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Determination of Materials Used in Green Roofs in Sustainable Structures via Value Engineering

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ABSTRACT

The construction industry globally faces the dual challenge of meeting rapid urbanization demands while adhering to environmental sustainability targets. Green roofs have emerged as an effective passive design strategy to mitigate the Urban Heat Island (UHI) effect, enhance building energy efficiency, and manage urban stormwater. However, in developing economies such as Turkey, their widespread adoption is constrained by high initial investment costs and a reliance on imported materials-specifically plastic drainage layers and peat-based substrates. To address these barriers, this research proposes a framework integrating Value Engineering (VE) methodology with a 40-year Life Cycle Cost (LCC) analysis. Using a 2,000 m^2 commercial Shopping Center (AVM) project in Balikesir, Turkey, as a primary case study, the study investigates the substitution of imported components with locally sourced volcanic pumice (bims). Technical evaluations indicate that the optimized pumice-based system not only complies with structural load limits (135 kg/m^2) but also provides enhanced thermal resistance ($\lambda \approx 0.12$ W/mK). The findings suggest that the VE-optimized system achieves a 42% reduction in initial investment costs compared to standard imported green roofs. Furthermore, the LCC analysis indicates that due to notable energy savings and extended membrane longevity, the proposed system amortizes its cost premium over a conventional roof within 6 to 7 years, offering a 34% total lifecycle saving. This research concludes that localized material optimization through Value Engineering positions green roofs as a technically robust, economically viable, and sustainable engineering solution.

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1. INTRODUCTION

1.1. GLOBAL ENVIRONMENTAL CONTEXT AND THE BUILDING SECTOR

The global construction industry is currently at a critical juncture where architectural progress must be rigorously aligned with environmental responsibilities. The 21st century is characterized by an escalating climatic crisis, driven largely by anthropogenic greenhouse gas emissions and the rapid depletion of finite natural resources. According to comprehensive data published by the International Energy Agency (IEA), the

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building and construction sector is a primary contributor to global environmental degradation, accounting for approximately 36% of global final energy consumption and nearly 39% of energy-related carbon dioxide (CO_2) emissions (IEA 2019). Recent global status reports emphasize that without a strategic and immediate transition toward low-carbon technologies and circular material usage, the sector's environmental footprint will continue to jeopardize international climate targets, specifically the 1.5 °C pathway established by the Paris Agreement (UNEP 2022).

As urban populations continue to expand, natural permeable surfaces and indigenous vegetation are systematically replaced by impervious, heat-absorbing materials such as concrete, steel, and asphalt. This profound alteration of the urban topography has led to the intensification of the "Urban Heat Island" (UHI) effect. The UHI effect is a microclimatic phenomenon where urban centers experience significantly higher ambient temperatures than their surrounding rural landscapes, often with a temperature differential of several degrees Celsius (Santamouris 2014). This phenomenon creates a deleterious feedback loop: rising outdoor temperatures diminish public health and urban comfort, which in turn necessitates a higher energy demand for mechanical cooling (HVAC systems). This increased energy consumption—if met by fossil-fuel-based grids—further accelerates greenhouse gas emissions, exacerbating the very climate change that drives the UHI effect. Recent findings in urban resilience research suggest that the integration of blue-green nature-based infrastructure is not merely an aesthetic choice but a critical requirement for the thermal stabilization and climate adaptation of modern cities (Vujovic et al. 2021).

In this context, the integration of Nature-Based Solutions (NBS) into the built environment has gained significant traction among policymakers, urban planners, and environmental engineers. Green roofs, or vegetative roof systems, represent a highly effective multifunctional passive design strategy for contemporary sustainable architecture. By utilizing the complex evapotranspiration properties of plants and the significant thermal mass of engineered substrates, green roofs provide a thermodynamic barrier that substantially improves the thermal envelope of buildings. Recent empirical studies indicate that green roofs act as a dynamic, high-performance insulation layer, thereby reducing sensible heat flux, lowering cooling loads in summer, and directly cutting operational carbon emissions through improved energy efficiency (Goda et al. 2023). Beyond thermodynamic benefits, these systems offer indispensable ecosystem services, including the retention and detention of 50-90% of incident rainfall (Castleton et al. 2010). This hydrological buffering provides a vital mechanism to mitigate urban flood risks and reduce the peak hydraulic load on municipal stormwater infrastructure, thereby enhancing urban resilience against the increasing frequency of extreme weather events associated with global climate instability (Peng and Jim 2015).

1.2. ECONOMIC BARRIERS IN DEVELOPING ECONOMIES: THE CASE OF TURKEY

Despite the well-documented environmental, thermodynamic, and social benefits, the transition to green roof technologies has been notably slow in developing countries, including Turkey. The primary impediment to scaling this sustainable technology is not a lack of engineering capability or technological understanding, but rather a deeply rooted economic barrier. Investors, developers, and project stakeholders often perceive green roofs as a "luxury landscaping addition" or an aesthetic afterthought, rather than an essential, functional building component (Bianchini and Hewage 2012). This perception is largely driven by the high initial capital expenditure (CAPEX) associated with current market standards and traditional green roof specifications, which often fail to account for long-term operational savings in initial feasibility studies.

Currently, the green roof sector in Turkey is heavily dependent on imported, proprietary material systems. These conventional assemblies typically rely on high-density polyethylene (HDPE) or polystyrene drainage boards, coupled with peat-based growing media imported from Northern Europe. This systemic dependency creates two major vulnerabilities. First, from an economic standpoint, it makes sustainable building projects highly susceptible to volatile foreign exchange rates, inflating construction budgets and deterring private sector investment. In the Turkish construction market, where material costs are sensitive to global economic fluctuations, this reliance on imports often renders green roof solutions financially unviable compared to traditional roofing methods. Second, from an ecological perspective, the use of imported materials significantly increases the "embodied carbon" of the building. The international logistics required to transport heavy peat soils across continents and the energy-intensive manufacturing processes of petroleum-based plastics ironically undermine the sustainability goals the green roof is intended to achieve (Berardi et al. 2014).

Recent studies highlight that the resilience of sustainable projects in post-pandemic markets is increasingly tied to reducing dependency on global supply chains through localized production and the utilization of regional resources (Zuo et al. 2021). The absence of localized, cost-effective material solutions has thus created a notable market gap that prevents the scaling of sustainable roofing practices across both public and private sectors. Current research in Global Decarbonisation and Sustainability emphasizes the absolute requirement for integrating circular economy principles and local material substitution—such as the reuse of mineral-based industrial or natural byproducts—to overcome these interconnected financial and ecological hurdles (Geisendorf and Eichler 2023). Consequently, bridging this gap requires a methodological shift that prioritizes local availability without compromising the rigorous technical standards required for modern building envelopes.

1.3. VALUE ENGINEERING AS A STRATEGIC TOOL

To bridge the gap between environmental necessity and financial viability, a systematic change in project management and structural design thinking is required. Value Engineering (VE) provides this necessary framework. Developed originally by Lawrence Miles during the resource scarcities of World War II to maintain industrial output without compromising quality, VE has evolved into a function-oriented, multidisciplinary methodology designed to enhance the "Value" of a product, project, or process. In the VE context, Value is mathematically and conceptually defined by the relationship between Function and Cost, where:

$$Value = \frac{Function}{Cost} \quad (1)$$

It is crucial to distinguish VE from conventional cost-cutting practices. Traditional cost-cutting often adopts a subtractive approach, compromising the quality, scope, or safety of a project to stay within a predetermined budget. In contrast, VE is additive in terms of value; it focuses on analyzing and fulfilling the required functions of a system—defined through rigorous "Verb-Noun" parameters—at the lowest possible lifecycle cost, without ever sacrificing performance, reliability, or structural integrity (Dell'Isola 1997).

By applying VE principles to green roof systems, this study does not seek to simplify the roof's architectural intent, but rather to identify materials that provide equivalent—or superior—functionality (e.g., "Manage Water," "Support Vegetation," "Insulate Building") at a significantly lower economic and environmental cost. Recent research in sustainable construction management emphasizes that VE, when integrated with sustainability metrics, allows for the identification of "low-carbon/low-cost" alternatives that traditional procurement methods often overlook due to a narrow focus on initial capital expenditure (Al-Saleh et al. 2022). This strategic tool enables the transition from a "product-based" selection (e.g., choosing a specific brand of drainage board) to a "function-based" selection (e.g., finding the most efficient way to drain water).

1.4. RESEARCH OBJECTIVE AND SCOPE

The central hypothesis of this research is that the strategic substitution of expensive, carbon-intensive, and logistics-heavy imported green roof components with locally abundant volcanic pumice (bims) can make these sustainable systems economically competitive with traditional roofing, while simultaneously enhancing their technical and thermodynamic performance.

To empirically evaluate this hypothesis, this study utilizes a high-profile commercial Shopping Center (AVM) project featuring a 2,000 m² terrace roof in Balikesir, Turkey, as a comprehensive case study. Balikesir is geologically home to some of the world's most significant and accessible pumice reserves. The highly vesicular, honeycombed, and porous nature of this local volcanic rock makes it an ideal candidate for testing localized material optimization in lightweight structural applications. Through a rigorous application of the SAVE International VE Job Plan—consisting of the Information, Function Analysis, Creative, Evaluation, Development, and Presentation phases—combined with a 40-year Life Cycle Cost (LCC) analysis, this research aims to:

Identify the primary cost drivers in conventional green roof systems by deconstructing their material assemblies into functional components using Pareto analysis

Assess the technical suitability of Balikesir pumice as a dual-function (drainage and substrate) material, examining its structural load-bearing capacity and thermal conductivity coefficients.

Quantify the long-term economic benefits and payback periods of the optimized system compared to both conventional gravel-ballasted roofs and imported green roof systems, accounting for long-term maintenance and energy efficiency savings.

By providing robust empirical data on both technical performance and economic feasibility, this article contributes significantly to the existing literature. It offers a highly replicable model for sustainable construction in resource-constrained or import-dependent economies, aligning with the global shift toward circular economy principles and regional resource autonomy (Geisendorf and Eichler 2023).

2. MATERIALS AND METHODS

To systematically address the economic and technical barriers associated with green roof implementation, this study utilizes a robust methodological framework integrating Value Engineering (VE) with Life Cycle Cost (LCC) analysis. This integrated approach aims to ensure that structural and architectural design decisions are not solely based on minimizing initial capital expenditure—a common limitation in traditional construction procurement—but rather on maximizing the functional value of the system over its entire service life.

2.1. THE VALUE ENGINEERING FRAMEWORK

Value Engineering (VE) is a function-oriented, multidisciplinary methodology designed to analyze required project functions and identify alternative ways to achieve those functions reliably at the lowest lifecycle cost (Dell'Isola 1997; Younker 2003). This research strictly followed the systematic Job Plan established by SAVE International (2020), executing the methodology through six sequential phases:

1. Information Phase: The foundational step involved gathering comprehensive architectural, structural, and climatic data regarding the case study building. Current market standards for green roof applications in the Turkish construction sector were analyzed to establish a realistic baseline. Detailed cost breakdowns of both conventional roofs and standard imported green roof systems were compiled. This phase aimed to ensure that all subsequent engineering decisions were grounded in accurate, real-world financial and technical landscapes.
2. Function Analysis Phase: This phase constitutes the conceptual core of the VE methodology. The components of a standard green roof were not analyzed as physical objects (e.g., "drainage board"), but rather by the exact functions they perform. Functions were defined using restrictive two-word "Verb-Noun" parameters (e.g., "Manage Water," "Provide Habitat," "Insulate Building"). A Function Analysis System Technique (FAST) diagram was developed utilizing "How-Why" logic to visually map the relationships between basic and secondary functions. A subsequent Pareto distribution analysis (the 80/20 rule) of the cost structure indicated a critical economic imbalance: the functions associated with imported plastic drainage boards and peat-based substrates accounted for approximately 69% of the total system cost, while contributing disproportionately less to the overall structural value. This identified them as the primary targets for value optimization.
3. Creative (Speculation) Phase: Having isolated the high-cost functions, structured brainstorming sessions were conducted to generate alternative solutions. The objective was to identify locally available, eco-friendly materials capable of fulfilling the essential functions of "water management" and "habitat provision" without the carbon footprint associated with international logistics. Volcanic pumice (bims), an abundantly available resource in the Balikesir region, emerged as a promising multi-functional alternative capable of acting simultaneously as a high-capacity drainage layer and a structural growing medium. Recent research in circular construction emphasizes that substituting synthetic components with mineral-based regional materials is essential for meeting low-carbon building requirements (Zuo et al. 2021).
4. Evaluation Phase: The ideas generated in the creative phase were subjected to screening using a Weighted Evaluation Matrix. To facilitate objective decision-making, critical success factors were established and weighted according to project priorities. Life Cycle Cost (LCC) was assigned the highest weight (30%), reflecting the study's focus on long-term economic sustainability. This was followed by Technical Performance (20%), Initial Investment Cost (20%), Material Durability (20%), and Energy Efficiency Contribution (10%).

5. Development Phase: The highest-scoring alternative—a hybrid system utilizing graded local pumice—was developed into a detailed, buildable technical scenario (Scenario C). During this phase, critical engineering parameters were estimated based on the specific material properties of Balikesir pumice. These included structural dead load estimations at full water saturation, thermal resistance (U-value) assessments, and hydrological retention capacities to align the system with building codes and safety standards. This phase ensures that the alternative material provides the same functional reliability as the imported baseline (Al-Saleh et al. 2022).
6. Presentation Phase: The developed scenario was economically modeled and benchmarked against both conventional and standard imported green roofs, culminating in the comprehensive 40-year LCC analysis presented in this study to facilitate stakeholder decision-making.

2.2. LIFE CYCLE COST (LCC) ANALYSIS FRAMEWORK

To evaluate the long-term economic feasibility of the proposed VE system, a Life Cycle Cost (LCC) analysis was conducted in accordance with ASTM E917-17 standards (ASTM International 2020). The LCC method is essential for evaluating sustainable building components like green roofs, which typically require a higher initial capital investment but yield significant operational and energy savings over their lifespan (Kats 2010). Recent research suggests that LCC provides a reliable framework for quantifying the economic value of nature-based solutions, particularly when accounting for fluctuating energy costs and long-term maintenance requirements (Oshoke and Ayarkwa 2023).

2.2.1. ANALYSIS PERIOD AND DISCOUNT RATE

The study period was set to 40 years (n = 40), representing the estimated functional lifespan of a high-quality building waterproofing system (such as TPO membranes) before major structural renovation or total replacement is required. To account for the time value of money and inflation, the Net Present Value (NPV) method was employed to discount all future operation, maintenance, energy, and replacement costs to their present-day equivalent. The NPV was calculated using the following standard economic equation:

$$NPV = \sum_{t=0}^{N} \frac{C_t}{(1+r)^t} \tag{2}$$

Where C_t represents the total net cost incurred in year t (including energy consumption, routine maintenance, and scheduled replacements), n is the length of the study period (40 years), and r denotes the real discount rate. For this study, a real discount rate of 8% (r = 0.08) was applied. This specific rate-defined as an inflation-adjusted real discount rate-is justified by historical long-term infrastructure investment returns and aligns with the prevailing real interest rates reported by the Central Bank of the Republic of Turkey (CBRT) for long-term project financing in the domestic construction sector. Current economic literature emphasizes that the choice of discount rate is critical in LCC models, as it significantly influences the present value of future energy savings in green infrastructure projects (Al-Saleh et al. 2022).

2.2.2. COST DATA SOURCES AND ENERGY ASSUMPTIONS

To maintain the fidelity of the economic model, initial investment costs for standard construction items (e.g., concrete screed, basic XPS insulation, gravel) were obtained from the official 2024 Unit Price Catalog published by the Turkish Ministry of Environment, Urbanization and Climate Change. Costs for specialized components—specifically TPO membranes, imported plastic drainage boards, and local Balikesir pumice—were derived from detailed local market research and direct manufacturer quotations valid for the current fiscal year.

Energy savings were estimated based on the calculated thermodynamic resistance provided by the vegetative and structural layers of the green roof. The reduction in HVAC (Heating, Ventilation, and Air Conditioning) electrical consumption was estimated by comparing the overall thermal transmittance (U-Value) of the optimized green roof against the baseline conventional roof. The resulting kilowatt-hour (kWh) savings were then monetized utilizing current commercial electricity and natural gas tariffs, providing a projection of long-term operational savings. Recent findings in urban climate research suggest that the integration of such passive insulation layers is vital for reducing operational carbon in Mediterranean climates, directly impacting the LCC results (Vujovic et al. 2021).

3. CASE STUDY

To evaluate the proposed Value Engineering (VE) methodology through practical application and move beyond theoretical economic modeling, a commercial Shopping Center (AVM) located in the province of Balikesir, Turkey, was selected as the primary case study. Commercial structures such as AVMs represent significant nodes of concentrated energy consumption within urban grids, often characterized by high internal heat gains and extensive roof surfaces. Therefore, optimizing their building envelopes—specifically the roof assembly—provides a scalable model for macro-level urban decarbonization and climate adaptation. Recent literature emphasizes that large-scale commercial retrofitting projects are essential catalysts for achieving regional sustainability targets, as they offer the highest potential for immediate energy reduction (Al-Saleh et al. 2022).

The selection of an AVM as the investigative unit allows for a rigorous assessment of how localized material substitution impacts both the structural load-bearing requirements and the long-term operational expenditures (OPEX) of high-occupancy buildings. By utilizing a real-world architectural context, the study aims to bridge the gap between abstract Value Engineering principles and the specific technical constraints of the Turkish construction sector.

3.1. PROJECT CONTEXT AND CLIMATIC CONDITIONS

The geographic and climatic context of a building fundamentally dictates the functional requirements of its roof system. Balikesir is geographically situated in a transitional climate zone, bridging the Mediterranean and Marmara microclimates (Köppen climate classification Csa/Csb). This specific topology poses dual challenges for building envelopes. The region experiences hot, arid summers with high solar radiation, necessitating significant mechanical cooling and driving up electricity costs, characterized by high Cooling Degree Days (CDD). Conversely, it experiences cool, moderately rainy winters that require effective stormwater management to prevent roof ponding, membrane degradation, and structural overloading due to hydraulic weight.

The selected AVM features a flat terrace roof area of 2,000 m². In its conventional state, a concrete slab of this magnitude acts as a thermal mass, absorbing solar radiation during diurnal cycles and transmitting heat into the building interior, thereby increasing HVAC loads. Consequently, this flat topology makes the AVM a suitable candidate to examine the economic and thermodynamic impact of material optimization through green roofing. Recent urban climate studies indicate that commercial structures in transitional zones are primary targets for energy-efficient retrofitting to mitigate the effects of localized heat accumulation (Vujovic et al. 2021).

Figure 1. Architectural layout and designated 2,000 m² green roof terrace area of the Balikesir Shopping Center.

Table 1 summarizes the structural and environmental characteristics of the investigated building, providing the baseline parameters used in the subsequent technical evaluations and Life Cycle Cost (LCC) calculations.

Table 1. Characteristics of the Case Study Building.

Feature	Specification / Value
Location	Balikesir, Turkey
Climate Zone	Transitional (Hot summers, cool/rainy winters)
Building Type	Commercial Shopping Center (AVM)
Analyzed Roof Area	2,000 m²
Roof Topology	Flat Terrace (1-2% slope)
Structural System	Reinforced Concrete
Local Material Source	Balikesir Pumice Quarries (Proximity < 50 km)

3.2. DEFINITION OF ANALYSIS SCENARIOS

To provide a comprehensive, objective comparative analysis of the VE intervention, three distinct roof configurations were mathematically modeled and analyzed for the 2,000 m² terrace area. These scenarios represent the evolution from standard market practice to optimized sustainable engineering:

1. Scenario A (Conventional Roof): This scenario represents the baseline configuration and the prevalent market practice in the Turkish commercial construction sector. It utilizes a standard "inverted roof" assembly, which includes a vapor barrier, a 5 cm Extruded Polystyrene (XPS) thermal insulation board, a standard double-layer bituminous waterproofing membrane, and a protective layer of river gravel ballast. While this configuration possesses the lowest initial capital expenditure (CAPEX), it is susceptible to lifecycle degradation. The bituminous membrane is subjected to thermal fluctuations and potential UV exposure, which can lead to micro-cracking and necessitates costly replacements over a 40-year period. Furthermore, this assembly offers limited ecological benefits and contributes to the localized intensification of the Urban Heat Island (UHI) effect.
2. Scenario B (Standard Imported Green Roof): This scenario reflects the conventional high-end approach to green roofing, frequently specified in international architectural projects. It utilizes a generic "extensive" green roof system composed of imported high-density polyethylene (HDPE) plastic drainage boards (25 mm) and peat-based engineered soils sourced from Northern Europe. While the technical performance regarding water retention is adequate, this system presents an economic and ecological challenge. The high capital cost, sensitivity to foreign currency volatility, and the significant embodied carbon footprint associated with international logistics and petroleum-based synthetics often render this system unsustainable for widespread adoption in emerging economies. Recent literature emphasizes that the environmental impact of long-distance substrate transport can diminish the net carbon sequestration benefits of the vegetative layer (Zuo et al. 2021).
3. Scenario C (Optimized Local Green Roof): This is the proposed alternative, developed through the Value Engineering Job Plan to address the limitations of Scenario B. It strategically substitutes imported plastic components and peat substrates with a 19 cm engineered local profile: a 7 cm coarse Balikesir pumice layer serving as a high-capacity drainage and passive insulation barrier, topped with a 12 cm substrate mixture of finer pumice and localized organic compost. To enhance 40-year Life Cycle Cost (LCC) savings, the conventional bituminous waterproofing is upgraded to a durable, root-resistant TPO (Thermoplastic Polyolefin) membrane. This upgrade, compliant with FLL green roofing guidelines, is intended to ensure the waterproofing layer survives the entire 40-year study period without replacement, thus securing the financial viability and long-term technical integrity of the system. This configuration aligns with circular economy principles by utilizing regional mineral resources to reduce the environmental footprint of the building envelope (Geisendorf and Eichler 2023).

4. TECHNICAL VERIFICATIONS OF THE PROPOSED SYSTEM

The core philosophy of the SAVE International Value Engineering (VE) methodology dictates that cost optimization must never come at the expense of required functionality, structural integrity, or safety (SAVE International, 2020). The objective is to increase the system's "Value" by maintaining or enhancing performance standards while reducing lifecycle costs. Therefore, before conducting the comparative economic evaluation, the proposed local pumice-based green roof (Scenario C) was subjected to technical evaluations. This step is essential to assess the suitability of substituting imported proprietary systems with regional materials and to determine if they meet the engineering requirements of standard market solutions (Al-Saleh et al. 2022).

4.1. STRUCTURAL DEAD LOAD ANALYSIS

A significant engineering constraint in the implementation of green roofs—particularly when retrofitting existing commercial structures—is the additional dead load imposed on the primary roof slab. This structural load becomes most critical and unpredictable when the vegetative and drainage layers are fully saturated with rainwater, representing the peak load condition. Standard extensive green roofs utilizing imported peat-based substrates (Scenario B) often present variable and heavy saturated loads due to the dense organic matter's tendency to compact over time and retain excess moisture. Such loads can necessitate structural reinforcements, such as steel cross-bracing or concrete jacketing, which significantly increase the initial investment and may render the project financially unviable.

In contrast, the engineered local system (Scenario C) utilizes Balikesir pumice, a pyroclastic igneous rock characterized by a highly vesicular, honeycombed volcanic structure. This unique cellular morphology provides an advantageous volume-to-weight ratio and a low bulk density compared to traditional organic substrates. Technical assessments based on regional material testing indicate that the fully saturated weight of the proposed 19 cm engineered profile—comprising a 7 cm coarse pumice drainage layer and a 12 cm substrate mixture of finer pumice and organic compost—is stabilized at approximately 135 kg/m².

This magnitude (1.35 kN/m²) remains within the standard live-load and dead-load bearing capacities of the existing reinforced concrete slab of the Balikesir Shopping Center. Consequently, the proposed VE system is intended to eliminate the requirement for structural modifications. By mitigating structural risk through material science, this localized optimization addresses a primary technical bottleneck that hinders green roof adoption in the Turkish construction sector. Current research in sustainable structural engineering confirms that mineral-based lightweight aggregates are superior for retrofitting urban buildings without compromising safety (Al-Saleh et al. 2022).

4.2. THERMAL CONDUCTIVITY AND PASSIVE INSULATION

Beyond structural safety, the VE methodology seeks to enhance secondary building functions, notably the function defined in the FAST diagram as “Insulate Building.” In standard imported green roof assemblies (Scenario B), high-density polyethylene (HDPE) or polystyrene drainage boards provide limited thermal resistance, functioning almost exclusively as a physical conduit for water management.

However, the 7 cm coarse pumice layer integrated into the foundation of Scenario C serves as a supplementary thermal barrier. Balikesir pumice exhibits a low thermal conductivity coefficient ($\lambda \approx 0.12$ W/mK) due to the atmospheric air trapped within its closed-cell volcanic vesicles. According to Fourier’s law of heat conduction, the thermal resistance (R) of a material is directly proportional to its thickness (d) and inversely proportional to its thermal conductivity (λ):

$$R = \frac{d}{\lambda} \tag{3}$$

By adding a 7 cm layer of pumice, the system introduces a supplementary thermal resistance to the roof assembly. When combined with the 12 cm growing substrate, this characteristic lowers the overall thermal transmittance (U-Value) of the roof envelope. By acting as a passive insulation layer, the pumice limits the transmission of solar radiation into the building during Balikesir’s arid summer months, while also contributing to the retention of interior ambient heat during winter periods.

This stabilization of indoor temperatures is intended to reduce the HVAC (Heating, Ventilation, and Air Conditioning) electrical and natural gas consumption of the building. This physical thermal performance forms the basis for the energy efficiency savings modeled in the subsequent 40-year LCC analysis. Recent findings in thermodynamic building simulations confirm that mineral-based substrate layers significantly enhance the damping of diurnal temperature fluctuations, thereby reducing operational carbon emissions (Vujovic et al. 2021).

4.3. STORMWATER MANAGEMENT AND HYDROLOGICAL PERFORMANCE

In transitional climate zones characterized by sudden rainfall events and extended periods of drought, urban stormwater management emerges as a critical ecological function for the building envelope. While standard imported 25 mm plastic dimple boards (Scenario B) facilitate rapid drainage into municipal systems, they provide limited active water retention capacity within the drainage layer itself.

In contrast, the highly porous structure of the local Balikesir pumice enables the engineered system to function as a hydrological buffer. The aggregate absorbs and retains significant volumes of water within its macro and micro-pores. This mechanism physically delays peak stormwater runoff times (attenuation), alleviating hydraulic stress on municipal stormwater infrastructure during severe weather events and contributing to the mitigation of urban flood risks. Current research in sustainable urban drainage systems (SuDS) indicates that mineral-based substrates enhance urban resilience by providing superior peak-flow reduction compared to synthetic drainage layers (Geisendorf and Eichler 2023).

Furthermore, this hydrological retention is a factor in the survival of the vegetative layer. During Balikesir's dry summer periods, the moisture trapped within the pumice vesicles is released back into the substrate via capillary action. This process facilitates the sustained hydration of the Sedum vegetation, which can reduce the requirement for artificial irrigation systems. Consequently, this performance characteristic contributes to the reduction of operational and maintenance costs over the building’s lifecycle. This hydrological behavior aligns with modern urban ecology objectives for Mediterranean climates, where water scarcity is a primary concern for green infrastructure survival (UNEP 2022).

5. RESULTS AND DISCUSSION

The comprehensive outcomes of the Value Engineering (VE) methodology, supported by the 40-year Life Cycle Cost (LCC) projection and technical evaluations, provide empirical evidence for the economic viability of localized material substitution. This section systematically deconstructs the financial performance of the engineered pumice-based green roof (Scenario C) against the established market baselines.

5.1. INITIAL CAPITAL EXPENDITURE (CAPEX) OPTIMIZATION

A primary financial barrier to green roof adoption in emerging economies is the initial Capital Expenditure (CAPEX). Construction stakeholders and developers often prioritize short-term budget compliance over long-term operational efficiency, a tendency that frequently overlooks the lifecycle benefits of sustainable assemblies. Table 2 provides a comparative breakdown of the initial construction costs for the 2,000 m² AVM terrace across the three defined scenarios, highlighting the immediate financial impact of material specification and the effectiveness of localized material substitution.

Table 2. Initial Investment Cost (CAPEX) Comparison for 2,000 m² Roof Area.

Cost Category	Scenario A (Conventional)	Scenario B (Standard Imported)	Scenario C (Optimized Local)
Waterproofing & Insulation	$18,500	$22,000	$24,500 (TPO Upgrade)
Drainage System	$1,500	$18,500 (Imported Plastic)	$3,500 (Local Pumice)
Substrate & Vegetation	N/A	$22,000 (Imported Peat)	$8,250 (Pumice/Compost)
TOTAL INITIAL COST	$25,000	$62,500	$36,250

Note: All costs were calculated using the official 2024 Unit Price Catalog and local market research, then converted from Turkish Lira (TL) to US Dollars (USD) to ensure international comparability and normalize currency fluctuations.

The tabulated data illustrates the financial challenge faced by private-sector investors. The Conventional Roof (Scenario A) represents the lowest upfront investment ($25,000), making it the default choice for projects where short-term capital liquidity is the primary constraint, despite its limited ecological performance.

Conversely, standard imported green roofs (Scenario B) represent a significant financial increase to $62,500—a 150% cost premium over the baseline. This cost disparity effectively deters large-scale investment in green infrastructure, as the "green premium" is perceived as excessive.

However, the VE intervention (Scenario C) modifies this economic paradigm. By substituting high-cost imported synthetics and peat with regional volcanic pumice, the optimized system achieves a notable 42% reduction in total initial costs compared to Scenario B. At $36,250, the localized green roof successfully reduces the financial gap between sustainable and conventional roofing. While Scenario C requires an initial premium of $11,250 over the conventional baseline, it incorporates high-performance components like the root-resistant TPO membrane. This strategic investment brings the cost of sustainable infrastructure down to a threshold that is significantly more accessible for commercial developers. Recent studies in construction economics confirm that localized supply chains not only reduce CAPEX but also enhance project resilience against global material price volatility (Zuo et al. 2021).

5.2. 40-YEAR LIFE CYCLE COST (LCC) ANALYSIS

While initial CAPEX dictates short-term financial feasibility, true economic sustainability in the built environment must be measured over the building's entire operational lifespan. To capture this long-term performance, Table 3 presents the outcomes of a comprehensive 40-year LCC analysis. This longitudinal model is not a simple summation of future costs; it is a sophisticated simulation that incorporates projected HVAC energy savings derived from improved thermal envelopes, routine operational maintenance, and the projected replacement cycles for the waterproofing membranes.

Table 3. 40-Year Life Cycle Cost (LCC) and Economic Impact Analysis.

Analysis Parameters	Scenario A (Conventional)	Scenario C (Optimized Local)	Variance / Economic Impact
Initial Investment Cost	$25,000	$36,250	Premium of +$11,250
40-Year Energy Costs (NPV)	$65,000	$35,000	Savings of -$30,000
Maintenance & Replacement	$25,000	$5,000	Savings of -$20,000
TOTAL LCC (40-Year)	$115,000	$76,250	Net Saving: $38,750

To account for the time value of money, all future cash flows—including recurring energy expenditures and non-recurring structural renovations—were mathematically discounted to their Net Present Value (NPV). In strict adherence to the requirements for long-term project financing in the Turkish construction sector, a real discount rate of 8% was applied (CBRT, 2024). This methodology ensures that future savings are not disproportionately inflated by nominal values, providing a grounded and realistic projection of the cumulative economic impact of each scenario. Modern LCC research confirms that utilizing such rigorous discounting methods is essential for identifying the point at which high-performance sustainable assemblies overcome their initial "green premium" and become net-profitable assets (Oshoke and Ayarkwa 2023).

The LCC projection indicates a shift in construction economics. Over the 40-year evaluation period, the Conventional Roof (Scenario A)—which initially appeared to be the most economical choice—becomes the configuration with the highest total expenditure ($115,000). This significant cost accumulation is driven by two primary factors: first, the relatively higher thermal transmittance of the assembly increases continuous HVAC energy consumption; second, the projected requirement for replacing the UV-exposed bituminous waterproofing membrane at least twice over the study period due to thermal fluctuations and material degradation.

In contrast, the Optimized Local Green Roof (Scenario C) functions as a thermodynamic and physical shield. The 19 cm pumice and substrate profile protect the underlying high-performance TPO membrane from extreme diurnal thermal fluctuations and UV radiation, effectively reducing major cyclical replacement costs. Combined with accumulated energy savings derived from enhanced thermal resistance (R), Scenario C achieves a total NPV of $76,250. This represents a substantial net lifecycle benefit of $38,750 over the conventional baseline. Consequently, the initial cost premium of $11,250 is amortized within an estimated payback period of 6 to 7 years, establishing the system as an economically viable long-term asset. Current research in building lifecycle management suggests that the integration of high-durability membranes with vegetative covers is a critical factor in achieving multi-decade financial sustainability in commercial real estate (Oshoke and Ayarkwa 2023).

5.3. SENSITIVITY ANALYSIS

LCC models are inherently reliant on future projections; therefore, to address potential economic uncertainties and ensure the robustness of the findings against macroeconomic volatility, a sensitivity analysis was conducted on Scenario C. The analysis tested the impact of sudden fluctuations in two critical variables: material cost inflation and discount rate adjustments.

1. Pessimistic Scenario (Material Cost Inflation): A sudden 10% increase in the unit price of local pumice, compost, and associated labor was mathematically modeled to simulate a supply shock. Because the base cost of these local materials is already exceptionally low compared to imported plastics, this 10% relative increase only marginally affected the total CAPEX. Due to the compounded mathematical value of long-term energy savings, the payback period was only extended by approximately 8 months. This demonstrates that the localized model possesses high economic resilience against regional inflation and supply chain disruptions.
2. Optimistic Scenario (Discount Rate Reduction): A 10% proportional decrease in the discount rate—shifting from a baseline of 8.0% to 7.2%—was analyzed. This scenario reflects potential external financial catalysts such as government subsidies, carbon tax incentives, or access to specialized green-financing instruments. In Net Present Value (NPV) calculations, a lower discount rate amplifies the present-day value of future cash flows, particularly energy savings. Consequently, this adjustment accelerated the projected payback period to under 6 years, enhancing the investment profile of the system. Current research in green finance suggests that such policy-driven incentives are primary drivers for the wide-scale adoption of sustainable building envelopes in emerging markets (Zuo et al. 2021).

The sensitivity analysis indicates that the proposed Value Engineering model is not a fragile economic construct dependent on idealized market conditions. Instead, it demonstrates a resilient and predictable long-term investment profile. By reducing dependency on the volatile currency fluctuations that often impact imported proprietary systems, the localized pumice-based solution provides a more stable financial trajectory for developers. Recent findings in construction economics confirm that utilizing regional mineral resources acts as a natural hedge against the global material price volatility that has characterized the post-pandemic market (Geisendorf and Eichler 2023).

6. CONCLUSION

The global imperative to mitigate climate change and enhance urban resilience has positioned green roofs as a significant component of sustainable architectural design. However, the widespread adoption of these systems, particularly in emerging economies, has been constrained by the industry perception of high initial capital costs and a reliance on imported, carbon-intensive materials. This research was initiated to systematically address these economic and technical barriers through a function-oriented approach.

By integrating the SAVE International Value Engineering (VE) methodology with a 40-year Life Cycle Cost (LCC) analysis, this study evaluates the prevailing industry misconception that green roofs are economically unviable additions. Utilizing a 2,000 m² commercial Shopping Center in Balikesir, Turkey, as an empirical case study, the research developed an optimized local green roof system (Scenario C) that substitutes imported plastic drainage boards and peat-based substrates with regional Balikesir pumice.

The findings yield three major scientific and economic conclusions:

- First, localized material substitution significantly lowers the financial barrier to entry without compromising structural integrity. Technical assessments demonstrated that the engineered pumice system adds a manageable saturated dead load of approximately $135\ kg/m^2 (1.35\ kN/m^2)$, which remains within the bearing capacity of standard commercial slabs. Concurrently, it provides supplementary passive thermal insulation due to its low thermal conductivity ($\lambda \approx 0.12\ W/mK$). Economically, substituting imported components resulted in a notable 42% reduction in Initial Capital Expenditure (CAPEX) compared to standard imported green roofs, bringing the cost down from $62,500 to a more competitive $36,250. This indicates that the perceived financial barrier is largely a function of material specification rather than the green roof technology itself.
- Second, the economic value of sustainable infrastructure is best realized through a lifecycle perspective. The 40-year LCC analysis indicates that the proposed "Optimized Local Green Roof" is financially viable even when compared to a standard "Conventional Roof" baseline. While conventional roofs

require lower upfront capital ($25,000), their operational performance and the projected requirement for cyclical membrane replacements make them the most expensive long-term option ($115,000 NPV). The proposed pumice-based system ($76,250 NPV) amortizes its initial cost premium within a projected payback period of 6 to 7 years through accumulated HVAC energy savings and extended membrane longevity. Furthermore, the sensitivity analysis confirmed that this economic model is resilient against market volatility, including material inflation and discount rate fluctuations.

- Third, local material optimization yields compounding environmental and ecological benefits. Beyond financial metrics, the proposed VE substitution carries ecological implications. By utilizing a regional volcanic resource, the project reduces the "embodied carbon" associated with the international logistics of heavy peat soils and the manufacturing of synthetic drainage layers. The system facilitates the mitigation of the Urban Heat Island (UHI) effect and aligns with circular economy principles by promoting regional resource autonomy. Recent research confirms that such localized Nature-Based Solutions (NBS) are essential for meeting the decarbonization targets of the 2030 sustainability agenda (UNEP 2022; Geisendorf and Eichler 2023).

6.1. LIMITATIONS AND FUTURE RESEARCH

While this study provides a robust economic and technical framework, it acknowledges certain limitations that warrant further investigation. The Life Cycle Cost (LCC) and thermodynamic calculations were modeled specifically for the transitional climate of the Marmara/Aegean region (Balikesir). The thermodynamic performance and water retention requirements of the pumice-based system may vary in extreme arid or high-alpine climates; therefore, the results should be contextualized when applied to significantly different geographic regions.

Future research should focus on conducting empirical, sensor-based field tests (in-situ monitoring) to evaluate the theoretical (U-Value) improvements and structural load stabilities estimated in this study. Furthermore, to enhance the water retention efficiency of the localized pumice during extended periods of drought, future studies could explore the integration of Internet of Things (IoT) soil moisture sensors and Artificial Intelligence (AI) driven irrigation algorithms. Such technological integration aligns the physical green roof assembly with smart city decarbonization grids, transforming building envelopes into active, data-driven ecological assets (Oshoke and Ayarkwa 2023).

In conclusion, this study demonstrates with replicable data that the Value Engineering (VE) approach—when coupled with rigorous lifecycle costing—facilitates the transformation of green roofs from an import-dependent, capital-intensive assembly into a high-value, technically resilient, and economically viable engineering investment. It provides a scalable framework for stakeholders, policymakers, and civil engineers in emerging economies to accelerate the integration of sustainable, nature-based infrastructure into the built environment.

AUTHOR CONTRIBUTIONS

Ahmet Eren Celik: Conceptualization, Methodology, Software, Data Curation, Writing – Original Draft. **Şenay Atabay**: Supervision, Writing – Review & Editing, Validation.

COMPETING INTERESTS

The authors declare that they have no competing interests.

DATA ACCESSIBILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ETHICAL APPROVAL

Not applicable.

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