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Mona Hassan Soliman

Doctor of Architecture, Professor
Fayoum University
63514, Professor Dr. Mohamed Saeed Suleiman Str., Fayoum, Egypt
<https://orcid.org/0000-0002-8462-2194>

Abdullah Badawy Mohammed

PhD in Architecture, Associate Professor
Fayoum University
63514, Professor Dr. Mohamed Saeed Suleiman Str., Fayoum, Egypt
<https://orcid.org/0000-0002-5145-5756>

Asmaa Ali Zaki*

Master, Assistant Lecturer
Fayoum University
63514, Professor Dr. Mohamed Saeed Suleiman Str., Fayoum, Egypt
<https://orcid.org/0000-0001-9892-1200>

AHP-based sustainability evaluation of global nanomaterial-enhanced residential buildings using regionally weighted criteria from Egyptian experts

Abstract. The rapid global urbanisation and the construction sector's critical environmental footprint necessitate innovative, sustainable solutions, with nanotechnology emerging as a key enabler. Despite this potential, current research lacked a holistic, systematic evaluation framework for nanomaterial-enhanced residential buildings that integrated the specific regional priorities of developing nations. This study addressed this knowledge gap by developing and applying a four-dimensional assessment model (environmental, economic, technical, and social) using the analytic hierarchy process. The model weights were derived from 55 Egyptian experts in architecture and sustainability, ensuring the results reflect crucial regional demands. The analysis revealed that the Environmental Criterion was deemed the most critical dimension, receiving the highest weight (0.3427), closely followed by the Economic Criterion (0.2774). The Technical Criterion ranked third (0.2337), while the Social Criterion was the least influential (0.1462). This priority setting confirmed that Operational Energy Cost Reduction (0.0916) and Maintenance Cost Reduction (0.0820) are the most decisive factors for sustainable performance in the regional context. The model was applied to four global case studies to determine their sustainable performance and ranking. The Sur Falveng building Phase Change Material Glass came in first place with a score of (73.85%) due to its comprehensive and balanced performance. The Seitzstrasse building Vacuum Insulation Panels followed in second place (71.51%). The Strucksbarg housing complex featuring self-cleaning Lotus-Effect paint ranked third (68.28%). Conversely, the Escala Condominiums tower utilising nano microcomposite rebar ranked last (57.86%), confirming that structural applications received lower overall priority as they did not directly contribute to the dominant operational metrics. This research provided a practical, evidence-based

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*Corresponding author



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tool for architects and policymakers, highlighting the necessity of aligning nanotechnology selection with regional evaluation frameworks to guide future sustainable design decisions in emerging markets

Keywords: analytic hierarchy process; nanotechnology; regional priorities; building envelope; residential architecture

INTRODUCTION

The rapid expansion of the global population, coupled with accelerating urbanisation, has placed unprecedented pressure on the built environment. Cities are facing increasing demands for housing, infrastructure, and services, which in turn exert significant strain on natural resources and contribute to environmental degradation. In parallel, the construction sector has emerged as a key driver of greenhouse gas emissions, energy consumption, and waste generation, highlighting the urgent need for innovative and sustainable approaches. In this context, integrating advanced technologies such as nanomaterials into residential buildings offers a promising avenue to enhance sustainability, reduce environmental impact, and improve the quality of urban living.

Population growth and increasing urbanisation present major challenges for humanity. The urban population is expected to reach about 7 billion people by 2050, compared to 4.2 billion in 2018, with urban migration projected to intensify in developing nations, reaching 54% by 2030 (Khanna, 2020). In this context, the construction and building sector stands at the forefront of industries requiring radical solutions, given its pivotal role in environmental degradation and climate change. According to L. Cabeza *et al.* (2022), the building sector's share of total global greenhouse gas (GHG) emissions was 21% in 2019, and CO₂ emissions from buildings witnessed a 50% increase between 1990 and 2019. Further research by L. Chen *et al.* (2023), confirms the magnitude of this sector's environmental impact, as construction activities consume 36% of global energy and contribute 39% of global CO₂ emissions. It is also responsible for producing about 40% of solid waste (Wang *et al.*, 2024). These figures underscore the necessity of finding innovative solutions to mitigate the environmental footprint of buildings. The concept of building sustainability, which aims to achieve a balance between environmental, economic, and social needs throughout a building's lifecycle, has thus become an imperative for achieving sustainable urban development.

In the search by S. Verma *et al.* (2022) for innovative and sustainable solutions, nanotechnology has emerged as a promising technique that could revolutionise the construction sector. This technology enables the enhancement of traditional materials' properties at the atomic and molecular levels, leading to increased building energy efficiency, improved durability, and better resistance to environmental factors. It also provides additional functionalities such as self-heating, anti-fogging, and the integration of structural safety. For example, studies have

shown that applying nanomaterials in residential buildings can increase energy efficiency by up to 30%, making them a fundamental component in achieving green and sustainable building goals. Furthermore, nano-insulation materials, such as aerogel and Vacuum Insulation Panels (VIPs), have demonstrated an ability to provide high thermal resistance with minimal thickness, contributing to the design of zero-energy buildings, which subsequently leads to reduced carbon emissions and improved environmental performance (Casini, 2020).

Nevertheless, despite the potential benefits of nanotechnology, there remains a lack of research that provides a comprehensive and systematic evaluation of its sustainable performance at the residential building level. Studies often focus on assessing separate technical aspects, such as mechanical properties or energy efficiency, without integrating them into a holistic evaluation framework that considers all dimensions of sustainability. Historically, sustainability assessment primarily relied on the triple bottom line (TBL) concept, which focuses on environmental, economic, and social factors (Mavi *et al.*, 2021). Decision contemporary research increasingly suggests that sustainable decision-making in the construction sector requires a more comprehensive framework that extends beyond these three dimensions. There is a growing consensus in the literature on the necessity of a crucial fourth dimension: technical performance (Aghazadeh & Yildirim, 2024). This dimension includes structural efficiency, quality standards, durability, and material lifespan. This dimension is critically important, as nanotechnology directly improves it, as noted by A. Oke *et al.* (2019), preventing premature failures and reducing the need for frequent replacement. This, in turn, contributes to achieving the other three dimensions of sustainability: it reduces resource consumption and waste (environmental dimension), lowers long-term maintenance costs (economic dimension), and enhances the safety and comfort of building occupants (social dimension). True sustainability requires a balance among these four dimensions: environmental, economic, social, and technical (Bhuiyan & Hammad, 2023).

This complexity, involving multiple and often conflicting criteria, makes the selection and evaluation of new materials and technologies an inherent multi-criteria decision problem. Addressing this requires adopting multi-criteria decision-making (MCDM) methodologies, as noted S. Khoshnava *et al.* (2018) and A. Rahim *et al.* (2021), which provide structured computational tools and mathematical



techniques for effectively evaluating multiple performance criteria. These methodologies are particularly effective in dealing with the complex numerical challenges associated with selecting sustainable alternatives.

Based on the foregoing, this research aimed to bridge this knowledge gap by providing a comprehensive and objective assessment of the sustainable performance of nanotechnology applied in residential buildings. The novelty of this research lies in providing a systematic framework that directly links the technical performance of nanotechnologies to local priorities, offering architects and researchers a practical tool for making more informed design decisions in the future and realising the vision of sustainable nano-architecture.

MATERIALS AND METHODS

This study adopted a multi-stage methodology to evaluate the sustainable performance of nanotechnology-enhanced residential buildings from a specific regional perspective. The approach was systematically structured around three main phases: (1) defining the criteria and indicators, (2) developing and weighting the evaluation model, and (3) applying the model to global case studies.

To define the criteria used, a rigorous and staged research methodology was followed to ensure comprehensiveness in the selection of studies for in-depth review. This included a systematic search across reliable academic databases such as ScienceDirect, Scopus, and Web of Science. A combination of keywords related to “sustainable building materials”, “Multi-Criteria Decision-Making (MCDM) methods”, and “evaluation criteria/frameworks” were utilised. The search was restricted to articles published between 2012 and 2024 that explicitly used MCDM methodologies to assess sustainable building material applications. Following initial filtering and the removal of duplicates, the remaining studies underwent a two-stage manual screening (reviewing titles and abstracts, followed by a full-text review) to ensure complete alignment with the study’s scope. This process resulted in the selection of 15 comprehensive studies for in-depth review, which formed the foundation for defining the final criteria and indicators.

Based on the comprehensive review of existing evaluation frameworks, the collected criteria were classified into the four main dimensions of sustainability: Environmental, Economic, Social, and Technical. The purpose of this classification was to provide a holistic framework for experts and sustainability stakeholders. To ensure the categorisation was comprehensive, care was taken to include criteria that captured the superior performance offered by nanomaterials, such as enhanced durability, thermal improvements, and weather resistance, which represent unique technical advantages of these materials. The potential for some criteria to intersect or influence more than one dimension of sustainability was also considered.

Based on the criteria derived from the systematic review, a multi-criteria evaluation model, designated “Nano-BSAM” (Nanomaterial Building Sustainability Assessment Model), was developed. The model employs a four-Level hierarchical structure where each Level represents a stage of analysis. Level 1 (Goal) represents the model’s ultimate objective: “Sustainability assessment of nanomaterial buildings”. Level 2 (Main criteria) comprises the four principal dimensions: Environmental, Economic, Technical, and Social. Level 3 (Sub-criteria) consists of nine sub-criteria, whose weights are derived from the aggregated weights of their underlying performance indicators. Finally, Level 4 (Performance indicators) includes 24 precise performance indicators, each representing a specific aspect of sustainable performance.

To introduce a regional context to the model, a pairwise comparison questionnaire based on the Analytic Hierarchy Process (AHP) was used to determine the relative weights of each criterion and indicator. The questionnaire was administered to a purposive sample of 55 Egyptian experts in architecture, environmental sustainability, and nano-building technologies. The rationale for selecting Egyptian experts was that their priorities directly reflect the specific climatic challenges (e.g., the urgent need for energy efficiency in a hot climate) and economic challenges (e.g., emphasis on operational and maintenance costs) prevalent in the region. This selection ensured that the derived weights were specialised and reflective of specific regional priorities, rather than generic ones. The participation of experts was entirely voluntary and complied with ethical principles (European Commission, 2021). To bolster the accuracy and reliability of the results, the consistency of all participants’ judgments was verified using the AHPcalc model (Goepel, 2024). This tool processes participant responses using the Eigenvector Method (EVM) to calculate consistency indices and the consistency ratio. Inconsistent responses (with a consistency ratio exceeding 10%) were reviewed with the participants in a feedback loop to ensure internal consistency, and these values were adjusted towards the ideal value suggested by the tool to improve consistency.

The Geometric Mean function in Excel was then employed to aggregate the individual expert judgments into a single, collective value for each pairwise comparison. This technique is the most common and reliable approach in group AHP as it preserves the internal consistency of the aggregated comparison matrices. These aggregated values were then directly entered into the Super Decisions V3 software interface to construct the final aggregated matrices. The Super Decisions programme automatically calculated the final relative weights for both the criteria and performance indicators, verifying that the final Consistency Ratio remained within the accepted threshold (less than 10%). Figure 1 presents the complete hierarchical structure of the Nano-BSAM model along with the final weights derived from the AHP analysis.

Goal	Sustainability assessment of nanomaterial building																							
Main criteria	Social [0.1462]			Technical [0.2337]					Economic [0.2774]			Environmental [0.3427]												
Sub-criteria	Social compatibility [0.1035]			Health and safety [0.0428]		Constructability [0.0440]		Comfort performance [0.0765]		Physical/functional performance [0.1132]		Operational & life cycle costs [0.1959]		Direct costs [0.0816]	Environmental impact [0.1509]	Resource efficiency [0.1918]								
Performance indicators	S1 local heritage compatibility (0.0241)	S2 Aesthetic aspect (0.0249)	S4 Skilled labour availability (0.0266)	S3 Local material availability (0.0279)	S5 Safety and security (0.0428)	T2 Ease of construction (0.0133)	T3 Maintainability & ease (0.0307)	T8 Acoustic comfort (0.0177)	T7 Luminous comfort (0.0206)	T6 Thermal comfort (0.0382)	T5 Fire resistance (0.0360)	T4 Weathering resistance (0.0366)	T1 Material durability (0.0406)	C5 Disposal or recycling cost (0.0223)	C3 Maintenance cost (0.0820)	C2 Operational energy cost (0.0916)	C4 Transportation cost (0.0205)	C1 Initial cost (0.0611)	E2 Recyclability and reusability (0.0345)	E1 Env. Impact reduction (0.0521)	E5 Air quality impact (0.0643)	E6 Renewable resource (0.0506)	E4 Resource efficiency (0.0542)	E3 Embodied energy efficiency (0.0870)

Figure 1. Nano-BSAM hierarchical evaluation model

Source: compiled by the authors

To fulfil the study’s objectives, four globally leading residential architectural projects that implemented nano-technologies were selected based on specific criteria. The selection criteria included: application to the building envelope and structure, diversity of nanotechnologies used, diversity of environmental conditions, and the addressing of a specific design problem. This methodology aimed to analyse the contribution of the nanomaterials and nano-technologies to the overall sustainability of these buildings, focusing on the problems they addressed. These buildings are: 1. The Seitzstrasse residential and office building in Munich, Germany (renovated 2004), which was the first building to achieve the “Ultra Low Energy House” standard in the city centre. The renovation utilised Vacuum Insulation Panels (VIPs) as the core nanotechnology in the building envelope, achieving exceptional thermal efficiency, increasing usable interior space, and improving natural light and thermal comfort. 2. The Strucksbarg housing complex in Hamburg, Germany (renovated 2007), a notable example of sustainable renovation. The project used an External Thermal Insulation Composite System (ETICS) integrated with Sto Lotusan coating based on nano “Lotus-Effect” technology, providing self-cleaning properties and weather resistance, thereby reducing periodic maintenance costs and preserving aesthetic appearance. 3. The Escala Condominiums residential tower in Seattle, Washington (completed 2009), an example of advanced engineering. The tower used high-strength, nano-enhanced rebar (ChrömX/MMFX2) as a solution to structural challenges. This material allowed for reduced rebar density compared to traditional

steel, facilitating concrete pouring and reducing execution time and effort. 4. The Sur Falveng residential building for the elderly in Domat/Ems, Switzerland (completed 2004), a pioneering example of innovative design in a mountainous climate. The building features a south-facing glass facade containing Phase Change Material (PCM) nanotechnology, which functions as a passive thermal storage. In winter, the material absorbs and stores heat, while in summer, it reflects excessive radiation to prevent overheating, significantly contributing to energy savings and maintaining a stable, comfortable internal environment.

Following the identification of the buildings, the methodology relied on a comprehensive analysis of the available information for each building and a descriptive performance evaluation based on the indicators defined in the Nano-BSAM model. The assessment model was then applied to these buildings through the following quantitative steps, which represent the methodological framework allowing the transition from descriptive evaluation to quantifiable, comparable results.

Data collection and quantitative conversion. Data on the performance of each building across the 24 performance indicators are compiled. A rating value (using a 5-point Likert scale) was assigned to each building for every performance indicator, along with a value of 0 for non-applicable (N/A) indicators, thus converting the qualitative assessments into numerical values.

Calculation of the weighted score for each indicator. The weighted score for each indicator is calculated by multiplying its numeric value (from the previous step) by its



relative weight obtained from the AHP analysis. The formula used is presented in equation (1):

$$WS_i = NV_i \times RW_i, \quad (1)$$

where WS_i – the weighted score for Indicator i ; NV_i – the numeric value (Likert score) assigned to Indicator i ; and RW_i – the relative weight of Indicator i derived from AHP analysis.

For instance, applying this formula to the “Maintenance cost reduction” indicator (C3), with a numeric value of 5 and a relative weight of 0.0820, yields a weighted score for C3 of $5 \times 0.0820 = 0.41$. This represents the actual contribution of that indicator to the final score.

Aggregation of final scores. The weighted scores of all indicators are summed to obtain the total overall score for each building. This aggregation is done at two levels: the Score for each main criterion (summing the weighted scores of all indicators belonging to that criterion, e.g., Environmental, Economic, etc.) and the Final building score (summing the scores of all four main criteria). The final overall score is then converted to a percentage. Given that the sum of the weights of all indicators is 1.00 (or 100%), the maximum possible score is $5 \times 1.00 = 5$. Therefore, the formula for converting the score to a percentage is given in equation (2):

$$\text{Percentage Score} = \frac{FS}{MaxS} \times 100, \quad (2)$$

where FS – the final overall score for the building; $MaxS$ – the maximum possible score (which equals 5 in this model).

For example, the final score for the Seitzstrasse building is the sum of the weighted scores for all 24 indicators. If the FS is 3.5755, the percentage score is $(3.5755/5) \times 100 = 71.51\%$.

RESULTS

The descriptive evaluations of the case studies were converted into quantifiable numerical data using the conversion key presented in Table 1. These results reflect the buildings’ overall sustainable performance from the perspective of regional priorities. Detailed results for each building are presented individually, followed by a summary of their general performance and final ranking. The following tables illustrate the quantitative performance assessment of the four selected study buildings based on the Nano-BSAM evaluation model. The weighted scores for each indicator and criterion are presented, alongside their relative weights. Table 2 presents the quantitative performance analysis of the Seitzstrasse residential and office building.

Table 1. Conversion key from descriptive evaluation to numerical value

Evaluation symbol	Description	Numerical value
+++	Excellent/Very positive	5
++	Highly achieved/Very positive	4
+	Achieved/Positive	3
±	Partially achieved/Challenging	2
-	Not achieved/Negative	1
N/A	Non-applicable	0

Source: compiled by the authors

Table 2. Quantitative performance analysis of the Seitzstrasse residential and office building

Criterion	Indicator	AHP weight	Qualitative rating	Numerical value	Weighted score (weight × value)	Detailed main criteria performance
EC	E.1	0.0521	++	4	0.2084	1.3339
	E.2	0.0345	++	4	0.138	
	E.3	0.0870	++	4	0.348	
	E.4	0.0542	++	4	0.2168	
	E.5	0.0643	+++	5	0.3215	
	E.6	0.0506	±	2	0.1012	
CC	C.1	0.0611	±	2	0.1222	0.9546
	C.2	0.0916	+++	5	0.458	
	C.3	0.0820	+	3	0.246	
	C.4	0.0205	+	3	0.0615	
	C.5	0.0223	+	3	0.0669	
SC	S.1	0.0241	+	3	0.0723	0.49
	S.2	0.0249	+++	5	0.1245	
	S.3	0.0279	++	4	0.1116	
	S.4	0.0266	±	2	0.0532	



Table 2. Continued

Criterion	Indicator	AHP weight	Qualitative rating	Numerical value	Weighted score (weight × value)	Detailed main criteria performance
TC	S.5	0.0428	+	3	0.1284	0.797
	T.1	0.0406	+++	5	0.203	
	T.2	0.0133	±	2	0.0266	
	T.3	0.0307	±	2	0.0614	
	T.4	0.0366	+	3	0.1098	
	T.5	0.0360	+	3	0.108	
	T.6	0.0382	+++	5	0.191	
	T.7	0.0206	+	3	0.0618	
	T.8	0.0177	±	2	0.0354	
Overall final score (FS)						3.5755

Source: compiled by the authors

Following Table 2, the weighted scores for the Seitzstrasse building show a total final score of 3.5755. The building recorded its highest performance in the Environmental Criterion (EC), achieving the highest weighted score among all criteria at 1.3339. The Embodied Energy Efficiency (E.3) and Indoor Air Quality Impact (E.5) indicators contributed highly to this score, rated (++) and (+++), respectively. The

Economic Criterion (CC) also scored highly (0.9546), with the Operational Energy Cost Reduction (C.2) indicator achieving the highest single weighted value in the entire assessment (0.4580 with a +++ rating). Conversely, the building's performance in the Social Criterion (SC) was the lowest among the criteria, scoring 0.4900. Table 3 presents the quantitative performance analysis of the Strucksbarg housing complex.

Table 3. Quantitative performance analysis of the Strucksbarg housing complex

Criterion	Indicator	AHP weight	Qualitative rating	Numerical value	Weighted score (weight × value)	Detailed main criteria performance
EC	E.1	0.0521	++	4	0.2084	1.15
	E.2	0.0345	±	2	0.069	
	E.3	0.0870	++	4	0.348	
	E.4	0.0542	++	4	0.2168	
	E.5	0.0643	++	4	0.2572	
	E.6	0.0506	-	1	0.0506	
	CC					
CC	C.1	0.0611	±	2	0.1222	0.8739
	C.2	0.0916	+	3	0.2748	
	C.3	0.0820	++	4	0.328	
	C.4	0.0205	++	4	0.082	
	C.5	0.0223	+	3	0.0669	
SC	S.1	0.0241	+	3	0.0723	0.5328
	S.2	0.0249	+++	5	0.1245	
	S.3	0.0279	++	4	0.1116	
	S.4	0.0266	±	2	0.0532	
	S.5	0.0428	++	4	0.1712	
	TC					
TC	T.1	0.0406	++	4	0.1624	0.8572
	T.2	0.0133	++	4	0.0532	
	T.3	0.0307	++	4	0.1228	
	T.4	0.0366	+++	5	0.183	
	T.5	0.0360	+++	5	0.18	
	T.6	0.0382	+	3	0.1146	
	T.7	0.0206	±	2	0.0412	
	T.8	0.0177	N/A	0	0	
Overall final score (FS)						3.4139

Source: compiled by the authors



Following Table 3, the weighted scores for the Strucksbarg housing building show a final total score of 3.4139. The building achieved the highest score in the Environmental Criterion (EC) at 1.1500, supported by the contribution of the Embodied Energy Efficiency (E.3) and the Negative Environmental Impact Reduction (E.1) indicators. This is followed by the Technical Criterion (TC) which scored 0.8572, recording high performance in the Weathering Resistance (T.4) and Fire Resistance (T.5) indicators, both with a (+++) rating. The Economic Criterion

(CC) scored 0.8739, with the most notable performance being in the Maintenance Cost Reduction (C.3) indicator, while the contribution of the Operational Energy Cost Reduction (C.2) indicator was comparatively lower, with a (+) rating. Conversely, the complex's performance in the Social Criterion (SC) was the lowest among the criteria, scoring 0.5328. The numerical scores for the building were derived from the detailed qualitative evaluation. Table 4 presents the quantitative performance analysis of the Escala Condominiums tower.

Table 4. Quantitative performance analysis of the Escala Condominiums tower

Criterion	Indicator	AHP weight	Qualitative rating	Numerical value	Weighted score (weight × value)	Detailed main criteria performance
EC						1.0124
	E.1	0.0521	++	4	0.2084	
	E.2	0.0345	++	4	0.138	
	E.3	0.0870	++	4	0.348	
	E.4	0.0542	++	4	0.2168	
	E.5	0.0643	N/A	0	0	
	E.6	0.0506	±	2	0.1012	
CC						0.6811
	C.1	0.0611	±	2	0.1222	
	C.2	0.0916	N/A	0	0	
	C.3	0.0820	+++	5	0.41	
	C.4	0.0205	++	4	0.082	
	C.5	0.0223	+	3	0.0669	
SC						0.5316
	S.1	0.0241	N/A	0	0	
	S.2	0.0249	++	4	0.0996	
	S.3	0.0279	++	4	0.1116	
	S.4	0.0266	++	4	0.1064	
	S.5	0.0428	+++	5	0.214	
TC						0.6678
	T.1	0.0406	+++	5	0.203	
	T.2	0.0133	+++	5	0.0665	
	T.3	0.0307	+++	5	0.1535	
	T.4	0.0366	+++	5	0.183	
	T.5	0.0360	N/A	0	0	
	T.6	0.0382	N/A	0	0	
	T.7	0.0206	+	3	0.0618	
	T.8	0.0177	N/A	0	0	
Overall final score (FS)						2.8929

Source: compiled by the authors

Following Table 4, the weighted scores for the Escala building show a final total score of 2.8929 (CRSI, n.d.). The building recorded its highest performance in the Environmental Criterion (EC) at 1.0124, supported by high performance across most environmental indicators (E.1-E.4) with a (++) rating, the most prominent contribution being from the Embodied Energy Efficiency (E.3) indicator at 0.3480. This is followed by the Economic Criterion (CC) at 0.6811, where the Maintenance Cost Reduction (C.3) indicator achieved the highest single weighted value in

this assessment (0.410 with a +++ rating), despite the Operational Energy Cost Reduction (C.2) indicator being non-applicable (N/A) for this building. Conversely, the building's performance was lowest in the Social Criterion (SC) at 0.5316, followed by the Technical Criterion (TC) at 0.6678. The lower scores for these criteria are due to multiple indicators falling outside the scope of application or assessment (N/A), such as (S.1), (T.5), (T.6), and (T.8). Table 5 presents the quantitative performance analysis of the Sur Falveng building.

Table 1. Quantitative performance analysis of the Sur Falveng building

Criterion	Indicator	AHP weight	Qualitative rating	Numerical value	Weighted score (weight × value)	Detailed main criteria performance
EC						1.1451
	E.1	0.0521	++	4	0.2084	
	E.2	0.0345	±	2	0.069	
	E.3	0.0870	±	2	0.174	
	E.4	0.0542	+++	5	0.271	
	E.5	0.0643	+++	5	0.3215	
	E.6	0.0506	±	2	0.1012	
CC						1.0029
	C.1	0.0611	±	2	0.1222	
	C.2	0.0916	++	4	0.3664	
	C.3	0.0820	+++	5	0.41	
	C.4	0.0205	++	4	0.082	
	C.5	0.0223	-	1	0.0223	
SC						0.6288
	S.1	0.0241	+	3	0.0723	
	S.2	0.0249	+++	5	0.1245	
	S.3	0.0279	++	4	0.1116	
	S.4	0.0266	++	4	0.1064	
	S.5	0.0428	+++	5	0.214	
TC						0.9157
	T.1	0.0406	++	4	0.1624	
	T.2	0.0133	++	4	0.0532	
	T.3	0.0307	+++	5	0.1535	
	T.4	0.0366	±	2	0.0732	
	T.5	0.0360	++	4	0.144	
	T.6	0.0382	+++	5	0.191	
	T.7	0.0206	+++	5	0.103	
	T.8	0.0177	±	2	0.0354	
Overall final score (FS)						3.6925

Source: compiled by the authors

Following Table 5, the weighted scores for the Sur Falveng housing building show a final total score of 3.6925, the highest score among the buildings evaluated. Performance was balanced, with the Environmental Criterion (EC) emerging as the highest weighted score at 1.1451. This is followed by the Economic Criterion (CC) at 1.0029, and then the Technical Criterion (TC) at 0.9157. The environmental performance was characterised by a high contribution from the Resource Efficiency and Water Consumption (E.4) and Indoor Air Quality Impact (E.5) indicators, both with a (+++) rating. In the Economic Criterion (CC), the performance was supported by the Maintenance Cost Reduction (C.3) indicator (+++ rating) and the Operational Energy Cost Reduction (C.2) indicator (++ rating). Conversely, the Social Criterion (SC) was the lowest among the criteria, scoring 0.6288. The score in the Economic Criterion was affected by low-scoring indicators, such as Disposal or Recycling Cost (C.5), which scored 0.0223 with a (-) rating. Figure 2 provides a visual comparison of the integrated performance of the four buildings across the main criteria, aiding in the understanding of each building’s relative strengths and weaknesses.

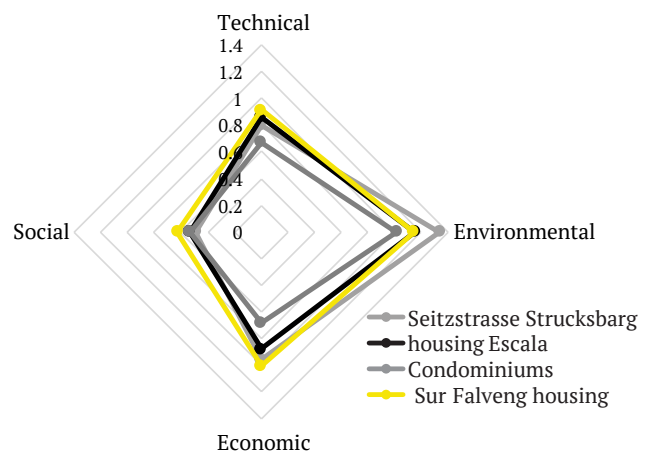


Figure 2. Comparative performance of the four buildings across main criteria based on regional weights
Source: compiled by the authors

Following Figure 2, the chart shows that Sur Falveng housing (yellow line) achieved the best overall performance with a score of 3.6925, while Escala Condominiums (grey line) came in last with a score of 2.8929. Sur Falveng



housing recorded the highest scores among all buildings in the Technical (0.9157), Social (0.6288), and Economic (1.0029) criteria. Seitzstrasse building (blue line) recorded the highest score in the Environmental Criterion (EC), reaching 1.3339. Escala Condominiums shows significantly lower performance in the Economic, Technical, and social criteria, due to the non-contribution (N/A) of highly weighted operational indicators like Operational Energy

Efficiency (C.2) and Thermal Comfort (T.6). The performance of Strucksberg housing (orange line) was balanced, ranking second for the Technical Criterion (TC) at 0.8572 and second for the Environmental Criterion (EC) at 1.1500 after Seitzstrasse. Table 6 summarises the final scores of the four buildings and shows their ranking based on their sustainable performance. The total scores were converted into a percentage for ease of comparison.

Table 6. Summary of final scores and ranking

Case study building	Nanotechnology used	Final weighted score (out of 5)	Percentage (%)	Rank
Seitzstrasse	VIPs (Vacuum Insulation Panels)	3.5755	71.51	2
Strucksberg housing	Sto Lotusan (Self-Cleaning Lotus Coating)	3.4139	68.28	3
Escala Condominiums	ChrömX (Corrosion-Resistant Rebar)	2.8929	57.86	4
Sur Falveng housing	GLASSXcrystal (PCM Phase Change Glass)	3.6925	73.85	1

Source: compiled by the authors

Overall, the comparative evaluation highlights clear differences in sustainable performance among the four case studies, reflecting the varying efficiency and applicability of different nanotechnologies in residential buildings. The results confirm that environmental and economic criteria exert the greatest influence on overall sustainability, while technical innovation plays a decisive supporting role in achieving balanced performance. These findings provide a solid basis for integrating region-specific priorities into future sustainable building assessments and for guiding architects and policymakers in selecting nanomaterials that maximise both environmental and operational benefits.

DISCUSSION

The Sur Falveng housing building (GLASSX®crystal – Phase Change Glass) secured the first position due to its outstanding alignment with regional sustainability priorities, particularly energy efficiency and indoor environmental control. The AHP weights highlighted performance indicators where the GLASSX® technology showed the highest contributions: Maintenance Cost Reduction (C.3) with the highest score in the assessment (0.410), Operational Energy Cost Reduction (C.2) (0.3664), and Indoor Air Quality Impact (E.5) (0.3215). These figures demonstrate that the system functions as an integrated facade, achieving immense operational savings (C.2, C.3) and superior functional environmental performance (E.5, T.6) that ideally corresponds to the regional need for reducing energy bills and relying on passive solutions. The Seitzstrasse Building (VIPs – Vacuum Insulation Panels) came in second place with a slight margin, confirming the importance of super-insulation technology in the regional context. The AHP weights reflected the highest priority given to the Operational Energy Cost Reduction (C.2) indicator, where VIPs achieved the highest contribution among all indicators (0.4580). Embodied Energy Efficiency (E.3) also contributed strongly (0.3480). However, the low contribution

of other indicators, such as Maintainability (T.3) (0.0614), reflected the complex technical nature and installation challenges of the material compared to the integrated solution that took first place, ultimately preventing it from securing the lead. The Strucksberg housing (Sto Lotusan – Self-Cleaning Lotus Paint) secured the third position, reflecting that its performance, despite excelling in specific aspects, had a lower impact on the overall sustainability of the building compared to energy efficiency solutions. The strengths of this technology primarily lie in the non-energy-related social and technical criteria, with high contributions in Maintenance Cost Reduction (C.3) (0.3280) and Embodied Energy Efficiency (E.3) (0.3480). However, the coating's indirect role in Operational Energy Cost Reduction (C.2) contributed to a relatively low value of 0.2748, placing it below technologies targeting the core problem of operational energy. The Escala Condominiums Tower (ChrömX – Corrosion-Resistant Rebar) came in last place due to its structural nature, which restricted the scope of its impact. Structural solutions inherently did not contribute to the indicators with the highest weights in the AHP model, such as Operational Energy Cost Reduction (C.2) and Thermal Comfort (T.6), where these two categories recorded zero contribution. The absence of assessment in the vital operational indicators (E.5, C.2, T.5, T.6, T.8) caused a significant reduction in its overall weighted score, placing it last despite its outstanding technical durability performance (T.1 Material Durability, 0.2030).

The study's findings confirm that nano-insulating and facade-enhancing materials significantly reduce energy consumption, which aligns perfectly with the outstanding performance of the first-place buildings, Sur Falveng (PCMs) and Seitzstrasse (VIPs). A field reports by A. Soni *et al.* (2022) and A. Tohlob & H. Morsi (2024) reinforces this conclusion, demonstrating a 28% reduction in cooling energy consumption and supporting the effectiveness of PCMs and VIPs in achieving energy efficiency. This is



consistent with the paramount regional priority of Operational Energy Cost Reduction (C.2), which received the highest weight (0.0916) in the AHP model (Kylili & Fokaides, 2016). Results further align with their general observation regarding functional environmental benefits, reinforced by the excellent performance of both Sur Falveng and Seitzstrasse in the Indoor Air Quality Impact (E.5) indicator, where they recorded a shared highest weighted value of 0.3215. Results also demonstrate significant alignment with the research by U. Konbr & H. Mamdouh (2022), which found that nanomaterials achieve high performance in energy efficiency (60.3%) and surrounding environment efficiency (71.7%). This supports the exceptional thermal performance of Sur Falveng and Seitzstrasse, as results confirmed an equal weighted contribution of 0.1910 for the Thermal Comfort (T.6) indicator for both. It also supports the strong third-place performance of Strucksbarg housing, whose environmental efficiency is attributed to its facade's self-cleaning properties (E.5 Air Quality Impact, 0.2572). Furthermore, the study's results are consistent with the general trend identified by A. Aljenbaz & Ç. Çağnan (2020), S. Resalati *et al.* (2021), which confirmed that the positive impacts of nanomaterials on sustainability outweigh their negatives. This specifically supports the economic performance of Sur Falveng in reducing maintenance costs (C.3 Maintenance Cost, 0.410), aligning with the reference that nanomaterials reduce maintenance costs. Environmentally, the high efficiency of the Seitzstrasse building in preserving Embodied Energy (E.3 Energy Consumption Efficiency, 0.3480) is consistent with the conclusion that these materials prevent energy loss. Findings regarding the excellent performance of Sur Falveng (PCMs) are further reinforced by quantitative data from a study focusing on the Egyptian climate, which showed that these materials can reduce energy consumption for cooling purposes by up to 38.79% (Ahmad *et al.*, 2025). Similarly, the thermal performance of VIPs is strongly supported by a study P. Akadiri *et al.* (2013) and K. El-Alfy *et al.* (2021) that showed their use reduces cooling energy consumption by 10.5%, reinforcing the strong performance of the Seitzstrasse building. Finally, the Escala Condominiums tower ranked last primarily due to the nature of the technology used, a structural application. Although this technology enhances structural strength and durability (T.1 Material Durability, 0.2030), structural solutions inherently did not contribute to the regional priority operational indicators. Consequently, our research demonstrates that overall sustainable performance is achieved not merely by using advanced technology, but by using technology that directly contributes to the indicators prioritised regionally, representing a unique contribution of our research in bridging this knowledge gap.

CONCLUSIONS

Based on the analysed results, this research provides a comprehensive sustainability assessment of the four residential buildings utilising nanotechnology. The regional priority-based assessment model (Nano-BSAM), developed

and applied herein, allowed for the unveiling of crucial insights regarding the alignment between nanotechnological effectiveness and local priorities for energy efficiency and reduced operational costs. The final performance ranking of these buildings closely demonstrates its conformance with the regionally weighted priorities established by Egyptian experts.

The final ranking clearly shows that regional priorities are the decisive factor for optimal sustainable performance. The analysis confirmed that the indicators for Operational Energy Cost Reduction (C.2, weight 0.0916) and Maintenance Cost Reduction (C.3, weight 0.0820) were the most influential elements in determining the final sustainability score. The Sur Falveng housing (PCM technology) achieved the highest overall score (3.6925), not for its superiority in a single criterion, but for achieving the most balanced and comprehensive performance across the highest-priority indicators, where its effectiveness in long-term operational savings (C.2 and C.3) contributed to its leading position. Conversely, the Seitzstrasse building (VIPs) came in second place (3.5755), thanks to achieving the highest single contribution in the entire assessment in the Operational Energy Cost Reduction indicator (C.2, 0.4580) and the highest Environmental Criterion score (1.3339), underscoring the vital role of super-insulation in regions that place significant emphasis on energy conservation. Furthermore, the study confirms that the nature of the application is more critical than the novelty of the material itself. Structural applications, such as the nano-enhanced rebar in the Escala Condominiums tower (last place, 2.8929), received a lower overall priority, primarily attributable to their lack of direct contribution to the highly weighted operational metrics (C.2 and T.6), which are considered paramount by regional decision-makers.

For designers and engineers, these findings highlight the practical value of the Nano-BSAM model. The decision regarding nanotechnology selection in future projects should be based on a comprehensive analysis of the specified regional evaluation framework, prioritising solutions that address high-priority performance indicators, such as maintenance costs and energy efficiency, thereby embodying the model's added value as a tool enabling sustainable design decisions. This contrasts sharply with solutions applied to the building envelope, which demonstrated a significantly greater impact on overall sustainability.

Promising areas of further research include the quantitative assessment of structural nano-applications to accurately model their long-term impact on comprehensive sustainability indicators, specifically focusing on durability, service life, and associated long-term maintenance costs of structural elements like nano-enhanced rebar. It is also important to develop modified assessment models, such as expanding the AHP framework to integrate a more detailed Life Cycle Assessment (LCA) of nanotechnology, aligning with expert concerns. Furthermore, research scope can be broadened through global comparative studies of expert-determined weights from different regions



(e.g., Europe or North America) to better understand the variations in global sustainability priorities.

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CONFLICT OF INTEREST

None.

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Мона Хассан Соліман

Доктор архітектури, професор

Університет Фаюм

63514, вул. Професора Мохамеда Саїда Сулеймана, м. Фаюм, Єгипет

<https://orcid.org/0000-0002-8462-2194>

Абдулла Бадаві Мохаммед

Доктор архітектури, доцент

Університет Фаюм

63514, вул. Професора Мохамеда Саїда Сулеймана, м. Фаюм, Єгипет

<https://orcid.org/0000-0002-5145-5756>

Асмаа Алі Закі

Магістр, асистент

Університет Фаюм

63514, вул. Професора Мохамеда Саїда Сулеймана, м. Фаюм, Єгипет

<https://orcid.org/0000-0001-9892-1200>

Оцінка сталості житлових будівель, удосконалених наноматеріалами, на основі АНР, з використанням регіонально зважених критеріїв від єгипетських експертів

Анотація. Швидка глобальна урбанізація та значний вплив будівельного сектору на навколишнє середовище вимагають інноваційних, стійких рішень, причому нанотехнології виступають ключовим каталізатором. Незважаючи на цей потенціал, поточним дослідженням бракує цілісної, систематичної структури оцінки житлових будівель, удосконалених наноматеріалами, яка б інтегрувала специфічні регіональні пріоритети країн, що розвиваються. Це дослідження вирішило цю прогалину знань шляхом розробки та застосування чотиривимірної моделі оцінки (екологічної, економічної, технічної та соціальної) із використанням методу аналізу ієрархій. Вагові коефіцієнти були отримані від 55 єгипетських експертів з архітектури та сталості, що гарантувало відображення результатами критичних регіональних потреб. Аналіз показав, що екологічний критерій був визнаний найбільш критичним виміром, отримавши найвищу вагу (0,3427), за ним тісно слідував економічний критерій (0,2774). Технічний критерій посів третє місце (0,2337), тоді як соціальний критерій був найменш впливовим (0,1462). Це визначення пріоритетів підтвердило, що зниження експлуатаційних витрат на енергію (0,0916) та зниження витрат на технічне обслуговування (0,0820) були найбільш вирішальними факторами сталої ефективності в регіональному контексті. Модель була застосована до чотирьох глобальних прикладів для визначення їхньої сталої ефективності та рейтингу. Будівля Sur Falveng зі склом з фазозмінним матеріалом (Phase Change Material Glass) посіла перше місце з оцінкою (73,85 %) завдяки своїй всебічній та збалансованій ефективності. За нею на другому місці слідувала будівля Seitzstrasse з вакуумними ізоляційними панелями (Vacuum Insulation Panels) (71,51 %). Житловий комплекс Strucksbarg із самоочисним покриттям «ефект лотоса» посів третє місце (68,28 %). Навпаки, вежа Escala Condominiums, що використовувала наномікрокомпозитну арматуру, посіла останнє місце (57,86 %), що підтвердило, що структурні застосування отримали нижчий загальний пріоритет, оскільки вони безпосередньо не сприяли домінантним експлуатаційним показникам. Це дослідження надало практичний, доказовий інструмент для архітекторів та політиків, підкреслюючи необхідність узгодження вибору нанотехнологій з регіональними рамками оцінки для керівництва майбутніми рішеннями щодо сталого проектування на ринках, що розвиваються

Ключові слова: аналітичний ієрархічний процес; нанотехнології; регіональні пріоритети; огорожувальні конструкції; житлова архітектура