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Valuation of Building Facade Design Effects Using ForestSoft Hypergraphs and Virtual Simulation Technology

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Abstract-Evaluating building facade designs requires balancing multiple criteria, such as energy efficiency, aesthetic appeal, and cost-effectiveness, which are often hierarchically organized and interconnected. Traditional methods struggle to capture these complexities and uncertainties. This paper proposes ForestSoft Hypergraphs, a novel framework integrating hierarchical ForestSoft Sets with hypergraph structures to model both the hierarchical nature of design criteria and their multi-party relationships. Using virtual simulation technologies, such as EnergyPlus and Radiance, we generate performance data for facade designs, which are evaluated within the ForestSoft Hypergraph framework. A case study with three design alternatives demonstrates the method's ability to provide comprehensive evaluations, identifying optimal designs while highlighting trade-offs. Comparative analysis with AHP shows improved handling of relational constraints. Results suggest that ForestSoft Hypergraphs offer a flexible and robust approach, though scalability and empirical validation require further exploration.

Keywords: ForestSoft Sets; ForestSoft Hypergraphs; Building facade design; Virtual simulation technology

1. Introduction

Building facades significantly influence a structure's energy performance, aesthetic value, structural integrity, and cost. Designing an optimal facade involves evaluating multiple criteria, which are often organized hierarchically and exhibit complex interdependencies. For example, energy efficiency depends on sub-criteria like insulation quality and window performance, while aesthetic appeal involves color harmony and material texture. These criteria may also interact, such as when high-quality insulation increases material costs. Traditional evaluation methods, such as the Analytic Hierarchy Process (AHP) [1] or TOPSIS [2], often treat criteria as independent or use simplistic aggregation, failing to capture their hierarchical and relational complexity.

Soft set theory, introduced by Molodtsov [3], provides a framework for handling uncertainty by parameterizing subsets of a universal set. Extensions like TreeSoft Sets and ForestSoft Sets [7] introduce hierarchical structures, making them suitable for modeling nested relationships. Hypergraphs [8], which allow edges to connect multiple vertices, represent multi-party relationships. Unlike previous soft hypergraph models [4], which focus on parameterizing hyperedges without hierarchical organization, ForestSoft Hypergraphs integrate ForestSoft Sets and hypergraphs to model both hierarchical and relational uncertainties, offering a unified approach for facade design evaluation. This research leverages virtual simulation technologies, such as EnergyPlus [5] and Radiance [6], to generate performance data, enabling comprehensive assessments.

The paper is structured as follows: Section 2 reviews related work, Section 3 details the methodology, Section 4 presents the proposed model, Section 5 provides results, Section 6 concludes with recommendations.

2. Literature Review

Facade design evaluation relies on computational tools and MCDM methods. EnergyPlus [5] simulates energy performance, while Radiance [6] analyzes lighting. These tools focus on individual criteria, lacking mechanisms for interdependence. MCDM methods like AHP [1] and TOPSIS [2] aggregate criteria but assume independence and flat structures, ignoring hierarchical relationships.

Soft set theory [3] handles uncertainty via parameterized subsets. Extensions like fuzzy soft sets [9] and ForestSoft Sets [7] introduce hierarchical modeling. Hypergraphs [8] represent multi-party relationships, and soft hypergraphs [4] combine soft sets with hypergraphs. However, soft hypergraphs lack hierarchical structures, limiting their applicability to nested criteria. ForestSoft Hypergraphs address this gap by integrating hierarchical ForestSoft Sets with hypergraphs, enabling comprehensive facade design evaluation.

A significant advancement in the extension of soft set theory has been led by Florentin Smarandache, who proposed several generalizations to address indeterminacy, multidimensionality, and hierarchical structures in uncertain environments. Smarandache [https://fs.unm.edu/TSS/] introduced six new types of soft sets: HyperSoft Set, IndetermSoft Set, IndetermHyperSoft Set, SuperHyperSoft Set, TreeSoft Set, ForestSoft Set [10-14]. The HyperSoft Set, which expands conventional soft sets by allowing multidimensional parameterization, was introduced to handle complex decision domains more effectively [10]. To accommodate undefined or partial information, Smarandache further developed the IndetermSoft Set and its relational counterpart, the IndetermHyperSoft Set, which integrates indeterminacy directly into the parameter space [15-16]. For modeling extremely complex and layered uncertainties, the SuperHyperSoft Set was presented as an advanced generalization over HyperSoft structures [14]. On the hierarchical side, the TreeSoft Set was designed to model criteria arranged in nested tree structures [15], while the ForestSoft Set extended this approach to represent multiple independent hierarchies simultaneously [17]. These models have collectively enriched the soft set framework, making it more versatile for multi-criteria decision-making in real-world scenarios. The complete theoretical formulations and formal definitions for these systems are available in Smarandache's collection of soft set extensions[10, 14, 15, 16, 17].

3. Methodology

This section presents the formal definition of ForestSoft Hypergraphs and outlines their application in the evaluation of building facade design alternatives. The methodology integrates hierarchical soft set structures and multi-relational modeling using hypergraphs, enabling a comprehensive and flexible framework for multi-criteria decision-making under uncertainty.

3.1 Definitions

3.1.1 ForestSoft Sets

To model hierarchical relationships among parameters, extensions such as TreeSoft Sets and ForestSoft Sets have been developed. A TreeSoft Set allows parameters to be organized in a single tree structure, while a ForestSoft Set generalizes this to accommodate multiple trees, enabling richer representation of nested criteria.

Definition 1: TreeSoft Set

Let U be the universal set and let $\mathcal{T} \subseteq E$ represent a tree of parameters. A TreeSoft Set T over U and $\mathcal{T}$ is defined as:

$$T = \{(e, F(e)) \mid e \in \mathcal{T}, F(e) \subseteq U\}$$

where $F(e)$ denotes the subset of elements in U that satisfy the parameter e.

Definition 2: ForestSoft Set

Given a forest $\mathcal{F} = \{\mathcal{T}_1, \mathcal{T}_2, \dots, \mathcal{T}_k\}$ composed of k disjoint trees, a ForestSoft Set F over U is defined as:

$$F = \bigcup_{i=1}^{k} T_i$$

where each T_i is a TreeSoft Set defined on tree $\mathcal{T}_i$.

Fuzzy Extension

To represent degrees of satisfaction, a fuzzy membership function $\mu_e: U \to [0,1]$ is associated with each parameter e.

The fuzzy ForestSoft Set is defined as:

$$F(e) = \{(x, \mu_e(x)) \mid x \in U\}$$

This formulation captures the partial fulfillment of parameters, facilitating more nuanced evaluations in multi-criteria environments.

3.1.2 Hypergraphs

A Hypergraph is a generalization of a standard graph in which edges, called hyperedges, can connect any number of vertices. This structure enables the representation of complex, multi-party relationships, which are common in systems with interdependent attributes, such as architectural design criteria.

Definition 3: Hypergraph

Let V be a set of vertices and E a set of hyperedges. A hypergraph $\mathcal{H}$ is defined as:

$$\mathcal{H} = (V, E), \text{ where } E = \{e_i \subseteq V \mid i \in I\}$$

Each hyperedge e_i can connect any number of vertices ≥ 1, enabling multidimensional linkage between criteria.

Example

A hyperedge $e = \{$ Insulation, Material Cost, Aesthetic Texture $\}$ may represent a situation where these three criteria must be jointly optimized.

3.1.3 ForestSoft Hypergraphs

To integrate both hierarchical structure and multi-relational dependencies, we define ForestSoft Hypergraphs as a unifying framework that combines ForestSoft Sets with hypergraphs.

Definition 4: ForestSoft Hypergraph

Let U be the universe of alternatives (e.g., facade designs), $\mathcal{F}$ be a forest of parameter trees, and $\mathcal{H} = (V, E)$ be a hypergraph defined over the criteria set V. A ForestSoft Hypergraph is defined as:

$$\text{FSH} = (\mathcal{F}, S), \text{ where } S = \{(e, F(e)) \mid e \in E\}$$

Then a ForestSoft Hypergraph is a soft set (F, E), where $F: E \to P(U)$, and $F(e)$ is the set of designs satisfying hyperedge e.

3.2 Application to Facade Design Evaluation

The proposed methodology applies ForestSoft Hypergraphs to evaluate facade designs across three major hierarchical criteria trees:

Energy Efficiency (T1):

a. Insulation Quality (E1)
b. Glazing Performance (E2)
c. Shading Effectiveness (E3)

Aesthetics (T2):

a. Color Harmony (A1)
b. Material Texture (A2)
c. Visual Proportion (A3)

Cost (T3):

a. Material Cost (C1)
b. Labor Cost (C2)
c. Maintenance Cost (C3)

3.2.1 Relational Modeling via Hyperedges

To capture interdependencies among criteria, hyperedges are defined as follows:

1. e1: High insulation (E1) and low material cost (C1)
2. e2: Complementary color harmony (A1) and material texture (A2)
3. e3: Balanced insulation (E1), glazing (E2), cost (C1), and color (A1)

These hyperedges represent complex decision constraints not captured in conventional hierarchical models.

3.2.2 Data Generation

Performance data for each design alternative is generated using the following simulation tools:

EnergyPlus: for thermal performance metrics (U-values)

Radiance: for lighting and visual aesthetics simulation

The outputs are normalized and mapped into fuzzy membership values using predefined functions (see Section 4.3).

3.2.3 Evaluation Procedure

1. Criterion Membership:

For each parameter e, compute the fuzzy membership score $\mu_e(x)$ for each design $x \in U$.

2. Hyperedge Membership:

For each hyperedge $e \subset V$, compute:

$$\mu_e(x) = \min_{e_i \in e} \mu_{e_i}(x)$$

This reflects the degree to which a design satisfies all involved criteria.

3. Aggregate Evaluation:

The overall performance score for a design is calculated as:

$$\text{Score}(x) = \sum_{e \in E} \lambda_e \cdot \mu_e(x)$$

Where λ_e denotes the weight assigned to hyperedge e, representing its relative importance.

3.2.4 Conceptual Diagram

A conceptual model (Figure 1) illustrates the forest of criteria trees, the design alternatives, and the hyperedges linking multiple nodes across trees. Fuzzy membership values are visually mapped to enhance interpretability and to demonstrate the relational structure of the evaluation framework.

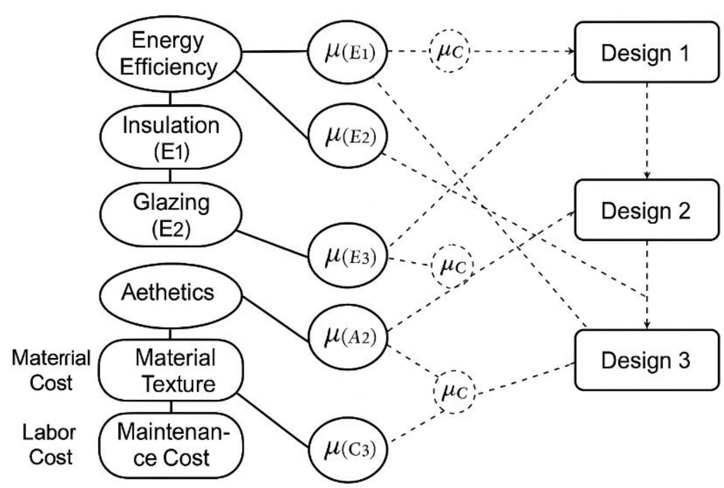

Figure 1. Conceptual Diagram

4. Proposed Model and Hypotheses

This section develops the mathematical foundation of the proposed ForestSoft Hypergraph Model, describing its construction, scoring logic, and implementation in facade design evaluation. The model unifies fuzzy membership, hierarchical trees, and relational hyperedges, providing a multi-layered approach to decision-making. Numerical and sensitivity analysis examples illustrate the method's flexibility and practical relevance.

4.1 Mathematical Model

Let $U = \{D_1, D_2, \dots, D_n\}$ be the universal set of facade design alternatives.
Let $\mathcal{F} = \{\mathcal{T}_1, \mathcal{T}_2, \dots, \mathcal{T}_k\}$ represent a forest of decision criteria trees, where each tree $\mathcal{T}_i$ contains parameters e_{ij}. Associated with each parameter e_{ij} is a fuzzy membership function:

$$\mu_{e_{ij}}: U \to [0,1]$$

which quantifies the degree to which design $D \in U$ satisfies criterion e_{ij}.
Let $\mathcal{H} = (V, E)$ be a hypergraph over the criteria set $V = \bigcup \mathcal{T}_i$, with hyperedges $e \in E \subset \mathcal{P}(V)$ representing multi-criteria interdependencies.

4.2 Membership Evaluation

(a) TreeSoft Set Membership

For a given design $D \in U$ and a criteria tree $\mathcal{T}_i$, the design's aggregated satisfaction score over that tree is computed as:

$$\mu_{\mathcal{T}_i}(D) = \sum_{e_{ij} \in \mathcal{T}_i} w_{ij} \cdot \mu_{e_{ij}}(D)$$

where $w_{ij} \in [0,1]$ is the weight of criterion e_{ij}, satisfying $\sum w_{ij} = 1$ within each tree.

(b) Hyperedge Membership

For each hyperedge $e = \{e_1, e_2, \dots, e_m\} \subset V$, the fuzzy membership of design D with respect to that hyperedge is:

$$\mu_e(D) = \min_{e_k \in e} \mu_{e_k}(D)$$

This implements fuzzy logic conjunction (AND), requiring all criteria in the hyperedge to be adequately satisfied.

(c) Overall Score of Design

Each hyperedge is assigned an importance weight $\lambda_e \in [0,1]$, satisfying $\sum \lambda_e = 1$. The total evaluation score for a design is computed as:

$$\text{Score}(D) = \sum_{e \in E} \lambda_e \cdot \mu_e(D)$$

This score serves as the final decision metric to rank and select the optimal design.

4.3 Hyperedge Membership Example

Consider the hyperedge:

$$e = \{ \text{Insulation (E1), Material Cost (C1)} \}$$

representing the relational constraint: prefer designs with high insulation and low cost.
Suppose:

1. The fuzzy membership for insulation is:

$$\mu_{E1}(D) = 1 - \frac{U_D - U_{\min}}{U_{\max} - U_{\min}}$$

2. The fuzzy membership for cost is:

$$\mu_{C1}(D) = 1 - \frac{C_D - C_{\min}}{C_{\max} - C_{\min}}$$

Then:

$$\mu_e(D) = \min(\mu_{E1}(D), \mu_{C1}(D))$$

This models the trade-off: a design with excellent insulation but high cost will receive a low membership for this hyperedge.

5. Results and Discussion

This section presents the outcomes of applying the ForestSoft Hypergraph framework to a set of facade design alternatives. The evaluation includes simulation-based data collection, fuzzy membership computation, hyperedge analysis, and comparative study with a classical methods.

5.1 Simulation Data

Design alternatives D1, D2, D3 were evaluated using EnergyPlus and Radiance simulations to extract key performance indicators. The results are summarized in Table 1.

Table 1: Simulation Data

Design	U-value (W/m^2 K)	Material Cost ($\$/m^2$)	Aesthetic Score
D_1	0.25	500	0.8
D_2	0.35	300	0.9
D_3	0.45	200	0.6

Using normalization and fuzzy logic functions, we derived fuzzy membership values for each criterion (Table 2).

Table 2: Membership Scores

Design	Energy	Aesthetics	Cost
D_1	0.80	0.80	0.20
D_2	0.60	0.90	0.70
D_3	0.40	0.60	0.90

These values feed into the hypergraph evaluation model.

5.2 Hyperedge Membership Evaluation

Hyperedges are defined to capture relational dependencies:

e_1 : {E1, C1} - insulation and material cost

e_2 : {A1, A2} - aesthetic harmony
e_3 : { E1, E2, C1, A1} - balanced performance

The minimum operator is applied across all criteria in each hyperedge to compute membership scores (Table 3).

Table 3: Hyperedge Membership Values

Design	μ_{e_1}	μ_{e_2}	μ_{e_3}
D1	0.20	0.80	0.20
D2	0.60	0.90	0.60
D_3	0.40	0.60	0.40

Assuming equal weights for all hyperedges, the final scores are:

$$\text{Score}(D_i) = \frac{1}{3} \cdot \left(\mu_{e_1} + \mu_{e_2} + \mu_{e_3}\right)$$

Thus:

1. $\text{Score}(D_1) = 0.40$
2. $\text{Score}(D_2) = 0.70$
3. $\text{Score}(D_3) = 0.53$

5.3 Sensitivity Analysis

To examine the model's robustness, we vary the cost of D_2 from \$300 to \$350. This shifts $\mu_{C1}(D_2)$ from 0.70 to approximately 0.50, thereby reducing its overall score. This sensitivity illustrates the impact of key parameters and reinforces the importance of accurate data normalization and weighting.

5.4 Hypotheses

To validate the efficacy of the proposed model, we formulate the following hypotheses:

H1: ForestSoft Hypergraphs effectively model hierarchical and relational dependencies among evaluation criteria in facade design.

H2: The integration of simulation-based data (EnergyPlus and Radiance) within the ForestSoft Hypergraph framework enhances evaluation accuracy compared to traditional MCDM methods.

These hypotheses are empirically evaluated in subsequent sections through comparative analysis and design ranking under varying conditions.

5.5 Comparative Analysis with Classical MCDM Models

To evaluate the performance and robustness of the proposed approach, we compare its results with multiple widely used MCDM models. Each model differs in how it handles criteria aggregation, interdependence, and uncertainty. The comparison includes the following methods:

1. AHP
   A pairwise comparison technique that uses eigenvalue calculations to derive criteria weights. It assumes criteria independence and hierarchy but lacks relational modeling.
2. TOPSIS
   Evaluates alternatives based on their relative distance to an ideal and anti-ideal solution. It does not model interdependence or hierarchy.
3. Fuzzy AHP
   Extends AHP by incorporating fuzzy logic to handle uncertainty in judgment. It improves upon classic AHP but still lacks explicit relational modeling.
4. PROMETHEE
   A ranking-based method using preference functions and outranking relationships. It allows partial preference modeling but does not consider hierarchical or multi-relational structures.

Evaluation Dataset

Each method was applied to the same dataset (Table 1 and Table 2), using the normalized or fuzzified scores. For methods requiring weights criteria, equal weights were assumed unless otherwise noted. Tables 4 and 5 illustrates the models' output comparison.

Table 4: Comparative Scores Across MCDM Models

Design	ForestSoft Hypergraph	AHP	Fuzzy AHP	TOPSIS	PROMETHEE
D_1	0.40	0.65	0.58	0.62	0.60
D_2	0.70	0.70	0.72	0.78	0.74
D_3	0.53	0.59	0.60	0.55	0.57

The evaluation revealed that all methods consistently ranked design D_2 as the top alternative, highlighting its balanced performance across energy efficiency, cost, and aesthetics. In contrast, the ForestSoft Hypergraph model assigned a notably lower score to D_1 compared to other methods, reflecting its strict enforcement of inter-criteria constraints—specifically, the trade-off between high insulation quality and elevated material cost. Models like TOPSIS and PROMETHEE tended to score D_1 more favorably, as they lack mechanisms to penalize violations of such relational dependencies. While Fuzzy AHP improved over the classical AHP by mitigating subjective bias through fuzzy logic, it still treated each criterion in isolation. Unlike these methods, the ForestSoft Hypergraph framework integrates both hierarchical structures and multi-criteria interactions, allowing it to more effectively identify and penalize trade-off inconsistencies.

Table 5. Strengths of ForestSoft Hypergraph Over Traditional Methods

Feature	ForestSoft Hypergraph	AHP	TOPSIS	Fuzzy AHP	PROMETHEE
Handles hierarchy	√	√	X	√	X
Models inter-criteria relations	√	X	X	X	X
Captures fuzziness/uncertainty	√	X	X	√	√
Penalize constraint violations	√	X	X	X	X

5.6 Comparative Conclusion

The comparative evaluation highlights the superiority of the proposed ForestSoft Hypergraph model in capturing the complexity of facade design assessments, where criteria are both hierarchically structured and relationally interconnected. Unlike traditional multi-criteria decision-making (MCDM) methods, which serve well for baseline analysis, these conventional approaches fall short in enforcing conditional dependencies such as requiring high insulation to be accompanied by reasonable cost or in flexibly adapting to fuzzy and simulation-derived inputs. The ForestSoft framework uniquely bridges these gaps by integrating hierarchical soft set theory with hypergraph-based relational modeling, offering a more realistic and context-aware decision-support system, particularly suited to architectural and engineering applications.

The approach further demonstrates several strategic strengths. It preserves the structural integrity of nested evaluation criteria, thereby maintaining hierarchical fidelity that flat models overlook. It also excels in capturing non-obvious, multi-criteria interactions something rarely achieved by methods like AHP or TOPSIS. The incorporation of fuzzy logic contributes to robust modeling by mitigating binary decision thresholds and enabling gradual, nuanced assessment of performance metrics. Although the current implementation performs well on small- to mid-scale datasets, scalability remains a consideration, especially for high-dimensional or city-scale design problems, where computational efficiency may demand parallelization or structural simplification. Sensitivity testing confirmed that the model behaves predictably under parameter variation, reaffirming its reliability and the importance of accurate input normalization and data calibration.

6. Conclusion and Recommendations

6.1 Conclusion

This paper ultimately introduces ForestSoft Hypergraphs as an innovative and comprehensive framework for evaluating facade design alternatives. By fusing soft hierarchical sets with hypergraph theory, the model offers a unified and dynamic structure capable of representing both complex criteria relationships and simulation-informed performance data. Compared to traditional MCDM tools, it provides enhanced interpretability, relational coherence, and accuracy in identifying optimal designs that balance energy efficiency, cost-effectiveness, and visual appeal. The case study confirms its practical viability in handling real-world architectural decision-making scenarios where conflicting objectives and uncertain data are common.

6.2 Strategic Recommendations

To expand the utility and applicability of this framework, several forward-looking initiatives are recommended:

1. Incorporate the ForestSoft Hypergraph model into existing parametric design environments such as Rhino/Grasshopper, allowing real-time evaluation and feedback within early-stage architectural workflows.
2. Conduct field experiments and post-occupancy evaluations to validate the simulation outputs against real performance data, thereby reinforcing the model's credibility and improving predictive accuracy.
3. Implement computational optimizations, including parallelized fuzzy evaluation and graph-based simplification techniques, to enable the application of the model to large-scale and multi-building design contexts.
4. Extend the model to encompass additional decision-making dimensions such as environmental sustainability, user comfort, and full lifecycle cost assessment, paving the way for holistic and future-ready design optimization.

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