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Material Selection Framework for Lift-Based Wave Energy Converters Using Fuzzy TOPSIS

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Abstract: Material selection is a crucial aspect in the design of reliable, efficient and long-lasting wave energy converters (WECs). However, to date, the development of tailored methodologies applied to the material selection of WECs remains vastly unexplored. In this paper, a material selection framework for the case of lift-based WECs is developed. The application of the methodology is demonstrated with the hydrofoils of the device. Offshore steel, high-strength offshore steel, aluminium alloys, and carbon- and glass-fibre-reinforced composites are considered and evaluated subject to relevant criteria for wave energy converters, namely structural reliability, hydrodynamic efficiency, offshore maintainability, total manufacturing cost and environmental impact. Candidate materials are assessed via fuzzy TOPSIS for three scenarios of the life cycle of the WEC: conceptual, commercial and future projection stages. Results show that the choice of optimal materials could change from present to future and that multi-criteria decision-making tools aided by a fuzzy approach are useful design tools for novel WECs when field data are scarce. Hence, methodologies such as the ones presented in this work can help in reducing the probability of mechanical failures of emerging WEC technology.

Keywords: wave energy converter; wave energy; lift-based wave energy converter; WEC; hydrofoil; material selection; multi-criteria decision making; failure mode analysis; fuzzy TOPSIS

Citation: Arredondo-Galeana, A.; Yeter, B.; Abad, F.; Ordóñez-Sánchez, S.; Lotfian, S.; Brennan, F. Material Selection Framework for Lift-Based Wave Energy Converters Using Fuzzy TOPSIS. *Energies* **2023**, *16*, 7324. https://doi.org/10.3390/en16217324

Academic Editor: Mariano Buccino

Received: 9 October 2023
Revised: 25 October 2023
Accepted: 25 October 2023
Published: 29 October 2023

1. Introduction

Over the last decade, wave energy has come closer to commercialisation with the aid of governmental support, private investment [1] and the interest of the offshore oil and gas sector to tackle climate change [2,3]. In conjunction with offshore wind and tidal energy, wave energy can complete the mix towards the decarbonisation of offshore energy systems and the race towards net zero [3]. Hence, large-scale wave energy converters (WECs) are set, now more than ever, to become a reality in the foreseeable future [2,4].

Among the candidate wave energy converters (WECs), lift-based WECs have shown great potential to become competitive in the offshore market due to their submerged mode of operation and ability to stall in storm conditions passively. Hence, the load alleviation capabilities of these devices make them strong contenders for commercialisation [4–7].

To date, most research efforts regarding lift-based WECs have focused on developing hydrodynamic models to predict power efficiency [4,5,8,9]. These models are necessary to improve the structural design of the device and optimise power performance. However, there has been almost no considerable effort towards failure mitigation strategies of lift-based WECs. Digital twin implementation [10], adaptive control systems [11,12], and the use of appropriate materials are some of the most prominent risk mitigation strategies for wave energy converters. In fact, to move up the ladder of technology readiness level (TRL) of lift-based WECs, the development of strategies that minimise the risk of failure is essential.

Material selection can be carried out through methods such as SPOTIS (Stable Preference Ordering Towards Ideal Solution) [13,14], COMET (Characteristic Objects Method) [14–16], SIMUS (Sequential Interactive Modelling for Urban Systems) [17], and DARIA-TOPSIS (Data Variability Assessment Technique for Order of Preference by Similarity to Ideal Solution) [18], which have been developed over recent decades to aid engineers in evaluating and identifying optimal materials. While these methods have relative strengths, they also have limitations that make them less suitable for early-stage analysis of novel systems with qualitative criteria and data constraints. For instance, SPOTIS requires a set of boundary conditions when assessing material selection criteria [13,14]. These limits are difficult to define when there is a scarcity of field data and the subject of study is novel. COMET depends on the formulation and ranking of characteristic objects that interrelate the different assessment criteria. Assessing such characteristic objects for a novel concept adds a level of complexity to an already difficult problem [14–16]. SIMUS might not be the most suitable choice either, since weighting factors can evolve with time and they are necessary to evaluate the WEC through different stages of product development [17]. DARIA-TOPSIS relies on assessing the variability of large data sets, which for a novel device are not available [18]. In contrast, fuzzy TOPSIS seems the most suitable option for an initial material selection assessment of a novel lift-based WEC, where a qualitative assessment of materials based on expert opinion needs to be performed.

Hence, in this work, we focus on developing a novel and systematical material selection framework for lift-based WECs using the fuzzy TOPSIS technique. Methodologies that emphasise the fitness-for-purpose of materials are vital to prevent the failure of novel technologies, and therefore the loss of investment. Therefore, the present paper contributes to the literature by introducing a multi-criteria decision making (MCDM) material selection framework, which is tailored to lift-based wave energy converters and is applicable to different stages of the product cycle. It is worth noting, however, that the impact of this work does not extend only to lift-based WECs, but also to other submerged marine energy harvesting mechanisms that operate in proximity to the ocean's free surface.

Importantly, MCDM methodologies have also found widespread use in various applications, encompassing areas like strategic planning [19–21], supply chain management [22–24], and product development [25,26], significantly enhancing decision-making processes. However, their adoption within the energy and renewable technology sector is limited, with only two dedicated papers highlighting their application for ocean energy systems, as demonstrated by [27]. Hence, the significance of the introduced framework is that it brings together multiple design considerations, such as structural reliability, cost, maintainability, environmental impact and sustainability, to evaluate the best material option in the context of a wave energy device.

Specifically, the proposed framework formulates a decision matrix relevant to the hydrofoils of the lift-based WEC to find the optimal material candidate. A team of experts carries out the assessment of the key material selection criteria. The structural reliability criterion is based on failure mode, effect, and criticality analysis (FMECA), whilst a fuzzy approach is employed to cope with the limited field data of lift-based WECs. Five material candidates are considered: offshore steel (S355), offshore steel (Duplex 1.4462), aluminium alloy Al-Mg, composite—CFRP and composite—GFRP. As a demonstrative case, we apply the framework to the hydrofoils of a lift-based WEC, and we analyse the results at three different life-cycle stages, namely the conceptual, commercialisation and future projection stages.

One of the key features of this work is the application of FMECA, a semi-quantitative risk assessment method, through expert elicitation to systematically review and analyse the way in which a lift-based WEC structure can fail to perform its intended function [28]. FMECA is performed because there is a lack of statistically significant data regarding the safety and reliability of the structural components of WECs, as indicated in multiple studies [29–32]. Furthermore, FMECA is the recommended practice for technology qualification and certification, as it helps in identifying weak structural points of a system and avoiding costly mistakes during product development.

The outcomes of an FMECA not only help identify failure mechanisms and load condition under which the structures should be analysed but also provides valuable insights into risk mitigation strategies that can be applied. Therefore, an FMECA conducted by a multidisciplinary group of experts is the closest to an advanced structural reliability analysis at an early design stage. Furthermore, its integration into the multi-criteria material selection framework offers immeasurable benefits by preventing commitment to a suboptimal design, whose correction must be carried out during the detailed design phase at best, the manufacturing phase, and the operation phase at worst.

The structure of the paper is as follows. Firstly, we present the material selection framework and introduce the lift-based WEC concept and the hydrofoils as the test case. Subsequently, we present the multi-criteria decision-making tool, namely the fuzzy TOPSIS technique. Afterwards, the key criteria used for material selection are introduced. Later, in the Section 5, the framework is applied to the three different life-cycle scenarios: conceptual, commercialisation and future projection stages. Lastly, we discuss the results and the findings of this work.

2. Methodology and Test Case

2.1. Material Selection Framework

The multi-criteria selection methodology for the materials of lift-based WECs is illustrated in the flow chart of Figure 1. The process starts by defining the subject of study—in this case, a lift-based wave energy converter. Subsequently, the material selection framework is constructed. Five different selection criteria relevant to lift-based WECs are selected, namely structural reliability, hydrodynamic efficiency, offshore maintainability, manufacturing costs and environmental impact. These criteria are key and were found to be relevant to increase the TRL of lift-based WECs based on the findings of the LiftWEC consortium [5,6,33–35], a three-year Horizon 2020 research project, which concluded in the first quarter of 2023 [36].

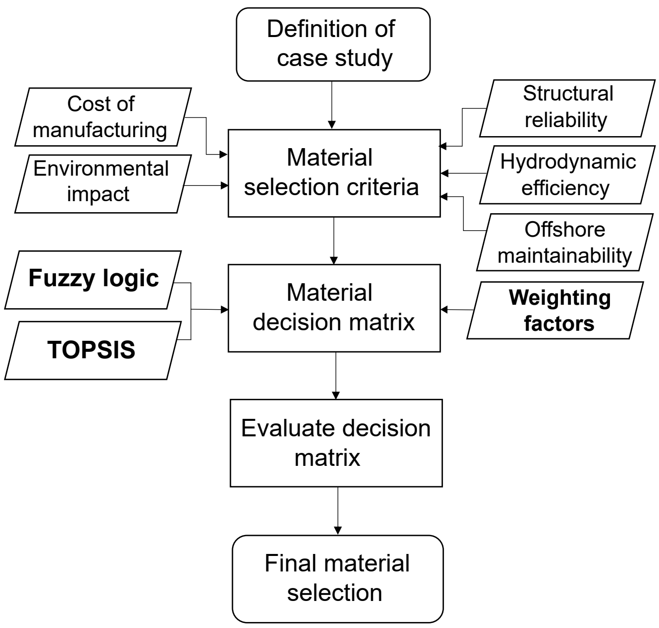

Figure 1. Flow chart illustrating the MCDM material selection framework, with fuzzy logic, TOPSIS and weighting factors highlighted in bold, as key elements of the decision matrix.

Subsequently, a material decision matrix is constructed and assessed using fuzzy logic and TOPSIS. The decision matrix is then evaluated to determine the optimal material for the structural component of the WEC under study. The decision matrix is assessed with respect to the key material selection criteria and according to the stage of development of the lift-based WEC. Prior to expanding on the key material selection criteria and implementing the methodology, the following section introduces the lift-based WEC concept and presents the structural component that will serve as the demonstrative case of the framework, namely the hydrofoils.

2.2. Lift-Based WEC

In this work, we adopt a spar buoy floating configuration of a lift-based WEC. The device is illustrated in Figure 2. In Figure 2, the device is submerged and positioned in proximity to the free surface. The device stays afloat with the aid of a horizontal spar buoy. The other primary structural components are the hydrofoils and central shaft, which together form the rotor of the device, while the stator constitutes the fixed part of the WEC. This configuration represents the final concept resulting from the LiftWEC project [36]. Note that further to the reduction in slamming and extreme loads achieved through submergence and passive stall, a floating prototype has the potential to reduce installation and maintenance costs [33].

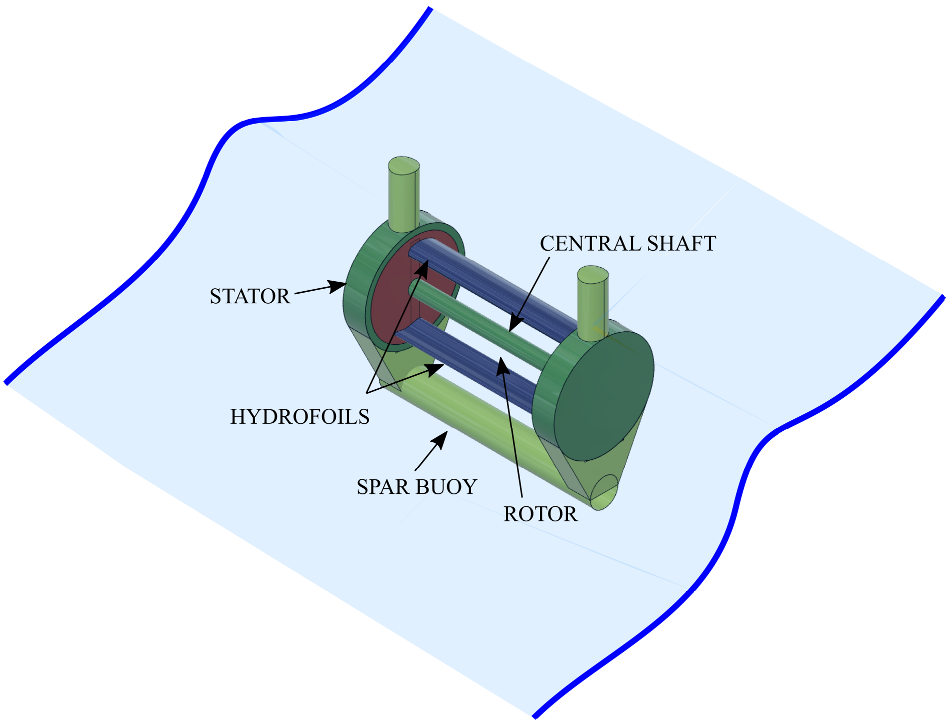

Figure 2. Floating lift-based WEC concept from LiftWEC project with horizontal spar buoy, two hydrofoils and a central shaft.

The main structural component of the rotor, and one of the primary components of the lift-based WEC, is the hydrofoil. Lift forces are generated through interactions between the foil and the waves, sustaining the rotation of the rotor to generate electrical power. To minimise drag, the foil is curved along the circumference of rotation, behaving similarly to a straight foil in straight flight. In our study, the reference hydrofoil is a NACA 0015 with a uniform cross-section. Figure 3 shows a schematic of the hydrofoil, which serves as the chosen test case for the material selection framework developed in this work. In Figure 3, the hydrofoil cross section comprises a leading edge and trailing edge at the front and back of the foil, respectively. The central part is the spar, providing structural strength to the hydrofoil.

The hydrofoils are the selected structural component to implement the framework developed in this work due to their significant role in the performance and functionality of a lift-based WEC. As a result, the selection criteria proposed in the flow chart of Figure 1 are derived from an understanding of the life cycle of the hydrofoils, which serve as the case study.

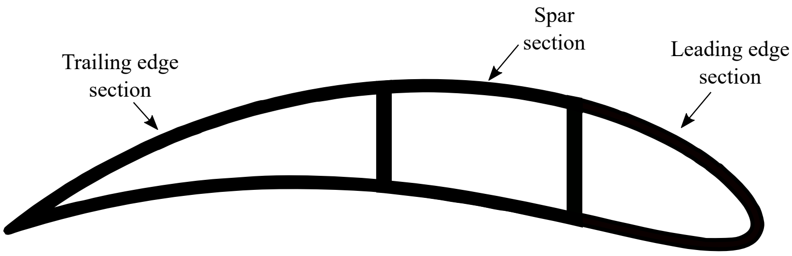

Figure 3. Curved hydrofoil cross-section for lift-based cycloidal rotor, showing the leading edge, spar and trailing edge sections.

For example, the relevant aspects of the life cycle of the hydrofoils of a lift-based WEC are illustrated in Figure 4, namely manufacturing, land transport, assembly, water transport, installation, operation, removal and disposal. In Figure 4, the life cycle begins with the selection of raw materials. In this paper, we focus on selecting materials from an economic, operationally efficient, and sustainable point of view. Therefore, the key life-cycle steps influenced by the material selection framework are manufacturing costs, environmental impact and efficient operational time, structural reliability, hydrodynamic efficiency and ease of maintenance, as discussed in more detail in Section 6.

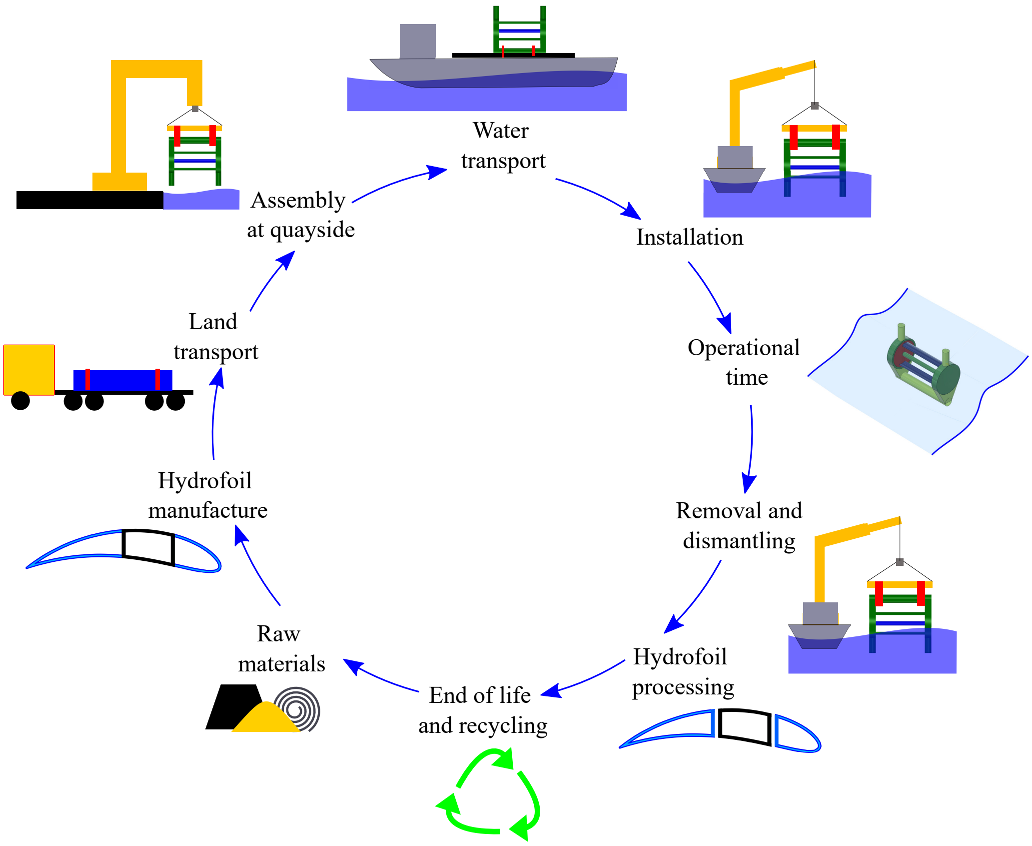

Figure 4. Material life cycle for lift-based wave energy converter.

3. Construction of Decision-Making Framework

3.1. Multi-Criteria Decision-Making

Multi-criteria decision making (MCDM) is an important branch of operational research applied to various engineering fields where the solution to a problem or the fittest option for a purpose depends on multiple criteria. These criteria are typically independent and can, at times, conflict with each other.

MCDM techniques aim to rank the order of candidate options and choose the "best" option, taking into account multiple criteria, each of which carries different weighting factors. MCDM techniques can handle both qualitative and quantitative values. While most MCDM techniques are designed for processing quantitative values, MCDM techniques combined with fuzzy logic theory can provide a solution when quantitative values are challenging to attain. This is the case, for example, of the conceptual design stage of a novel WEC, where decision makers may have only qualitative information based on their experience. Therefore, because the present study tackles a material selection problem of a novel device at conceptual, commercialisation, and future stages, proceeding with a multi-criteria decision-making problem with qualitative values is the proposed approach in this work, provided that there is a team of experts conducting the assessment.

The present study employs a well-documented MCDM technique called the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). TOPSIS considers the solution with the shortest Euclidean distance to the ideal solution [37–39]. The TOPSIS technique has been successfully applied to multiple engineering fields [40–43], and an open-source implementation in Python is available in [44]. While TOPSIS has been used in the marine context [45,46], it has not been applied extensively to assess offshore renewable energy. Therefore, this paper aims to assess its capability as a decision-making tool for wave energy converters. Specifically, the present study illustrates a unique application of TOPSIS on the material selection of the hydrofoils of lift-based wave energy converters, as it brings together the experience of a multidisciplinary group of experts. Table 1 provides a summary of the skills and expertise of the multidisciplinary team involved in this work.

Table 1. Expert information table, where "Expert ID" indicates the authors of this paper with the corresponding name initials. The table includes details on each expert's years of experience and their respective field of expertise in the second and third columns.

Expert ID	Years of Experience	Field of Expertise
First author (AAG)	+10 years	Hydrodynamics and fluid–structure interactions of offshore renewable assets
Second author (BY)	+10 years	Structural integrity and reliability of offshore renewable assets
Third author (FA)	+10 years	Structural assessment of composite and steel structures
Fourth author (SOS)	+20 years	Materials and hydrodynamics of tidal turbines
Fifth author (SL)	+20 years	Structural integrity of offshore renewable assets
Sixth author (FB)	+30 years	Offshore engineering and structural integrity of offshore renewable assets

3.2. Fuzzy Logic

Fuzzy logic within an MCDM problem addresses the uncertainty inherent in expert judgment. It involves the use of fuzzy qualitative variables instead of numeric values to rank the weight or assess a given criterion in the TOPSIS decision matrices. As part of the fuzzy process, qualitative values are translated into a set of quantitative values that the MCDM algorithm can use to do algebraic operations through a set of membership functions.

The present study employs the fuzzy TOPSIS technique for the material selection of the hydrofoils of a lift-based WEC. The evaluation of material options for critical components, especially in the case of novel concepts like lift-based WECs, presents significant challenges when considering multiple comprehensive criteria, such as those in the current study, including structural reliability, hydrodynamic efficiency, offshore maintainability, manufacturing costs, and environmental impact. Hence, the fuzzy framework provides a robust approach to deal with the ambiguity in the expert judgements concerning the selected criteria. An example of a fuzzy decision matrix used in the fuzzy TOPSIS approach is illustrated in Table 2.

Table 2. Example of TOPSIS decision matrix, with fuzzy terminology for candidates 1 to 5 and criteria Q1 to Q5, without weighting factors.

	Q1	Q2	Q3	Q4	Q5
Candidate 1	High	Average	High	Average	High
Candidate 2	High	Average	High	High	High
Candidate 3	Average	Average	Very High	Very High	Average
Candidate 4	Very High	High	Average	High	High
Candidate 5	High	High	Average	Average	High

In Table 2, linguistic terms that represent fuzzy numbers are used to assess different candidates versus different criteria (Q1. . . Q5). Note that a fuzzy number is represented by a triplet, i.e., a triangular fuzzy number. The definition of the triangular fuzzy number is given by Equation (1), such that

$$\mu = \begin{cases} 0, & x < a_1 \\ (x - a_1)/(a_2 - a_1), & a_1 \leq x \leq a_2 \\ (a_3 - x)/(a_3 - a_2), & a_2 \leq x \leq a_3 \\ 0, & x > a_3, \end{cases} \tag{1}$$

whilst the relationship between fuzzy numbers and linguistic terms is given in Table 3. In Table 3, the linguistic terms are transformed into fuzzy numbers using a conversion scale of 1–10, and five linguistic terms are considered. The linguistic terms are used to evaluate the key selection criteria and also the weighting factors of the criteria when they are incorporated in the decision matrix tables.

Table 3. Fuzzy numbers and corresponding linguistic terms considered to assess the decision matrices for the material selection framework of this work.

Fuzzy Number	Linguistic Term
(1, 2, 3)	Very low
(2, 3.5, 5)	Low
(4, 5.5, 7)	Average
(6, 7.5, 9)	High
(8, 9, 10)	Very high

Lastly, Figure 5 illustrates the membership functions relating to the fuzzy numbers and the linguistic terms shown in Table 3. Triangular fuzzy numbers are chosen because they provide a useful representation of the area of influence of the linguistic term. As illustrated in Figure 5, each linguistic term is defined by a lower and upper bound and a mean value where the membership function μ is maximum. In fact, for a triangular fuzzy number, μ could be interpreted as a rough approximation of a Gaussian distribution. The membership function of Figure 5 is used to defuzzify Table 2, and provide a table with numeric values that can be used in the TOPSIS algorithm. The defuzzified table is shown in Table 4.

Table 4. Defuzzification of TOPSIS decision matrix presented in Table 2 using membership function of Figure 5.

	Q1	Q2	Q3	Q4	Q5
Candidate 1	6, 7.5, 9	4, 5.5, 7	6, 7.5, 9	4, 5.5, 7	6, 7.5, 9
Candidate 2	6, 7.5, 9	4, 5.5, 7	6, 7.5, 9	6, 7.5, 9	6, 7.5, 9
Candidate 3	4, 5.5, 7	4, 5.5, 7	8, 9, 10	8, 9, 10	4, 5.5, 7
Candidate 4	8, 9, 10	6, 7.5, 9	4, 5.5, 7	6, 7.5, 9	6, 7.5, 9
Candidate 5	6, 7.5, 9	6, 7.5, 9	4, 5.5, 7	4, 5.5, 7	6, 7.5, 9

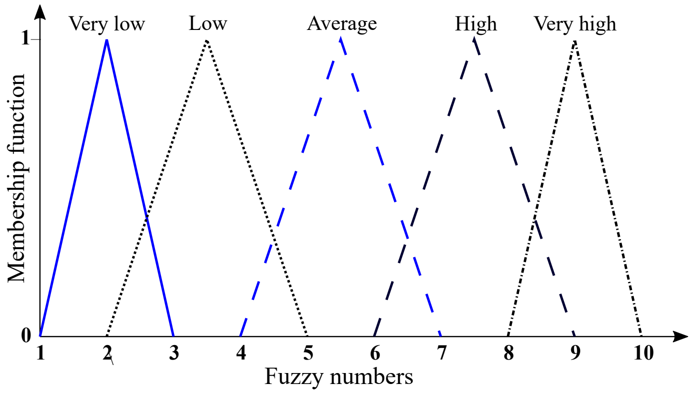

Figure 5. Membership function used in this work of five fuzzy triangular numbers.

3.3. Decision Matrix Formulation

In this section, we present the formulation of the material decision matrix as specified in the flowchart of Figure 1. We recall, also from Figure 1, that the key criteria for material selection are structural reliability, hydrodynamic efficiency, offshore maintainability, cost of manufacturing and environmental impact. These criteria are listed in Table 5, along with some of the relevant aspects that are considered in Section 4 for assessing each key criterion. It is important to note that these key criteria are the outcome of a workshop held between the team of experts listed in Table 1 and the LiftWEC consortium [36].

Table 5. Key criteria for material selection and relevant aspects considered in this work to rank each criterion.

Key Criterion	Relevant Aspects
Structural reliability	Criticality of structural failure, yield and fatigue strength of material
Hydrodynamic efficiency	Corrosion, erosion and biofouling resistance of materials
Offshore maintainability	Industry experience, corrosion and erosion resistance of material
Cost of manufacturing	Waste treatment and raw material cost, embodied energy (MJ/kg)
Environmental impact	Recyclability, human health impact and green house gas impact

An important element in the decision matrix is the selection of weighting factors for each of the chosen key criteria. The weights reflect the relative importance of each criterion in the context of the test case under study [47,48], which, in this instance, is the hydrofoils of the lift-based WEC. In this work, we have chosen a subjective approach, where the weight of each criterion is determined by the group of experts based on their expertise [48]. In particular, given the novelty of the device, a subjective approach, where the expertise of the team is utilised, is particularly useful. Hence, a weight vector for the key criteria is described by

$$W = [w_1, w_2, \ldots, w_n], \tag{2}$$

where $w_1, w_2, \ldots, w_n$ are the weighting factors, and n is the total number of key criteria to be assessed. In vector (2), each weighting factor w_j is computed such that

$$w_j = \frac{1}{m}\sum_{i=1}^{m} w_i, \tag{3}$$

where m is the total number of experts and w_i is the weighting factor provided by the i-th expert when asked to rank each of the key criteria. With the weighting factors and the key criteria, the decision matrix is formulated. The decision matrix is shown in Table 6. In Table 6, the cells in grey and yellow are the inputs and outputs of the matrix, respectively.

Table 6. Decision matrix table formulated in this study to assess the best candidate material for the hydrofoils of a lift-based WEC.

	Weighting Factors					
Candidate	**Structural Reliability**	**Hydrodynamic Efficiency**	**Offshore Maintainability**	**Total Cost**	**Environmental Impact**	**Ranking**
Offshore steel (S355)						
Offshore steel (Duplex 1.4462)						
Aluminium alloy Al-Mg						
Composite—CFRP						
Composite—GFRP						

The inputs of the decision matrix of Table 6 are assessed in a fuzzy manner. Subsequently, the inputs are defuzzified, and the TOPSIS technique is applied. The TOPSIS steps are computed in this work, following [43], and are presented in the Excel sheet included as Supplementary Material of this work. The example case of the commercialisation stage is included in the Supplementary Material. As a summary, the TOPSIS steps are (1) construction of a normalised decision matrix, (2) construction of weighted normalised decision matrix, (3) determination of ideal positive (A^+) solution, (4) computation of separation distance from positive ideal (d^+) solution for each case of the decision matrix, (5) computation of closeness coefficient (cc) of each case of decision matrix and (6) ranking of solutions through the closeness coefficient. For more in-depth information about the implementation of these TOPSIS steps, readers are referred to [43] and the Supplementary Material provided with this work.

In retrospect, our study employs the fuzzy TOPSIS method for material selection due to its effectiveness in handling qualitative criteria ratings and uncertainties. It is suitable for early-stage analysis when data are limited. While other methods like SPOTIS, COMET, SIMUS, and DARIA-TOPSIS have merits, fuzzy TOPSIS aligns well with the goals of this research. For example, SPOTIS relies heavily on quantitative boundary data inputs, which are scarce for novel WEC concepts. COMET is based on the assessment of characteristic objects which contain information from different criteria. For a novel WEC concept, where limited field data exist and where the assessment criteria might be independent of each other, the ranking of characteristic objects is challenging. SIMUS does not use weights, and therefore its applicability to different life stages of a WEC is difficult to study because design priorities could evolve with time. DARIA-TOPSIS is more suitable for problems with large data sets, which are not available for novel WECs. In contrast, fuzzy TOPSIS allows dealing with the novelty of lift-based WECs by incorporating expert opinion and weighting into the decision matrix whilst providing robustness to the solution through a fuzzy approach. Furthermore, the capability to transform linguistic data into computable rankings makes fuzzy TOPSIS well suited where field data are limited, but expert judgment can provide meaningful insights, as in early-stage WEC analysis. Its simple computation steps and ability to identify solutions closest to the ideal also align with the objectives of this research. While an extensive empirical comparison of methods could enhance analysis, fuzzy TOPSIS provides a practical and effective framework for material selection, given the constraints and aims of this initial research on WEC hydrofoils. As data availability improves in later stages, incorporating other selection approaches may provide useful perspectives. Overall, fuzzy TOPSIS provides a robust platform to integrate disparate qualitative considerations into a coherent decision-making process for material selection in novel WECs.

4. Key Criteria for Material Selection

One of the challenges in assessing some of the criteria presented and in the decision matrix of Table 6, is that they are neither discrete nor directly quantifiable. In fact, many of these criteria involve different aspects to determine a ranking level. Hence, each key criterion is evaluated through the combination of different aspects and also with the aid of the fuzzy TOPSIS technique. The relevant aspects of each key criterion considered in this work are also listed in Table 5. We describe these aspects in detail in the following subsections and consider the case of the conceptual design stage of the hydrofoils for illustration purposes.

4.1. Structural Reliability Based on FMECA

Structural reliability is defined as the ability of an asset to fulfil its intended purpose under environmental and operational conditions for a given period. It is one of the primary design considerations for critical components. The expected structural reliability from a structural component depends on its function, interconnectivity to other parts, consequence, and likelihood of potential failure [49]. Therefore, a failure mode, effect, and criticality analysis (FMECA) can be a valuable tool for making informed judgments about structural reliability before entering the detailed design phase.

In summary, FMECA assesses the potential failures and ranks them based on the severity (S) of failure, the likelihood of occurrence (O) of failure, and the difficulty of detection (D) of failure. Action priority (AP) ratings are derived from the FMECA process, helping with effective risk management by either accepting the risk or mitigating it before moving to the following stages of the life cycle of a product. The FMECA process is illustrated in the flow chart of Figure 6. Further, FMECA can be conducted using both semi-quantitative and qualitative methods [50]. For novel concepts such as lift-based WECs, there are very limited field data on the failure rates of critical structural components. Hence, the present study addresses this issue by performing a series of workshops between the expert group whose judgements are recorded in qualitative variables.

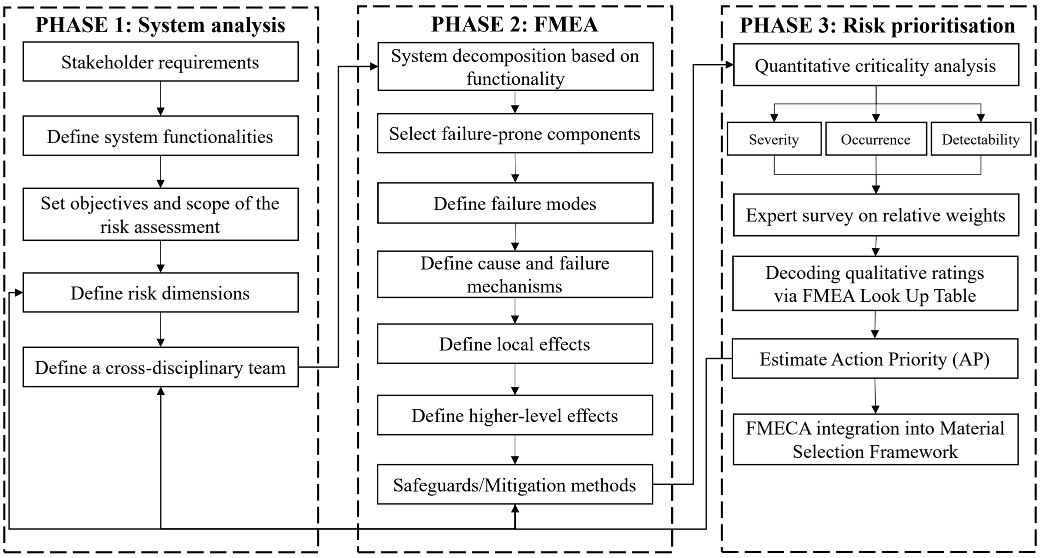

Figure 6. FMECA flowchart showing phase 1: System analysis, phase 2: FMEA and phase 3: Risk prioritisation.

Table 7 shows the FMECA carried out for the hydrofoils of the lift-based WEC, considering offshore steel (S355) at the conceptual design stage. Following the procedure described in Figure 6, the most critical failure modes are identified and listed in the first column of Table 7. The failure modes are categorised by their severity (S), based on their assessed impact on the rest of the structural components. Then, the failure mechanisms and failure causes associated with each failure mode are determined. The corresponding qualitative ratings of occurrence (O) and detection (D) are assigned for each failure mechanism and cause, and action priority (AP) numbers are determined following the failure mode and effects analysis (FMEA) handbook manual [51]. A summary of the AP tables used in this work to conduct the FMEA is included in the Supplementary Materials.

Table 7. FMECA performed for hydrofoils fabricated with offshore steel (S355) showing failure mode and severity (S), failure mechanism and failure cause, with corresponding occurrence (O) and detection (D) rating. Ratings are assigned based on the expert opinion. The acronyms VH, H, M, L and VL refer to very high, high, medium, low and very low, respectively.

Failure Mode	**Severity (S)**	**Failure Mechanism**	**Failure Cause**	**Occurrence (O)**	**Detection (D)**	**Action Priority**
Excessive plastic deformation	H	Yielding	Multi-directional loading	M	M	H
	VH	Yielding	Out-of-phase operational load	L	L	L
	H	Buckling	Misalignment and geometrical imperfections	L	H	M
	VH	Yielding	High bending moment midspan of hydrofoil	M	M	H
	VH	Brittle fracture	Low temperature and overload	VL	VH	L
	H	Impact loading	Dropped objects, ocean debris	L	VH	M
	VH	Impact loading	Mammals collision	L	M	M
Cracking	H	High-cycle fatigue	High-cycle fatigue loading	M	H	H
	M	Low cycle fatigue	Shear force and delamination	L	VH	L
	H	Corrosion fatigue	Pitting and cyclic loading	M	M	M
Corrosion, Wear and Erosion	M	Low energy yield	Loss of suction force at leading edge	H	L	M
	H	Electrochemical	Corrosive environment	M	L	M
	M	Erosion	Ocean debris	M	L	L
Cavitation	VH	Localised intensive pressure	Low pressure zones and bubbles	L	L	L
Excessive vibration	M	Resonance	Loss of pitch control and velocity control rare sea states	L	M	L

The AP results of the FMECA shown in Table 7 indicate that yielding due to multidirectional loading, high bending moments midspan of the foils, and fatigue due to high-cycle cyclical loading in operational conditions are the critical mechanisms in which failure can occur in the hydrofoils. Thus, these failure mechanisms need to be prioritised in terms of structural reliability and in the development of risk mitigation strategies.

Although FMECA is conducted considering that the hydrofoils are made of offshore steel (S355), it is possible to draw reasonable conclusions for other materials regarding critical failure root causes and failure modes, i.e., how the failure would manifest itself. In this regard, yield strength is considered highly critical for offshore steel (S355), and with an increase in the material yield strength, it is reasonable to assume that failure due to mix mode overloads midspan of the hydrofoil can be avoided. Hence, the higher the yield strength, the lower the risk of yielding in the material.

In terms of high-cycle fatigue, one can consider the fatigue strength or endurance limit defined by the S-N (stress–life) curves under a high-cycle loading regime. Additionally, the stress concentration at the internal edges of the spar caps of the hydrofoils is another point to consider in fatigue-related failures. Therefore, rigorous control and adequate control techniques during the fabrication of the spar caps of the hydrofoils are recommended for offshore steel (S355) and other materials. The degree to which such control processes will be effective can be reflected in the rating given for the material options through their fatigue strength.

In light of the discussion given above, the ratings related to the structural reliability criterion for different material options are provided in Table 8. With respect to yield strength, composite—CFRP is regarded as very high, followed by offshore steel (S460)—Duplex 1.4462, whilst offshore steel (S355) and composite—GFRP are rated as average, and aluminium is rated as low.

For fatigue strength, the ratings take into account factors such as endurance limit, stress concentration due to connection types, and defect control techniques. Once again, composite—CFRP is rated as very high due to its very high endurance limit, followed by offshore steel (S460)—Duplex 1.4462 and offshore steel (S355) because of their well-established control mechanisms reflected in their S-N curves.

In addition to the deterministic strength characterisation of the materials, the structural reliability ratings consider aleatory and epistemic uncertainties associated with the material properties and the experimental methods to acquire these properties. Table 8 presents the details of the ratings given for the different criteria to assess the structural reliability of each material, namely yield strength, fatigue strength and uncertainty in quantification of these properties. Equal weighting is given to the different criteria. The structural reliability ratings of Table 8 are assessed using fuzzy TOPSIS and are highlighted in bold. We recall that these ratings are given considering the conceptual design stage and are for illustration purposes only.

Table 8. The structural reliability ratings related to different material options [52–54] considering the conceptual design stage. The resulting rankings for structural reliability are highlighted in bold.

Materials	Yield Strength	Fatigue Strength	Uncertainty	Structural Reliability
Offshore steel (S355)	Average	High	Very high	**High**
Offshore steel (Duplex 1.4462)	High	High	High	**High**
Aluminium alloy Al-Mg	Low	Very low	Very high	**Average**
Composite—CFRP	Very high	Very high	Low	**High**
Composite—GFRP	Average	Average	Very low	**Low**

4.2. Hydrodynamic Efficiency

Figure 7a depicts a single-foil lift-based WEC rotating under a regular wave. Considering the foil as a single point vortex [5,12], the inflow velocity of the foil U is estimated through the vectorial sum of the velocity component due to the rotation of the foil v, the wave velocity component w and the induced velocity due to the circulation of the foil and the memory effect on the free surface due to the wake of the foil q, as described in [5]. Figure 7b shows the vectorial sum of w, v and q used to estimate U and α, where α is the angle measured between U and v.

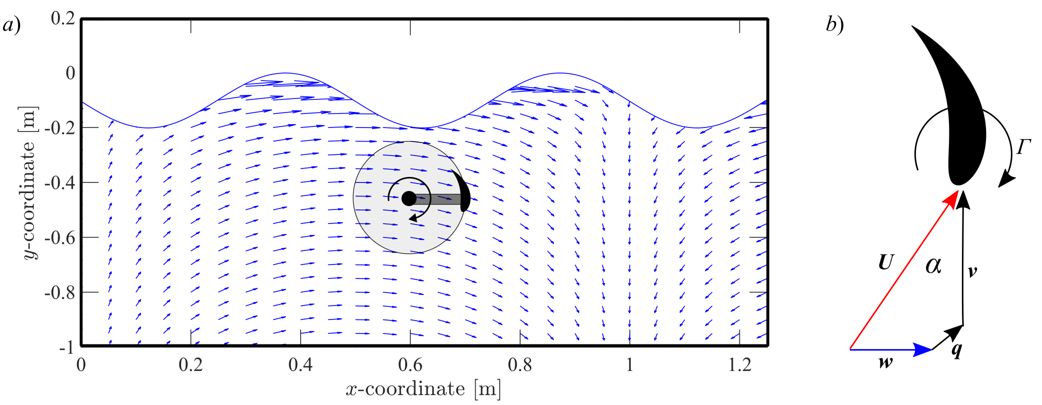

Figure 7. (**a**) Single foil wave cycloidal rotor beneath surface level and interacting with wave velocity field and (**b**) velocity triangle of the foil due to wave velocity component w, induced velocity due to the circulation of the foil and the memory effect on the free surface q and velocity component due to rotation of foil v [5,35].

The single-point vortex model uses lift and drag coefficient curves to compute the radial and tangential forces on the foil. In this work, we consider lift and drag coefficient curves of a symmetric NACA 0015 with a smooth and rough surface ($k/c = 0.00282$)

at Reynolds 220,000. The lift and drag curves for the smooth and rough surface foil are available in [55]. Note that k is the height of the roughness and c is the chord length. It is worth mentioning that barnacles or roughness have a significant effect on the drag curve of symmetric foils but not on the lift curve [55]. In fact, the drag increases significantly at pre-stall angles, i.e., below the static stall angle of the foil. This has also been observed in non-symmetric foils [56], and therefore, for curved foils such as the ones of the lift-based WEC, a drag increase due to roughness is also expected.

Figure 8a,b show the mean radial ($\bar{c}_{rad}$) and tangential ($\bar{c}_{tan}$) force coefficients, respectively, on the hydrofoil of a single-foil lift-based WEC. Results are plotted for a smooth and rough surface hydrofoil and compared with experimental measurements at Re = 300,000 in attached flow conditions [5] at wave periods $T = 1.6$ s, 1.8 s and 2.0 s.

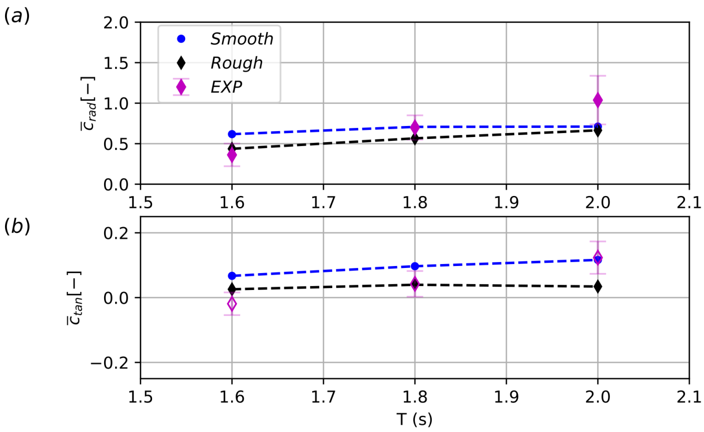

Figure 8. (**a**) Radial and (**b**) tangential force coefficient validation with simulated results for rough and smooth hydrofoils and compared versus experimental data [5].

Although Figure 8a does not show significant differences between $\bar{c}_{rad}$ of the smooth and rough surface hydrofoil, it can be seen in Figure 8b, that as T increases, the impact of surface roughness in $\bar{c}_{tan}$ becomes significant, and therefore it is detrimental to power performance. It could be expected that biofouling effects become less significant when the rotor operates past stall ($T_p \geq 2.0$ s) in separated flow conditions. However, the optimal power and structural operational point of the lift-based WEC is in the attached flow, and therefore, biofouling could play an important role in power performance. A summary of the literature of the drop in performance of lift-based devices is shown in Table 9. The table shows that the drop in performance found through our numerical simulations is reasonable to expect and similar to the drop in performance of vertical axis tidal turbines (VATTs).

Table 9. Summary of the effect of surface degradation in different lifting devices.

Lifting Device	Surface Anomaly	Performance Drop	Reference
Wind turbine	Leading edge erosion	2–4%	[57,58]
	Surface erosion	3%	[59]
HATTs	Surface erosion	6–8%, 13%	[60,61]
	Heavy bio-fouling	19%	[62]
VATTs	Surface erosion	40–65%	[63]
Marine propeller	Biofouling	3–30%	[64]
Lift-based WEC	Biofouling	30–40%	Present work

Lastly, and in order to feed into the MCDM material selection framework, we assess the hydrodynamic performance of hydrofoils made of different materials, assuming the conceptual design stage. From Figure 8, it can be inferred that lift-based WECs with hydrofoils that are more resistant to surface imperfections will perform hydrodynamically better. Hence, we consider corrosion, erosion and biofouling resistance in Table 10, as the key criteria to determine the hydrodynamic efficiency of the different candidate materials. Equal weighting is given to the criteria, and results are shown in Table 10. For metals, even though they can be subject to biofouling [65], we assume cathodic protection and therefore, in Table 10, they are ranked with high resistance to biofouling. In contrast, CFRP is found to be more adversely affected by biofouling than GFRP [66].

Table 10. Hydrodynamic efficiency of materials based on corrosion, erosion and biofouling resistance for the conceptual design stage. The resulting rankings for hydrodynamic efficiency are highlighted in bold.

Material	Corrosion Resistance	Erosion Resistance	Biofouling Resistance	Hydrodynamic Efficiency
Offshore steel (S355)	Average	High	High	**High**
Offshore steel (Duplex 1.4462)	High	High	High	**High**
Aluminium alloy Al-Mg	Very High	High	High	**Very High**
Composite—CFRP	Very High	Average	Low	**Average**
Composite—GFRP	Very High	Very low	Average	**Average**

4.3. Offshore Maintainability

In this work, offshore maintainability refers to the level of complexity and downtime duration to repair components or systems in the offshore environment. Although offshore maintainability is also affected by aleatory factors [67], such as weather conditions and accessibility, deterministic factors, such as industry experience, corrosion and erosion resistance of materials [68], can decrease downtime of WECs due to material-related failures. Therefore, we assess the offshore maintainability of materials in Table 11 in terms of industry experience, i.e., years of experience of industries using these materials offshore, and in terms of corrosion and erosion resistance of the material.

Table 11. Offshore maintainability of materials based on corrosion and erosion rate for metals and composites [68,72], assuming the conceptual design stage. The resulting rankings for offshore maintainability are highlighted in bold.

Material	Industry Experience	Corrosion Resistance	Erosion Resistance	Offshore Maintainability
Offshore steel (S355)	High	Average	High	**Average**
Offshore steel (Duplex 1.4462)	High	High	High	**High**
Aluminium alloy Al-Mg	Very high	Very High	High	**Very High**
Composite—CFRP	Low	Very High	Average	**Low**
Composite—GFRP	Low	Very High	Very low	**Very Low**

In terms of industry experience in the offshore marine environment and shipbuilding, steel and aluminium have a long history [69], which dates back to the late 19th century. Thus, maintenance techniques and methods are available to carry out fast and efficient repairs compared to composites. In offshore wind turbines, for example, downtime due to failures in the steel tower usually account for less than 10 hours per failure, whilst at the same time, they have the lowest failure rate ($\lambda < 0.001$) [70]. In contrast, composite blade failures account, on average, for about 100 hours per failure, with a higher probability of occurrence ($\lambda > 0.01$).

Regarding surface degradation prevention, self-healing coatings for metals have been designed to reduce both corrosion and erosion rates [71]. In fact, the average corrosion rate reported for carbon steel is 0.2 mm/year [72]. Two potential alternatives to carbon steel, namely aluminium alloys and duplex stainless steel, are well known to be more corrosive resistant; therefore, they have lower maintenance requirements [68,73,74]. In contrast, composites are free from corrosion. However, composite blades can be subject to severe leading edge erosion [58,75], and it has been demonstrated that the erosive wear of GFRP composite is higher than that of CFRP composite [76]. In terms of metals, coating technology has been developed to prevent severe erosion in several industries, such as the marine sector.

Offshore maintainability is ranked in Table 11 based on the observations made in this section regarding industry experience, corrosion and erosion resistance, assuming the conceptual design stage of the hydrofoils of the lift-based WEC. In Table 11, industry experience is given a weight factor of 0.5, whilst corrosion and erosion resistance are given a weight factor of 0.25, respectively.

4.4. Cost of Manufacturing

Insights and trends in total manufacturing costs for lift-based WECs can be gained by studying several other industries. The aerospace sector, for example, is a mature sector that has recently explored the use of composites to lower manufacturing costs through lightweight, high-strength structures.

Similarly, a much younger sector, the tidal energy sector has shifted from using steel to composites. This transition has allowed for the production of highly complex blade shapes and has helped mitigate the inertia effects associated with large mass blades [77,78].

Within the wind turbine sector, the demand for large lightweight blades has driven the adoption of composite materials. Advances in composite manufacturing technology, particularly through techniques such as resin infusion [79], have established composites as the standard material for blade manufacturing. Notably, carbon fibre blades have gained prevalence over glass fibre composites due to their superior strength-to-weight ratio. Furthermore, while carbon fibre is more expensive, its lower mass helps offset the cost differential when compared to glass fibre blades [80].

In contrast, metals are still widely used in the oil and gas, maritime, and wave energy sectors. They are favoured for their ease of maintenance, relatively low raw material costs and well-established recycling methods. In comparison, waste treatment costs of composites are still high [81], although industry efforts are underway to reduce these expenses. Furthermore, innovative recycling approaches, where blade shapes are adapted for construction and where no chemical processes are involved, have emerged recently [82]. Additionally, given that recycled fibres are employed in limited volumes as a structural composite in several applications, their high cost also carries the greatest degree of unpredictability.

While the traditional primary factor for material selection has been the cost of raw materials, in Table 12, we employ waste treatment, raw materials, and embodied energy as criteria to assess the total manufacturing costs of our candidate materials. This approach allows for a comprehensive interpretation of the total manufacturing cost. Embodied energy costs in Table 12 are sourced from [83], whilst raw material costs are referenced from [84]. Waste treatment is assessed in a similar approach to recyclability, which is detailed in the following section. Energy usage, also referred to as embodied energy, is a significant factor in the manufacturing cost of a material. Therefore, it serves as an important indicator of the total manufacturing cost.

Table 12. Total manufacturing cost estimate for different materials, based on waste treatment, raw materials cost and energy usage costs, assuming the conceptual design stage. * True ratings for waste treatment are reversed. The resulting rankings for total cost are highlighted in bold.

	Waste Treatment *	Raw Material	Embodied Energy (MJ/kg)	Total Cost
Offshore steel (S355)	Low	Very low	Low	**Very low**
Offshore steel (Duplex 1.4462)	Low	Very low	Low	**Very low**
Aluminium alloy Al-Mg	Very low	Average	High	**Average**
Composite—CFRP	High	Very high	Very high	**Very high**
Composite—GFRP	High	High	Low	**Average**

Results of Table 12 show that based on the current state-of-the-art manufacturing processes, waste treatment techniques and raw material costs, CFRP is the most expensive material, while variations in offshore steel are the least expensive. Equal weighting is given to the criteria, and the conceptual design stage is assumed for Table 12.

The rankings of Table 12 may change over time. However, any modification to the components or manufacturing processes of a hydrofoil can lead to short-term cost increases, posing financial risks for developers, investors, and supply chains. It may also reduce the competitive advantage and confidence in product dependability gained through prior methods. In the long term, the economic benefits of manufacturing method alterations may become evident once the short-term effects have subsided. Therefore, the relative security of a well-established procedure must be balanced against the potential long-term benefits. Additionally, new methods or materials could be enforced through environmental regulations. However, developers who proactively adopt materials and processes with a reduced ecological impact have the opportunity to achieve cost reductions before such regulations are enforced.

4.5. Environmental Impact, Manufacturability and Recyclability

For the case of lift-based WECs, previous studies have considered offshore steel and composites as suitable material candidates [4–6,12]. However, no comprehensive environmental justification has been provided. Similar to the analysis performed in the previous sections, we can understand some of the environmental impacts of candidate materials by studying lessons from more established offshore sectors.

For example, numerous studies have been carried out to examine the life-cycle assessment and environmental impact of wind turbine blades [85–87]. Specifically, Liu and Barlow [83] showed that, regardless of the recycling process, the manufacturing stage of a typical wind turbine blade accounts for more than 96% of the whole blade life-cycle energy consumption, while transport and O&M account only for 1.6% and 1.7%, respectively, [83]. In particular, when the rotor assembly is performed at the quayside, the environmental impact of transport can be reduced even further [4,33,34].

In agreement with the findings of [83], Morini et al. [87] showed that wind turbine production and end-of-life (EoL) steps consume much energy and result in considerable pollution, including greenhouse gas emissions. Furthermore, most of the composite materials used for wind turbine blade manufacturing rely on fibres. These fibres include glass-fibre-reinforced polymers (GFRP) and carbon-fibre-reinforced polymers (CFRP), for which there currently needs to be satisfactory recycling routes [88,89].

To address this need, a parameter called "net impact" was introduced to measure the overall effect of a wind turbine blade on the environment, considering its lifetime impact, EoL impact, and recycling benefits. After analysing data and reviewing the literature, Refs. [88,90,91] showed that CFRP blades have twice the lifetime impact of GFRP blades. This includes the combined effect of manufacturing, transportation, and operation and maintenance (O&M).

In fact, GFRP composites have an improved circular economy than CFRP composites because they are made of recycled glass fibres and resin. This reduces the need for new raw materials and reduces waste [33]. Furthermore, GFRP composites can be melted down and reused to create new products. In contrast, CFRP is more challenging to recycle due to the strength and durability of the carbon fibres. Specifically, the CFRP recycling process involves separating the carbon fibres from the resin, which can be time-consuming and expensive.

Regarding the EoL impact and recycling benefit of composite blades, Liu et al. [88] considered different options: landfill, incineration, various recycling methods, and life extension from 2 to 10 years. After a thorough analysis, it was determined that the net impact of a CFRP blade is nearly 85% higher than that of a GFRP blade, considering a mechanical recycling process. However, in the case of chemical recycling, which is not available yet on a commercial scale, the net impact of a CFRP blade would only be 25% higher than that of a GFRP blade [88].

Notably, metallic materials for blades, aluminium alloy and steel are more recyclable than composites. Aluminium has advantages over steel due to its higher recycling rate, lower production energy requirements, and inherent reusability properties. However, metallic materials have higher terrestrial ecotoxicity, carcinogenic human health impacts, and greenhouse gas emissions than composites [78].

The observations presented in this section are summarised in Table 13. The candidate materials are evaluated in terms of their recyclability, human health (HH) impact and greenhouse gas (GHG) emissions. We assume a weight factor of 0.5 for GHG, 0.3 for HH and 0.2 for recyclability. Table 13 shows that the materials with the lowest possible environmental impact are offshore steel, both S355 and Duplex 1.4462, while the material with the highest environmental impact is composite CFRP.

Table 13. Environmental impact assessment. * True ratings of recyclability are inverted. The resulting rankings for total environmental impact are highlighted in bold.

Material	Recyclability *	HH Impact	GHG Impact	Total Impact
Offshore steel (S355)	Low	Very High	Low	**Low**
Offshore steel (Duplex 1.4462)	Low	Very High	Low	**Low**
Aluminium alloy Al-Mg	Very Low	High	Average	**Average**
Composite—CFRP	High	Very Low	Very high	**High**
Composite—GFRP	Average	Low	Average	**Average**

5. Results and Discussion

This section presents and discusses the results obtained by solving the multi-criteria decision-making problem regarding the material selection for the hydrofoils of a lift-based WEC. Three scenarios are evaluated: the conceptual design stage, the commercialisation stage and the future projection stage. Three scenarios with different technology readiness levels (TRL) are evaluated: the conceptual design stage (TRL 1–4), the commercialisation stage (TRL 5–8) and the future projection stage (TRL 9).

For this section, i.e., results and discussion, the candidate materials are offshore steel (S355), offshore steel (Duplex 1.4462), aluminium alloy Al-Mg, composite—CFRP and composite—GFRP. These materials are assessed for structural reliability, hydrodynamic efficiency, offshore maintainability, total cost and environmental impact, which were the criteria discussed previously in Section 4. The true ratings of total cost and environmental impact are reversed to solve the fuzzy TOPSIS algorithm.

Table 14 presents the results of the multi-criteria decision matrix used to select the best material candidate at the conceptual design phase. The qualitative weights are assigned for each criterion based on expert opinion, considering the importance of each criterion in this design phase. The ratings for each material candidate in all considered criteria are given in qualitative terms such as very high (VH), high (H), average (AV), low (L), and very low (VL). The terms VH, H, AV, L and VL are colour coded in dark green, green, yellow, orange and red, respectively. The same terminology is applied to the weighting factors. The results are obtained after applying the fuzzy TOPSIS multi-criteria decision algorithm, as described in Section 3.

For the conceptual design stage, results indicate that offshore steel (Duplex 1.4462) is the ideal material for hydrofoils of the lift-based WEC, with offshore steel (S355) also being a suitable choice. The weighting factors considered for the conceptual design phase favour the materials with high structural reliability and hydrodynamic efficiency. Specifically, offshore steel (Duplex 1.4462) has been a widely used material in the offshore oil and gas industry due to its good fatigue and ultimate tensile strength. Moreover, it exhibits good resistance to erosion and corrosion, resulting in minimal performance loss in terms of power production. These results can be found reasonable given that innovative solutions must first have the ability to fulfil their intended purpose under given environmental and operational conditions for a specific period of time, which is here encapsulated by criteria such as “structural reliability” and “hydrodynamic efficiency”.

Table 14. Results of fuzzy TOPSIS-based material selection for the hydrofoil component—Conceptual design phase (TRL1–TRL4).

	Weighting Factors					
	VH	H	L	AV	L	
Candidate/Criteria	Structural Reliability	Hydrodynamic Efficiency	Offshore Maintainability	Total Cost	Environmental Impact	Ranking
Offshore steel (S355)	H	H	AV	VH	H	0.845
Offshore steel (Duplex 1.4462)	H	H	H	VH	H	0.895
Aluminium alloy Al-Mg	AV	VH	VH	AV	AV	0.681
Composite—CFRP	H	AV	L	VL	L	0.316
Composite—GFRP	L	AV	VL	AV	AV	0.196

In contrast, CFRP is considered less favourable due to its higher cost and greater environmental impact, which outweigh its advantages in terms of structural reliability. Finally, the aluminium alloy emerges as a significant competitor to the offshore steel options. These results are in line with various experimental tests in the field of marine renewables [92–95], where the manufacturing of small-scale prototypes are fabricated in-house, typically within university or small research centre facilities. Hence, lowering the cost of the testing campaigns.

An important consideration is that the weighting factors applied to the decision-making process require more in-depth scrutiny as the project development of the lift-based WEC progresses. This is because as the TRL of the lift-based WEC increases, some risk aspects can be mitigated through design modifications and protection systems. Therefore, structural reliability would not have the same weighting. With further research and the development of larger-scale devices, uncertainties in the ratings are expected to be reduced. Consequently, the focus should shift to the cost of fabrication and environmental impact. This scenario is investigated in the present study by increasing the weighting factors of "total cost", "offshore maintainability", and "environmental impact" criteria. We refer to this stage as the commercialisation stage, as shown in Table 15.

Table 15. Results of fuzzy TOPSIS-based material selection for the hydrofoil component—commercialisation phase, current status.

	Weighting Factors					
	H	L	H	VH	AV	
Candidate/Criteria	Structural Reliability	Hydrodynamic Efficiency	Offshore Maintainability	Total Cost	Environmental Impact	Ranking
Offshore steel (S355)	H	H	AV	VH	H	0.837
Offshore steel (Duplex 1.4462)	H	H	H	VH	H	0.917
Aluminium alloy Al-Mg	AV	VH	VH	AV	AV	0.677
Composite—CFRP	H	AV	L	VL	L	0.248
Composite—GFRP	L	AV	VL	AV	AV	0.240

For the commercialisation scenario shown in Table 15, high-strength offshore steel (Duplex 1.4462) receives the highest rating, followed by offshore steel (S355) and the aluminium alloy. This ranking results from the prioritisation of overall cost and environmental impact, which is crucial for mass production of the lift-based WEC. Although the weighting factors differ between the commercialisation and the conceptual stages, the optimal material remains the same for both stages. This is because composites are considered more expensive, harder to maintain and have a higher environmental impact. In fact, these results are also in line with the materials used by some of the world's leading wave energy companies, such as Mocean Energy, which currently employs offshore steel for their device [96,97].

Finally, in addition to the analysed scenarios mentioned above, it is useful to consider a scenario that represents a future projection. This scenario can help us understand how material selection for the hydrofoil of the lift-based WEC can evolve in the future. To this end, the rating given for the candidates CFRP and GFRP are modified based on the assumption that they cost less and exhibit higher structural reliability due to the reduced uncertainty around their fatigue and ultimate strength characteristics. Furthermore, it is assumed that CFRP and GFRP are environmentally competitive with offshore steel and aluminium candidates.

It can be argued that decision makers will be more likely to prioritise more environmentally friendly solutions during intensive commercialisation activity. Therefore, the weighting factor regarding environmental impact could be increased relative to other criteria. Table 16 shows the modifications made for the weighting factors, the ratings of the candidate materials and the material selection rankings based on this future projection.

Table 16. Results of fuzzy TOPSIS-based material selection for the hydrofoil component—future projection.

	Weighting Factors					
	AV	L	AV	H	VH	
Candidate/Criteria	Structural Reliability	Hydrodynamic Efficiency	Offshore Maintainability	Total Cost	Environmental Impact	Ranking
Offshore steel (S355)	H	H	AV	AV	H	0.445
Offshore steel (Duplex 1.4462)	H	H	H	AV	H	0.574
Aluminium alloy Al-Mg	AV	VH	VH	AV	AV	0.357
Composite—CFRP	VH	AV	H	H	H	0.772
Composite—GFRP	H	AV	AV	H	H	0.555

In Table 16, it is evident that the difference between the composite and offshore steel solutions reduces significantly. In fact, the MCDM results show that in the future and under the right conditions, CFRP might even become a preferred choice over other materials. To make composite solutions competitive with offshore steel (S355) and (Duplex 1.4412) solutions, their cost must decrease significantly. Additionally, there is a great need for solutions to lower their environmental impact in terms of carbon footprint and recyclability in the realm of wave or tidal stream energy converters, as the lift-based WEC shares similarities between both technologies.

A summary of the trends identified in our analysis is presented in Figure 9. Figure 9 shows that the optimal material solutions change depending on the design stage of the lift-based WEC. While metals seem to be a more fit-for-purpose material during the early stages of concept design and commercialisation, it is likely that in the future, trends will change, and composites become a more suitable option for the hydrofoils of lift-based WECs.

It is important to highlight that the current results for material selection under different scenarios are in alignment with the current trends in materials used for offshore renewable structural components, such as tidal and wind turbines, requiring high structural reliability and minimal cost. Nevertheless, further research is required in the detailed design stage, looking at the overall cost of fabrication, hydrodynamic efficiency, analytical and experimental analysis in fatigue loading, and carbon footprint calculation considering construction in different locations.

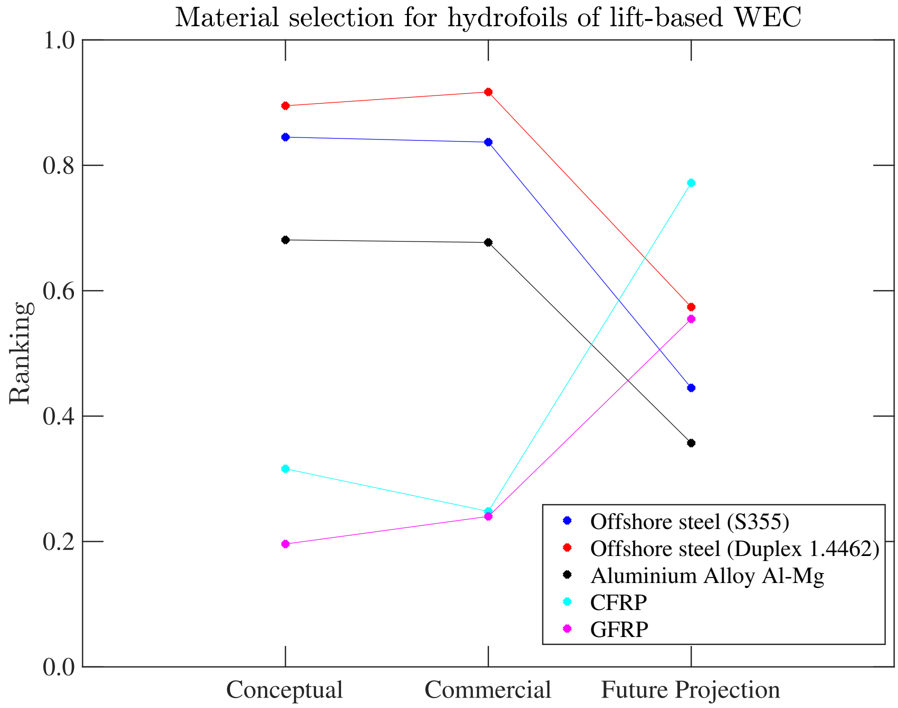

Figure 9. Rankings of materials for the hydrofoils of a lift-based WEC during three different design stages: conceptual, commercial and future projection stages.

Furthermore, the rankings of the key criteria presented in this work might vary subject to the team of experts and the assumptions made to assess each criterion. Nonetheless, this work focuses on developing a holistic methodology for the material selection of the structural components of a lift-based WEC, with the hydrofoils as a demonstrative case. Hence, the rankings presented are not definite answers; instead, they should be considered as representative examples to implement the material selection framework.

Future work could include the assessment of the structural reliability of materials through coupled structural hydrodynamic models [98], in which stress cycle counting is performed and fatigue is quantified to determine the material performance. Furthermore, the hydrodynamic model is to be expanded from single-point vortex representations to more advanced numerical methods, i.e., CFD or panel methods, in which surface roughness can be modelled.

Secondly, the robustness of the current methodology can be evaluated, as recommended in [99], with readily available comparison tools [100]. The use of different metrics, such as the weighted Spearman's rank correlation coefficient [18], could be implemented to compare multiple MCDM methods with the current proposed framework.

Lastly, the current methodology is planned to be benchmarked for different types of offshore marine renewables, particularly those operating with hydrofoils or blades. It is of interest to find out whether the optimal material selection varies depending on the mode of operation, i.e., floating, submerged, wave or tidal device.

6. Conclusions

Material selection frameworks for novel wave energy devices, where limited field data are available and multiple factors in performance are involved, must be developed in order to prolong the life of WECs, thereby helping to reduce their levelled cost of energy. However, the development of such frameworks is currently missing in the literature for most types of WECs.

To address this research gap, the present work introduced a multi-criteria decision-making material selection framework for lift-based WECs, specifically with the demonstrative case of the hydrofoils of the device. Different criteria were considered to assess the appropriateness of different materials, namely structural reliability, hydrodynamic efficiency, offshore maintainability, total manufacturing cost and environmental impact. To deal with the uncertainty and the novelty of the task, a fuzzy TOPSIS technique was applied to determine the ranking of each criterion and then to determine the ranking of each candidate material for the hydrofoils.

Three scenarios were considered to evaluate the applicability of the material selection framework: conceptual, commercialisation and future projection stages. In the conceptual stage, results indicated that high-strength offshore steel was the ideal material due to its high structural reliability and hydrodynamic efficiency. Similarly, high-strength steel remained the top-rated material during the commercialisation stage. However, in the commercialisation stage, it is expected that ease of maintenance, overall cost, and a reduced environmental impact become more important considerations. Therefore, other reasonable alternatives could be offshore steel (S355) or aluminium alloy solutions.

In the future projection stage, the multi-criteria decision analysis was performed under the assumption that composite solutions, such as CFRP and GFRP, would decrease in total cost and become more environmentally friendly. In this scenario, CFRP emerges as a favourable solution. Hence, for composites to compete with steel solutions, significant cost and carbon footprint reduction methods are imperative.

While the rankings and assumptions used in this work to assess each of the key criteria can vary depending on the team of experts or TRL level of the lift-based WEC, the development of multi-criteria decision-making tools for lift-based WECs, and for any other WEC, is essential and currently missing in the literature. Hence, as lift-based WEC technology approaches a commercial readiness level, it is envisioned that this type of analysis becomes an accompanying tool to minimise the risk of mechanical failure through appropriate material selection.

The novelty of the presented framework lies in the adaption of a well-established multi-criteria decision-making method, i.e., fuzzy TOPSIS, to the unexplored field of material selection of lift-based WECs, with an application case of the hydrofoils. Key criteria relevant to the hydrofoils of the hydrofoils of lift-based WEC were identified and assessed through expert opinion. The assessment of these criteria is unique and novel for this type of device since this exercise has not been carried out previously. The team of experts, the selection of fuzzy logic and the failure mode, effect and criticality analysis account for the fact that there is a limited set of field data for lift-based WECs, and therefore, the proposed approach allows for a flexible and robust assessment of the key material selection criteria for the hydrofoils of the lift-based WEC. The presented results are not final but a demonstration of the applicability of this methodology to the material selection of the hydrofoils of lift-based WECs. However, the methodology is not limited to this example but is applicable and adaptable to the wider field of marine renewable, particularly those that also operate with hydrofoils or blades.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en16217324/s1, Figure S1: Action Priority Tables used in FMECA assessment; Table S1: Fuzzy TOPSIS implementation example "conceptual design".

Author Contributions: Conceptualization, A.A.-G., B.Y., F.A. and S.L.; formal analysis, A.A.-G., B.Y., F.A. and S.L.; writing—original draft preparation, A.A.-G.; writing—review and editing, A.A.-G., B.Y., F.A., S.O.-S., S.L. and F.B.; Funding acquisition, F.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Union's Horizon 2020 Research and Innovation Programme, which funded this project under Grant Agreement No. 851885.

Data Availability Statement: Data are contained within the article or Supplementary Material.

Acknowledgments: The authors would like to thank all the members of the LiftWEC consortium for the fruitful discussion and input that has made this work possible. We would also like to thank the European Union's Horizon 2020 Research and Innovation Programme, which funded this project under Grant Agreement No. 851885.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AP	Action priority
FMEA	Failure Mode and Effect Analysis
FMECA	Failure Mode, Effect, and Criticality Analysis
GFRP	Glass fiber reinforced polymer
CFRP	Carbon fiber reinforced polymer
GHG	Greenhouse gas
VH	Very high
H	High
AV	Average
L	Low
VL	Very low
HATT	Horizontal axis tidal turbine
HH	Human Health
MCDM	Multi-criteria Decision-Making
O&M	Operation and maintenance
OPEX	OPerational EXpenditure
PTO	Power Take-off
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TRL	Technology readiness level
VATT	Vertical axis tidal turbine
WEC	Wave Energy Converter

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