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Development of a hybrid multi-criteria decision-making framework (AHP-TOPSIS) for evaluating and selecting optimal restoration solutions (digital and physical)

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ABSTRACT

Sustainable development and energy efficiency improvement in the building sector require complex and multifaceted decision-making in the renovation process. Aiming to overcome the challenges of evaluating multiple renovation options that include both physical changes (such as insulation and mechanical systems) and the integration of digital solutions (such as smart energy management systems), this research develops a novel hybrid framework based on multi-criteria decision-making (MCDM) methods. The framework combines the analytical hierarchy process (AHP) to extract and accurately weight the evaluation criteria – considering economic, technical, environmental and occupant comfort dimensions – and the TOPSIS method to finally rank the solutions. AHP ensures that the weights of the criteria reflect the real preferences of the stakeholders, while TOPSIS makes the selection process transparent and repeatable by identifying the optimal solution close to the ideal solution. The application of this model to a residential renovation example demonstrates its effectiveness in selecting the most optimal combination package to increase building performance and resource efficiency.

Introduction

-Problem Definition:

The building sector, especially the existing residential infrastructure, contributes significantly to energy consumption and carbon emissions. With increasing regulatory requirements and the need for communities to increase energy efficiency and improve the quality of life of residents, the renovation process is no longer limited to superficial repairs, but requires a comprehensive and strategic approach to integrate new technologies. Currently, deciding on the best set of renovation measures – which includes traditional physical decisions (such as insulation or window replacement) and the integration of digital solutions (such as sensors, intelligent building management systems, and BIM for renovation) – faces increasing complexity.

Selecting the optimal set of solutions is a classic multi-criteria decision-making (MCDM) problem, as multiple criteria with conflicting objectives (such as initial cost versus long-term energy savings, or ease of installation versus level of technological complexity) must be evaluated simultaneously. Traditional evaluation methods often fail to model these conflicts and fail to properly translate the subjective preferences of experts and stakeholders into objective calculations. This leads to the selection of solutions that may be cost-effective in one dimension (such as cost) but not optimal in another (such as long-term performance or usability).

Despite the existence of MCDM methods such as AHP and TOPSIS, there is a research gap in the development of a coherent hybrid framework that specifically focuses on the separation and accurate weighting of “physical” and “digital” criteria in the context of residential renovation. Most studies either focus on only one aspect (digital only or physical only) or use a single method that lacks the comparative weighting power of AHP or the final ranking power of TOPSIS. The fundamental need is to develop a structured model that can evaluate a set of renovation options based on a well-defined hierarchy of criteria, efficiently, and taking into account the interactions between digital and physical components.

Therefore, the main problem of this research is to develop and validate a hybrid AHP-TOPSIS framework that allows for the systematic evaluation and optimal selection of renovation solutions (including both digital and physical dimensions) in residential projects. The ultimate goal is to provide a precise tool for project managers and building owners to optimize their investments in a way that ensures maximum long-term returns in energy consumption, comfort, and building durability using a transparent and data-driven decision-making process.
Problem Classification:

2-1 First Paper:
Main Topic: Multi-Criteria Decision Making in Evaluating Digital Resilience Solutions: Using AHP and TOPSIS
Resilience in urban infrastructure, especially buildings, is no longer just a physical approach to dealing with natural disasters or crises; it increasingly relies on the capabilities of digital systems. These digital solutions include smart sensor networks for monitoring the condition of structures, AI-based damage prediction platforms, and emergency communication systems that are activated when an event occurs. However, evaluating these solutions is challenging because their success criteria include high uncertainty, algorithmic interdependencies, and the need for computational infrastructure that make traditional evaluation difficult.

The multidimensional and contradictory nature of evaluating these systems places them at the heart of multi-criteria decision-making (MCDM) issues. A resilience system may be very fast in terms of response time (performance criterion), but vulnerable in terms of cybersecurity (risk criterion) or have a high initial implementation cost. To overcome these contradictions, there is a need for a hierarchical analytical structure; hence, AHP (Analytical Hierarchy Process) is chosen as an ideal tool to structure the complexity of the problem, extract criteria from the experts’ perspectives, and assign precise and logical weights to each of these criteria.

After AHP converts the weights extracted from the experts' mental space into quantitative data, the final evaluation stage requires a tool for the final ranking of the different digital resilience options. TOPSIS (Preference Ranking Technique Based on Similarity to the Ideal Solution) is used for this purpose. TOPSIS provides a relative score for each solution by calculating the distance of each option from the ideal solution (best performance across all criteria) and the distance from the negative solution (worst performance). Therefore, the AHP-TOPSIS combination forms a complete framework that both manages weighting properly and ultimately leads to a final and justifiable ranking for the optimal selection of digital retrofit solutions in infrastructure projects.

2-2 Second article:

Main topic: A multi-criteria decision-making framework for residential building renovation using pairwise comparison and TOPSIS methods

2.2.1-Increasing demand for efficient renovation and decision-making complexity

With the increasing aging of the global residential building stock and increasing concerns about energy efficiency and occupant comfort, the demand for comprehensive and effective renovation programs has become a necessity. Successful renovation requires the selection of a set of interventions that must simultaneously meet multiple considerations such as initial costs, return on investment (ROI), energy consumption reduction, property value enhancement, and occupant satisfaction. This situation transforms the selection process from a simple decision into a complex problem in which conflicting objectives must be managed in a coherent manner.

2.2.2- Challenge in determining criteria weighting and the need for deductive methods

The biggest challenge in large-scale renovations is the prioritization and correct weighting of different criteria. Criteria such as "thermal comfort" or "environmental sustainability" are subjective and qualitative in nature and are difficult to measure precisely. Standard analytical methods are often unable to capture and quantify the qualitative judgments of experts and stakeholders. As a result, a research gap is felt in how to derive valid and reliable weights for these criteria, before the final ranking stage.

2.2.3- The necessity of a hybrid AHP-TOPSIS framework

To fill this gap, the use of a hybrid MCDM framework is essential. The pairwise comparison method (which is the core of the AHP hierarchical process) provides a powerful tool for converting experts' subjective judgments about the relative importance of criteria into structured numerical weights. After the weights of the criteria have been established through pairwise comparisons, there is a need for a method to evaluate and rank different renovation options (e.g. different energy package options, comfort package, etc.) based on these weights. TOPSIS method is chosen as the final ranking tool due to its ability to find the optimal solution that is closest to the ideal solution and furthest from the undesirable solution.

2-2-4- Research Objective and Expected Contribution

The main objective of this research is to develop and validate an operational framework that, by integrating the power of pairwise comparison structuring (AHP) and the power of TOPSIS ranking, facilitates the process of optimal selection of renovation interventions in residential buildings. This framework allows decision makers to select the best renovation package that provides maximum benefits against existing constraints (financial and technical), while maintaining transparency in the weighting of qualitative and quantitative criteria. The contribution of this research is to provide a comprehensive decision-making model to guide renovation investments aimed at sustainability and improving building performance.

Mathematical Modeling:

3-1 First Article:

3-1-1-Definition of the Decision Space and the Set of Options

Mathematical Modeling The decision-making process begins with a precise definition of the problem space. First, all potential solutions for digital resilience are identified and defined as a set of alternatives. These alternatives can include the implementation of sensor-based monitoring systems, the use of machine learning-based damage prediction models, or a combination of these. At the same time, all criteria that are critical to evaluating the success of these solutions are determined and categorized. These criteria should cover various dimensions of technical efficiency, security considerations, reliability, and implementation costs.

3-1-2-Hierarchical Structuring and Prioritization with AHP

After determining the criteria, modeling moves towards structuring them, which is done by AHP. In this step, all criteria are organized hierarchically, with the main objective (selection of the optimal solution) at the top, and the main criteria and their sub-criteria at lower levels. The heart of this section is the process of pairwise comparisons; in this step, the relative importance of each criterion relative to another criterion of the same level is assessed by experts based on a standard numerical scale. These comparisons lead to the formation of comparison matrices whose goal is to extract the final weight vector for each criterion.

3-1-3-Calculating consistency and extracting the final weight

After completing the pairwise comparison matrices, a crucial step in mathematical modeling is to calculate the consistency of the judgments made. This check ensures that the prioritizations applied by the experts are logical and free from fundamental contradictions. If the degree of inconsistency exceeds a certain threshold, the comparison process must be repeated. After confirming the compatibility, the final weight (main priority) for each criterion is extracted using specific algebraic methods based on matrix normalization. These weights serve as key inputs for the next stage of modeling.

3-1-4-Forming the evaluation matrix and determining ideal and negative solutions in TOPSIS

With the extracted weights, the model enters the TOPSIS phase. In this stage, the performance of each of the digital retrofit alternatives against each of the criteria is recorded to form a complete performance matrix. Then, using the weights calculated in the previous stage, this matrix is normalized to eliminate the effect of different measurement scales. Next, two reference points are defined in the decision space: the "positive ideal solution" which represents the best possible performance across all criteria (exploiting maximum values) and the "negative ideal solution" which represents the worst possible performance across all criteria (exploiting minimum values).

3-1-5-Calculating the distance and final ranking

The final step of the modeling is to calculate the distance of each alternative from the two ideal reference points defined in the previous paragraph. For each solution, the Euclidean distance (or similar) from the positive ideal solution and the distance from the negative ideal solution are calculated. Using these two distances, a "relative proximity score" is determined for each alternative, indicating how close each solution is to the desired conditions and how far away from the undesirable conditions it is. Finally, the alternatives are ranked in descending order based on this final score, and the most optimal digital retrofit solution is determined for implementation.

3-2 Second Article:

3-2-1-Definition of the decision set and the initial performance matrix

Modeling begins with a complete definition of the decision structure. A set of renovation alternatives (e.g., different combinations of technical packages such as insulation, heating system upgrades, and the use of new materials) are considered as the main variables. Then, a set of criteria (e.g., cost, energy savings, lifespan, and occupant satisfaction) covering different aspects of the renovation are defined. The performance of each alternative against each criterion is recorded in a raw evaluation matrix using available data or engineering estimates.

3.2.2-Determining criterion weights through pairwise comparison and normalization

The next crucial step is to determine the relative importance of the criteria, which is done using pairwise comparison logic. In this process, experts compare the importance of one criterion to another in pairs. These comparisons are reflected in matrices, and then, using specific methods in matrix algebra, the final weight of each criterion is calculated. In this step, the values in the raw performance matrix are also normalized based on the type of criterion (benefit or cost) so that all inputs are on a common, unitless scale.

3-2-3-Definition of reference solutions in the normalized space

After normalizing the data and determining the weights extracted from the pairwise comparison, the model leans towards the TOPSIS algorithm. In this section, two critical reference points are defined in the criteria space. The "positive ideal solution" is the point at which each criterion shows the best possible performance (most energy savings, lowest cost, highest satisfaction score). In contrast, the "negative ideal solution" is the point at which each criterion records the worst possible performance. These two points serve as the final reference for evaluating the relative efficiency of the alternatives.

3-2-4-Calculating the distance and determining the relative proximity
Mathematical modeling in this step calculates the Euclidean distance of each renovation alternative from two defined reference points. The distance from the positive ideal solution (closeness to the optimum) and the distance from the negative ideal solution (distance from the worst case) are carefully measured. Then, a key index called "relative proximity to the ideal solution" is calculated for each alternative. This index shows a balance between proximity to the best case and distance from the worst case and expresses the overall quality of each renovation package.

3-2-5-Final ranking and optimal conclusion
In the last modeling step, all renovation alternatives are ranked based on the "relative proximity" index obtained. The alternative that obtains the highest value of this index is considered the most optimal renovation solution for residential buildings, as it has achieved the best balance between all quantitative and qualitative criteria, according to the prioritized weights. This final output provides an objective and analytical basis for final decision-making

. 1- Problem-solving method:
4-1First article:
-4-1-1Weight assignment phase with AHP method (pairwise comparison)
The problem-solving method begins with the criterion importance determination phase, which is managed by the Analytic Hierarchy Process (AHP). First, the digital resilience problem structure is arranged hierarchically, with the ultimate goal (choosing the best solution) at the top, and a set of evaluation criteria (such as data accuracy, technical complexity, and maintenance cost) at lower levels. Then, using the pairwise comparison tool, experts systematically determine the relative weight of each criterion compared to its peers. This process leads to the creation of a final weight vector that indicates the importance of each criterion in the overall decision-making model.

-4-1-2Normalization phase and decision matrix formation (entry into TOPSIS)
After obtaining accurate weights from AHP, the model enters the performance evaluation phase. First, the performance of each of the digital retrofit solutions (alternatives) against all criteria is recorded and an initial performance matrix is formed. This data must be normalized to eliminate different measurement scales and determine the true impact of the weights. At this stage, based on the type of criterion (for example, utility criteria such as "error reduction rate" and cost criteria such as "implementation time"), the data is transformed so that they all fall into the same evaluation space.

-4-1-3Final ranking phase with TOPSIS
The final step is to use the TOPSIS algorithm for the final ranking of the solutions. Using the weights extracted in the AHP stage, this method calculates the distance of each solution from two reference points: the positive ideal solution (best possible performance) and the negative ideal solution (worst possible performance). Finally, a relative closeness index is calculated for each solution, indicating how close that solution is to the optimal state. The solution that obtains the highest relative closeness score is proposed as the most efficient digital retrofit strategy for implementation.

4-2Second article:

-4-2-1Renovation criteria prioritization stage using pairwise comparison (AHP)
The problem-solving method begins by creating a hierarchical decision-making structure, with the final goal, namely "optimal selection of the residential renovation package", at the top. This structure includes key evaluation criteria such as economic (initial cost, return on investment), technical (improved thermal performance, durability of the structure), and environmental (reduced energy consumption) aspects. Using pairwise comparison logic, experts systematically compare the relative importance of each criterion against

other criteria at the same level. These comparisons are recorded in the form of matrices and finally, by applying the weight calculation methods in AHP, the priority or final weight of each criterion in determining the final result is determined.

-4-2-2Formation of the normalized performance matrix and definition of reference points with TOPSIS

After determining the weights of the criteria, the practical evaluation stage of the renovation alternatives (different technical packages) begins. The performance of each renovation package against each quantitative and qualitative criterion is evaluated and the data is recorded in a performance matrix. This matrix must be normalized so that different scales do not affect the results. Then, the TOPSIS algorithm is activated and two key reference points are defined in the decision space: the “positive ideal solution” which represents the best possible performance across all criteria, and the “negative ideal solution” which represents the worst possible performance.

-4-2-3Relative Distance Calculation and Final Ranking Step

In the final step, TOPSIS calculates the distance of each proposed renovation package from two defined reference points; one is the distance from the positive ideal and the other is the distance from the negative ideal. Using these distances and the weights obtained from AHP, a relative proximity index is calculated for each renovation alternative. This index shows how close each option is to the best case and how far it is from the worst case simultaneously. Finally, the renovation packages are ranked in descending order based on this index, and the package that scores the highest is selected as the optimal strategy for the renovation of the residential building.

1.Literature Review

5-1First Article:

-5-1-1Literature Review and Strengths of the Hybrid Model

The current research literature in the field of building renovation and retrofitting has increasingly shifted towards the use of multi-criteria decision-making models (MCDM). The main strength of the hybrid AHP-TOPSIS model in this context is its ability to combine two crucial aspects: First, AHP allows for the consideration of expert opinions against the uncertainties of the initial data by providing a systematic process for assigning subjective weights through pairwise comparisons. Second, TOPSIS allows for the objective ranking of technical retrofit alternatives (such as the use of sensors, BIM modeling, or smart materials) by providing a quantitative measure based on the distance from ideal solutions. This combination has enabled a comprehensive assessment of qualitative and quantitative aspects in complex digital retrofit environments.

-5.1.2Identification of common methodological weaknesses and limitations

However, the existing literature has weaknesses that need attention. One major weakness is the extreme sensitivity of the results to the accuracy of the inputs to the AHP phase; small changes in pairwise comparison judgments can lead to significant changes in the final TOPSIS ranking, which requires the use of robust consistency measurement methods. Also, in many studies, criteria related to “technology adoption” or “long-term flexibility” of digital models are not properly integrated into the AHP weighting phase, and an excessive focus on short-term cost-performance criteria is seen. This leads to ignoring the long-term strategic benefits of digital retrofitting.

-5.1.3Pathways for Future Research and Model Development

Future research in this area should focus on overcoming the current weaknesses. Future research directions should include the integration of fuzzy or grey systems techniques into AHP or TOPSIS to better handle the inherent uncertainty of data related to renovation projects. Furthermore, future studies need to go beyond the standard AHP-TOPSIS models and move towards dynamic approaches, such as Dynamic MCDM or integration with techniques such as ANP (Analytic Network Process) to consider interdependencies between criteria. Also, validating these models with larger field data in real digital retrofit projects could greatly enhance the practical validity of these frameworks

5-2 Second article:

5-2-1-Framework, strengths and added value of the hybrid model

The research literature on optimizing the renovation process of residential buildings relies heavily on the use of multi-criteria decision-making (MCDM) frameworks, and the combination of the pairwise comparison method (AHP) with TOPSIS is considered one of the most powerful approaches. The main strength of this model lies in its ability to transform the subjective decisions of experts about the importance of parameters such as sustainability, cost, and technical performance (which are weighted through AHP) into a structured and justifiable final ranking by TOPSIS. This framework allows project managers to select from among different renovation packages the option that is both technically superior and most aligned with the project's financial and strategic priorities.

5-2-2-Identification of structural and methodological weaknesses

Despite its widespread application, the existing literature in this area faces limitations. The key weakness of the AHP-TOPSIS model is the strong dependence on human inputs in the first stage; that is, the final accuracy of the model is highly dependent on the consistency and impartiality of the comparative judgments of experts. In addition, many early studies have considered dynamic environmental criteria and long-term implementation risks (such as changes in energy regulations or fluctuations in material prices) as fixed and have failed to properly model the time-varying nature of renovation projects, which reduces the accuracy of the model's prediction.

5.2.3-Future Research Perspective and Model Development

Future research in this field should focus on enriching the model with concepts of dynamics and uncertainty. The main direction should be towards integrating fuzzy sets or using gray sets in AHP to more effectively manage the ambiguity inherent in the evaluation of renovation quality criteria. Also, to overcome the assumption of independence of criteria in traditional AHP, future research should move towards using the Analytic Network Process (ANP) to fully consider the interdependencies between economic, technical, and environmental criteria in residential building renovation and provide a more optimal and realistic solution.

Evaluation axis	**Residential Renovation Domain (General)**	**Digital Resilience Domain**	**Key Research Gaps**
Model strengths	Ability to use subjective weighting (AHP) and objective ranking (TOPSIS) to select the overall renovation package.	Strong application in evaluating technical parameters - data accuracy and complexity of implementing new technologies.	Incorporation of dynamic technology variables: How digital technologies affect the long-term sustainability of innovation is not yet properly modeled in AHP.
Methodological weaknesses	High sensitivity to human inputs (AHP judgments); ignoring long-term implementation risks.	Over-focusing on short-term efficiency (sensor performance and modeling accuracy) and ignoring user acceptance.	Uncertainty modeling: Need to use more advanced methods (such as Fuzzy AHP) to manage uncertainty in the evaluation of emerging technologies.
Modeled criteria	Economic (cost/return on investment) and basic performance (thermal/structural) metrics	Technical-digital metrics (BIM complexity, cyber maintenance requirements, software upgradeability)	Full integration of criteria: Lack of a standard model that evaluates digital and traditional weights in an integrated manner and taking into account interdependencies.
Proposed future research	Move towards dynamic models (Dynamic MCDM) to account for market and regulatory changes over the life of the project.	Need for broader validation of models on real-world retrofit projects (Empirical Validation) with a focus on cyber and operational risks.	Development towards ANP/Dynamic TOPSIS: Urgent need to use ANP to consider interdependencies (Feedback Loops) between criteria in both domains.

Conclusion:

The existing research literature clearly shows that the combination of Analytic Hierarchy Process (AHP) for subjective weighting and the ranking method using the distance from the ideal solution (TOPSIS) for the final ranking has provided a solid and reliable basis for decision-making in complex residential building renovation projects. This combined model (AHP-TOPSIS) has been very efficient in evaluating different renovation options in terms of cost-performance due to its hierarchical structure and its ability to document expert judgments.

However, a major weakness common to both domains (general renovation and digital retrofitting) is the static nature and high sensitivity of the traditional AHP methodology to initial inputs. This weakness is a serious limitation in the era of digital transformation where retrofitting technologies (such as Building Information Modeling (BIM) or structural monitoring sensors) are changing rapidly. The literature still lacks an integrated framework that can effectively model the interdependencies between traditional criteria (e.g. thermal stability) and digital criteria (e.g. software upgradability) and also reduce the uncertainty inherent in long-term predictions.

Therefore, the final conclusion is that future advances in this field require a leap from traditional MCDM to dynamic and comprehensive models. Using ANP to understand the dependencies and employing fuzzy systems to reduce uncertainty will not only help improve the ranking accuracy in evaluating digital retrofit solutions, but also ensure that the selected retrofit packages are resilient and long-term sustainable in the face of future market and technological changes. This integration will be key to achieving an optimal retrofit strategy in residential buildings.

Resources

1. A multi-criteria decision-making framework for residential building renovation using pairwise comparison and TOPSIS methods
2. Multi-criteria decision making in evaluating digital retrofitting solutions: utilising AHP and TOPSIS