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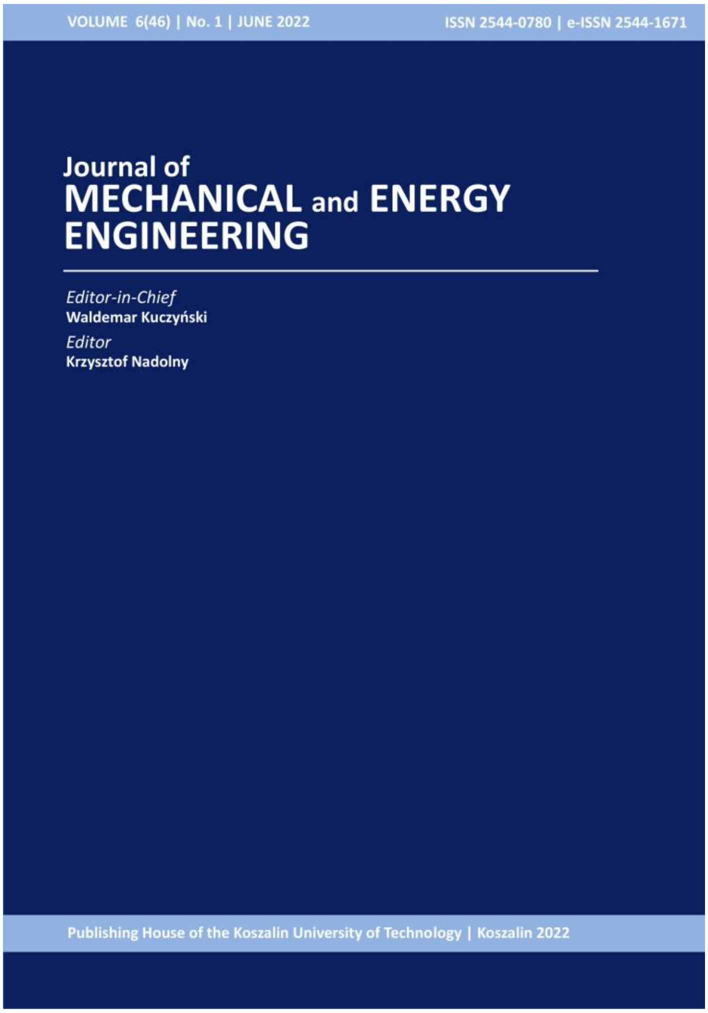
DOI: 10.30464/jmee.2022.6.1.77

Cite this article as:
Nwaoha T. C.; Udosoh N. E. Facilitating optimal operations of a wave energy converter using a preeminent mooring line: an entropy weight-VIKOR method. Journal of Mechanical and Energy Engineering, Vol. 6(46), No. 1, 2022, pp. 77-84.



VOLUME 6(46) | No. 1 | JUNE 2022
ISSN 2544-0780 | e-ISSN 2544-1671

Journal of
MECHANICAL and ENERGY
ENGINEERING

Editor-in-Chief
Waldemar Kuczyński
Editor
Krzysztof Nadolny

Publishing House of the Koszalin University of Technology | Koszalin 2022

Journal of Mechanical and Energy Engineering

Website: jmee.tu.koszalin.pl

ISSN (Print): 2544-0780
ISSN (Online): 2544-1671
Volume: 6(46)
Number: 1
Year: 2022
Pages: 77-84

Article Info:
Received 30 December 2021
Accepted 11 January 2022

Journal of
MECHANICAL and ENERGY
ENGINEERING

ISSN: 2544-0780 | e-ISSN: 2544-1671
Vol. 6(46) | No. 1 | June 2022 | pp. 77-84
DOI: 10.30464/jmee.2021.6.1.77

FACILITATING OPTIMAL OPERATIONS OF A WAVE ENERGY CONVERTER USING A PREEMINENT MOORING LINE: AN ENTROPY WEIGHT-VIKOR METHOD

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(Received 30 December2021, Accepted 11 January 2022)

Abstract: This study employed viable methods for the selection of a preeminent mooring line amongst other alternatives for the mooring of a floating wave energy converter (WEC) in shallow waters. Conventional mooring lines for WEC mooring are identified for an optimal selection exercise. A combination of the Entropy Weight and Visekriterijumska Optimizacijia I Kompromisno Resenje (VIKOR) methods is utilized in the aforementioned exercise. The two methods are effectively used in an assessment of the attributes and performance of various mooring lines in practical application. The result obtained demonstrated that a steel wire rope is the best mooring line suitable for WEC system operations. It constitutes a good reference to marine and offshore engineering industries in decision making related to optimal mooring lines suitable for the mooring of a WEC system in shallow waters.

Keywords: mooring line, alternatives, criteria, wave energy converter, entropy weight, VIKOR

1. INTRODUCTION

The evaluated demand for electrical energy globally as of 2014 attained 19,800 tera-watt hours annually, with a global wave energy reserve of the same range [1, 2]. The use of green energy from ocean waves could make a vast difference in addressing air pollution and climate problems such as drastic weather and global warming caused by colossal fossil fuel oil. Due to the enormous potential of wave energy, different ideas concerning wave energy converters (WEC) have been explored in order to obtain energy from ocean waves [3]. Wave energy converters transform the potential and kinetic energies associated with ocean waves into electrical or mechanical energy. There are various prototypes of WEC [4, 5]. For the energy efficiency of the WECs, they need to be installed in high-energy zones. The wave conditions are high in these zones, and as a result, the converter and its mooring system would be under intense loads. Some WECs are motion-dependent. They need oscillation in waves, usually in resonance, to acquire energy. These oscillations will make the mooring system perform high amplitude motions at a high frequency, thereby creating higher dynamic tensions in the mooring lines, particularly when it is in resonance. A good mooring system is required for the stability of wave energy converters in order to maintain the devices stationary in opposition to the environmental loads that will be acting on the devices.

Numerous studies have been conducted to evaluate the effectiveness of the various mooring lines for different offshore installations as evidenced in the papers by [6-8]. In [9], a review of design issues and choices of mooring systems for WECs are explained. The authors discussed a variety amongst the commonly used mooring systems and their compatibility for WECs. An evidence of the use of an Entropy Weight-Visekriterijumska Optimizacijia I Kompromisno Resenje (VIKOR) method in the mooring line selection for WECs system operations has not been observed in the literature available. Rather, it is that the literature available revealed how the Entropy Weight-VIKOR method has been used to solve various problems in different fields of studies, as evidenced in the papers by [10-14]. In [10], an Entropy Weight-VIKOR method is used in an assessment of the environmental quality of various countries. The utilization of the Entropy Weight-

VIKOR method in choosing an appropriate supplier in manufacturing industry is demonstrated in [11]. In 2021, Priti, *et al*. [12] demonstrated the strength of the Entropy Weight-VIKOR method in the process optimization in micro-machining of the CFRP composite. Narayanamoorthy *et al*. [13] proved that the Entropy Weight-VIKOR method can be used in robot selection. Sharma, *et al*. [14] in 2017, enabled the Entropy Weight-VIKOR method in a parametric optimization of a solar air flow channel. The step by step approach of the application of the Entropy Weight-VIKOR methodfound in the literature available will be technically utilized in this study.

In view of the above, this study aims at evaluating mooring lines used for mooring offshore systems and to recommend a preeminent one for optimal mooring of a WEC in shallow waters using the Entropy Weight-VIKOR method. The strength of this powerful tool will be systematically applied in the problem under investigation. The novelty of this research lies in an integration of qualitative and quantitative data in the optimization of a mooring line for the station-keeping of floating wave energy converters that can withstand environmental loads.

2. METHODOLOGY

The WEC system may achieve an optimal stability during operations in shallow waters environment using mooring lines. Due to advances in technology and competiveness in industries, various mooring lines exist. According to Qiao *et. al*. [9], chain, steel wire, polypropylene nylon, polyester and high modulus polyethylene (HMPE) mooring lines can be used in WEC system stability operations in shallow waters. Using engineering judgement and experts' opinions, such criteria as the cost, abrasion resistance, fatigue resistance, an ease of installation and elasticity must be considered in the selection of mooring lines in a shallow waters environment. Therefore, identifying the most effective one in a cost effective manner tends to be a challenge. To meet this challenge, an integrated Entropy Weight-VIKOR method is employed in this research. The respective functions are:

1. The Entropy Weight method is used to estimate the weights of the criteria for the mooring line selection for WEC optimal operations.
2. The VIKOR method is employed to identify/select a preeminent mooring line for optimal WEC operations.

In Figure 1, the information flow starts from the system identification, followed by revealing the criteria that need to be considered in the selection of mooring lines. The next step is review the revealed criteria to ensure that they are relevant and that an appropriate number of these have been identified for the subject under investigation. This is followed by a weight estimation using the Entropy Weight method. The next step is to review the weights to find whether the weights are reasonable. If the weights are acceptable, the VIKOR method is utilised in an identification/selection of a preeminent mooring line. Finally, the mooring lines will be ranked using their estimated values assigned to them.

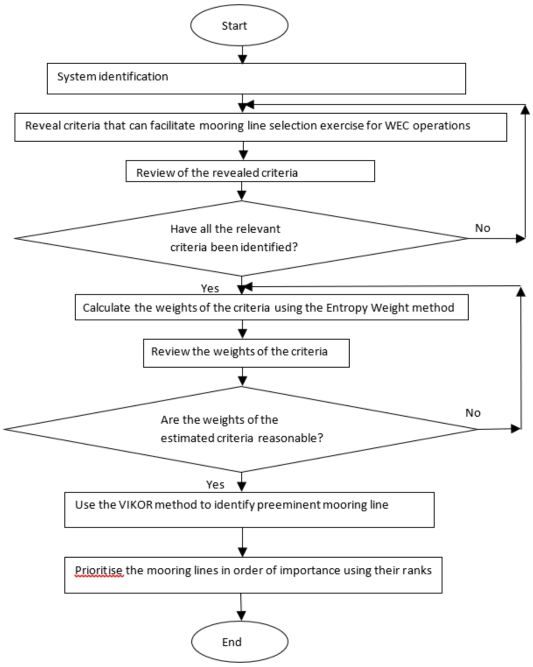

Fig. 1. A flowchart of Entropy Weight-VIKOR Technique application in the selection of mooring lines for optimal WEC operations

2.1. Entropy Weight Method

The Entropy Weight method is used in this study to determine the weights of the criteria used in the evaluation of the alternatives. The first step is the normalization of the values measured. The value normalized is denoted as γ_{ij} . The mathematical definition is outlined as follows [15, 16]:

$$\beta_{ij} = \frac{y_{ij}}{\sum_{i=1}^{m} y_{ij}}. \tag{1}$$

The entropy value e_j, is mathematically described as follows:

$$e_j = -g\sum_{i=1}^{m}\beta_{ij}Ln\beta_{ij}\ (j = 1,2...n), \tag{2}$$

where:

$$g = \frac{1}{Ln(m)}, \tag{3}$$

and m - number of alternatives.

The entropy value e_j , is used to develop the weight, the w_j formula is as follows:

$$w_j = \frac{1-e_j}{\sum_{j=1}^{n}(1-e_j)}\ (j = 1,2....n). \tag{4}$$

2.2. VIKOR Method

VIKOR is a method developed for the purpose of a multi-criteria optimization of complex systems in various fields. VIKOR determines the compromise ranking and solutions achieved with the given weights of criteria. It focuses on the ranking and the selection of the best alternative from other alternatives in the presence of contradictory criteria. This method introduces a multiple criteria ranking index based on a particular measure of closeness to the ideal solution [17, 18]. The steps in the VIKOR Method are outlined as follows [17, 18]:

1. Determination of the best value $(\boldsymbol{z_i^+})$ and the worst value $(\boldsymbol{z_i^-})$ out of all criterion ratings
2. Computation of utility measure values (T_i) and regret measure values (U_i) using Equation 5:

$$T_i = \sum_{j=1}^{m}\left[w_j * \frac{z_i^+ - z_{ij}}{z_i^+ - z_i^-}\right], \tag{5}$$

where $w_j =$ the weight of the criterion

$$U_i = max_j\left[w_j * \frac{z_i^+ - z_{ij}}{z_i^+ - z_i^-}\right] \tag{6}$$

3. Computation of Q_i, for *j* = 1, 2, 3 … *m*

Where T^* = min T_i , T^- = max T_i, U* = min U_i, U^- = max U_i..

The weight for the decision-making strategy of the maximum group utility is denoted as "*c*", while the weight for the individual regret is expressed as "1–*c*". The value of "*c*" is usually accepted to be 0.5. The computation of Q_i for each alternative can be calculated using Equation 7.

$$Q_i = c\left(\frac{T_i - T^*}{T^- - T^*}\right) + (1-c)\left(\frac{U_i - U^*}{U^- - U^*}\right), \tag{7}$$

where *c* is the weight for a decision-making strategy of the maximum group utility and 1 – *c* is the weight for the individual regret. *c* is usually accepted to be 0.5. The best alternative was ranked by the minimum value of Q_i.

4. Ranking the best alternative(s) by the minimum value of Q_i . The ranking is acceptable if the following two conditions are met:

   Condition 1: Acceptable merit/advantage:

$$Q\,(a2) - Q\,(a1) \geq DQ, \tag{8}$$

where $a2$ and $a1$ are the second and first ranked alternatives by Q_i respectively.

$$DQ = \frac{1}{P-1}, \tag{9}$$

where *P* is the number of alternatives.

Condition 2: Acceptable stability in decision-making. This means that alternative $a1$ must also be the best ranked alternative by T_i or / and U_i.

5. A proposed set of compromise solutions is made if one of the conditions in step 4 is not satisfied, which includes:

- alternatives $a1$ and $a2$, which are the first and second ranked alternatives, if only condition 2 is not satisfied,
- alternatives *a1* and *a2* ….. *a*(*n*) if only condition 1 is not met: the closeness of alternative $a(n)$ ranked nth by Q_i is obtained using

$$(Q\,a(n)) - Q\,(a1) < DQ \tag{10}$$

3. A TEST CASE OF USING ENTROPY-VIKOR METHODOLOGY IN AN OPTIMAL SELECTION OF A MOORING LINE FOR A WEC SYSTEM

In this study, Entropy Weight-VIKOR methodology is systematically used to illustrate how a preeminent mooring line can be identified and selected for optimal mooring of a WEC in shallow waters. The phases and steps of the aforementioned methodology explained in the previous section are logically applied in this section. The various mooring lines that will be considered as alternatives are outlined as chain, steel wire, polypropylene nylon, polyester and HMPE lines. The criteria such as the cost, abrasion resistance, fatigue resistance, an ease of installation and elasticity will be used to facilitate the selection exercise of the mooring lines under investigation.

3.1. Estimation of the weight of the Criteria of Mooring Lines for Optimal Mooring of a WEC System using the Entropy Weight Method

Three experts are employed in this exercise to perform decision making. They have equal experience in the subject under investigations. Their varied experience is complementary in the weight estimation exercise using the Entropy Weight method. With the aid of the benefit criteria rating scales found in Tables 1 and linguistic terms associated with cost estimation, the rating of such criteria as the cost, abrasion resistance, fatigue resistance, an ease of installation and elasticity associated with various alternatives were respectively estimated by various experts. Due to uncertainties associated with the costs of acquiring various mooring lines, the experts utilized linguistic terms such as low, average and high. Their associated rating scales are (0,1,2,3), (4,5,6,) and (7,8,9,10) respectively. A benefit criterion with a value being greater than another benefit criterion is more desirable and vice versa. For the non-beneficial criteria (i.e. the cost), smaller values are desired.

Each alternative and their associated criteria are estimated by Experts 1-3. Expert 1 estimated the criteria of alternatives: the chain rope = {4,8,6,8,2}, the steel wire rope = {5,7,8,5,3}, the nylon rope ={1,3,2,3,9}, the polyester rope = {5,7,8,2,8} and HMPE = {8,4,8,2,2}. Expert 2 rated in the same manner the chain rope as {3,9,5,9,3}, the steel wire rope = {6,8,7,6,3}, the nylon rope = {2,2,2,2,8), the polyester rope = {6,8,8,3,8} and the HMPE rope = {7,5,9,3,2}. Expert 3, rated in similar approach the chain rope as {4,7,5,7,2}, the steel wire rope = {4,8,8,5,2}, the nylon rope = {1,2,2,2,7}, the polyester rope= {6,9,7,2,7} and the HMPE rope = {8,5,9,2,2}. The average of the rating scores by the three experts is calculated to obtain the final rating score, as demonstrated in Table 2.

Tab. 1. Benefit criteria rating scale [19]

Low	Average	High
0 1 2 3	4 5 6	7 8 9 10

Tab. 2. Rating of alternatives in respect to criteria

Alternatives	Cost	Abrasion Resistance	Fatigue Resistance	Ease of installation	Elasticity
Chain rope	4	8	5	8	2
Steel wire rope	5	8	8	5	3
Nylon rope	1	2	2	2	8
Polyester rope	6	8	8	2	8
HMPE rope	8	5	9	2	2
$\sum_{j=1}^{m} y_{ij}$	24	31	32	19	23

To normalize the decision matrix in Table 2, each value (y_{ij}) was divided with the summation of the values in its column to arrive at the normalized matrix in Table 3.

Tab. 3. The normalized decision matrix

Alternatives	Cost	Abrasion Resistance	Fatigue Resistance	Ease of installation	Elasticity
Chain rope	4	8	5	8	2
Steel wire rope	5	8	8	5	3
Nylon rope	1	2	2	2	8
Polyester rope	6	8	8	2	8
HMPE rope	8	5	9	2	2
$\sum_{j=1}^{m} y_{ij}$	24	31	32	19	23

Tab. 4. The normalized decision matrix multipled with their respective ln values

Alternatives	Cost	Abrasion Resistance	Fatigue Resistance	Ease of installation	Elasticity
Chain rope	0.1667 × ln (0.1667)	0.2581 × ln (0.2581)	0.1563 × ln (0.1563)	0.4211 × ln (0.4211)	0.0870 × ln (0.0870)
Steel wire rope	0.2083 × ln (0.2083)	0.2581 × ln (0.2581)	0.2500 × ln (0.2500)	0.2632 × ln (0.2632)	0.1304 × ln (0.1304)
Nylon rope	0.0417 × ln (0.0417)	0.0645 × ln (0.0645)	0.0625 × ln (0.0625)	0.1053 × ln (0.1053)	0.3478 × ln (0.3478)
Polyester rope	0.2500 × ln (0.2500)	0.2581 × ln (0.2581)	0.2500 × ln (0.2500)	0.1053 × ln (0.1053)	0.3478 × ln (0.3478)
HMPE rope	0.3333 × ln (0.3333)	0.1613 × ln (0.1613)	0.2813 × ln (0.2813)	0.1053 × ln (0.1053)	0.0870 × ln (0.0870)

Each normalized value in Table 3 was multiplied with its natural logarithm (ln) value to obtain the results presented in Table 5.

Tab. 5. Result of normalized decision matrix multiplied with their respective ln values

Alternatives	Cost	Abrasion Resistance	Fatigue Resistance	Ease of installation	Elasticity
Chain rope	- 0,2987	- 0.3496	- 0.2901	- 0.3642	- 0.2124
Steel wire rope	- 0.3268	- 0.3496	- 0.3466	- 0.3513	- 0.2656
Nylon rope	- 0.1325	- 0.1768	- 0.1733	- 0.2370	- 0.3673
Polyester rope	- 0.3466	- 0.3496	- 0.3466	- 0.2370	- 0.3673
HMPE rope	- 0.3662	- 0.2943	- 0.3568	- 0.2370	- 0.2124
$\sum_{j=1}^{m} y_{ij}$	- 1.4708	- 1.5199	- 1.5134	- 1.4265	- 1.4250

Using equation 3,

$$g = \frac{1}{Ln(m)} = \frac{1}{ln\,5} = 0.621335, \tag{11}$$

the entropy value e_j is mathematically described in equation 2. Therefore, e_j is calculated in Table 6.

The weight value is mathematically described in Equation 4 as

$$w_j = \frac{1-e_j}{\sum_{j=1}^{n}(1-e_j)}\ (j= 1,2\dots n). \tag{12}$$

Therefore, w_j is calculated in Table 7.

Tab. 6. Entropy values for five criteria

Alternatives	Cost	Abrasion Resistance	Fatigue Resistance	Ease of installation	Elasticity
$\sum_{i=1}^{m} \beta_{ij} Ln\beta_{ij}$	-1.4708	- 1.5199	- 1.5134	- 1.4265	- 14250
e_j	0.9139	0.9444	0.9403	0.8863	0.8854

Tab. 7. Weights of the criteria

Alternatives	Cost	Abrasion Resistance	Fatigue Resistance	Ease of installation	Elasticity
$\sum_{i=1}^{m} \beta_{ij} Ln\beta_{ij}$	-1.4708	- 1.5199	- 1.5134	- 1.4265	- 14250
e_j	0.9139	0.9444	0.9403	0.8863	0.8854
$1 - e_j$	0.0861	0.0556	0.0597	0.1137	0.1146
w_j	0.2004	0.1294	0.1389	0.2646	0.2667

3.2. Application of the VIKOR Method in an Identification of a Preeminent Mooring Line for Optimal Mooring of a WEC System

The VIKOR method is used in this section to estimate the rank of the alternatives such as the chain rope, the steel wire rope, the nylon rope, the polyester rope and the HMPE rope. In this study, the weights of the criteria such as the Cost, Abrasion Resistance, Fatigue Resistance, an Ease of Installation and Elasticity are 0.2004, 0.1294, 0.1389, 0.2646 and 0.2667 respectively as evidenced in the previous section. The weights are used to facilitate the application of the VIKOR method in an estimation of the ranks of the chain rope, the steel wire rope, the nylon rope, the polyester rope and the HMPE rope in a logical manner.

The best and worst values are found for each criterion in Table 8. For the beneficial criteria, the maximum value is the best and the minimum value is the worst. For non-beneficial criteria, the minimum value is the best, while the maximum value is the worst. The unity measure T_i can be calculated using Equation 5. The results of the calculation are outlined in Table 9. The individual regret U_i values are obtained for each alternatives using Equation 6, and the results are displayed in Table 10. The individual regret U_i value is the highest value in each row.

Tab. 8. Best, $z_i^+$and worst, z_i^-values

Alternatives	Cost	Abrasion Resistance	Fatigue Resistance	Ease of installation	Elasticity
Chain rope	4	8	5	8	2
Steel wire rope	5	8	8	5	3
Nylon rope	1	2	2	2	8
Polyester rope	6	8	8	2	8
HMPE rope	8	5	9	2	2
Best, z_i^+	1	8	9	8	8
Worst, z_i^-	8	2	2	2	2

Tab. 9. Estimation of utility measure values T_i for each alternative

Alternatives	Cost	Abrasion Resistance	Fatigue Resistance	Ease of installation	Elasticity	T_i
Chain rope	0.0859	0.0000	0.0794	0.0000	0.2667	0.4320
Steel wire rope	0.1145	0.0000	0.0198	0.1323	0.2223	0.4889
Nylon rope	0.0000	0.1294	0.1389	0.2646	0.0000	0.5329
Polyester rope	0.1431	0.0000	0.0198	0.2646	0.0000	0.4275
HMPE rope	0.2004	0.0647	0.0000	0.2646	0.2667	0.7964

Tab. 10. Estimation of the regret measure values U_i for each alternative

Alternatives	Cost	Abrasion Resistance	Fatigue Resistance	Ease of installation	Elasticity	U_i
Chain rope	0.0859	0.0000	0.0794	0.0000	0.2667	0.2667
Steel wire rope	0.1145	0.0000	0.0198	0.1323	0.2223	0.2223
Nylon rope	0.0000	0.1294	0.1389	0.2646	0.0000	0.2646
Polyester rope	0.1431	0.0000	0.0198	0.2646	0.0000	0.2646
HMPE rope	0.2004	0.0647	0.0000	0.2646	0.2667	0.2667

The value of T^* and U^* were estimated in Table 11, which are the best values of T_i and U_i. The values of T^- and U^-, which are the worst values of T_i and U_i are estimated in Table 11. The computation of Q_i for each alternative is calculated using Equation 7, and the results obtained are presented in Table 12.

Tab. 11. Alternatives and their unity measures, T_i and regret values U_i

Alternatives	T_i	U_i
Chain rope	0.4320	0.2667
Steel wire rope	0.4889	0.2223
Nylon rope	0.5329	0.2646
Polyester rope	0.4275	0.2646
HMPE rope	0.7964	0.2667
T^* U^*	0.4275	0.2223
T^- U^-	0.7964	0.2667

Tab. 12. Ranks of alternatives obtained

Alternatives	T_i	U_i	Q_i	Rank of alternatives
Chain rope	0.4320	0.2667	0.5061	3
Steel wire rope	0.4889	0.2223	0.0832	1
Nylon rope	0.5329	0.2646	0.6193	4
Polyester rope	0.4275	0.2646	0.4764	2
HMPE rope	0.7964	0.2667	1	5
T^* U^*	0.4275	0.2223		
T^- U^-	0.7964	0.2667		

3.3. Acceptance of Rank Choice

The acceptance of the rank choice can be determined using Condition 1 and Condition 2 as follows.

Condition 1:

$$Q(a2) - Q(a1) \geq DQ. \tag{13}$$

Using Equation 8,

$$DQ = \frac{1}{P-1} = \frac{1}{5-1} = 0.25 \tag{14}$$

Q(a2) = 0.4764 as shown in Table 12, *Q(a1)* = 0.0832 as shown in Table 12.

$$\begin{gathered} 0.4764 - 0.0832 \geq 0.25 = \\ = 0.3932 \geq 0.25 \end{gathered} \tag{15}$$

Since *Q(a2) – Q(a1)* ≥ *DQ,* Condition 1 is satisfied. Condition 2 is also satisfied, since *a1* is the best ranked alternative by U_i.

3.4. Result Discussion

Based on the result obtained in Table 13, the chain rope has a Q_i of 0.5061, the nylon rope has a Q_i value of 0.6193, the polyester rope has a Q_i value of 0.4764, the HMPE rope has a Q_i value of 1.000 and the steel wire rope, which was the first ranked alternative, has the lowest Q_i value of 0.0832. In order for the steel wire rope to be adopted as the best alternative according to the VIKOR method, it is required to meet Conditions 1 and 2. Based on the result obtained, the two conditions were satisfied since *Q(a2) - Q(a1)* equals to 0.3932, which is greater than *DQ*, 0.25. Condition 2 is also satisfied since the steel wire rope is also the best ranked alternative by U_i. It is viable to conclude that the method has successfully determined a preeminent mooring line suitable for a floating WEC.

4. CONCLUSIONS

This study effectively applied the Entropy Weight-VIKOR approach in the selection of a preeminent mooring line suitable for WEC operations in shallow waters. A comprehensive review of the problem presented was carried out. The weights of such criteria as the cost, abrasion resistance, fatigue resistance, an ease of installation and elasticity were estimated using the Entropy Weight method in order to facilitate the selection of a preeminent mooring line from amongst the chain rope, the steel wire rope, the nylon rope, the polyester rope and the HMPE rope using the VIKOR method. The algorithm of the VIKOR method was used to identify the preeminent mooring line. The result obtained showed that the steel wire rope is the preeminent mooring line/the best alternative. This research can be used by marine and offshore engineering experts to make rational decisions in the planning and execution of WECs operations in shallow waters.

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