doi: 10.5937/SimTerm24394P

Material Selection of Wave Energy Turbine Blade by using MCDM Solver

Dušan Petković[a], Miloš Madić[a]

[a]Faculty of Mechanical Engineering University of Niš, Niš, RS, dusan.petkovic@masfak.ni.ac.rs

Abstract: Selection of materials is a complex and multi-criteria decision making problem, which requires a lot of knowledge and experience. Selection process is influenced by few factors such as thermal, mechanical, electrical, chemical, physical and technological properties as well as their price and availability. This paper considers material selection problems of wave energy extraction turbine blade by using MCDM approach. Due to help decision makers in solving this complex task, a decision support system named MCDM Solver. MCDM Solver was used in decision-making process to rank materials for the turbine blade with respect to several criteria. Based on the results the best ranked materials are Carbon fiber reinforced polymer, titanium alloys and Glass fiber reinforced polymer.

Keywords: Material selection, Wave energy extraction turbine blade, Multi-criteria decision making, MCDM Solver, Decision support system.

1. Introduction

Engineering design is significantly depended on objectives of performance, cost and environmental sensitivity, which are often limited by materials. To optimize product design, it is necessary to select the materials which best meet the needs of the design, maximizing its performance and minimizing its cost.

Material selection is the process of choosing the best material for a particular design. In mechanical design, this process enters at every stage of the design process. In the total design model material selection is rated as one of the fundamental parameters along with market investigation, product design specification, component design, design analysis, manufacture and assembly [1].

The objectives and criteria in the material selection process are often in conflicts which involves certain trade-offs amongst decisive factors. Therefore, only with a systematic and structured mathematical approach the best alternative for a specific engineering product can be selected [2]. 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 [3-4].

Decision support system (DSS) is a special class of information system oriented to the decision-making process and aims to support, mainly business decision-doing processes [5]. DSS is a symbiosis of information systems, application of functional knowledge and ongoing decision-making process [6]. 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 material selection of wave energy extraction turbine blade. A real time case study was solved by using MCDM Solver with obtained complete rankings.

2. Wave energy

The energy from ocean waves is the most conspicuous form of ocean energy, possibly because of the wave destructive effects. The waves are produced by wind action and are therefore an indirect form of solar energy. The wave energy absorption is a hydrodynamic process in which relatively complex diffraction and radiation wave phenomena take place [7].

The utilization of wave energy involves a chain of energy conversion processes. Each of the processes is characterized by its efficiency and constraints which must be controlled. Particularly relevant is the hydrodynamic process of wave energy absorption.

The main disadvantage of wave power, as with the wind from which is originates, is its (largely random) variability in several time-scales: from wave to wave, with sea state, and from month to month (although patterns of seasonal variation can be recognized). The assessment of the wave energy resource is a basic prerequisite for the strategic planning of its utilization and for the design of wave energy devices.

2.1. Oscillating water column (OWC)

The oscillating water column (OWC) wave energy harnessing method is considered as one of the best techniques of converting wave energy into electricity. These devices stand on the sea bottom (Figure 1) or fixed to a rocky cliff.

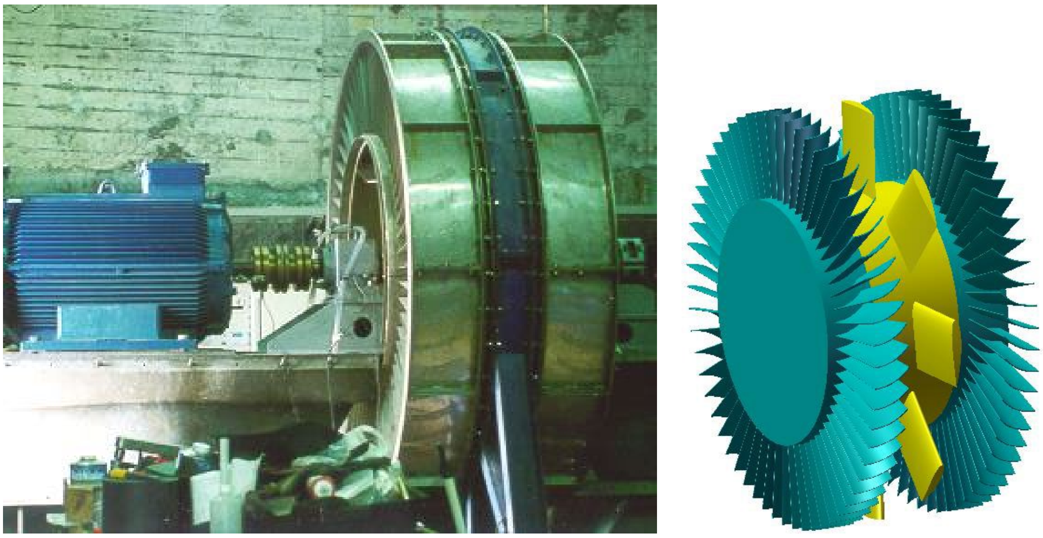


Figure 1. Back view of the 400 kW OWC plant on the island of Pico, Azores, Portugal, 1999 [7]

It is an economically viable design due to its simple geometrical construction, and is also strong enough to withstand against the waves with different heights, periods and directions. The design (Figure 2) consists of an OWC chamber and a circular duct, which reciprocally moves the air from and into the chamber during the process of wave approach and retreat. A self-rectifying turbine mounted inside the duct is designed to turn in one direction only although the airflow moves bi-directionally [8]. A matching generator is coupled to the turbine to produce electricity.

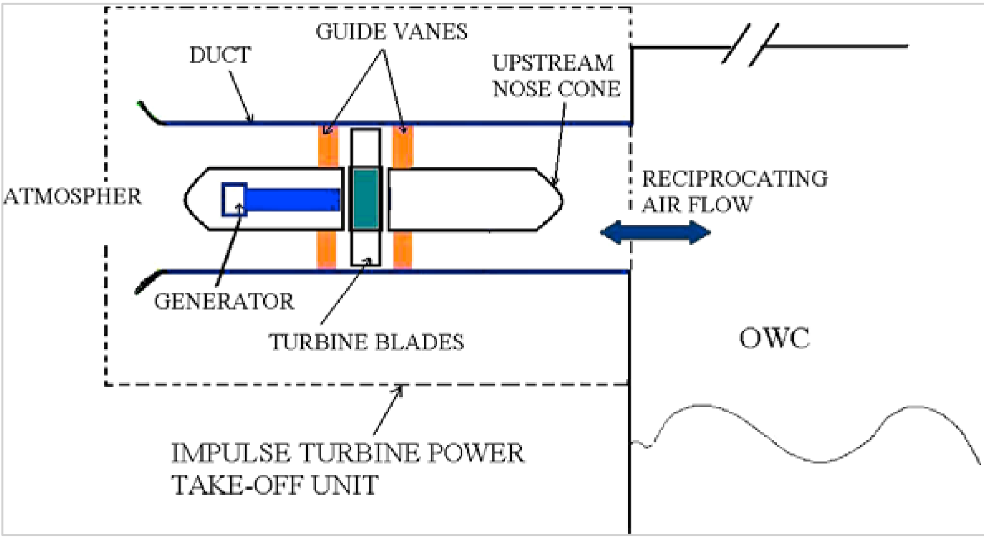


Figure 2. Impulse turbine power take-off unit with OWC [9]

The turbine's blade is designed to convert the pneumatic energy of air produced by the OWC to mechanical shaft power. This will be transmitted to a generator to produce electricity.

3. MCDM Solver

MCDM Solver is an "on-line" DSS which was developed within the doctoral dissertation of Dušan Petković [10]. The developed DSS is located on the "Virtuode" Company web site (https://virtuodeportalapp.azurewebsites.net/WebTools/Home) and it is available to everyone who registers by creating an account (Figure 3). This DSS offers the possibility of working with maximization, minimization and target criteria [11].

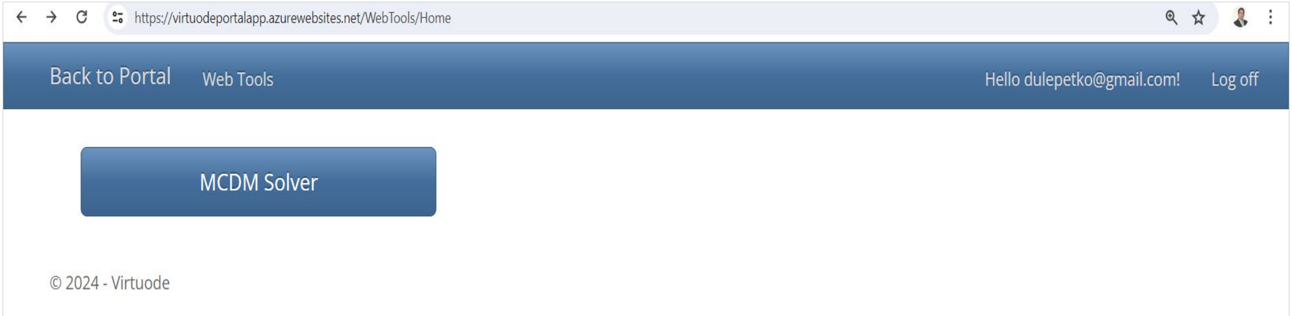


Figure 3. MCDM Solver – initial layout

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 [12], Comprehensive VIKOR [13] and Comprehensive WASPAS [10, 14] methods.

Developed DSS architecture is flexible and easy to upgrade, so it enables the inclusion of new models that will come in future. MCDM Solver has a user-friendly interface, which enables a simple and efficient way of entering the necessary data which not strictly related to material selection process [15]. Its use simplifies the solution of the MCDM problems because it does not require expert knowledge from the decision making theory from the user.

4. Turbine blade material selection

4.1. General requirements

A material selection process begins by considering the material requirements which are needed for a specific application. Therefore it is necessary to select criteria that can be used to select the most suitable turbine blade material. Mechanically speaking, a blade is considered as a tie rod loaded in tension due to the centrifugal load. The latter could easily be translated to a tensile force equivalent F, so the blade must support the axial tensile load F. The blade height, h, is specified once the turbine diameter and the hub-to-tip ratio have been chosen. The cross sectional area (A_b) is fixed by the optimum aerodynamic design [16]. Here, maximizing performance means minimizing the mass while still carrying the load F safely. In other words, the blade must be as light as possible to reduce stress r. This is known to be highly concentrated at the blade root and proportional to material density (q_b) multiplied by the square of specific (tip) blade speed [9].

4.2. Materials screening

Thakker et al [9] was carried out selection of candidates for turbine blade materials based on criteria such as: strength, specific weight, corrosion resistance, ease of manufacture and availability. Strength is maximum tolerance of loads before failure. The component should be designed to perform its function without failure. When the stress level caused by the load, e.g., centripetal force, reaches the ultimate stress (tensile strength) the material fails. The yield stress (lower than tensile strength), which is the starting point of plastic deformations (yield point) is another measure of strength. Specific weight (density) is important because centripetal force is proportional to the specific weight. Also, the material should have a good corrosion resistance to perform in a severe environment such as that of sea salt atmosphere. Additionally, it is important that the material can be processed by the most common methods such as by forging, casting, machining and welding. Finally, the material should be readily available.

Taking into account before mentioned criteria the best materials for manufacturing the turbine blades are:

1. Titanium alloys;
2. Nickel alloys;
3. Aluminum alloys;
4. GFRP (Glass fiber reinforced polymer);
5. Stainless steel alloys;
6. Copper alloys;
7. Silicon nitrides;
8. CFRP (Carbon fiber reinforced polymer).

4.3. Materials ranking

Material selection process should be finalized by using the MCDM approach for selected materials ranking. For this purpose MCDM Solver has been used. Criteria for ranking the materials were:

- *Stiffness* (rigidity): Minimum deformation (strain) under a given load; the blade should be designed to bear the aerodynamic transverse load. The modulus E, in effect, denotes stiffness or rigidity for any kind of applied load, i.e., tension, compression or shear.
- *Elongation at break* (ductility): This is an index measure of the material ability for plastic deformation in tension. It is defined as the amount of plastic or permanent deformation determined after fracture by realigning and fitting together the broken end of the specimen.
- *Fatigue strength:* The majority of engineering failures are caused by fatigue, which is defined as the tendency of the material to fracture by means of progressive brittle cracking under repeating alternating or cyclic stresses of intensity considerably below the normal strength. Although the fracture is of brittle type, it may take some time to propagate, depending on both the intensity and frequency of the stress cycles. Nevertheless, there is very little, if any, warning before failure if the crack is not noticed.
- *Cost of manufacture* (economic): The raw cost of the material and the cost of processing/manufacturing should be minimized. Though the material (blade) manufacturing cost could not be established a priori, the raw cost would be a strong indication for selecting an economic blade material.
- Initial decision matrix with selected materials properties and expected cost is shown in Table 1.

Table 1. Initial decision matrix for materials ranking

No.	Material	Stiffness E/ ρ (MJ/kg)	Elongation at break (%)	Expected cost (£/kg)	Fatigue strength (MPa)
1	Titanium alloys	24	10	30	630
2	Nickel alloys	24	30	7	230
3	Aluminum alloys	28	14	1	140
4	GFRP	13	3	9	600
5	Silicon nitrides	92	0.5	45	200
6	Copper alloys	16	40	4	160
7	Stainless steel	26	25	5	240
8	CFRP	73	2	45	500
	Target value	92	40	1	630

5. Results and discussion

Two scenarios are presented to test *MCDM Solver* and analyze sensitivity of the results to the change in weight of criteria.

Scenario 1: significance of the criteria (criteria weights) is evaluated by the authors of this paper by means of *MCDM Solver* (Figure 4) which has MDL (modified digital logic) as background [10]. The authors of this article mean that *fatigue strength* is the most significant criterion, followed by *stiffness*, *expected cost* and *elongation at break*, respectively.

Scenario 2: criteria weights are taken from previous study (0.250 0.125 0.250 0.375) [9], where the most significant criterion is also *fatigue strength* and the least significant is *elongation at break*, while *stiffness* and *expected cost* are considered equally significant.

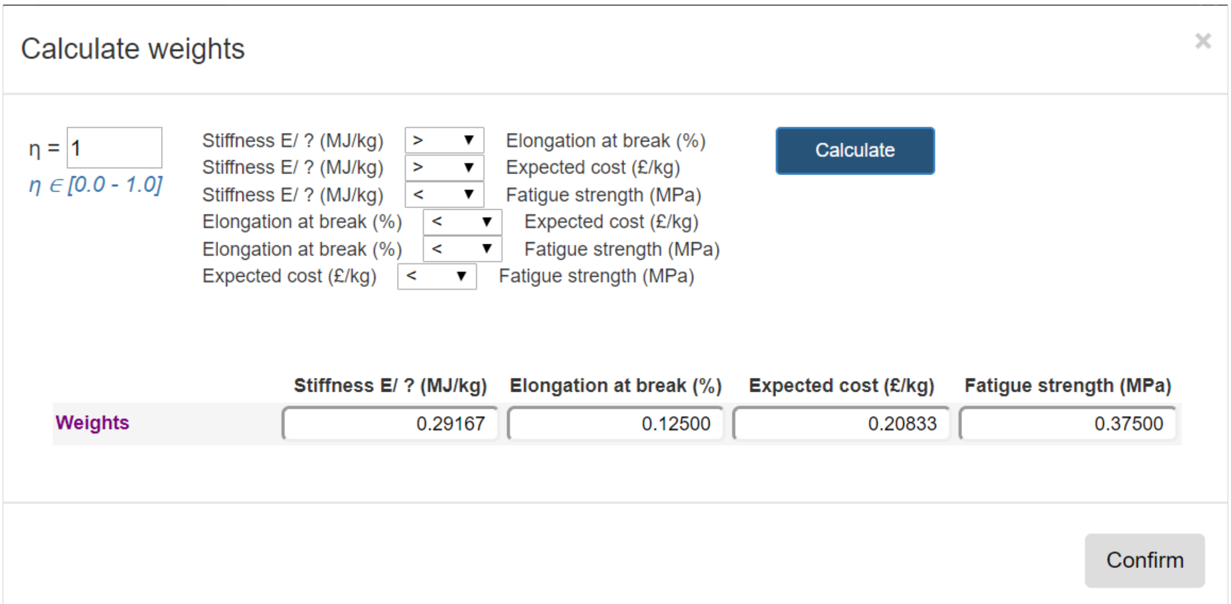
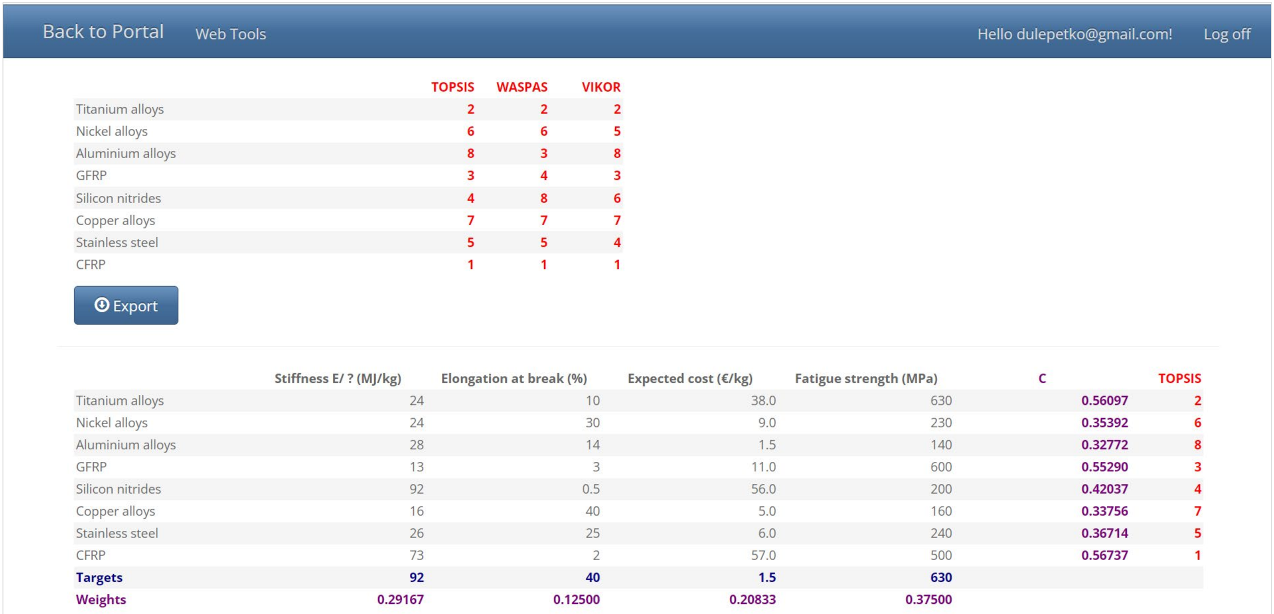


Figure 4. Pairwise significance evaluation of the criteria by MCDM Solver

5.1. Scenario 1

Ranking results for Scenario 1 are shown in Figure 5 and also given in Table 2.



	TOPSIS	WASPAS	VIKOR
Titanium alloys	2	2	2
Nickel alloys	6	6	5
Aluminium alloys	8	3	8
GFRP	3	4	3
Silicon nitrides	4	8	6
Copper alloys	7	7	7
Stainless steel	5	5	4
CFRP	1	1	1

	Stiffness E/ ? (MJ/kg)	Elongation at break (%)	Expected cost (€/kg)	Fatigue strength (MPa)	C	TOPSIS
Titanium alloys	24	10	38.0	630	0.56097	2
Nickel alloys	24	30	9.0	230	0.35392	6
Aluminium alloys	28	14	1.5	140	0.32772	8
GFRP	13	3	11.0	600	0.55290	3
Silicon nitrides	92	0.5	56.0	200	0.42037	4
Copper alloys	16	40	5.0	160	0.33756	7
Stainless steel	26	25	6.0	240	0.36714	5
CFRP	73	2	57.0	500	0.56737	1
Targets	**92**	**40**	**1.5**	**630**		
Weights	**0.29167**	**0.12500**	**0.20833**	**0.37500**		

Figure 5. Ranking result – Scenario 1

Based on the results, rank of the first three ideal solutions/alternatives is: CFRP, titanium alloys and GFRP respectively. In the above order of the ideal solutions, CFRP is without any doubt the best alternative while titanium alloys and GFRP is the second and third promising candidates respectively.

Table 2. Ranking results - Scenario 1

No.	Material	TOPSIS		WASPAS		VIKOR	
		C(i)	Rank	Q(i)	Rank	P(i)	Rank
1	Titanium alloys	0.561	2	0.325	2	0.243	2
2	Nickel alloys	0.354	6	0.388	6	0.773	5
3	Aluminum alloys	0.328	8	0.351	3	1.000	8
4	GFRP	0.553	3	0.297	4	0.250	3
5	Silicon nitrides	0.420	4	0.306	8	0.807	6
6	Copper alloys	0.338	7	0.348	7	0.851	7
7	Stainless steel	0.367	5	0.408	5	0.739	4
8	CFRP	0.567	1	0.324	1	0.150	1

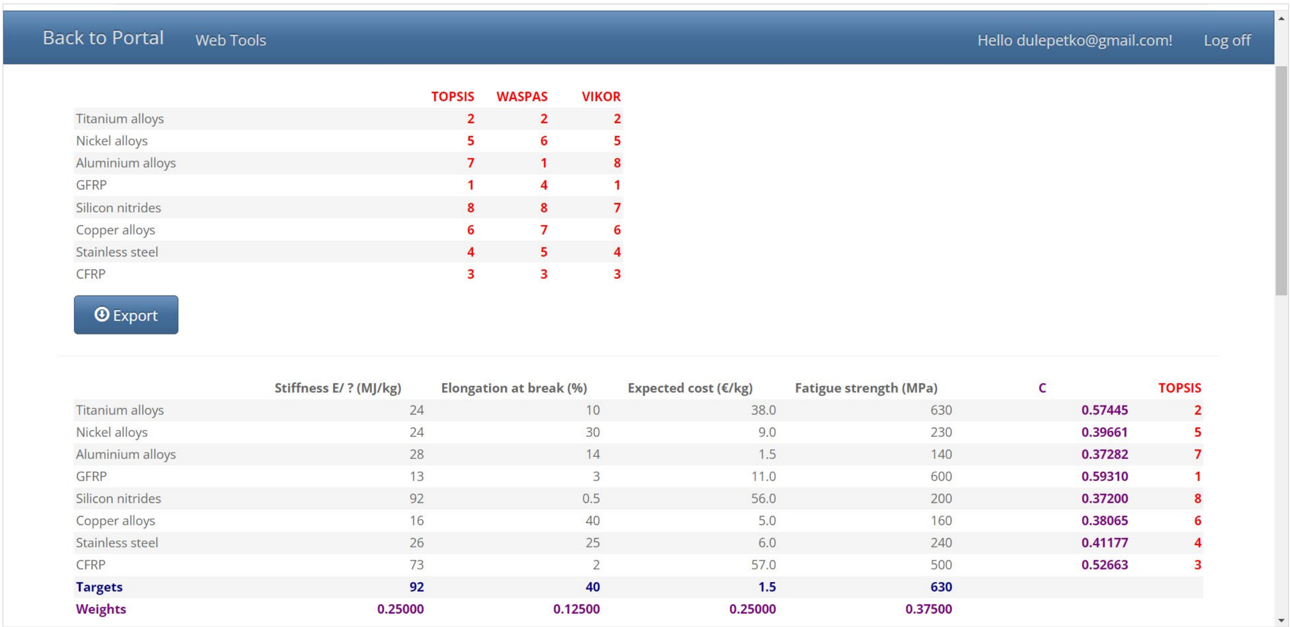
5.2. Scenario 2

Ranking results for Scenario 2 are given in Table 3 and shown in Figure 6 too.

Table 3. Ranking results – Scenario 2

No.	Material	TOPSIS		WASPAS		VIKOR	
		C(i)	Rank	Q(i)	Rank	P(i)	Rank
1	Titanium alloys	0.574	2	0.375	2	0.112	2
2	Nickel alloys	0.397	5	0.320	6	0.712	5
3	Aluminum alloys	0.373	7	0.412	1	0.942	8
4	GFRP	0.593	1	0.350	4	0.074	1
5	Silicon nitrides	0.372	8	0.265	8	0.903	7
6	Copper alloys	0.381	6	0.312	7	0.801	6
7	Stainless steel	0.412	4	0.346	5	0.680	4
8	CFRP	0.527	3	0.374	3	0.327	3

As could be seen, the ranking of materials for turbine blade is obtained as: GFRP-Titanium alloys-CFRP.



	TOPSIS	WASPAS	VIKOR
Titanium alloys	2	2	2
Nickel alloys	5	6	5
Aluminium alloys	7	1	8
GFRP	1	4	1
Silicon nitrides	8	8	7
Copper alloys	6	7	6
Stainless steel	4	5	4
CFRP	3	3	3

	Stiffness E/ ? (MJ/kg)	Elongation at break (%)	Expected cost (€/kg)	Fatigue strength (MPa)	C	TOPSIS
Titanium alloys	24	10	38.0	630	0.57445	2
Nickel alloys	24	30	9.0	230	0.39661	5
Aluminium alloys	28	14	1.5	140	0.37282	7
GFRP	13	3	11.0	600	0.59310	1
Silicon nitrides	92	0.5	56.0	200	0.37200	8
Copper alloys	16	40	5.0	160	0.38065	6
Stainless steel	26	25	6.0	240	0.41177	4
CFRP	73	2	57.0	500	0.52663	3
Targets	92	40	1.5	630		
Weights	0.25000	0.12500	0.25000	0.37500		

Figure 6. Ranking result – Scenario 2

In other words, GFRP is observed to be the most appropriate for this application, but not without doubt since WASPAS method ranked it as the fourth preferable one. Titanium alloys have the stable second preference while CFRP has also stable the third preference.

5.3. Comparison of results

The afore-stated material selection MCDM problem was solved by past researchers [9] using TOPSIS method. In this section the comparison of the obtained complete rankings is presented. It has to be noted that past researches while applying TOPSIS methods have used a little different criteria weights, which may affects significantly final rankings.

The results show difference between the first and third ranked material. Namely, previous authors' research gives GFRP as the most appropriate material while CFRP is third-ranked material. This paper is turned out that CFRP is best ranked material and titanium alloys second ranked material without any doubt while GFRP is third-ranked. In both scenarios titanium alloys are second-ranked material. This is due to the increase in stiffness weight where CFRP is superior and the decrease in expected cost weight where they are equal. Moreover in both scenarios it can be seen that the ranking parameters are very close and do not single out any material as absolutely superior. In this regard, all three materials should be considered as potential for making turbine blades, with the final decision being influenced by some limiting or new criterion, such as impossible purchase, difficulty in manufacturing, etc.

The different sensitivity of the methods in relation to the weighting coefficients of the criteria is also evident, which is a consequence of the mathematical procedure that is in the background of the methods. The highest sensitivity is observed with the WASPAS method for the first-ranked material, while the matching of the ranks for the other materials is the highest (total of 6), Figure 7.

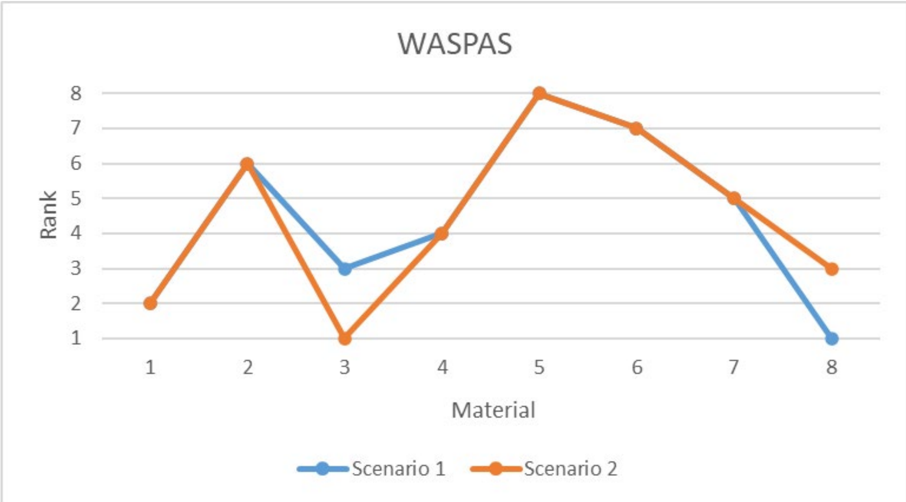


Figure 7. Ranking results by WASPAS method

In Figure 8 can observed the highest deviation/sensitivity with the TOPSIS method, where the match is only for the second-ranked material, which is otherwise absolutely stable.

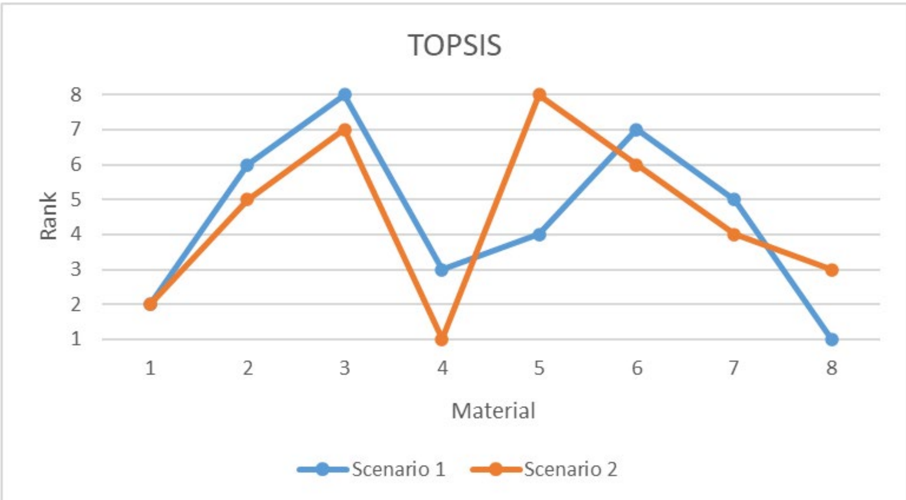


Figure 8. Ranking results by TOPSIS method

Additionally, VIKOR method gives matching of 50% but not for the first and third ranked material (Figure 9).

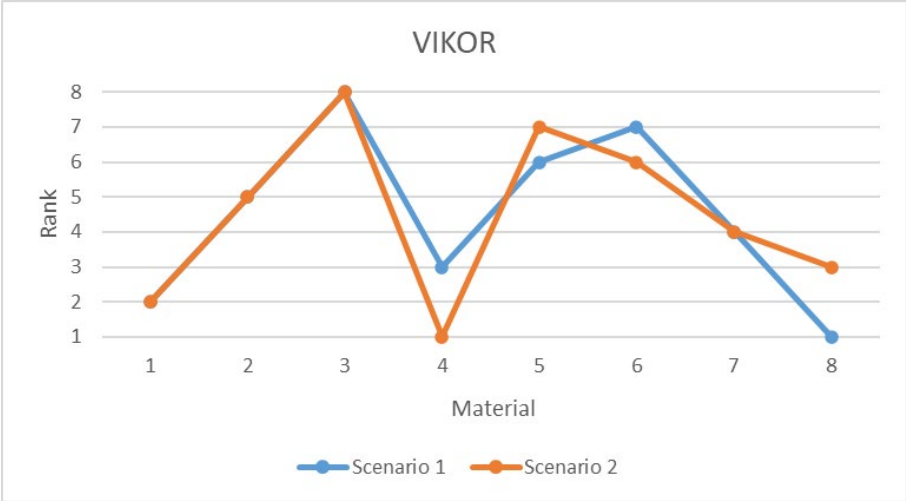


Figure 9. Ranking results by VIKOR method

6. Conclusion

In this paper MCDM Solver is proposed for material selection of wave energy extraction turbine blade. The detail procedure of MCDM use was demonstrated while solving the material selection problem in two scenarios. The conclusions can be as follows:

- MCDM Solver has been used directly for choosing a turbine blade component material and can also be extended to cover other machines such as fans and pumps.
- Without any doubt, it can be claimed that the best ranked materials are GFRP, Titanium alloys and CFRP.
- The obtained ranking results have good correlation with those derived by the past researchers using different criterion weights. In both scenarios, it is observed that the first tree top-ranked materials exactly match with those derived by the past researchers.
- TOPSIS method is most sensitive for criteria weight change
- Computational procedure is relatively simple and can be easily traced by decision maker.
- Solving different MCDM problems by using MCDM Solver doesn't require the use of specialized software packages since the method can be easily implemented.

Acknowledgements

This research was financially supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Contract No. 451-03-65/2024-03).

References

[1] Charles JA, Crane FAA, Furness JAE. Selection and use of engineering materials, 3rd ed. Oxford, UK: Butterworth-Heinemann; 1997
[2] Petković D., Madić M., Radenković G., Manić M., Trajanović M., Decision Support System for Selection of the Most Suitable Biomedical Material, *Proceedings, ICIST 2015*, Kopaonik, March 8-10, 2015, pp. 27-31
[3] Chatterjee P., Chakraborty S., Material selection using preferential ranking methods, Materials and Design, Vol. 35 (2012), pp. 384-393
[4] Petković D., Madić M., Radenković G., Gear material selection using WASPAS method, *Proceedings, SMAT 2014,* Craiova, Romania, October 23-25, 2014 pp. 45-48
[5] Petković D., Madić M., Radenković G., Živković P., An example of MCDM Solver application for material selection problems, *Proceedings, DEMI 2019,* Banja Luka, May 24-25, 2019, pp.
[6] Čupić M., Tummala R., Suknović M., Odlučivanje - formalni pristup, Fakultet organizacionih nauka, Beograd, 2001
[7] Falcão A.F.O., Modelling of Wave Energy Conversion, Instituto Superior Técnico, Universidade de Lisboa, 2014
[8] Falcao A.F.O., First-generation wave power plants: current status and R&D requirements, J Off-Shore Mech Arctic Eng, Vol. 126 (2004), pp. 384–388.

[9] Thakker A., Jarvis J., Buggy M., Sahed A., A novel approach to materials selection strategy case study: Wave energy extraction impulse turbine blade, Materials and Design Vol. 29 (2008), pp. 1973–1980
[10] Petković D., Selection of biomaterials - Multi-criteria decision analysis and development of decision support system, PhD dissertation, University of Niš, Faculty of Mechanical Engineering, Niš, 2017
[11] Petković D., Madić M., Radenković G., Knee Prosthesis Biomaterial Selection by Using MCDM Solver, Advanced Technologies & Materials, Vol. 46 (2) (2021), pp. 37-41
[12] Petković D., Madić M., Non-conventional machining processes selection using MCDM Solver, Innovative Mechanical Engineering, Vol. 1, No. 2 (2022), pp. 48 - 57
[13] Jahan A., Bahraminasab M., Edwards K.L., A target-based normalization technique for materials selection, Materials and Design, Vol. 35 (2012), pp. 647-654
[14] Jahan A., Mustapha F., Ismail M.Y., Sapuan S.M., Bahraminasab M., A comprehensive VIKOR method for material selection, Materials and Design, Vol. 32 (2011), pp. 1215-1221
[15] Petković D., Madić M., Radenković G., Ranking of Biomedical Materials by Using Comprehensive WASPAS Method, *Proceedings, MASING 2015*, Faculty of Mechanical Engineering Niš, September 17-18, 2015, pp. 339-344
[16] Setoguchi T, Santhakumar S, Maeda H, Takao M, Kaneko K., A review of impulse turbine for wave energy conversion, J Renew Energy, Vol. 23 (2001), pp. 261–292