Arch. Metall. Mater. **70** (2025), 1, 227-233

DOI: https://doi.org/10.24425/amm.2025.152537

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ASSESSING COST-EFFECTIVE MATERIALS FOR MULTI-FUNCTIONAL CRUTCHES: AN INTEGRATED MCDM FRAMEWORK

Material selection significantly impacts crutch performance and durability, posing challenges due to various criteria and complex decision-making in engineering design. This study introduces an innovative methodology for evaluating material options in developing cost-effective multifunctional crutches. Integrating the CRITIC method for factor weighting, MARCOS for alternative measurement and ranking, and TOPSIS for preference ranking, the framework assesses seven potential materials across ten criteria. Key findings highlight cost, adjustability, and density as critical factors, with aluminium identified as the optimal frame material followed by fiberglass, striking a balance between attributes. Sensitivity analysis confirms the robustness of this approach, providing valuable insights for material selection in engineering systems and assistive technology design, enhancing crutch performance and user satisfaction. This novel approach combines established decision-making techniques, enhancing the efficiency of material selection processes for crutch design.

Keywords: CRITIC method; MARCOS method; TOPSIS method; Crutch materials; Decision-making frameworks

1. Introduction

The advancement of assistive technology is crucial in enhancing the life quality of individuals with mobility impairments [1]. Within this realm, multifunctional crutches are essential aids, providing crucial support and mobility assistance to a wide range of users. However, the effectiveness and longevity of these crutches depend significantly on the materials chosen for their construction [2]. Material selection in engineering design poses a complex decision-making hurdle, particularly when multiple criteria must be weighed simultaneously [3,4]. This research addresses this issue by introducing an inventive approach to evaluate material choices for developing cost-effective multifunctional crutches.

Material selection in crutch design significantly impacts performance, durability, and overall effectiveness in various scenarios. Engineers and designers must navigate a complex decision-making process involving multiple criteria. Traditional approaches often fall short in addressing this complexity, necessitating systematic methodologies for comprehensive evaluation of material alternatives. To meet this demand, the proposed methodology integrates three established multi-criteria decision-making techniques: Critic [5], MARCOS [6], and TOPSIS method [7]. These methods collectively offer a robust framework for assessing material options effectively.

Material selection profoundly impacts the performance, durability, and cost-effectiveness of engineered products, especially in multifunctional devices like assistive technologies, which require balancing diverse criteria to meet complex user needs [8]. Making decisions about materials involves navigating trade-offs between conflicting objectives, necessitating systematic methodologies [9]. Frizziero et al. (2019) demonstrated a structured industrial design methodology for innovating crutches, focusing on factors such as adaptability, adjustability, lightness, ergonomics, reliability, hygiene, material strength, durability, affordance, dimensions, appearance, and comfort of use [10]. Their study explored three materials using quality function deployment, with similar approaches seen in related literature. Notably, no existing papers have applied a multicriteria decision-making approach to crutch design, which would assign specific weights to each criterion based on user preferences.

Prior research has illustrated the use of integrated Multi-Criteria Decision-Making (MCDM) techniques in material selection across diverse engineering sectors, such as automobile manufacturing, pipe production, furniture production, and project selection [11-17]. These studies typically integrate multiple

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methods for weighting criteria and ranking alternatives. Addressing a gap in the current literature, this paper proposes the integration of the CRITIC, MARCOS, and TOPSIS methodologies for material selection, aiming to enhance decision-making processes in this field.

The research objectives of this study are as follows:

- Identify the various factors influencing crutch design, including considerations for material alternatives.
- Incorporate three established multi-criteria decision-making (MCDM) techniques into the evaluation process.
- Assess the significance of ten essential criteria used to evaluate material alternatives in crutch construction.

2. Material and methods

2.1. Factor Identification

Identifying factors for crutch material selection involves a systematic approach to evaluate essential aspects comprehensively. Initially, defining selection objectives prioritizes crutch design goals, including strength, weight, cost-effectiveness, durability, comfort, adjustability, and safety. Stakeholder input from users, healthcare professionals, engineers, and designers provides insights into preferences and priorities, ensuring considerations directly impact user satisfaction. Reviewing industry standards ensures compliance with safety and performance regulations. A literature review consolidates existing research and best practices. Brainstorming with multidisciplinary teams generates and prioritizes factors, validating their alignment with stakeholder needs and standards. This iterative process guides informed material selection for crutches, enhancing performance and user experience while meeting stringent safety and quality requirements. TABLE 1, and TABLE 2 provide the list of factors along with data finalized for the study.

2.2. CRITIC Method

It is a technique used to determine the relative importance or weights of criteria in a decision-making process. Here are the step-by-step methodologies involved in applying the CRITIC method:

Step 1 – Formulation of decision matrix.

$$\mathrm{Max}\left\{f_1(a), f_2(a), \ldots, f_m(a) / a \in A\right\}$$

TABLE 1

Factors identified

Factor	Description	Ref.
Tensile Strength (C1)	Tensile strength is crucial for crutches, ensuring they support the user's weight without deformation or failure.	[18]
Density (C2)	Density indicates how much mass is packed into a given volume of material, with lower densities being lighter and thus reducing user fatigue.	[19]
Weight (C3)	Weight refers to the material's heaviness, and lighter materials are preferable for crutches to minimize user strain, especially during extended use.	[20]
Cost (C4)	Cost denotes the monetary expense associated with obtaining and using the material, a crucial consideration for budget-conscious users and healthcare systems.	[21]
Adjustability (C5)	Adjustability relates to how easily the material can be customized to fit the user's needs, such as adjusting crutch height or angle.	[22]
Corrosion Resistance (C6)	Corrosion resistance measures the material's ability to withstand damage from chemical reactions like rusting, crucial for durability.	[23]
Durability (C7)	Durability indicates how well the material withstands wear and tear over time, affecting maintenance needs.	[24]
Comfort (C8)	Comfort considers factors like padding and ergonomic design, influencing user experience during prolonged crutch use.	[25]
Stiffness (C9)	Stiffness refers to the material's resistance to deformation under load, providing stability but potentially affecting comfort.	[26]
Safety (C10)	Safety encompasses features like slip resistance and impact absorption, critical for preventing injuries during crutch use.	[27]

TABLE 2

Factor Information (Converted on Scale 1-10)

Alternative\Factor	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Aluminium (A1)	7	7	8	6	8	9	8	7	7	8
Mild Steel (A2)	8	4	4	6	4	7	9	6	8	7
Carbon fibre (A3)	10	9	10	3	3	8	9	8	9	9
Fiberglass (A4)	6	8	7	6	7	8	8	7	7	8
Titanium (A5)	9	5	9	2	4	10	9	8	9	9
Beech Wood (A6)	5	8	7	4	5	3	6	7	4	6
HDPE (A7)	4	5	8	5	6	6	7	7	5	7

Step 2 – Normalization of the input matrix

$$x_{aj} = \frac{f_j(a) - f_{j^*}}{f_j^* - f_{j^*}}$$

f_j^* – Ideal value – Best solution

f_{j^*} – Non-deal value – Worst solution

Step 3 – Estimation of standard deviation for the normalized matrix

$$\sigma_j = \left(x_j(1), x_j(2), \ldots, x_j(n)\right)$$

Step 4 – Estimation of Criterion information C_j

$$C_j = \sigma_j \cdot \sum_{k=1}^{m} \left(1 - r_{jk}\right)$$

Step 5 – Calculate weight of the criteria

$$w_j = \frac{C_j}{\sum_{k=1}^{m} C_k}$$

2.3. MARCOS methodology

MARCOS presents an innovative approach that finds use in various contexts.

Step 1: Formation of initial and extended decision matrix. The initial decision matrix consists of ‘m’ criteria against ‘n’ number of alternatives. When dealing with group decision-making scenarios, matrices containing evaluations from experts are combined to form an initial matrix for group decision-making. For obtaining extended decision matrix (X), simply anti-ideal solution (AAI) and ideal solution (AI) are identified for all the criteria as per equation (5). The AAI represents the least favourable option, whereas the AI is an alternative distinguished by its superior characteristics based on type of criteria.

$$X = \begin{array}{c} \\ AAI \\ A_1 \\ A_2 \\ \cdots \\ A_m \\ AI \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{bmatrix} x_{aa1} & x_{aa2} & \cdots & x_{aan} \\ x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{22} & \cdots & x_{mn} \\ x_{ai1} & x_{ai2} & \cdots & x_{ain} \end{bmatrix} \end{array}$$

Step 2: Normalization. The normalized decision matrix is calculated as follow:

$$n_{ij} = \frac{x_{ai}}{x_{ij}} \text{ if } j \in C$$

$$n_{ij} = \frac{x_{ij}}{x_{ai}} \text{ if } j \in B$$

where elements x_{ij} and x_{ai} represent the elements of the matrix *X*.

Step 3: Weighted Matrix (*v*). It is calculated as follows.

$$v_{ij} = n_{ij} \times w_j$$

Step 4: Calculate Utility Degree.

$$S_i = \sum_{i=1}^{n} v_{ij}$$

$$K_i^+ = \frac{S_i}{S_{ai}} \qquad K_i^- = \frac{S_i}{S_{aai}}$$

Step 5: Calculate Utility function

$$f\left(K_i\right) = \frac{K_i^+ + K_i^-}{1 + \frac{1 - f\left(K_i^+\right)}{f\left(K_i^+\right)} + \frac{1 - f\left(K_i^-\right)}{f\left(K_i^-\right)}}$$

$$f\left(K_i^-\right) = \frac{K_i^+}{K_i^+ + K_i^-} \qquad f\left(K_i^+\right) = \frac{K_i^-}{K_i^+ + K_i^-}$$

Step 6: Calculate Ranking.

2.4. TOPSIS method

Step1: Determine the objective, and pinpoint attributes.

Step 2: Calculate the normalized decision matrix.

$$R_{ij} = \frac{m_{ij}}{\sqrt{\sum_{j=1}^{M} m_{ij}^2}}$$

Step 3: Decide the relative importance weights such that sum of weights to be equal to 1.

Step 4: Calculate the weighted normalized matrix

$$V_{ij} = w_j R_{ij}$$

Step 5: Calculate the ideal and negative ideal solutions

$$A^+ = \left\{V_{ij}^+ 1, \ldots\ldots . V_n^+\right\} = \left\{\left(\max V_{ij} \mid i \in_I\right), \left(\min V_{ij} \mid i \in I''\right)'\right.$$

$$A^- = \left\{V_{ij}^- 1, \ldots\ldots . V_n^-\right\} = \left\{\left(\max V_{ij} \mid i \in_I\right), \left(\min V_{ij} \mid i \in I''\right)'\right.$$

Step 6: Calculate distances by below two equations

$$D_j^+ = \sqrt{\sum_{i=1}^{n} \left(v_{ij} - v_j^+\right)^2} \qquad D_j^- = \sqrt{\sum_{i=1}^{n} \left(v_{ij} - v_j^-\right)^2}$$

Step 7: Calculate of relative closeness to the ideal solution

$$P_i^* = \frac{D\vec{j}}{D_j^+ + D_j^-}$$

Step 8: Obtain the ranking based on the value of P_i^*.

3. Results and discussion

The CRITIC method was employed to determine the importance of each criterion in the material selection process for multifunctional crutches. The corresponding weight coefficients (W_j) for each criterion are presented in TABLE 3.

The MARCOS method evaluates alternative options based on various criteria to determine their suitability for material selection in multifunctional crutches. TABLES 4 and 5 present the initial decision matrix and the weighted normalized matrix,

TABLE 3

Normalized decision matrix and calculation of weights

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
A1	0.500	0.600	0.667	1.000	1.000	0.857	0.667	0.500	0.600	0.667
A2	0.667	0.000	0.000	1.000	0.200	0.571	1.000	0.000	0.800	0.333
A3	1.000	1.000	1.000	0.250	0.000	0.714	1.000	1.000	1.000	1.000
A4	0.333	0.800	0.500	1.000	0.800	0.714	0.667	0.500	0.600	0.667
A5	0.833	0.200	0.833	0.000	0.200	1.000	1.000	1.000	1.000	1.000
A6	0.167	0.800	0.500	0.500	0.400	0.000	0.000	0.500	0.000	0.000
A7	0.000	0.200	0.667	0.750	0.600	0.429	0.333	0.500	0.200	0.333
W_j	0.084	0.121	0.082	0.178	0.141	0.067	0.089	0.087	0.083	0.069
Rank	**6**	**3**	**8**	**1**	**2**	**10**	**4**	**5**	**7**	**9**

TABLE 4

Extended initial decision matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
AAI	**4.000**	**4.000**	**4.000**	**2.000**	**3.000**	**3.000**	**6.000**	**6.000**	**4.000**	**6.000**
A1	7	7	8	6	8	9	8	7	7	8
A2	8	4	4	6	4	7	9	6	8	7
A3	10	9	10	3	3	8	9	8	9	9
A4	6	8	7	6	7	8	8	7	7	8
A5	9	5	9	2	4	10	9	8	9	9
A6	5	8	7	4	5	3	6	7	4	6
A7	4	5	8	5	6	6	7	7	5	7
AI	**10.000**	**9.000**	**10.000**	**6.000**	**8.000**	**10.000**	**9.000**	**8.000**	**9.000**	**9.000**

respectively, which are essential components in the MARCOS methodology.

Normalization is crucial as it standardizes the values across criteria, allowing for a fair comparison between alternatives. For example, Alternative A3 achieves high normalized values across most criteria, indicating its strong performance in those areas compared to other alternatives.

TABLE 5, on the other hand, displays the weighted normalized matrix, where the normalized values are weighted based on the importance of each criterion. Weighting ensures that criteria with higher significance contribute more to the evaluation process. Consequently, the weighted normalized matrix provides a more accurate representation of each alternative's overall performance across all criteria. For instance, Alternative A1 obtains relatively higher scores in the weighted normalized matrix, indicating its favourable performance when considering the importance of each criterion.

The provided data outlines the results obtained from the MARCOS method for evaluating alternative options in the context of material selection for multifunctional crutches. TABLE 6 presents the calculated values for each alternative, including Si (standard deviation), Ki^- (negative deviation), K^+ (positive deviation), $f(K^-)$, $f(K^+)$, $f(Ki)$, and the final rank. Upon analyzing the results presented in TABLE 6, it becomes evident that Alternative A1 emerges as the top-ranked option. This indicates that Alternative A1 exhibits the most favorable combination of attributes and performance across the evaluated criteria. It achieves a high score in terms of Si (standard deviation), indicating consistency and reliability in its performance across the criteria. Additionally, Alternatives A3 and A4 also demonstrate strong performance, securing positions closely behind Alternative A1 in the ranking. Conversely, Alternatives A6 and A7 obtain lower ranks in the assessment. This suggests that

TABLE 5

Weighted normalized matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
AAI	**0.052**	**0.051**	**0.037**	**0.061**	**0.058**	**0.045**	**0.019**	**0.009**	**0.047**	**0.019**
A1	0.091	0.089	0.074	0.184	0.154	0.135	0.026	0.011	0.082	0.025
A2	0.104	0.051	0.037	0.184	0.077	0.105	0.029	0.009	0.094	0.022
A3	0.130	0.115	0.092	0.092	0.058	0.120	0.029	0.013	0.106	0.028
A4	0.078	0.102	0.064	0.184	0.135	0.120	0.026	0.011	0.082	0.025
A5	0.117	0.064	0.083	0.061	0.077	0.150	0.029	0.013	0.106	0.028
A6	0.065	0.102	0.064	0.122	0.096	0.045	0.019	0.011	0.047	0.019
A7	0.052	0.064	0.074	0.153	0.116	0.090	0.022	0.011	0.059	0.022
AI	**0.130**	**0.115**	**0.092**	**0.184**	**0.154**	**0.150**	**0.029**	**0.013**	**0.106**	**0.028**

these alternatives may exhibit deficiencies or shortcomings in certain criteria compared to their counterparts. Despite achieving lower ranks, these alternatives still offer valuable insights that can inform decision-making processes, potentially highlighting specific areas for improvement or optimization.

TABLE 6

Results of MARCOS method

Ai	Si	Ki^-	K^+	$f(K^-)$	$f(K^+)$	$f(Ki)$	Rank
A1	0.871	2.186	0.871	0.285	0.715	0.782	1
A2	0.712	1.787	0.712	0.285	0.715	0.639	5
A3	0.782	1.963	0.782	0.285	0.715	0.702	3
A4	0.827	2.076	0.827	0.285	0.715	0.743	2
A5	0.727	1.826	0.727	0.285	0.715	0.653	4
A6	0.591	1.485	0.591	0.285	0.715	0.531	7
A7	0.662	1.662	0.662	0.285	0.715	0.595	6

Aluminum secures the top rank primarily ue to its balanced performance across several key attributes. It boasts high tensile strength, reasonable density, and a favorable weight-to-strength ratio, making it suitable for a wide range of applications from aerospace to automotive industries. Additionally, Aluminum is cost-effective relative to its performance, offering good adjustability and corrosion resistance, further enhancing its appeal.

Following closely behind, Fiberglass earns its position due to its notable durability and excellent corrosion resistance, making it particularly well-suited for applications requiring resilience in challenging environmental conditions. While Fiberglass may not match Aluminum's strength-to-weight ratio, its overall performance across other factors such as comfort and stiffness contribute to its high ranking.

Steel, despite its higher density compared to Aluminum and Fiberglass, maintains a solid third position. It offers exceptional tensile strength and durability, often at a lower cost, making it a preferred choice for applications demanding robustness and safety. Steel's adjustability and safety profile further solidify its position in various structural roles.

The rankings also highlight the specialized strengths of other materials like Carbon Fiber, renowned for its unmatched stiffness-to-weight ratio, and Titanium, prized for its superior corrosion resistance and strength. These materials, while ranking lower overall, remain highly valuable in niche applications where their specific properties are critical.

3.1. Comparison with other MCDM methods

Based on the comparative study (TABLE 8) across nine different methods (M1 to M9) for evaluating alternatives (A1 to A7), certain consistent patterns emerge. Analyzing the rankings provided by each method reveals a convergence of assessments for several alternatives. Notably, Alternative A1 receives the highest ranking from the majority of methods, with seven out of nine methods placing it at the top. Consequently, A1 emerges as the clear frontrunner and should be considered the top-ranked alternative. Conversely, Alternative A6 consistently garners lower rankings across most method. This consensus suggests that A6 should be placed at the bottom of the list. By considering the rankings provided by the maximum number of methods for each alternative, a comprehensive and justified ranking can be established, providing valuable insights for decision-making processes.

TABLE 7

Results of TOPSIS method

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Pi	Rank
A1	0.03	0.05	0.03	0.08	0.08	0.03	0.03	0.03	0.03	0.03	0.02	**1**
A2	0.03	0.03	0.02	0.08	0.04	0.02	0.04	0.03	0.03	0.02	0.06	**3**
A3	0.04	0.06	0.04	0.04	0.03	0.03	0.04	0.04	0.04	0.03	0.06	**5**
A4	0.03	0.05	0.03	0.08	0.07	0.03	0.03	0.03	0.03	0.03	0.03	**2**
A5	0.04	0.03	0.04	0.03	0.04	0.03	0.04	0.04	0.04	0.03	0.07	**7**
A6	0.02	0.05	0.03	0.06	0.05	0.01	0.03	0.03	0.02	0.02	0.06	**6**
A7	0.02	0.03	0.03	0.07	0.06	0.02	0.03	0.03	0.02	0.02	0.05	**4**
V^+	0.04	0.06	0.04	0.08	0.08	0.03	0.04	0.04	0.04	0.03		
V^-	0.02	0.03	0.02	0.03	0.03	0.01	0.03	0.03	0.02	0.02		

TABLE 8

Comparative study

Ranking of Mater	M1	M2	M3	M4	M5	M6	M7	M8	M9
A1	1	1	5	1	1	1	1	1	3
A2	5	5	7	5	5	3	5	5	5
A3	3	3	3	3	3	5	3	3	1
A4	2	2	4	2	2	2	2	2	3
A5	4	4	6	4	4	7	4	4	1
A6	7	7	1	7	7	6	7	7	7
A7	6	6	2	6	6	4	6	6	5

M1 – EDAS, M2 – MARCOS, M3 – COPRAS, M4 – AHP, M5 – SAW, M6 – TOPSIS, M7 – ARAS, M8 – WASPAS, M9 – COCOSO.

3.2. Sensitivity Analysis

A sensitivity analysis was conducted to judge whether the weights of the criteria impact the ranking of the alternatives [28]. To do so, the most significant criteria was 'C4' having weight of 0.178. The weight of C4 was decreased by 5%. The weights of remaining criteria were adjusted.

$$\tilde{W}_{n\beta} = \left(1 - \tilde{W}_{n\alpha}\right) \frac{\tilde{W}_{\beta}}{\left(1 - \tilde{W}_{n}\right)}$$

Where, $\tilde{W}_{n\beta}$ represents the new value of the criteria to be evaluated, $\tilde{W}_{n\alpha}$ represents the modified value of the most significant criteria, $\tilde{W}_{\beta}$ represents original value of criteria to be evaluated, and $\tilde{W}_{n}$ represents the original value of the most significant criteria.

Fig. 1 shows the weights used in sensitivity analysis by creating 20 different weight scenarios. These weights are given as input to MARCOS and TOPSIS method to check for any change in the rankings. Fig. 2 depicts only one alternation in ranking in scenario 12 and scenarios 13 respectively. The change is common in both the methods. This represents the robustness of the criteria weights and the robustness of the integrated framework consisting of CRITIC-MARCOS and CRITIC-TOPSIS.

4. Conclusion

In conclusion, the selection of materials for crutch design significantly influences performance and durability, presenting engineers with complex challenges in balancing various criteria. This study introduces an innovative methodology aimed at evaluating material options to develop cost-effective and multifunctional crutches. By integrating the CRITIC method for factor weighting, MARCOS for alternative measurement and ranking, and TOPSIS for preference ranking, the framework comprehensively assesses seven potential materials across ten critical criteria. Key insights from the study underscore the pivotal roles of cost-effectiveness, adjustability, and density in material selection. Aluminum emerges as the optimal choice for crutch frames due to its favorable balance across attributes, offering high strength, moderate weight, and good adjustability. Fiberglass follows closely, excelling in durability and corrosion resistance, reinforcing its suitability for structural components.

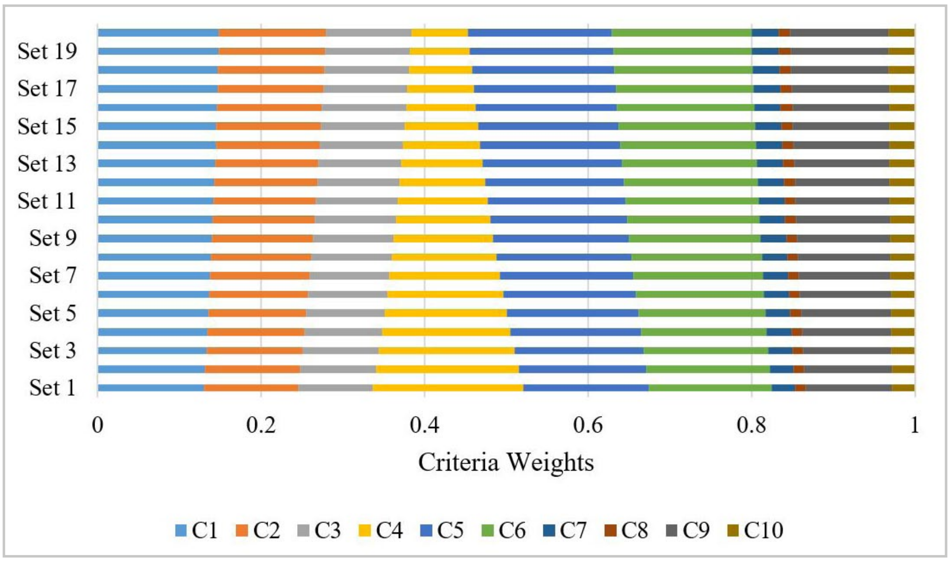

Fig. 1. Weights used in 20 Scenario

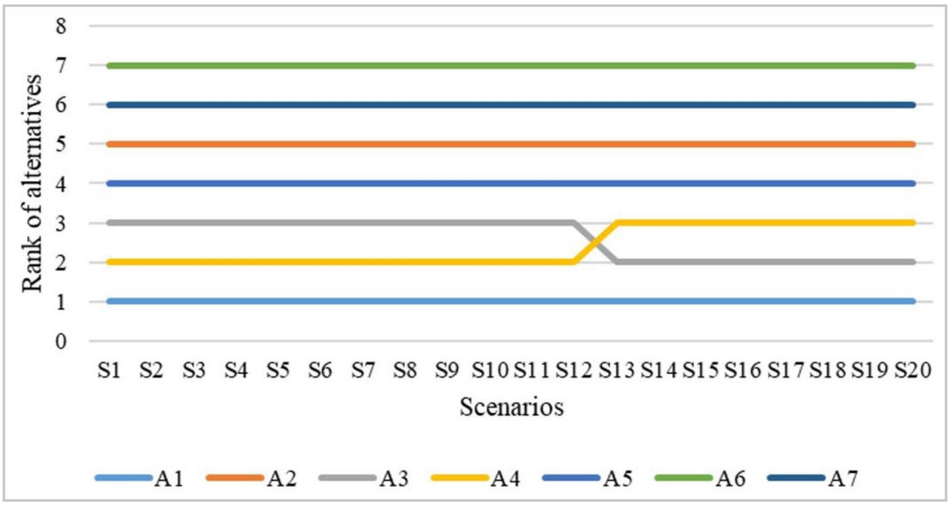

Fig. 2. Sensitivity analysis (MARCOS and TOPSIS)

The sensitivity analysis conducted validates the robustness of this integrated approach, providing valuable guidance for engineers and designers in enhancing crutch performance and user satisfaction. This novel methodology not only streamlines material selection processes but also enhances decision-making efficiency in engineering systems and assistive technology design. By leveraging established decision-making techniques, this framework supports the development of innovative solutions that meet diverse functional requirements and ensure the long-term reliability of crutches in practical use scenarios.

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