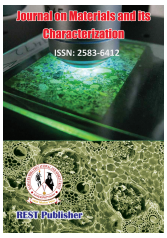
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Fuzzy Cognitive Modelling of Criteria Interactions in High Performance Nanomaterial Selection

Nivetha Martin[1], R Priya[2*], B. Kavitha[2], R. Gayathri[2]

[1]*Arul Anandar College (Autonomous), Karumathur, Madurai, India.*
[2]*Sethu Institute of Technology, Virudhunagar, Tamil Nadu, India.*

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ABSTRACT

Nanomaterials are widely applied in diverse fields owing to their significant properties and high efficiency. The choice of nanomaterials is inherited with intricacy as the decision making involves multiple conflicting criteria. The conventional methods identifies the criterion weightage of nanomaterial selection but fall short of exploring the interactions among the criteria. This study proposes a fuzzy cognitive based modelling to determine the key criteria of selecting nanomaterials. The proposed FCM approach also facilitates in addressing the interactions among the criteria. The FCM modelling discussed in this work considers six core criteria and sensitively analyzes criterion interactions. The results of this work support the decision makers in evolving optimal decisions on nanomaterials with high performances. The integration of fuzzy logic with cognitive modelling also facilitate in handling uncertainty in decision making.

1. INTRODUCTION

The advancements in nanotechnology have transformed the landscape of engineering materials. The materials confined to nanoscale are embedded with unique physical, chemical, mechanical , electrical properties. These nanomaterials are widely applied in several systems and processes. However, the selection of these materials are dependent on diverse criteria especially on the conflicting and intricate attributes of mechanical, electrical, thermal and environmental aspects. Researchers have discussed the applications of multi-criteria decision making methods in ranking nanomaterials. Linkov et al applied multi - criteria decision analysis in classifying the nanomaterial risks. Vaziri et al, Solimon et al, Zribi et al, Piling et al and Ding et al employed the methodology of multi criteria decision analysis especially Analtyic Hierarchy Process to evaluate nanomaterial integrated entities. Falinkski et al developed a decision framework considering performance and economic factors. Singh and Agrawal formulated multi attribute decision making approach of nanomaterial selection. Zhang et al applied life cycle assessment in selecting nanomaterial based packaging materials. These mathematical decision models are leveraged to rank the nanomaterials, however criteria decision and criterion interactions are not discussed. As decision making on nanomaterials is highly intricate in nature, it is essential to choose a feasible decision tool to study on the choice of criteria and their interactions. Fuzzy Cognitive Maps (FCM) are identified as the flexible and robust decision framework to examine the criterion interactions. FCMs are basically characterized as directed graphs with nodes and edges

*Corresponding author email-id: iampriyaravi@gmail.com

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representing the factors and their interactions respectively. The edge weights generally assume values from [-1,1]. FCMs are competent in addressing the interactions among the factors of the study. Researchers have also applied FCM in material management. Li and Peng, Dursun et al and Alpeeva and Volkova developed FCM models in evaluating material selection. However,FCM is not applied in exploring the criteria selection of nanomaterial to the best of our knowledge. This has motivated the authors to evolve a FCM based decision approach in examining the criterion interaction of high performance nanomaterial selection. The remaining contents of this work are structured into the following sections. The section 2 explains the FCM methodology. The section 3 discusses the results and performs sensitivity analysis. The alst section summarizes the work.

2. FCM METHODOLOGY IN CRITERIA SELECTION

This section discusses the steps involved in the FCM decision-making approach for criteria selection and interaction.

Step 1. Define the Concepts (Criteria)

Let

$$C = \{C_1, C_2, C_3, C_4, C_5, C_6\}$$

represent six major criteria.

TABLE 1. Criteria considered in the FCM

Criterion	Description
C_1	Particle Size
C_2	Surface Area
C_3	Structural Stability
C_4	Electrical Conductivity
C_5	Biocompatibility
C_6	Production Cost

These six criteria sufficiently represent the fundamental aspects governing nanomaterial performance.

Step 2. Construct the FCM

The FCM is represented by a directed graph

$$G = (V, E, W),$$

where

- Nodes = Criteria
- Edges = Causal relationships

Each edge has a fuzzy weight

$$w_{ij} \in [-1, 1],$$

where

- +1 = Strong positive influence
- +0.5 = Moderate positive influence
- 0 = No influence
- −0.5 = Moderate negative influence
- −1 = Strong negative influence

Step 3. Linguistic Assessment

Experts define the interactions using the linguistic variables as mentioned in Table 2.

TABLE 2. Linguistic description of causal influence

Influence	Weight
Very High Positive	0.9
High Positive	0.7
Medium Positive	0.5
Weak Positive	0.3
No Relation	0
Weak Negative	−0.3
Medium Negative	−0.5
High Negative	−0.7
Very High Negative	−0.9

Step 4. Formulation of Connection Matrix

The FCM weight matrix becomes

$$W = \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{16} \\ w_{21} & w_{22} & \cdots & w_{26} \\ \vdots & \vdots & \ddots & \vdots \\ w_{61} & w_{62} & \cdots & w_{66} \end{bmatrix}.$$

Generally, w_{ij} represents the degree of causal influence of criterion C_i on criterion C_j, with

$$w_{ij} \in [-1, 1].$$

Step 5. Initialization of the State Vector and Dynamic Updating

The initial activation of the criteria is assumed as

$$A^{(0)} = \begin{bmatrix} a_1^{(0)} & a_2^{(0)} & a_3^{(0)} & a_4^{(0)} & a_5^{(0)} & a_6^{(0)} \end{bmatrix},$$

where values belong to

$$a_i^{(0)} \in [0, 1].$$

The FCM updates as

$$A^{(t+1)} = f\left(A^{(t)} W\right),$$

where

$$f(x) = \frac{1}{1 + e^{-\lambda x}}$$

is the sigmoid activation function.

Usually,

$$\lambda = 1.$$

In this case, we have

$$f(x) = \frac{1}{1 + e^{-x}}.$$

Step 6. Convergence to Steady-State Vector

The iterations continue until

$$\left\| A^{(t+1)} - A^{(t)} \right\| < \varepsilon$$

or

$$A^{(t+1)} = A^{(t)}.$$

The resulting vector is called the **steady-state activation vector**.

Step 7. Importance of Criteria Using Centrality Measures

Out-degree

The overall influence of criterion C_i is measured using the out-degree, which measures how much criterion C_i affects other criteria:

$$OD_i = \sum_{j=1}^{n} |w_{ij}|.$$

In-degree

The in-degree measures how much criterion C_i is influenced by other criteria:

$$ID_i = \sum_{j=1}^{n} |w_{ji}|.$$

Centrality

The centrality of criterion C_i is calculated as

$$C_i^{\text{centrality}} = OD_i + ID_i.$$

The criterion with the largest centrality is considered the most influential criterion in the nanomaterial selection process.

The proposed FCM workflow is presented in Fig 1.

The FCM graph relating the criteria of nanaomaterial selection is presented in Fig. 2 The intensity of the connection matrix is presented in Fig 3

The Final State Vector is represented in Table 3

TABLE 3. Criterion and State Vector Value

Selection Criterion	Final State Vector Value
Particle Size	0.4668
Surface Area	0.5923
Structural Stability	0.4419
Electrical Conductivity	**0.6603**
Biocompatibility	0.5735
Production Cost	0.3321

The convergence of the vectors is represented in Fig 4.

The significance of the criteria is determined using centrality measures and it is represented in Fig.5.

On performing the sensitivity analysis, we determine the inferences as in Table 3. The graphical representation is presented in Fig. 6.

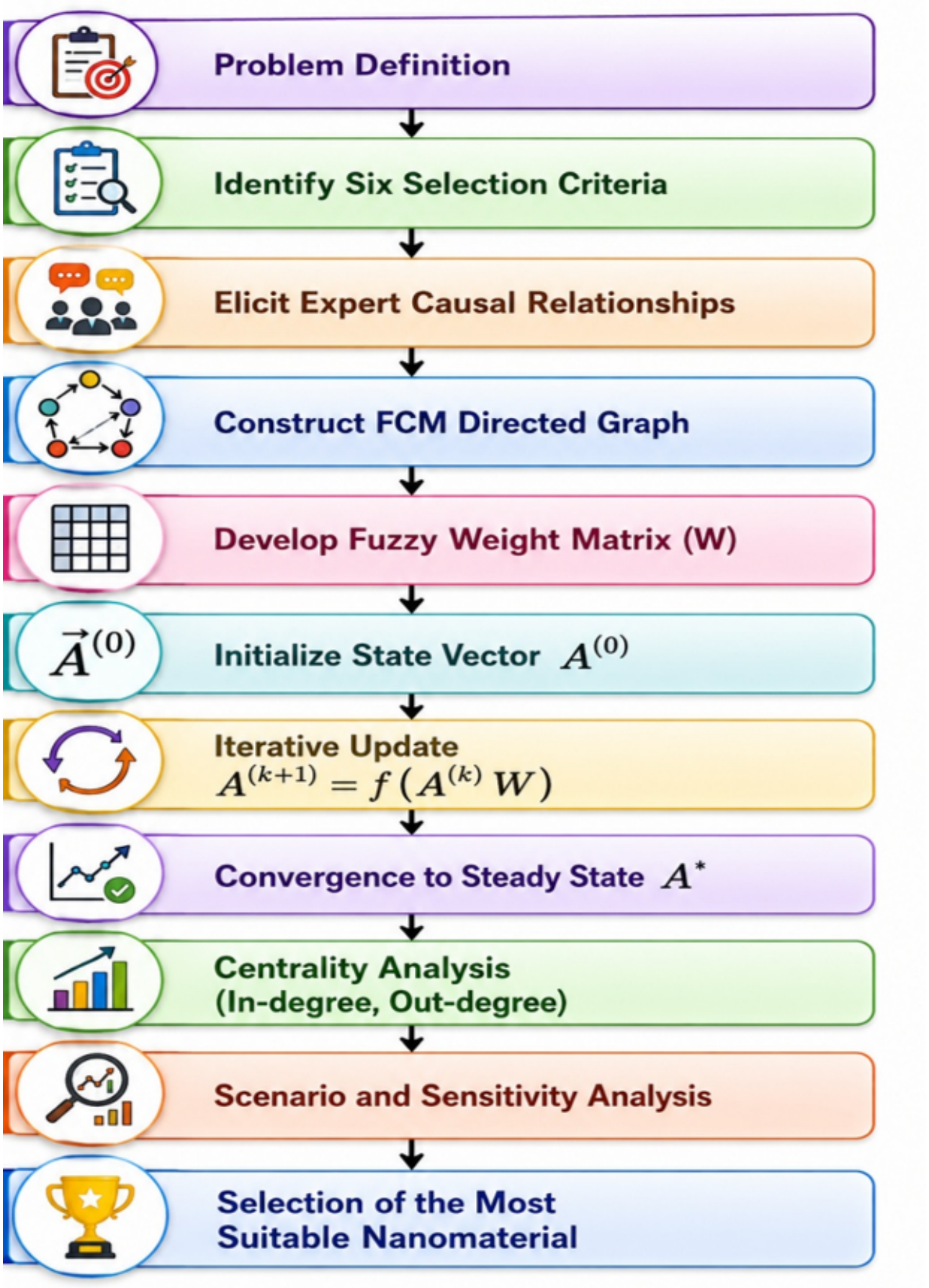


FIGURE 1. FCM Workflow

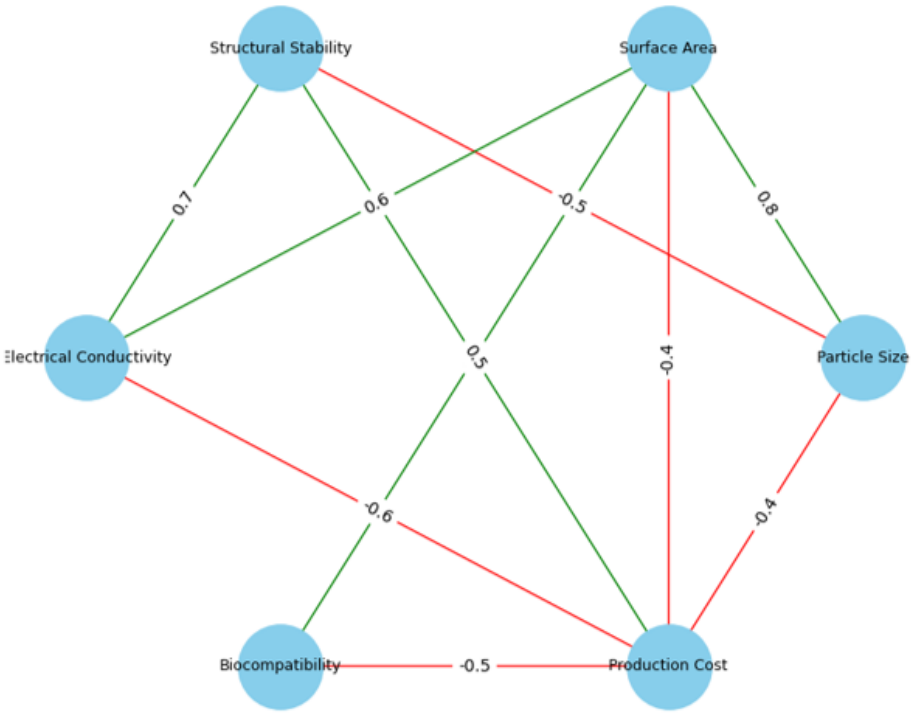


FIGURE 2. FCM Network of Nanomaterial Criteria

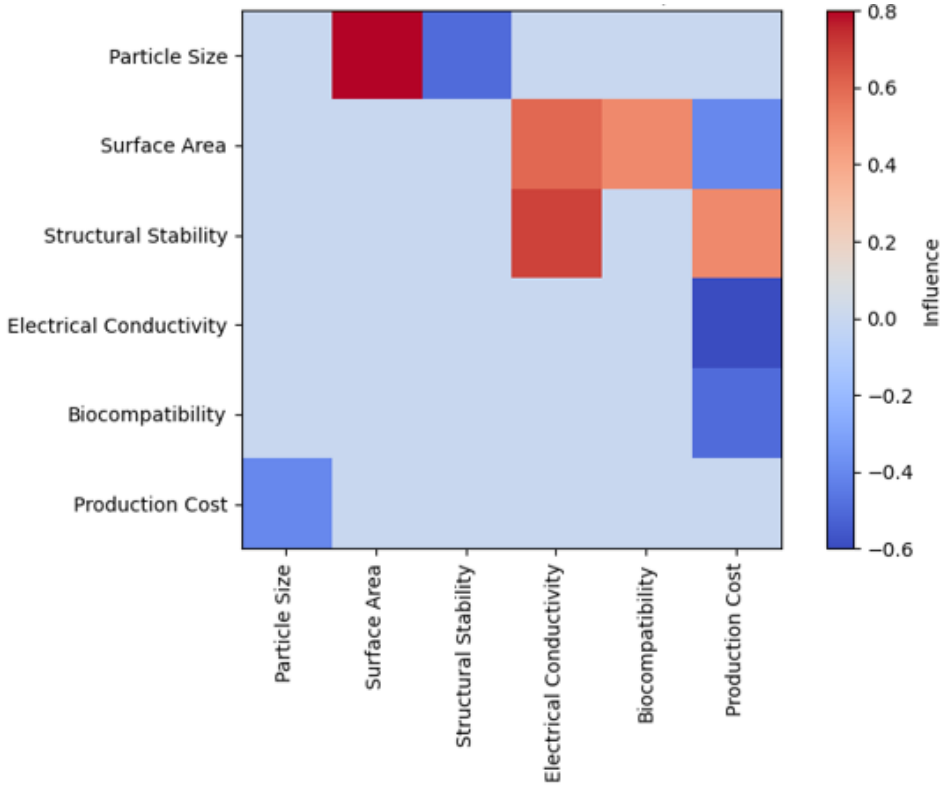


FIGURE 3. Connection Matrix Heatmap

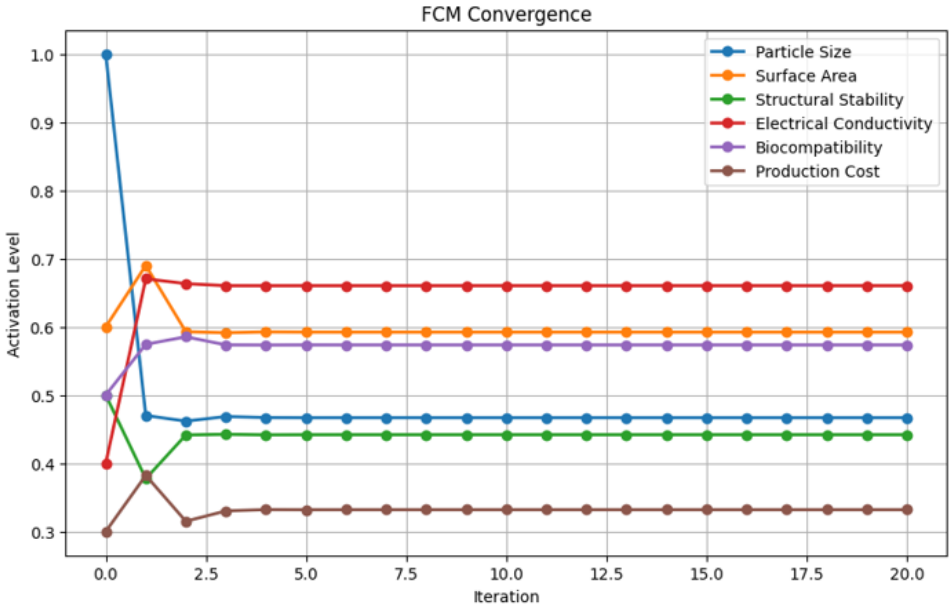


FIGURE 4. Convergence Plot

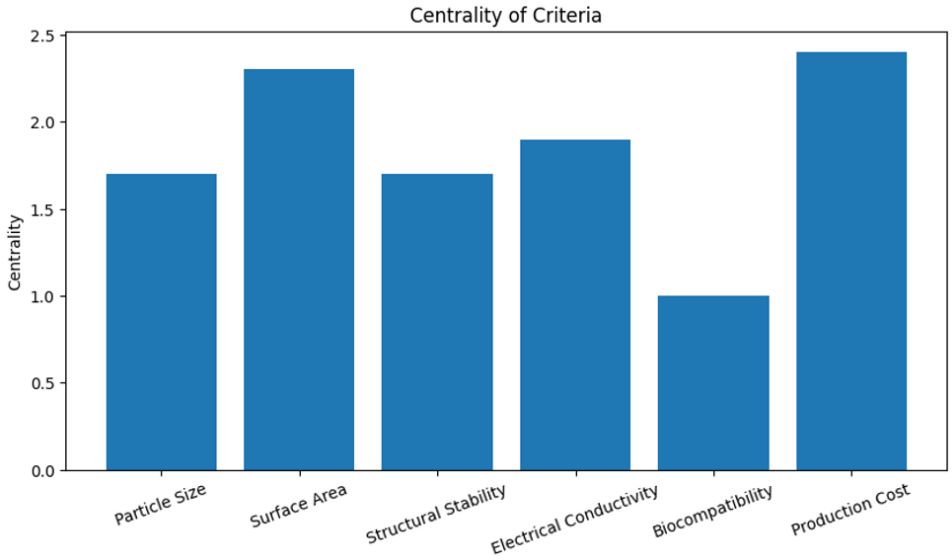


FIGURE 5. Centrality Measures

TABLE 4. Inferences of Sensitivity Analysis

Criterion	Sensitivity	Inferences
Electrical Conductivity	0.6603	Most influential criterion
Surface Area	0.5923	Second most influential
Biocompatibility	0.5735	Highly sensitive criterion
Particle Size	0.4668	Moderately influential
Structural Stability	0.4419	Moderate influence
Production Cost	0.3321	Least influential

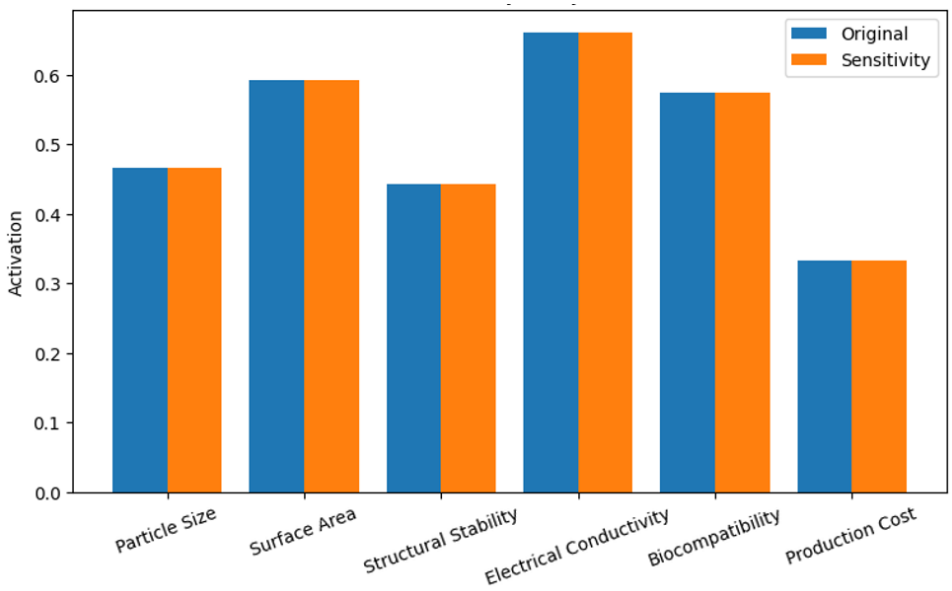


FIGURE 6. Sensitivity Analysis

3. CONCLUSION

This research work develops a FCM decision making approach considering the criterion selection of nanomaterial. This approach also facilitates in exploring the criterion interaction among the criteria of nanomaterial selection. The integration of fuzzy logic with cognitive modelling facilitates in handling uncertainty in making optimal decisions on high performance nanomaterials. This work stands distinct as it considers not the conventional idea of ranking the nanomaterials, rather it considers higher cognitive level of examining the critical criteria and their interactions. The sensitivity analysis and the centrality measures support the decision makers to make optimal decisions. This decision approach shall be extended using the representations of intuitionistic and neutrosophic based on the needs of the decision makers.

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