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Design and Selection of Paddle Materials for High-level Rowing Competition Applications Using Multi-Criteria Decision Analysis

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Abstract

The study evaluated a variety of material alternatives including wood, bamboo, carbon fiber reinforced polymer (CFRP), and ceramics for use in high-performance paddleboard. The selection process considers factors such as strength, density, cost, and durability with a focus on the most relevant material criteria for the product. The weighted addition method is used to evaluate and rank several alternative materials that have been selected based on these criteria. Wood and bamboo are chosen for their sustainability, CFRP for their superior strength-to-weight ratio, and ceramics for their resistance to extreme conditions. The study found that CFRP had the highest score of around 85.40 due to its superior strength and lightweight. The framework proposed in this study could provide tools for rowing teams to optimize paddle materials so that they offer the potential for increased speed and performance in the competition.

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Introduction

The performance of paddle materials in high-level rowing competitions plays a crucial role in determining an athlete's speed and competition outcomes. However, wood is still the most widely used material in the construction of paddles [1], [2]. Determining the most suitable material for the paddle is a challenge that exists in the manufacturing process, this is because each material has its characteristics and limitations. For example, carbon fiber materials have advantages such as being strong and lightweight, but this material requires advanced manufacturing technology and is relatively expensive [3]. In addition, fiberglass materials are not able to provide the same strength and rigidity as more affordable materials such as carbon fiber [4]. Paddle applications require standard materials such as carbon fiber reinforcement polymer (CFRP) because this material has advantages such as lightweight and high durability. In addition, it is also necessary to consider the use of alternative materials from Indonesia such as bamboo which has a sustainable and easy-to-find characteristic profile, but more research is needed to see how the characteristics of this material are suitable to be used as a paddle product. The properties of CFRP are perfect for improving athlete performance while demanding repetitive rowing cycles. Evaluating and identifying various alternative materials is the main point to be considered comprehensively both from a technical and non-technical perspective. Conventional methods also often fail to handle the complexity and multidimensionality of the right material selection criteria. Therefore, it is necessary to have a solution that can accommodate various factors interacting with each other in making appropriate material decisions. Multi-criteria decision analysis (MCDA) emerged as an effective solution to the above problems.

MCDA is a technique used in identifying, evaluating, and prioritizing how alternative materials are selected based on predetermined criteria. In this study, techniques such as rating and lightweight are the main criteria for assessing materials. In addition, MCDA also assesses how other material criteria have been determined by manufacturers in making a product. For example, the criteria of modulus of elasticity, corrosion resistance, strength, and cost. This technique also provides a practical, systematic, and objective study in evaluating and ranking which material criteria are more dominant for a product to help manufacturers make the right and more careful decision [5]. Various existing studies have examined how MCDA is chosen as the right method to evaluate material selection [6-12].

Research conducted by Kumar (2021) has identified and evaluated how MCDA methods such as the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) have successfully assessed hybrid bio composite materials. The results show the importance of combining thermoset fibers and polymers in mechanical strength performance [6]. In addition, other MCDA methods such as the two-tuple linguistics method managed to identify improvements in precision in overcoming information loss and handling qualitative data for the proper material selection itself [7]. In addition, research conducted by Chidambaram et al. (2022) provides a new overview of one of the existing methods in MCDA such as the Weighted Product Method (WPM) in evaluating material preferences based on specific strength and corrosion resistance criteria. In this method, the importance of accurate ranking in selecting materials is emphasized [8]. The selection of materials that have various combinations of criteria in product design such as paddle is chosen plastic material because it is to facilitate the selection process [9]. Research conducted by Simskus et al. (2020) using MCDA methods such as Quality Function Deployment (QFD) succeeded in identifying important and optimal parameters in the design of paddle products for sprint rowing competitions [10]. In addition, the technique of combining six MCDA algorithms in selecting suitable materials was developed in a hybrid model. The results of the study show that the existence of various algorithm methods can have integrated results, and the reliability of material selection results can be improved [11]. Other MCDA methods such as the Simple Ranking Procedure (SRP) are carried out with a simple ranking method where this method covers more normalization steps. One of the mistakes of the MCDA method is that there is no normalization in the existing material selection process because manufacturers often eliminate this technique. Different from previous research, this technique uses a criterion weighting method so that by integrating this advanced method with other MCDA methods such as TOPSIS and two-tuple linguistics can identify and evaluate more deeply in determining the appropriate material criteria [12].

This study aims to evaluate and identify the most suitable and appropriate materials for paddle construction design comprehensively according to various material criteria given and analysed through the MCDA method. The MCDA method analysis integrates the most effective approaches to generate material recommendations. Various criteria factors are made to interact with each other regarding the material, characteristics and how those criteria are involved in making MCDA technical decisions in paddle products. This research can indirectly contribute significantly to designing and selecting the right materials for sports competition products such as rowing.

Methods

The MCDA method was chosen because of its systematic, practical, and structured approach that involves several important steps. This method can start by identifying what material criteria are best suited to the paddle product. As a result, eight criteria have been identified for materials that are designed accordingly such as 1) strength, 2) modulus of elasticity, 3) fracture toughness, 4) durability, 5) cost, 6) density, 7) corrosion resistance, and 8) thermal and UV stability. This material criterion was chosen because it is directly related to two important segmentations both product and the athlete. In terms of products, it is very important to resist the repetitive cycles that exist in competitions so that it is suitable for material criteria such as strength and endurance while in terms of athletes, lighter weights can increase the speed and efficiency of athletes. In addition, considering costs is also efficient in balancing budget efficiency with product performance. Pre-defined criteria are essential to ensure that the paddle product is made to offer the performance and durability currently required in rowing competitions [13]. The analysis of the identified material criteria determines the importance of which criteria first match the product [14].

Materials that are selected appropriately and carefully are carried out using MCDA methods such as the Weighted Sum Method (WSM) which combines objective and subjective criteria in helping the identification process of decision-making [15]. The weights in each criterion are determined based on the author's analysis by comparing the material characteristics with each other so that in this case each criterion has a dialogue. This approach ensures that each criterion is measured based on the impact that is most suitable for the performance of the paddle. In addition, alternative materials such as wood, bamboo, and CFRP were chosen because of their prevalence in the market that is already widely circulated and has been used as a suitable material in the production of paddles for rowing competitions. In the next step, the performance of each material is analysed through software-based simulations and literature reviews from previous studies. After that, the selected material is validated using the preference value of the material criteria. If the material criteria are needed, it is given the notation "1", if it is not needed, it is given the notation "0". Next, several alternative materials are ranked based on the results of decision calculation. Materials that have a higher value are the best. By combining this structured methodology, the material selection process in rowing can produce the optimal performance and durability required in high-level rowing competitions. The measurement of criteria in the MCDA process is performed using software "material selection software", rather than physical testing. The software simulates material characteristics such as strength and modulus of elasticity based on predefined parameters and data from validated material databases. These simulations are used to assess material performance in the MCDA framework. This method provides accurate results without the need for physical laboratory equipment.

Result and Discussion

Requirements Shape How Something Functions and Function Shapes its Form

The paddle design is a perfect example of the principle that "the requirements form a function, and function determines its shape," as seen in Figure 1. The invention and evolution of paddle design can be considered a technical and mechanical marvel. Several references, such as engineering journals, explain the basic principles of designing components such as paddles that are closely related to lightweight, high strength, and high elastic modulus requirements. In this case, the materials used in paddle production are usually made of fiberglass and carbon fiber. The material was chosen because it offers a unique combination of strength and elastic modulus without increasing the product's weight [5]. The primary function of the paddle is to transfer power from the paddler to the water efficiently; to achieve this, the paddle must have a specially designed shape. For example, a curved or spoon-shaped paddle design increases the surface area in contact with water, allowing for more efficient force transfer with each stroke. The ergonomic design of the paddle handle is also optimized to ensure the comfort and efficiency of the rower during long competitions [16]. Uzan et al. (2021) [5] discuss the evolution of paddle materials in competitive sports, focusing on innovations like carbon fiber composites. Meanwhile, Dean (2000) [16] provides a comprehensive analysis of the mechanical properties of modern paddle materials, comparing their tensile strength and fatigue resistance.

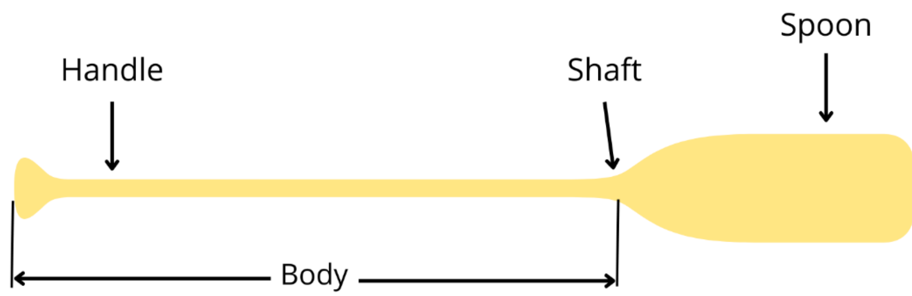

Figure 1. The paddle product is a functional unit.

Paddle products can be broken down into more specific functional units. Rowing generally consists of three main components: (1) Handle, (2) Body, (3) Spoon. Each functional unit of the paddle design, from material selection to its shape, is tailored to its functional needs. These technical requirements determine paddle performance and shape evolving design innovations. For example, oval oars of carbon composite material offer great torsion strength and are lightweight, providing a stable, firm handle and allowing angle adjustment based on product mechanics. This fundamental principle of design ensures that the specific needs of athletes dictate the functionality, which in turn influences the overall shape and construction of the paddle and is evident in every stage of rowing material development. The effectiveness of paddle design in competitive rowing comes from specific factors such as the optimized weight distribution, which reduces fatigue, and the spoon-shaped blade, which maximizes water contact for better propulsion. Continuous research and development in this field resulted in increasingly sophisticated designs and made modern rowing the perfect combination of art, engineering, and science [17].

Converting Design Needs into a Set of Criteria for Selecting Materials

Converting design requirements into criteria for material selection is an essential step in the paddle design process. The design conversion process can be seen in Figure 2. Figure 2 shows the process of transforming design requirements into a set of criteria for material selection. This diagram illustrates how the design requirements (constraints and objectives) as well as material data (attributes and documentation) are processed through a 'selection engine' that includes screening, ranking, and documentation to arrive at the final material selection. The chosen material criteria must withstand massive loads and have a sufficient modulus of elasticity to effectively transfer energy from the rower, thereby improving its performance during rowing. The carbon fiber selected based on previous journals offers a unique combination of lightweight and very high strength, making it an important player in rowing competitions [17], [18], [19]. Carbon fiber offers an excellent strength-to-weight ratio so it can allow athletes to generate more power with less effort while maintaining structural integrity even under repetitive stress.

The material selection process is obtained based on the appropriate product specification. This process is then translated into target values or limits in determining the appropriate material. Parameters that play an important role in paddle products to consider include modulus of elasticity, strength, and lightweight. In this study, material criteria refer to specific performance requirements that must be met by the material such as weight and strength criteria while material properties refer to the characteristics inherent in the material itself such as elasticity and tensile strength criteria. After making a list of material criteria needed in rowing products, then these criteria are evaluated based on their ability to meet the desired product specifications. This existing approach allows an engineer to screen materials that fail to meet standards and requirements to achieve the optimal combination of desired properties [20]. The material selection process involves cost, environmental, and material factors that must be economical to produce [21], [22]. Materials such as carbon fiber have a higher carbon footprint in the manufacturing process however, they offer superior performance. On the other hand, materials like bamboo are more environmentally friendly because they can be renewed and recycled. Therefore, material selection decisions must consider the balance between technical performance and environmental impact. A systematic methodology in material selection ensures that every step in the process is well documented so that decisions can be traced and re-evaluated if necessary. For example, Ashby showed that material selection can be optimized by using material property graphs to display materials that meet criteria on relevant axes of material properties. Design requirements for paddles can be seen in Table 1 [23]. Table 1 presents the design requirements for the paddle that focuses on strength and stiffness. The goal is to minimize mass while considering independent variables such as shaft diameter and material selection where it aims to meet the functional demands of the paddle.

Table 1. Design Requirements for the Paddle

Design Requirements		
Function	Objective	Free Variable
Strength	Minimize the mass m	Shaft diameter
Stiff beam (square)		The choice of material
Meaning light		

To provide a clear illustration, the author will limit the discussion to the handle and spoon, which transmit strength and resistance to the handle, and the hydrodynamic efficiency of the spoon [24],

[25]. When transmitting its strength, durability, and maintaining durability, the material must meet several requirements: 1) It must be strong to withstand force without breaking, 2) it must be rigid enough for energy transmission, 3) it must be resistant to cracks and damage, 4) it must be resistant to wear and damage, 5) it must have a suitable length, 6) it must be light to improve performance, 7) it must be resistant to corrosion, 8) must have an attractive appearance, 9) must be resistant to temperature changes and UV radiation. Tables 2 and 3 show how these material criteria translate into requirements for application in paddle products.

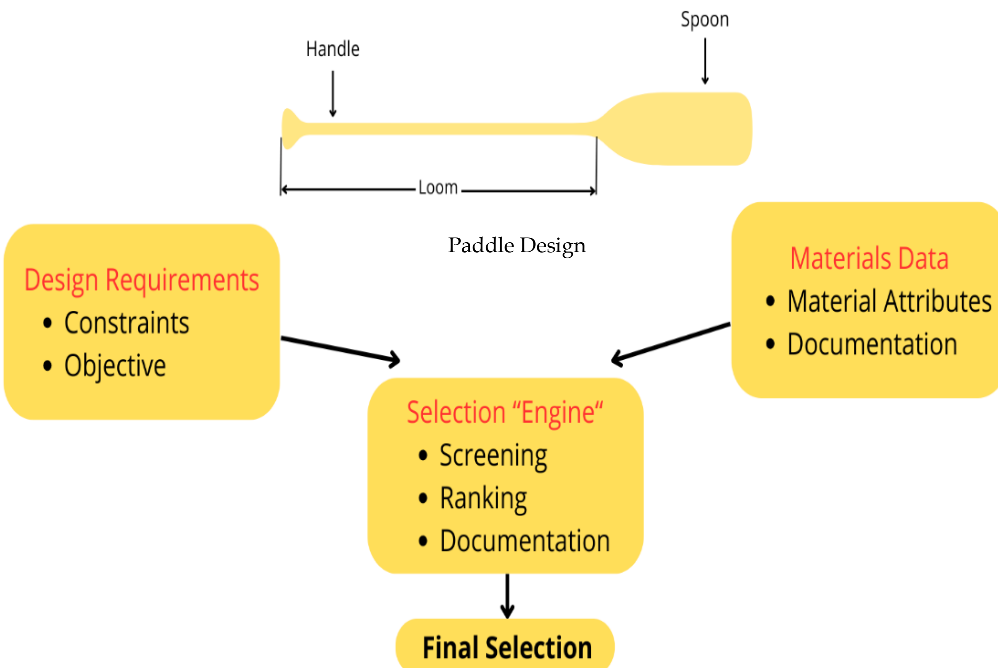

Figure 2. Converting Design Needs into a Set of Criteria for Selecting Materials.

Composite materials such as carbon fiber are selected for paddle design. This material was chosen because it meets the criteria for material properties such as modulus of elasticity and strength, enabling a lighter-weight and more responsive paddle fabrication process. The selected carbon fiber material can also reduce fatigue during competition and increase the rower's speed efficiency when competing. A structured, rational, and careful approach to material selection ensures that the resulting paddle design and fabrication process meets the specifications required to support performance under planned conditions of use [26].

Handle and Spoon Geometry

The design of the handle and spoon in the paddle are two critical components that determine the rower's efficiency and comfort when using the paddle. The handle part determines how comfortable the handle is. It is designed to provide comfort and safety [27]. At the same time, the spoon part must ensure that the power transfer process to the rower can work optimally to provide the appropriate speed during rowing. Selecting suitable materials and ergonomic design plays a crucial role in improving performance and reducing the risk of injury for rowers. The following analysis will discuss various aspects of handle and spoon design, including the handle trajectory, handle techniques, paddle force, and innovations in handle design. This research includes studying the evaluation and efficiency of the force generated during rowing. Handle and spoon analysis can be seen in Figure 3.

Table 2. The Essential Criteria for Selecting Materials Handle and Spoon Paddle

No.	Criteria of Materials	Constraints	Material of properties
1.	Strength	Must be able to withstand force without breaking	Strength, Stiffness
2.	Modulus of elasticity	It must be rigid enough for energy transmission	Young's Modulus
3.	Fracture toughness	Must be aware of cracks and damage	Fracture Toughness
4.	Durability	Must withstand wear and impact	Wear Resistance, Hardness
5.	Density	It must be lightweight to improve performance	Density
6.	Corrosion resistance	Must be resistant to corrosion	Corrosion resistance
7.	Cost	Must be able to have an efficient and economical cost	Finish Quality
8.	Thermal and UV Stability	Must be resistant to temperature changes and UV radiation	Thermal Stability, UV Resistance

The paddle handle is usually oval with a transverse profile that is wider horizontally than vertically to provide a more ergonomic handle. These handles can generally be made of wood and then designed to be removable and reassembled. Trajectory analysis of the handle is used to assess the user's rowing technique and fatigue. Measurements were made using the Vicon motion capture system. The results showed that fatigue can be indicated by the increased stroke time and decreased handle speed. Assessors evaluate rowing techniques based on the handle's position within specified limits, the area the handle trajectory covers outside the specified range, the timing of improper rowing techniques, and the handle's slope [28]. Analysis of the forces acting on rowing movements with two types of handles in the semi-prone position resulted in a greater force output than regular handles so that the speed performance of the rowing paddles could move optimally. The handle technique also influences rowing efficiency. The paddle force-angle measurement system evaluates paddle performance on water. This system provides innovative and valuable information for rowers that can help improve performance by providing accurate data on rowing angle and force [29]. A handle for a sculling paddle has a truncated elliptical profile with finger grooves running diagonally along the tubular body. This helps facilitate the paddle by providing a more ergonomic and comfortable handle [30].

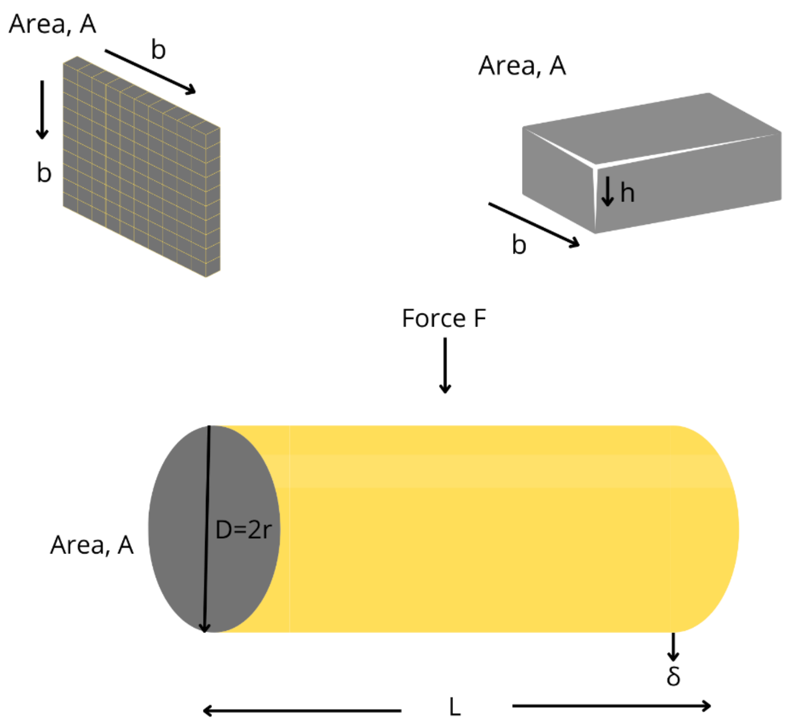

Figure 3. Handle and Spoon Geometry.

Performance Analysis

The performance evaluation of paddle design and material selection in bearing the load is fundamental to analysing. In the context of water sports, the handle and spoon are crucial components that directly affect the efficiency and speed of the boat. Therefore, understanding the various factors that affect rowing performance is critical. This analysis covers aspects such as the paddle's geometry design, the material's characteristics, and how the combination of the two can affect the overall performance [31], [32], usually referred to as the material index. Reference references have widely discussed the general steps for determining the material index [23] which can be seen in Equations (1) to (3).

Material performance indications are determined based on the primary function and selected critical constraints. These functions and constraints can be expressed as two stiffness formulas and one strength formula:

$$M_1 = \frac{E^{1/2}}{\rho} \quad (1)$$

The second Material Index can be defined as:

$$M_2 = \frac{E^{1/3}}{\rho} \quad (2)$$

The Third Material Index can be defined as:

$$M_3 = \frac{{\sigma_f}^{2/3}}{\rho} \quad (3)$$

Critical Criteria Analysis

In the material selection and adjustment process, material criteria for rowing include cost, mechanical properties, and sustainability. An engineer must be able to design what considerations must be considered when designing a product. The mechanical characteristics of the material, such as modulus of elasticity and strength, and cost implications determine the most selected material for rowing [33]. Modulus of elasticity refers to a material's ability to deform under stress, an important factor in ensuring the paddle can flex without breaking under heavy loads. 'Massive loads' in this context refer to the repeated forces exerted on the paddle during competitive rowing strokes. Some material characteristics in the handle and spoon of the paddle have been discussed earlier in Tables 1 and 2. The conceptual design stage is crucial because improper design can lead to extensive rework and production problems [34], [35]. Effective conceptual design involves thoroughly assessing design solutions to meet product design specifications [36]. Additionally, the fabrication method and materials used play an important role in the design of the paddle. Material perception and user-centered design require critical provision of materials to meet product requirements [37].

The digital logic decision matrix method is an effective tool to overcome the weighting of complicated criteria. This method makes decisions by comparing two criteria simultaneously to reduce complexity [38], [39]. More specific material selection and appropriate databases can improve decision-making in the evaluation matrix. Remember that all qualitative criteria must be converted into numbers, and all data must be normalized before making numerical decisions. The results showed a selection of materials suitable for paddles: bamboo, wood, CFRP, and ceramics [23].

Tables 3 and 4 show the weighting criteria for material components, namely the handle and spoon on the paddle using the digital logic method. Each criterion of the existing material is compared in a matrix. The value "1" is defined as a preference for material criteria that are more needed in the product, while the value "0" states the opposite definition [40]. This process is repeated for each pair of material criteria. Equation (4) is the equation used to determine the weight of each criterion on the material.

$$\text{Weight } (\alpha) = \frac{\text{unit positive decision } (+)}{\textit{Total positive decision}} \tag{4}$$

In Table 3, the most important criterion for the paddle handle is Strength, with the highest weight of 0.25, followed by the modulus of elasticity, 0.21. Then, durability, with a weight of 0.14. Fracture Toughness and Corrosion resistance weigh 0.11 each, while Density and Thermal and UV Stability each have a lower weight of 0.07. Cost has the lowest weighting of 0.04. In Table 4, which weight the material criteria for paddle spoons, strength remains the most critical criterion with the same weight of 0.25, followed by the modulus of elasticity with a weight of 0.21. Fracture toughness and corrosion resistance: Each criterion has a higher weight, 0.14. This weighting shows a significant improvement compared to the paddle handle. Thermal and UV stability and density have lower weighting criteria of 0.04 and 0.07, respectively. Durability and cost are important criteria, with weights of 0.11 and 0.04. The main difference between the two tables is that the durability and fracture toughness criteria are prioritized for paddle spoon products compared to paddle handles. The modulus of elasticity and strength remain the most critical criteria in both components, but the spoon paddle shows the importance of the requirements of durability and toughness.

Table 3. Weighting of Material Criteria for Handle Paddle Using the Digital Logic Method

Criteria (n)	1	2	3	4	5	6	7	8	+	Weight (α)
Strength-1		1	1	1	1	1	1	1	**7**	**0.25**
Modulus of elasticity-2	0		1	1	1	1	1	1	**6**	**0.21**
Fracture toughness-3	0	0		0	0	1	1	1	**3**	**0.11**
Durability-4	0	0	1		1	1	0	1	**4**	**0.14**
Density-5	0	0	1	0		0	1	0	**2**	**0.07**
Corrosion resistance-6	0	0	0	0	1		1	1	**3**	**0.11**
Cost-7	0	0	0	1	0	0		0	**1**	**0.04**
Thermal and UV Stability-8	0	0	0	0	1	0	1		**2**	**0.07**
Total positive decision (n(n-1)/2)									**28**	**1.00**

Tables 5 and 6 show the four materials evaluated: Bamboo, Wood, CFRP, and Ceramics for paddles. CFRP has the highest power of 1500 MPa, followed by ceramics, which has 300 MPa. Bamboo and wood have lower strengths, 125 MPa, and 90 MPa, respectively. Bamboo and wood have a low modulus of elasticity values of 20 GPa and 12 GPa, respectively. The highest modulus of elasticity was found in ceramics (400 GPa). Ceramics performed poorly on the fracture toughness criterion, while CFRP performed very well. The durability of ceramics and CFRP is better than that of bamboo and wood. Ceramic has a higher weight, while bamboo has a lower weight. Ceramics and CFRP have better corrosion resistance, followed by wood and bamboo. In terms of cost, bamboo is cheaper, while CFRP is more expensive. CFRP is the material that has the highest thermal and UV stability, while wood is considered acceptable.

Table 4. Weighting of Material Criteria for Spoon Paddle Using the Digital Logic Method

Criteria (n)	1	2	3	4	5	6	7	8	+	Weight (α)
Strength-1		1	1	1	1	1	1	1	**7**	**0.25**
Modulus of elasticity-2	0		1	1	1	1	1	1	**6**	**0.21**
Fracture toughness-3	0	0		1	1	0	1	1	**4**	**0.14**
Durability-4	0	0	0		1	1	0	1	**3**	**0.11**
Density-5	0	0	0	0		0	1	1	**2**	**0.07**
Corrosion resistance-6	0	0	1	0	1		1	1	**4**	**0.14**
Cost-7	0	0	0	1	0	0		0	**1**	**0.04**
Thermal and UV Stability -8	0	0	0	0	0	0	1		**1**	**0.04**
Total positive decision (n(n-1)/2)									**28**	**1.00**

Table 5. Scaling β values for each material option of the handle paddle

Criteria	α	Bamboo (β)	Wood (β)	CFRP (β)	Ceramics (β)
Strength-MPa	0.25	125	90	1500	300
Modulus of elasticity – GPA	0.21	20	12	250	400
Fracture Tougness – Mpa $(m)^{1/2}$	0.11	Fair	Good	Excellent	Poor
Durability	0.14	Acceptable	Good	Excellent	Excellent
Density – g/cm^3	0.07	0.80	0.90	1.60	6.0
Corrosion Resistance	0.11	Acceptable	Good	Excellent	Excellent
Cost	0.04	Acceptable	Good	Poor	Acceptable
Thermal and UV stability	0.07	Acceptable	Acceptable	Excellent	Excellent

Tables 5 and 6 present the scale of values (β) for various material choices on paddle handles and spoons based on quantitative values obtained from material standard values (ASTM) and qualitative values obtained based on the analysis of the range of values provided by the authors. The range of values consists of; "0" is defined as unacceptable; "20" which is defined as Poor; "40" which is defined as Fair; "60" which is defined as Acceptable; "80" which is defined as Good; and "100" is defined as Excellent. These values are reanalysed using Equations (5) and (6), where orange is the material criterion that must be maximized, green is the material criterion that must be minimized, and then normalized values as in Tables 7 and 8. The criteria evaluated include Strength, Modulus of Elasticity, Fracture Toughness, Durability, Density, Corrosion Resistance, Cost, and Thermal and UV Stability.

$$\beta = \frac{numerical\ value\ of\ property}{largest\ value\ in\ the\ list} \text{ X } 100 \quad (5)$$

$$\beta = \frac{lowest\ value\ in\ the\ list}{numerical\ value\ of\ property} \text{ X } 100 \quad (6)$$

Table 6. Scaling β values for each material option of the spoon paddle

Criteria	α	Bamboo (β)	Wood (β)	CFRP (β)	Ceramics (β)
Strength-MPa	0.25	125	90	1500	300
Modulus of elasticity – GPA	0.21	20	12	250	400
Fracture Tougness – Mpa $(m)^{1/2}$	0.14	Fair	Good	Excellent	Poor
Durability	0.11	Acceptable	Good	Excellent	Excellent
Density – g/cm^3	0.07	0.80	0.90	1.60	6.0
Corrosion Resistance	0.14	Acceptable	Good	Excellent	Excellent
Cost	0.04	Acceptable	Good	Poor	Acceptable
Thermal and UV stability	0.04	Acceptable	Acceptable	Excellent	Excellent

Table 7. Normalization scaling β values for each material option of the handle paddle

Criteria	α	Bamboo (β)	Wood (β)	CFRP (β)	Ceramics (β)
Strength-MPa	0.25	8.30	6.00	100	20.0
Modulus of elasticity – GPA	0.21	5.00	3.00	62.5	100
Fracture Tougness – Mpa $(m)^{1/2}$	0.11	40.0	80.0	100	20.0
Durability	0.14	60.0	80.0	100	100
Density – g/cm^3	0.07	100	88.9	50.0	13.3
Corrosion Resistance	0.11	60.0	80.0	100	100
Cost	0.04	60.0	80.0	20.0	60.0
Thermal and UV stability	0.07	60.0	60.0	100	100

Table 8. Normalization scaling β values for each material option of the spoon paddle

Criteria	α	Bamboo (β)	Wood (β)	CFRP (β)	Ceramics (β)
Strength-MPa	0.25	8.30	6.00	100	20.0
Modulus of elasticity – GPA	0.21	5.00	3.00	62.5	100
Fracture Tougness – Mpa $(m)^{1/2}$	0.14	40.0	80.0	100	20.0
Durability	0.11	60.0	80.0	100	100
Density – g/cm^3	0.07	100	88.9	50.0	13.3
Corrosion Resistance	0.14	60.0	80.0	100	100
Cost	0.04	60.0	80.0	20.0	60.0
Thermal and UV stability	0.04	60.0	60.0	100	100

Tables 9 and 10 present scale and normalization (γ) calculation results for various material choices on paddle handles and spoons. The value of γ obtained using Equation (7).

$$(\gamma) = (\alpha) * (\beta) \tag{7}$$

Where,

α: Weight; β: The normalized value of material choice.

Table 9. The calculation for scaling and normalization results of the handle paddle

Criteria	Weight, α	Bamboo		Woods		CFRP		Ceramics	
		β	γ	β	γ	Β	γ	β	γ
Strength-1	0.25	8.30	2.07	6.00	1.50	100	25.0	20.0	5.00
Modulus of elasticity-2	0.21	5.00	1.05	3.00	0.63	62.5	13.1	100	21.0
Fracture toughness-3	0.11	40.0	4.40	80.0	8.80	100	11.0	20.0	2.20
Durability-4	0.14	60.0	8.40	80.0	11.2	100	14.0	100	14.0
Density-5	0.07	100	7.00	88.9	6.22	50.0	3.50	13.3	0.93
Corrosion resistance-6	0.11	60.0	6.60	80.0	8.80	100	11.0	100	11.0
Cost-7	0.04	60.0	2.40	80.0	3.20	20.0	0.80	60.0	2.40
Thermal and UV Stability -8	0.07	60.0	4.20	60.0	4.20	100	7.00	100	7.00
Total	**1.00**		**36.1**		**44.5**		**85.4**		**63.5**

Table 10. The calculation for scaling and normalization results of the spoon paddle

Criteria	Weight, α	Bamboo		Woods		CFRP		Ceramics	
		β	γ	β	γ	β	γ	Β	Γ
Strength-1	0.25	8.30	2.07	6.00	1.50	100	25.0	20.0	5.00
Modulus of elasticity-2	0.21	5.00	1.05	3.00	0.63	62.5	13.1	100	21.0
Fracture toughness-3	0.14	40.0	5.60	80.0	11.2	100	14.0	20.0	2.80
Durability-4	0.11	60.0	6.60	80.0	8.80	100	11.0	100	11.0
Density-5	0.07	100	7.00	88.9	6.22	50.0	3.50	13.3	0.93
Corrosion resistance-6	0.14	60.0	8.40	80.0	11.2	100	14.0	100	14.0
Cost-7	0.04	60.0	2.40	80.0	3.20	20.0	0.80	60.0	2.40
Thermal and UV Stability -8	0.04	60.0	2.40	60.0	2.40	100	4.00	100	4.00
Total	**1.00**		**35.5**		**45.1**		**85.4**		**61.1**

In Table 9, CFRP shows the highest score of 85.4, which indicates superior performance across all criteria. CFRP excels primarily in strength (25.0), fracture toughness (11.0), and durability (14.0) despite having a low value in cost (0.80). Ceramics have excellent performance with a total score of 63.5, where the material shows the best criteria for corrosion resistance and modulus of elasticity. Still, they have low cost and fracture toughness. Bamboo and wood had total scores of 36.1 and 44.5, respectively. Bamboo's weakness shows significant fracture toughness and elastic modulus. Material evaluation for spoon paddles also shows similar results in Table 10, where CFRP again dominates with a total score of 85.4, which shows appropriate criteria for paddles in terms of durability, modulus of elasticity, and strength. The ceramic has a total score of 61.1 and is superior in corrosion resistance and modulus of elasticity but inferior in fracture toughness and cost. Bamboo and wood had scores of 35.5 and 45.1, respectively, with similar weaknesses in Table 9 for paddle handles.

CFRP is a suitable material from these two tables for the components discussed, such as the handle and spoon on the paddle. This material is superior in fracture toughness, durability, and strength. Ceramic also shows performance following product specifications, but its weakness is fracture toughness, making it less ideal for use than CFRP. While CFRP is preferred because its strength-to-weight ratio is identified as superior. Other alternative materials such as fiberglass and aluminium can still be used in some of these product designs, but they have the same strength and fatigue resistance, making CFRP preferable for high-performance paddles. In conclusion, the choice of material in rowing products plays an important role in the performance of athletes so by choosing the right material, CFRP can be recommended as a material that has high strength and lightweight in rowing competitions. This research provides in-depth insights into how factors such as their strength and durability influence material selection decisions.

Conclusion

This study has evaluated and identified CFRP as the best material for making paddles, especially in handle and spoon components compared to other alternative materials such as wood, bamboo, and ceramics. With MCDA analysis, CFRP material received the highest score of 85.40. This decision score is calculated based on a weighted sum of various criteria such as strength, weight, cost, and durability with a score of 100 as the maximum score. A score of 85.40 can be defined as this material has superior strength, lightness, and durability compared to other materials. This MCDA analysis assists engineers in creating rowing products that prioritize athletes to help maintain their performance with minimized material fatigue.

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