost criterion [67]. Considering the function of the hip joint and its service environment, based on all of the above, the criteria for the selection of biomaterials for the femoral part of hip endoprosthesis are as follows:

1. Yield stress in MPa (C1);
2. Tensile strength in MPa (C2);
3. Fatigue strength in MPa (C3);
4. Elongation in % (C4);
5. Elasticity modulus in GPa (C5);
6. Density in kg/m³ (C6);
7. Relative toughness (C7);
8. Corrosion resistance (C8);
9. Biocompatibility (C9);
10. Machinability (C10).

Regarding yield stress, the biomaterial for the hip prosthesis should have the highest possible value.

In terms of the hip endoprosthesis, the highest possible tensile strength of the biomaterial is desirable. Based on stress analysis and the shape of the endoprosthesis, it was calculated that the material should have a tensile strength greater than 95 MPa [74]. However, taking into account the projected service life of the prosthesis, this value should be as high as possible [49].

The fatigue strength of a material is the maximum stress that it can withstand for a certain number of load cycles. Considering that the number of steps a person takes in 20 years is about $2000 \times 365 \times 20 \approx 10^7$ steps, i.e., cycles, it is necessary to take the dynamic (fatigue) strength of the material for 10^7 cycles as a criterion for selecting the hip endoprosthesis biomaterial. In the literature, it is stated that the minimum value of the flexural dynamic strength of the body of the hip endoprosthesis is 33 MPa [74], but the fatigue strength should be as high as possible.

For the material used to make the body of the hip endoprosthesis, which is the most loaded part, a material with high toughness is preferred, in order to avoid sudden and unwanted premature breakage [57]. Hence, higher values of elongation are desirable.

Regarding the requirements for hip prosthesis production, it is desirable to have a modulus of elasticity as close as possible to the modulus of elasticity of the femur, so that the load is evenly transferred from the bone to the body of the prosthesis and vice versa. Therefore, the target value of this criterion is desirable, i.e., to be as close as possible to the modulus of elasticity of cortical bone (14 GPa) [58,65,70].

It is known that metals have a much higher density than biological tissues, which is also one of their main disadvantages for biomedical applications. In this regard, biomaterials with a density close to cortical bone (2.1 g/cm³) are most preferred [49].

Fracture toughness as a criterion for the selection of the metallic biomaterial was already discussed in Section 4.1.2. Everything mentioned there also applies to the selection of biomaterials for the hip prosthesis.

Corrosion resistance is very important when considering the design requirements of permanent implants. The reason is their environment with body fluids, which are aqueous solutions of salts, both accompanying enzymes and proteins, which are very aggressive for the implanted metallic biomaterial. Since the hip prosthesis is installed with a projected service life of 15–20 years, this requirement is very rigorous for the selection [49,54,59,75].

Biocompatibility as a criterion for the selection of metallic biomaterials was already discussed in Section 4.1.2. Since the hip endoprosthesis is installed as a permanent implant, this criterion is very rigorous [59,75].

Machinability as a criterion for the selection of metallic biomaterial was already discussed in Section 4.1.2. Biomaterial cost is an important criterion for choosing any material; however, when making permanent implants, it is negligible. Therefore, this criterion was not considered in the initial decision-making matrix. The initial decision-

making matrix for hip prosthesis biomaterial selection is given in Table A3. The procedure for the determination of the criteria weights as well as the computed values are shown in Appendix A.

4.2.3. Case Study 2—Ranking Results

Based on the results shown in Table 3 and Figure 8, it can be concluded that the best-ranked metallic biomaterials for the body of the hip endoprosthesis are M12 (Protasul 100 (Ti-6Al-7Nb)—two-phase titanium alloy) and M15 (Ti-15Mo-5Zr— β metastable titanium alloy), both from titanium-based alloys. In addition to the above, it should be emphasized that there is no stable ranking of these two materials, because by applying the WASPAS and TOPSIS methods, M12 is the second-ranked, while only with the VIKOR method is it the best-ranked biomaterial. Additionally, WASPAS recommends M15 as the best candidate, while TOPSIS recommends M7, which is also a serious candidate for this application.

Table 3. Ranking results—case study 2 (determined by using MCSI for $\eta = 1$; the first three best ranked materials are highlighted).

No.	TOPSIS		WASPAS		VIKOR	
	C(i)	Rank	Q(i)	Rank	P(i)	Rank
M1	0.31059	14	0.49658	14	0.99262	14
M2	0.32923	13	0.53911	11	0.94838	13
M3	0.41753	10	0.59748	9	0.5774	8
M4	0.30558	15	0.53317	12	1	15
M5	0.37383	11	0.49616	15	0.9333	12
M6	0.56664	5	0.6056	8	0.20032	6
M7	0.60806	1	0.63975	3	0.07027	4
M8	0.51629	8	0.60614	7	0.64589	9
M9	0.37006	12	0.50988	13	0.7612	11
M10	0.52711	7	0.62369	6	0.30244	7
M11	0.53481	6	0.63011	5	0.18257	5
M12	0.59714	2	0.66704	2	0	1
M13	0.58041	4	0.63605	4	0.06465	3
M14	0.44623	9	0.57241	10	0.72884	10
M15	0.59240	3	0.69360	1	0.06339	2

Since the situation is unclear about the best candidate, further analysis of the case is needed. For that purpose, sensitivity analysis of the rank stability of the applied MCDM methods to the variation in the criteria weights was performed by using four values for confidence level η , i.e., 0.7, 0.8, 0.9, and 1 (shown in Table 4). Values of the criteria weights for the four considered confidence levels are shown in Table 4 with the initial decision matrix. Table 4 also shows the variation in the criteria weights in the range of about 20%, which is enough for testing the methods' sensitivity. Based on the sensitivity analysis, it can first be concluded that the WASPAS method has repeated the highest robustness to the change in the criterion weights and has maintained absolute stability in the first-, second-, third-, as well as the last-ranked biomaterials. Contrary, the VIKOR method does not maintain a stable first, second, third, and last rank, pointing out its sensitivity to the criteria weights, which is conditional, taking into account the condition of acceptable advantage (C1). The TOPSIS method has proposed M7 as the best alternative, while WASPAS proposed M15. TOPSIS has proposed M15 and M12 for the second- and third-ranked biomaterial for $\eta = 0.7$ and 0.8, respectively, while with an increasing confidence level, they alternate. VIKOR has proposed steady M7 as the best alternative for a confidence level of 0.7, 0.8, and 0.9, but replaced it with M12 for a confidence level of 1.

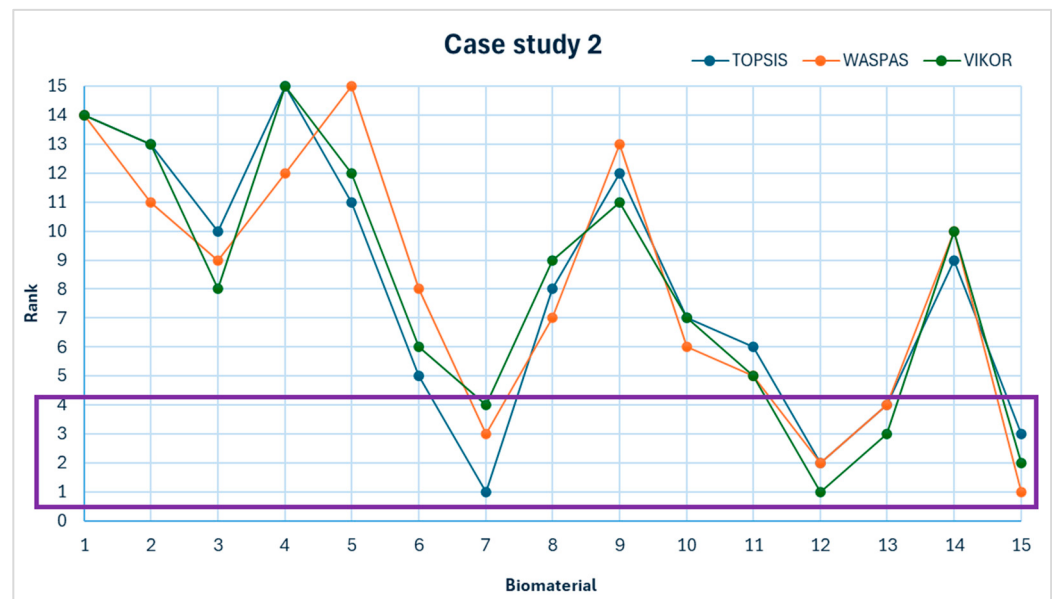


Figure 8. Ranking results—case study 2 (determined by using MCSI for $\eta = 1$; purple rectangle—the first four best ranked biomaterials).

Table 4. Ranking results—case study 2 for $\eta = 0.7, 0.8, 0.9$, and 1.0 .

MCDM Method	TOPSIS				WASPAS				VIKOR			
η	0.7	0.8	0.9	1	0.7	0.8	0.9	1	0.7	0.8	0.9	1
M1	13	14	14	14	13	13	14	14	13	13	13	14
M2	12	13	13	13	11	11	11	11	12	12	12	13
M3	9	9	10	10	7	7	7	9	8	8	8	8
M4	15	15	15	15	12	12	12	12	14	14	15	15
M5	14	12	12	11	15	15	15	15	15	15	14	12
M6	4	5	5	5	8	8	9	8	5	5	5	6
M7	1	1	1	1	3	3	3	3	1	1	1	4
M8	6	8	8	8	9	9	8	7	10	9	9	9
M9	11	11	11	12	14	14	13	13	9	10	10	11
M10	8	7	7	7	4	6	6	6	6	7	7	7
M11	7	6	6	6	5	5	5	5	7	6	6	5
M12	3	3	2	2	2	2	2	2	2	2	2	1
M13	5	4	4	4	6	4	4	4	4	4	4	3
M14	10	10	9	9	10	10	10	10	11	11	11	10
M15	2	2	3	3	1	1	1	1	3	3	3	2

Additionally, within the TOPSIS method, the metrics difference (based on which the TOPSIS ranking was performed) between the first- (M7) and the second-ranked material (M12) is as follows: $C(7) - C(12) = 0.60806 - 0.59714 = 0.01092$, while between the second and the third one, it is as follows: $C(12) - C(15) = 0.00474$ (less than 1%). Within the WASPAS method, the difference is a bit larger $Q(15) - Q(12) = 0.02656$, and $Q(12) - Q(7) = 0.02729$. On the other hand, within the VIKOR method, the difference between the first- and the fourth-ranked one is $P(12) - P(7) = \text{abs}(0 - 0.07027) = 0.07027$, which is a very little value and it has no acceptable advantage ($1/(m - 1) = 0.071$, $m = 15$) between the alternatives, so M12, M15, M13, and M7 are considered as the first-ranked alternatives [9].

Finally, based on the results, it is completely clear that stainless steels are not suitable for making this type of implant, which was perhaps expected due to their poorer biocompatibility and weaker mechanical properties. Based on all of the above, the proposed most suitable materials for the body of the hip prosthesis would be $M7 = M15 = M12$. In other

words, there is not one superior best-ranked biomaterial for this application. Therefore, the list of the three proposed biomaterials, i.e., M7 (Micro-Melt® BioDur® Carpenter CCM® Co-Cr based-alloy, Carpenter Technology (Europe) S.A., Mont-Saint-Guibert, Belgium), M15 (Ti-15Mo-5Zr), and M12 (Ti-6Al-7Nb) is the best choice for the hip prosthesis. Other candidates from the proposed list are not appropriate enough to be considered as biomaterials for this application.

The results obtained for this case study are in accordance with most previous studies. The most used and most proposed metallic biomaterial for the body of the hip prosthesis is Ti-6Al-7Nb due to an excellent combination of biocompatibility and mechanical properties, excluding wear resistance [49,54,57–59,61,63,64,67]. Co-Cr alloys are widely used in total hip replacements worldwide, with significant prevalence over other materials such as Ti alloys and ceramics [54]. Generally, compared to Ti, Co-Cr alloys offer greater wear resistance but are less biocompatible [62,63,76]. The study of Sofuoğlu also highlighted wrought Co-Cr alloy and Ti6Al4V as the best alternatives for hip prosthesis using the RIM method [17]. Also, Çelik and Eroğlu, who applied the analytic hierarchy process (AHP), identified Co-Cr-Mo as the best alternative [77].

The most promising alloy, Ti-15Mo-5Zr, has received a considerable amount of attention in the past few decades but further investigations are still recommended to increase its reliability in the human body in long-term service [58,65,70].

5. Conclusions

As part of this research, a DSS named MCSI was developed, whose primary aim was to assist in decision-making for the selection of biomaterials. The developed MCSI, in addition to solving the MCDM problem with beneficial and cost criteria, can also be successfully used to solve the MCDM problem with target-based criteria. In this way, the material selection process is generally carried out much faster and more easily by using MCSI, because it comes down to the selection of potential materials and pairwise significance evaluation of the selected criteria. Thanks to it, a complex mathematical apparatus is avoided and the ranking process becomes reliable, fast, and comfortable to work with.

Computational procedures are relatively simple and can be easily followed by the decision-maker. Solving different MCDM problems by using MCSI does not require the use of specialized software packages since the method can be easily implemented.

The detailed procedure for MCSI use was shown while solving two case studies of biomaterial selection. The first case study analyzed biomaterial selection for a plate for internal bone fixation. In the second case study, the biomaterial selection problem for hip prosthesis was solved.

The ranking results showed that the Ti-6Al-7Nb alloy and wrought nitrogen-strengthened low-nickel stainless steel are the most preferable biomaterials for the plate for bone fixation. Also, one of the conclusions is that three proposed biomaterials, i.e., Co-Cr-Mo alloy, Ti-15Mo-5Zr, and Ti-6Al-7Nb, are the best choice for the hip prosthesis. Additionally, based on this study, one can conclude that stainless steels are inferior to titanium and Co-Cr alloys for permanent implants like total hip replacement.

The direction of further improvement in MCSI should go towards the transformation of the DSS into a knowledge-based decision support system. The future system would represent an intelligent decision support system, composed of an expert system and a decision support system. For such a system, in addition to the already existing database and model database subsystems, it is necessary to add a knowledge base subsystem. The knowledge base should contain qualitative data in the form of memorized experts' knowledge in the field of biomaterials and inference mechanisms.

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Abbreviations

The following abbreviations are used in this manuscript:

DSS	Decision support system
MCDM	Multi-criteria decision-making
MCSI	MCDM Solver
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
WASPAS	Weighted Aggregated Sum Product Assessment
VIKOR	VIšekriterijumsko KOmpromisno Rangiranje

Appendix A

In this section, the screenshots and necessary table-arranged data are shown. All presented data are important to understand MCSI and its use. Figure A1 shows the initial layout of MCSI.

Figure A2 shows an example of how an Excel sheet (initial decision matrix with target-based criteria) must be prepared to be uploaded to MCSI.

Pairwise significance evaluation of the criteria by MCSI and criteria weights determined values for case study 1 are shown in Figure A3.

Figure A4 shows the ranking lists with the metrics for case study 1 as a screenshot of the MCSI user interface.

Table A1 provides a list of metallic biomaterial candidates with basic data.

The initial decision matrix for the plate biomaterial selection with target values for the criteria is given in Table A2. In this table, values for C1, C2, C3, C4, and C5 are numeric attributes that represent an absolute measure of material properties. Values for C6, C7, C8, and C9 are categorical data with qualitative description that were converted to numerical values using an 11-point fuzzy scale. Finally, the C10 criterion is the ratio values.

The MCSI calculation of the subjective weightings (confidence level $\eta = 1$) of the criteria was carried out based on the pairwise comparison method, where the criteria are presented with a worksheet and asked to compare the importance of two criteria at a time (Figure A3). Thereby, the tensile strength (C2) and biocompatibility (C8) are considered as the most influential criteria with a weight of 0.139. Yield strength (C1) and corrosion resistance (C7) are the second most influential criteria with a weight of 0.128. Density (C5) and relative material cost (C10) are the least influential criteria with a weight of 0.061. Other criteria are between them, as shown in Table A2.

Figure A5 shows the pairwise significance evaluation of the criteria by MCSI and the determined values of the criteria weights for case study 2.

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Figure A1. MCSI—initial layout.

AutoSave [Off] Data preparation for uploading - Saved to this PC

File Home Insert Draw Page Layout Formulas Data Review View Automate Help ACROBAT PDF-XChange

Clipboard Font Alignment Number Styles Cells Editing Sensitivity Add-Ins Analyze Data

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1		Criterion 1	Criterion 2	...	Criterion n									
2	Alternative 1	X11	X12	...	X1n									
3	Alternative 2	X21	X22	...	X2n									
4	...	...	...	...	...									
5	Alternative m	Xm1	Xm2	...	Xmn									
6	Target values of criteria	T1	T2	...	Tn									
7														

Figure A2. An example of data preparation for MCSI.

Figure A3. Pairwise significance evaluation of the criteria using MCSI—case study 1.

The initial decision matrix for the hip prosthesis biomaterial selection with target values for the criteria is given in Table A3. In this table, values for C1, C2, C3, C4, C5,

and C6 are numeric attributes that represent an absolute measure of material properties. Values for C7, C8, C9, and C10 are categorical data with qualitative descriptions that were converted to numerical values using an 11-point fuzzy scale.

The MCSI calculation of the subjective weightings (confidence level $\eta = 1$) of the criteria was carried out based on the pairwise comparison method, where the criteria are presented with a worksheet and asked to compare the importance of two criteria at a time (Figure A5). Thereby, biocompatibility (C9) was proven as the most influential criterion with a weight of 0.144, followed by fatigue strength (C2) with a weight of 0.139 and corrosion resistance (C8) with a weight of 0.133. Yield strength (C1) and tensile strength (C2) are the fourth- and fifth-ranked criteria, respectively. Finally, machinability (C10) is the least influential criterion with a minimal possible weight of 0.05. Other criteria are between C2 and C10, as shown in Table A3.

MCDM Solver

Step 3: Review results

	TOPSIS	WASPAS	VIKOR
M1	15	13	15
M2	12	7	10
M3	9	1	7
M4	14	8	12
M5	11	14	11
M6	4	11	5
M7	3	10	4
M8	6	12	8
M9	13	15	14
M10	8	4	9
M11	7	6	6
M12	1	3	1
M13	5	5	3
M14	10	9	13
M15	2	2	2

Export

	Yield stress (MPa)	Ultimate tensile stress (MPa)	Elongation (%)	Elasticity modulus (GPa)	Density (g/cm3)	Relative toughness	Corrosion resistance	Biocom.	Machin.	Relative cost	C	TOPSIS
M1	250	585	57	193	7.95	0.865	0.41	0.41	0.865	2.4	0.36091	15
M2	450	825	45	193	7.86	0.865	0.5	0.59	0.865	3.1	0.43561	12
M3	580	930	52	200	7.64	0.865	0.5	0.745	0.865	1	0.51072	9
M4	450	840	39	195	7.75	0.745	0.5	0.59	0.865	2.6	0.41394	14
M5	585	1035	25	241	8.28	0.59	0.745	0.745	0.335	21.9	0.46863	11
M6	880	1350	22	241	8.28	0.59	0.745	0.745	0.41	23.1	0.56775	4
M7	1115	1420	28	241	8.29	0.59	0.745	0.745	0.335	87	0.57665	3
M8	1340	1400	21	235	8.43	0.59	0.665	0.59	0.255	37.5	0.54337	6
M9	415	1035	60	243	9.22	0.59	0.665	0.665	0.335	36.2	0.42652	13
M10	550	670	22	103	4.51	0.335	0.955	0.955	0.5	13.1	0.52587	8
M11	710	880	12	105	4.43	0.335	0.865	0.865	0.41	18	0.52614	7
M12	850	950	12	105	4.52	0.335	0.955	0.955	0.41	15.5	0.58704	1
M13	820	900	6	112	4.45	0.335	0.865	0.955	0.41	16	0.55505	5
M14	570	690	15	103	4.48	0.335	0.865	0.865	0.5	16.5	0.48953	10
M15	920	960	25	78	5.06	0.335	0.865	0.865	0.41	19.4	0.57799	2
Targets	1340	1420	60	18	2.1	0.865	0.955	0.955	0.865	1		
Weights	0.12778	0.13889	0.07222	0.10000	0.06111	0.09444	0.12778	0.13889	0.07778	0.06111		

Export

Figure A4. Cont.

	Yield stress (MPa)	Ultimate tensile stress (MPa)	Elongation (%)	Elasticity modulus (GPa)	Density (g/cm ³)	Relative toughness	Corrosion resistance	Biocom.	Machin.	Relative cost	Q	WASPAS
M1	250	585	57	193	7.95	0.865	0.41	0.41	0.865	2.4	0.47867	13
M2	450	825	45	193	7.86	0.865	0.5	0.59	0.865	3.1	0.54989	7
M3	580	930	52	200	7.64	0.865	0.5	0.745	0.865	1	0.64050	1
M4	450	840	39	195	7.75	0.745	0.5	0.59	0.865	2.6	0.53910	8
M5	585	1035	25	241	8.28	0.59	0.745	0.745	0.335	21.9	0.46466	14
M6	880	1350	22	241	8.28	0.59	0.745	0.745	0.41	23.1	0.51537	11
M7	1115	1420	28	241	8.29	0.59	0.745	0.745	0.335	87	0.51996	10
M8	1340	1400	21	235	8.43	0.59	0.665	0.59	0.255	37.5	0.50810	12
M9	415	1035	60	243	9.22	0.59	0.665	0.665	0.335	36.2	0.44765	15
M10	550	670	22	103	4.51	0.335	0.955	0.955	0.5	13.1	0.56698	4
M11	710	880	12	105	4.43	0.335	0.865	0.865	0.41	18	0.55239	6
M12	850	950	12	105	4.52	0.335	0.955	0.955	0.41	15.5	0.59301	3
M13	820	900	6	112	4.45	0.335	0.865	0.955	0.41	16	0.55713	5
M14	570	690	15	103	4.48	0.335	0.865	0.865	0.5	16.5	0.53661	9
M15	920	960	25	78	5.06	0.335	0.865	0.865	0.41	19.4	0.60526	2
Targets	1340	1420	60	18	2.1	0.865	0.955	0.955	0.865	1		
Weights	0.12778	0.13889	0.07222	0.10000	0.06111	0.09444	0.12778	0.13889	0.07778	0.06111		
Export												
	Yield stress (MPa)	Ultimate tensile stress (MPa)	Elongation (%)	Elasticity modulus (GPa)	Density (g/cm ³)	Relative toughness	Corrosion resistance	Biocom.	Machin.	Relative cost	P	VIKOR
M1	250	585	57	193	7.95	0.865	0.41	0.41	0.865	2.4	0.96259	15
M2	450	825	45	193	7.86	0.865	0.5	0.59	0.865	3.1	0.53136	10
M3	580	930	52	200	7.64	0.865	0.5	0.745	0.865	1	0.34875	7
M4	450	840	39	195	7.75	0.745	0.5	0.59	0.865	2.6	0.61966	12
M5	585	1035	25	241	8.28	0.59	0.745	0.745	0.335	21.9	0.53465	11
M6	880	1350	22	241	8.28	0.59	0.745	0.745	0.41	23.1	0.28385	5
M7	1115	1420	28	241	8.29	0.59	0.745	0.745	0.335	87	0.25942	4
M8	1340	1400	21	235	8.43	0.59	0.665	0.59	0.255	37.5	0.36803	8
M9	415	1035	60	243	9.22	0.59	0.665	0.665	0.335	36.2	0.73832	14
M10	550	670	22	103	4.51	0.335	0.955	0.955	0.5	13.1	0.50918	9
M11	710	880	12	105	4.43	0.335	0.865	0.865	0.41	18	0.33352	6
M12	850	950	12	105	4.52	0.335	0.955	0.955	0.41	15.5	0.00151	1
M13	820	900	6	112	4.45	0.335	0.865	0.955	0.41	16	0.20215	3
M14	570	690	15	103	4.48	0.335	0.865	0.865	0.5	16.5	0.65273	13
M15	920	960	25	78	5.06	0.335	0.865	0.865	0.41	19.4	0.08705	2
Targets	1340	1420	60	18	2.1	0.865	0.955	0.955	0.865	1		
Weights	0.12778	0.13889	0.07222	0.10000	0.06111	0.09444	0.12778	0.13889	0.07778	0.06111		
Export												
Step 2 << >>												

Figure A4. Screenshot of biomaterials ranking lists and metrics for all methods—case study 1 ($\eta = 1$).

Table A1. List of potential biomaterials for the plate.

No.	Commercial Name	Alloy	UNS Number	State	Standard
M1	BioDur [®] 316LS Stainless *	Stainless steel	S31673	Annealed	ASTM F138 [78]
M2	Carpenter 22Cr-13Ni-5Mn *		S20910	Annealed	ASTM F1314 [79]
M3	BioDur [®] 108 Alloy (X4CrNiMoN23-21-1) *		S29108	Annealed	ASTM F2229 [80]
M4	BioDur [®] 734 Stainless *		S31675	Annealed	ASTM F1586 [81]
M5	BioDur [®] Carpenter CCM [®] Alloy *	Co-Cr-based alloy	R31537	Annealed	ASTM F799 [82], ASTM F1537 [83]
M6	BioDur [®] CCM Plus [®] Alloy *		R31537	Annealed 1093 °C/1 h	ASTM F799 [82], ASTM F1537 [83]
M7	Micro-Melt [®] BioDur [®] Carpenter CCM [®] alloy *		R31537	Worm-worked	ASTM F1537 [83]
M8	Carpenter MP35N Alloy *		R30035	35% cold reduction, aged 538 °C/4 h	ASTM F562 [84]
M9	Carpenter L-605 Alloy *		R30605	Annealed 1204 °C	ASTM F90 [85]
M10	CP Titanium Grade 4	Ti-based alloy	R50700	Annealed	ASTM F67 [86]
M11	Ti 6Al-4V ELI		R56401	Recrystallization annealed	ASTM F136 [87]
M12	Protasul-100 **, (Ti-6Al-7Nb) *		R56700	Annealed 700 °C/1 h	ASTM F1295 [88]
M13	Ti-5Al-2.5Fe		-	Centrifugally casted	DIN 3.7110 [89]
M14	HAYNES [®] Ti-3Al-2.5V alloy ***		R56320	Annealed 704 °C	ASTM F2146 [90]
M15	Ti-15Mo-5Zr		-	Quenched	-

* Carpenter Technology (Europe) S.A., Mont-Saint-Guibert, Belgium; ** Zimmer GmbH, Winterthur, Switzerland;

*** Haynes International, Haynes International, Lenzburg, Switzerland.

Table A2. Initial decision matrix for plate biomaterial selection with criteria weights.

Biomaterial	C1 (MPa)	C2 (MPa)	C3 (%)	C4 (GPa)	C5 (g/cm ³)	C6	C7	C8	C9	C10
M1	250	585	57	193	7.95	0.865	0.41	0.41	0.865	2.4
M2	450	825	45	193	7.86	0.865	0.5	0.59	0.865	3.1
M3	580	930	52	200	7.64	0.865	0.5	0.745	0.865	1
M4	450	840	39	195	7.75	0.745	0.5	0.59	0.865	2.6
M5	585	1035	25	241	8.28	0.59	0.745	0.745	0.335	21.9
M6	880	1350	22	241	8.28	0.59	0.745	0.745	0.41	23.1
M7	1115	1420	28	241	8.29	0.59	0.745	0.745	0.335	87
M8	1340	1400	21	235	8.43	0.59	0.665	0.59	0.255	37.5
M9	415	1035	60	243	9.22	0.59	0.665	0.665	0.335	36.2
M10	550	670	22	103	4.51	0.335	0.955	0.955	0.5	13.1
M11	710	880	12	105	4.43	0.335	0.865	0.865	0.41	18
M12	850	950	12	105	4.52	0.335	0.955	0.955	0.41	15.5
M13	820	900	6	112	4.45	0.335	0.865	0.955	0.41	16
M14	570	690	15	103	4.48	0.335	0.865	0.865	0.5	16.5
M15	920	960	25	78	5.06	0.335	0.865	0.865	0.41	19.4
Target values	1340	1420	60	18	2.1	0.865	0.955	0.955	0.865	1
Criteria weights	$\eta = 0.7$	0.118	0.121	0.088	0.105	0.070	0.098	0.114	0.120	0.089
	$\eta = 0.8$	0.121	0.127	0.083	0.103	0.067	0.097	0.119	0.126	0.085
	$\eta = 0.9$	0.125	0.133	0.078	0.102	0.064	0.096	0.123	0.132	0.081
	$\eta = 1.0$	0.128	0.139	0.072	0.100	0.061	0.094	0.128	0.139	0.078

Calculate weights

$\eta = 1$
 $\eta \in [0.0 - 1.0]$

Yield stress (MPa)

>

▼

Tensile strength (MPa)

Yield stress (MPa)

<

▼

Fatigue strength (MPa)

Yield stress (MPa)

>

▼

Elongation (%)

Yield stress (MPa)

>

▼

Elasticity modulus (GPa)

Yield stress (MPa)

>

▼

Density (g/cm3)

Yield stress (MPa)

>

▼

Relative toughness

Yield stress (MPa)

<

▼

Corrosion resistance

Yield stress (MPa)

<

▼

Biocom.

Yield stress (MPa)

>

▼

Machin.

Tensile strength (MPa)

<

▼

Fatigue strength (MPa)

Tensile strength (MPa)

>

▼

Elongation (%)

Tensile strength (MPa)

>

▼

Elasticity modulus (GPa)

Tensile strength (MPa)

>

▼

Density (g/cm3)

Tensile strength (MPa)

=

▼

Relative toughness

Tensile strength (MPa)

<

▼

Corrosion resistance

Tensile strength (MPa)

<

▼

Biocom.

Tensile strength (MPa)

>

▼

Machin.

Fatigue strength (MPa)

>

▼

Elongation (%)

Fatigue strength (MPa)

>

▼

Elasticity modulus (GPa)

Fatigue strength (MPa)

>

▼

Density (g/cm3)

Fatigue strength (MPa)

>

▼

Relative toughness

Fatigue strength (MPa)

=

▼

Corrosion resistance

Fatigue strength (MPa)

=

▼

Biocom.

Fatigue strength (MPa)

>

▼

Machin.

Elongation (%)

<

▼

Elasticity modulus (GPa)

Elongation (%)

>

▼

Density (g/cm3)

Elongation (%)

<

▼

Relative toughness

Elongation (%)

<

▼

Corrosion resistance

Elongation (%)

<

▼

Biocom.

Elongation (%)

>

▼

Machin.

Elasticity modulus (GPa)

>

▼

Density (g/cm3)

Elasticity modulus (GPa)

=

▼

Relative toughness

Elasticity modulus (GPa)

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▼

Corrosion resistance

Elasticity modulus (GPa)

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▼

Biocom.

Elasticity modulus (GPa)

>

▼

Machin.

Density (g/cm3)

<

▼

Relative toughness

Density (g/cm3)

<

▼

Corrosion resistance

Density (g/cm3)

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▼

Biocom.

Density (g/cm3)

>

▼

Machin.

Relative toughness

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▼

Corrosion resistance

Relative toughness

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▼

Biocom.

Relative toughness

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▼

Machin.

Corrosion resistance

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Biocom.

Corrosion resistance

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▼

Machin.

Biocom.

>

▼

Machin.

Calculate

	Yield stress (MPa)	Tensile strength (MPa)	Fatigue strength (MPa)	Elongation (%)	Elasticity modulus (GPa)	Density (g/cm3)	Relative toughness	Corrosion resistance	Biocom.	Machin.
Weights	0.11667	0.10000	0.13889	0.07222	0.08889	0.06111	0.09444	0.13333	0.14444	0.05000

Confirm

Figure A5. Pairwise significance evaluation of the criteria using MCSI—case study 2.

Figure A6 shows the ranking lists with the metrics for case study 1 as a screenshot of the MCSI user interface.

Table A3. Initial decision matrix for hip prosthesis biomaterial selection with criteria weights.

Biomaterial		C1 (MPa)	C2 (MPa)	C3 (MPa)	C4 (%)	C5 (GPa)	C6 (g/cm³)	C7	C8	C9	C10
	M1	250	585	330	57	193	7.95	0.865	0.41	0.41	0.865
	M2	450	825	320	45	193	7.86	0.865	0.5	0.59	0.865
	M3	580	930	380	52	200	7.64	0.865	0.5	0.745	0.865
	M4	450	840	370	39	195	7.75	0.745	0.5	0.59	0.865
	M5	585	1035	300	25	241	8.28	0.59	0.745	0.745	0.335
	M6	880	1350	700	22	241	8.28	0.59	0.745	0.745	0.41
	M7	1115	1420	760	28	241	8.29	0.59	0.745	0.745	0.335
	M8	1340	1400	700	21	235	8.43	0.59	0.665	0.59	0.255
	M9	415	1035	440	60	243	9.22	0.59	0.665	0.665	0.335
	M10	550	670	430	22	103	4.51	0.335	0.955	0.955	0.5
	M11	710	880	550	12	105	4.43	0.335	0.865	0.865	0.41
	M12	850	950	540	12	105	4.52	0.335	0.955	0.955	0.41
	M13	820	900	580	6	112	4.45	0.335	0.865	0.955	0.41
	M14	570	690	320	15	103	4.48	0.335	0.865	0.865	0.5
	M15	920	960	600	25	78	5.06	0.335	0.865	0.865	0.41
Target values		1340	1420	760	60	14	2.1	0.865	0.955	0.955	0.865
Criteria weights	η = 0.7	0.111	0.095	0.125	0.090	0.098	0.071	0.100	0.119	0.121	0.071
	η = 0.8	0.113	0.096	0.130	0.084	0.095	0.067	0.098	0.124	0.129	0.064
	η = 0.9	0.115	0.098	0.134	0.078	0.092	0.064	0.096	0.129	0.137	0.057
	η = 1.0	0.117	0.100	0.139	0.072	0.089	0.061	0.094	0.133	0.144	0.050

Back to Portal Web Tools Hello dulepetko@gmail.com! Log

MCDM Solver

Step 3: Review results

	TOPSIS	WASPAS	VIKOR
M1	14	14	14
M2	13	11	13
M3	10	9	8
M4	15	12	15
M5	11	15	12
M6	5	8	6
M7	1	3	4
M8	8	7	9
M9	12	13	11
M10	7	6	7
M11	6	5	5
M12	2	2	1
M13	4	4	3
M14	9	10	10
M15	3	1	2

Export

	Yield stress (MPa)	Tensile strength (MPa)	Fatigue strength (MPa)	Elongation (%)	Elasticity modulus (GPa)	Density (g/cm ³)	Relative toughness	Corrosion resistance	Biocom.	Machin.	C	TOPSIS
M1	250	585	330	57	193	7.95	0.865	0.41	0.59	0.865	0.31059	14
M2	450	825	320	45	193	7.86	0.865	0.5	0.59	0.865	0.32923	13
M3	580	930	380	52	200	7.64	0.865	0.5	0.745	0.865	0.41753	10
M4	450	840	370	39	195	7.75	0.745	0.5	0.59	0.865	0.30558	15
M5	585	1035	300	25	241	8.28	0.59	0.745	0.745	0.335	0.37383	11
M6	880	1350	700	22	241	8.28	0.59	0.745	0.745	0.41	0.56664	5
M7	1115	1420	760	28	241	8.29	0.59	0.745	0.745	0.335	0.60806	1
M8	1340	1400	700	21	235	8.43	0.59	0.665	0.59	0.255	0.51629	8
M9	415	1035	440	60	243	9.22	0.59	0.665	0.665	0.335	0.37006	12
M10	550	670	430	22	103	4.51	0.335	0.955	0.955	0.5	0.52711	7
M11	710	880	550	12	105	4.43	0.335	0.865	0.865	0.41	0.53481	6
M12	850	950	540	12	105	4.52	0.335	0.955	0.955	0.41	0.59714	2
M13	820	900	580	6	112	4.45	0.335	0.865	0.955	0.41	0.58041	4
M14	570	690	320	15	103	4.48	0.335	0.865	0.865	0.5	0.44623	9
M15	920	960	600	25	78	5.06	0.335	0.865	0.865	0.41	0.59240	3
Targets	1340	1420	760	60	14	2.1	0.865	0.955	0.955	0.865		
Weights	0.11667	0.10000	0.13889	0.07222	0.08889	0.06111	0.09444	0.13333	0.14444	0.05000		

Export

Figure A6. Screenshot of biomaterials ranking lists and metrics for TOPSIS method—case study 2 ($\eta = 1$).

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