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Assessment of Green Building Materials' Attributes to Achieve Sustainable Building Façades Using AHP

Marwa M. Gomaa Mayhoub [1,*], Zeyad M. Tarek El Sayad [2], Ahmed AbdelMonteleb M. Ali [3,4] and Mona G. Ibrahim [1,5]

[1] Department of Environmental Engineering, Egypt-Japan University of Science and Technology, Alexandria 21934, Egypt; mona.gamal@ejust.edu.eg
[2] Department of Architectural Engineering, Faculty of Engineering, Alexandria University, Alexandria 21526, Egypt; zelsayad1@alexu.edu.eg
[3] Department of Architectural Engineering, Faculty of Engineering, Assiut University, Assiut 71515, Egypt; ahmed.abdelmonteleb@aun.edu.eg or ahm.ali@qu.edu.sa
[4] Department of Architecture, College of Architecture and Planning, Qassim University, Qassim 52571, Saudi Arabia
[5] Environmental Health Department, High Institute of Public Health, Alexandria University, Alexandria 21526, Egypt
* Correspondence: marwa.mayhoub@ejust.edu.eg

Abstract: The need to enhance the performance of building façades and mitigate adverse environmental impacts has promoted the hypothesis of integrating green materials towards sustainable buildings. Façade designers tend to select building materials based on their green characteristics (origin) or green performance; however, this study highlights the importance of integrating both into the decision process. The main objective is to develop a new assessment process for selecting green building façade materials based on green performance and green originality. Furthermore, the evaluation framework considers four green building rating systems as a reference to allocate credits for the relevant criteria. Applying the proposed criteria in this study helps maximize the points for accreditation when incorporating green building materials in building façades. Moreover, the Analytic Hierarchy Process (AHP) is used to assign the proposed criteria's weighting importance based on the four rating systems' average points. After that, performing sensitivity analysis to identify each criterion's influence is conducted. The study concluded that involving minimum levels of adverse impacts is the preferable criteria regarding the green origin concept. As for the green performance, promoting the performance of indoor air quality is the most favorable selection criteria.

Keywords: façade material selection; green building materials (GBMs); green building rating systems; analytic hierarchy process (AHP); green origin; green performance

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1. Introduction

Building materials significantly affect the depletion of natural resources and their impact on buildings' emissions and energy usage [1]. Consequently, following the sustainability measures (environment, social, and economic) [2] and green architecture approach [3] is required to decrease the impacts of materials on the environment and building occupants. Green architecture focuses on the relationship between the building and nature, minimizing environmental impacts, health hazards, and energy and conserving natural resources [4]. In this context, the green building concept involves using eco-friendly and low-impact materials, conserving resources and energy efficiency, and optimizing indoor health for occupants [5]. The characteristics of building façades affect environmental footprint and energy performance; therefore, more awareness needs to be dedicated to their design, construction, and building materials [6].

Various researchers contribute to achieving a specific principle of green buildings to optimize the performance of the building. For instance, more solid building massing is recommended to mitigate heat gains and losses rather than glazed façades as an expensive façade solution [6]. Additionally, using a building's thermal mass can enhance thermal comfort and reduce energy consumption, considering the building location and type of usage [7]. Moreover, applying insulation materials for opaque façades can decrease building envelopes' thermal bridges and optimize the buildings' thermal and acoustic performance [8]. Consequently, the external wall properties significantly impact indoor air quality and energy efficiency [9]. Therefore, implementing sustainable building façades using green materials contributes to their impact on the environment and the thermal performance of the building.

Many studies have highlighted the concept of green building materials, as there is no standard of green building materials [2]. Furthermore, proper green material can be chosen based on the required material performance and the available technologies [10]. Green material is defined by Kubba [11] to have no negative impact on the environment and consider building occupants' health and well-being through indoor air quality. Utilizing green materials is an essential factor in the optimum design of sustainable buildings [1]. Previous studies determined the optimal building material among several alternatives, considering different specifications. For instance, Autoclaved Aerated Concrete panel with external insulation is regarded as the best alternative for a residential building façade in Australia, depending on the AHP results [12]. Another study by Vilcekova et al. [13] mentioned foam glass as the best alternative thermal insulation based on the environmental and thermal aspects. Moreover, "photovoltaic materials" are considered the most sustainable materials for building façades with the high priority result of AHP, according to Balali et al. [14]. Consequently, accomplishing effective and healthier building façades affects the industry to produce materials with fewer consuming resources, low environmental impact, and good thermal performance.

The Analytic Hierarchy Process AHP, proposed by Saaty [15], is a common and preferable applied method for Multi-Criteria Decision Making (MCDM) method to solve problems related to prioritizing criteria [16]. This ranking process has attracted various researchers in several fields as it is a simple way of making judgments according to several criteria and minimizing inconsistencies in opinions [17]. The AHP method focuses on making paired comparisons based on a fundamental scale ratio within a hierarchy [18]. Moreover, the AHP process identifies the preferences in making a decision, dealing with a multi-dimensional scaling problem, and transforming it to a uni-dimension scale [18]. Furthermore, sensitivity analysis is an essential part of the AHP process, allowing decision-making to identify the critical inputs' focus and consider their weighting coefficients' variation [19].

Thus, to optimize green building façades using the most efficient environmentally friendly materials, this research proposes a benchmark determining the weighted relative importance of the green building materials' attributes. Furthermore, the AHP method is applied as a verified and consistent method for assigning weights to the assessment criteria.

The organization of this paper is as follows; the introduction is the first section which illustrates a brief survey of the main concepts. The following section defines the main attributes of green building materials (green origin, green performance). Then, Section 3 discusses literature related to selecting green building materials based on different criteria. After that, the research methodology section is presented. Next, the results and discussion are described following by the conclusion and the future scope.

2. Research Scope

As mentioned in the introduction section, building materials significantly impact the environment and building users. Hence, using green materials has possible benefits related to optimizing thermal comfort, indoor health, energy efficiency, lower environmental impacts, etc. This paper aims to assess green materials for building façades according to sustainability measures and considering their green origin and green performance.

The green origin concept means that the material is considered green based on its green characteristics (for example, it is composed of recycled or renewable resources and has minimal impact on the environment). However, the green performance concept refers to its performance over its entire life cycle, including the building's operation phase (for example, considering occupants' health and well-being and not exposing harmful substances).

The authors indicate that having a building material with green origin features does not necessarily mean that its performance is green. For instance, Gomaa et al. [20] simulated an educational building's external wall system in a hot desert climate using Autoclaved Aerated Concrete Block AAC (a green alternative material) for brickwork as a conventional material. This study mentioned that the green material positively impacts thermal comfort. Moreover, the green material slightly enhanced energy efficiency results–based on the total energy consumption–from 3245.07 to 3239.1 KWh compared to the conventional material. Another example, Phase Change Materials (PCMs), can stabilize an indoor environment for users without needing extra energy for heating or cooling [7]. However, commonly used PCMs in buildings as heat storage material have been reviewed by Chandel et al. [21] regarding their release of toxic gases that affect human health and have the potential for fires.

Therefore, the study concept adapted in this research (Figure 1) presents the proper selection of green materials in building façade to obtain a sustainable building. The choice of green material in this study is based on its performance and its origin. Based on this concept, different evaluation criteria are proposed for obtaining a high-performance façade for sustainable buildings.

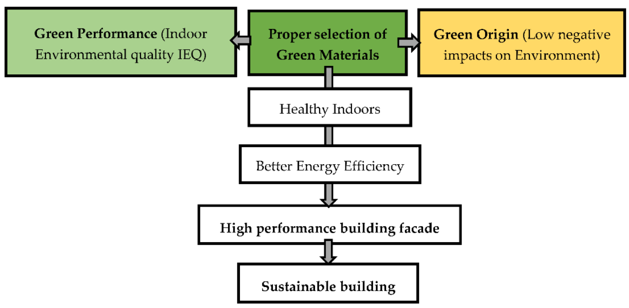

Figure 1. Flow chart of the research concept.

3. Literature Review

Various researchers have evaluated façade building materials based on different aims and criteria. The following subsections identified the assessment criteria of green building materials and the main objectives for several studies. The authors divided the purposes of selecting green materials into three parts to clarify the importance of emerging concepts of green origin and green performance to optimize building façades. Moreover, comparing green building rating systems based on the materials-related criteria and credits helped to develop the optimal selection criteria for building façade green materials.

3.1. Criteria for Selecting Green Building Materials

Various researchers have addressed the green material selection problem through many approaches. Table 1 illustrates the different assessment criteria of green building materials carried out by several studies. The table presents the green materials' evaluation criteria for various building elements, not just façades (for instance, selecting green flooring [22] and roofing materials [23]). Other studies aimed to identify the green building materials' selection criteria based on different purposes (for instance, considering energy efficiency [24], the building's life cycle [25], and sustainability ranking [2]). The authors highlight the sub-criteria related to the green materials' main attributes–green origin and green performance–for building façades to be used for the proposed evaluation framework (Section 5.1).

Table 1. Overview of multi-criteria assessment for selecting green building materials.

Ref.	Main and Sub-Criteria				
[12]	Four main criteria are considered: **Environmental impacts** Embodied energy/carbon emission Heating load Cooling load Resource sustainability		Life cycle costs Material cost Labor cost Transport cost Maintenance cost Design cost	**Performance** Weight Thermal resistance Thermal mass Acoustic insulation Resistance to decay	**Social benefits** Aesthetics Suitability to location Suitability to climate
[14]	Five main criteria are considered: **Environment** Low or non-toxic Compatibility with the environment Compatibility with the climate Decreasing environmental pollution Decreasing indoor heat Decreasing acoustic pollution Decreasing urban heat islands and greenhouse gases Saving natural resources	**Economic** Possessing lightweight Decreasing construction cost Decreasing purchase cost Decreasing implementation cost Decreasing life cycle cost Decreasing maintenance cost	**Technical and executive** Thermal insulation of materials Acoustic insulation of materials Repair-ability Resistant to earthquake Implementation speed Resistant to explosion Building's life cycle Ease of implementation Safety increase Compatibility with executive codes Recyclability Novelty of materials	**Social** Beauty Compatibility with society's architecture Compatibility with society's culture Increasing society's knowledge about sustainability Considering historical values	**Energy consumption** Decreasing energy consumption Energy renewability Storing energy Compatible with energy consumption codes Ability to use ventilation energy Decreasing embodied energy
[2]	Five main criteria are considered based on sustainability pillars (environment, social, and economic): **Resource efficiency** Recycled content Natural or renewable Resource-efficient manufacturing process Locally available Salvaged, refurbished Reusable or recyclable Recycled product packaging Durable	Affordability Affordable from cradle to gate Affordable during operation Affordable recycles process	**Water efficiency** Water conservation from cradle to gate Water conservation during operation Water conservation in recycle process	**Indoor air quality** Low or non-toxic Minimal chemical emissions Low VOC-assembly Moisture resistant Healthfully maintained Systems or equipment	**Energy efficiency** Energy efficiency from cradle to gate Energy efficiency during operation Energy efficiency in recycle process

Table 1. *Cont.*

Ref.	Main and Sub-Criteria					
[22]	Six main criteria are considered:					
	Environmental/Health Safety/health of end-users The climatic condition of the region Material environmental impact Carbon emissions and toxicity Ozone Depletion Potential Environmental statutory compliance	**Economic/Cost** Maintenance/replacement cost Labor/installation cost Total LCC Capital/initial cost Material embodied energy cost	General factor Material availability The geographic location of the site Building and space usage The knowledge base in construction Withstand natural disasters Type of building material Building certification for use Design concept Spatial scale: building size/mass Project site geometry/condition Distance Building orientation	**Socio-Cultural** Knowledge of the custom material Compatible with traditions Compatible with client's preference material Compatible with regional cultural Restriction on usury Family structure: type & size of the family unit	**Technical** Life expectancy Fire/heat resistance Moisture/weather resistance The available technical skills Resistance to decay/scratch/chemicals Maintenance requirement Recyclability and reusability Ease to replace/remove Weight & mass of material Renewability Compatible with other materials UV Resistance	**Sensorial** Temperature Odor Lighting effect Acoustic Aesthetic Texture Color Thickness/Thinness Hardness Glossiness/Fineness Structure Translucence
[23]	Six main criteria are considered:					
	Environmental impact Environmental statutory compliance Zero or low toxicity Minimize pollution Ozone depletion Material effect on air quality	**Life cycle cost** Initial cost Maintenance cost Disposal cost	**Resource efficiency** Raw material extraction Wastage in use Embodied energy Environmental impact during material harvest	**waste minimization** Environmentally disposal options Recycling and reuse	**Performance capability** Fire resistance Resistance to decay Energy-saving, thermal insulation Ease of Construction Life expectancy Maintainability	**social benefit** Use of local materials Health and safety Aesthetics
[5]	Four main criteria are considered based on the life cycle of building (ecological, social &: health, and economic impacts)					
	Manufacturing & Construction Stage Local Availability Embodied Energy Recycled Content		**In-Use stage** Material toxicity Chemical emissions Flammability Moisture resistant Contribution to Energy efficiency/thermal comfort of buildings Contribution to acoustic comfort Water conservation Durability/longevity Healthfully maintained Functionality	**End of Life Stage** Reusability Recyclability Biodegradability	**Whole Life Cycle** Affordable & life-cycle cost (LCC) Technical quality	

Table 1. *Cont.*

Ref.	Main and Sub-Criteria	
[26]	Two main criteria include: **Environmental criteria** LCA CO_2 emissions Health impact	**Technological indicators** Density Specific heat Fire Classification Water vapor diffusion resistance
[10,24]	**Energy efficiency as a single main criterion is considered** [24]: Local materials Recycled content Renewable sources Low-density industrial process Using human resources/renewable energy Consuming less energy at the site Low thermal conductivity	**Criteria based on the slightest 'Greenness' requirement** [10]: Mechanical properties (for structural materials) Thermal performance during the operating phase Acoustic performance Durability Weight and dimension limits Safety requirements Aesthetic Cost Impact on the environment and human health Performances connected to the specific use of buildings

[yellow] The color represents the green origin criteria, [green] this color represents the green performance criterion, and [blue] this color represents the main proposed criteria.

3.2. Selecting Façade Building Materials Based on the Green Performance

Research focused on building facades' green performance aims to minimize energy consumption and achieve indoor thermal comfort. Lin et al. [27] focused on different thickness variables of thermal mass, insulation, and other design variables in a green building located in China to consider the China Standard for Green Buildings and the building energy efficiency design standard simulating retrofit strategies. Fonseca et al. [28] simulated the addition of external EPS and XPS as insulation façade materials to a residential building aiming to evaluate energy-savings, thermal comfort, and cost savings. Huang et al. [29] added an external vacuum insulation panel in addition to other retrofitting approaches by simulating an actual residential building in China to identify energy and cost savings. Furthermore, evaluating the improvement of including 12 cm of insulation materials (EPS and rock wool) in addition to several retrofit scenarios have been made by Bellia et al. [30] in a university building in Italy to recognize energy renovation measures and applying the cost-optimum retrofit.

El-Darwish et al. [31] added EPS as an internal insulation material to a higher educational building in Egypt to minimize energy consumption. Mahdy et al. [32] evaluated three sets of external walls for low-income residential housing in three different Egyptian climatic zones to minimize energy consumption, achieve indoor thermal comfort, and guarantee maximum cost-effectiveness. Targeting to enhance the performance of building facades, some studies [6,33] assessed different wall systems in accordance with Montreal weather conditions (cold climate zone) for low-rise commercial buildings using Fuzzy measures. An optimization model for designing a sustainable building is developed by Wu et al. [34], considering energy consumption, indoor environmental quality, and life cycle cost, including exterior wall insulation and window-to-wall area ratio.

3.3. Selecting Façade Building Materials Based on the Green Origin

Studies have been conducted targeting the green origin of building materials to mitigate the environmental impacts using life cycle assessment (LCA). Prateep et al. [9] proposed using six different wall construction schemes in tropical climate zones to identify the environmental impacts and the social assessment. Ben-Alon et al. [35] suggested utilizing an alternative wall construction (cob earthen) for conventional materials (concrete masonry and wood wall) and identified cob construction's environmental performance from a life cycle perspective. Assessing different wall systems based on their Global Warming Potential and Fossil Fuel Consumption using LCA has been studied by Dekkiche et al. [36] in a certified LEED gold building. Vilcekova et al. [13] analyzed different building materials for exterior walls in terms of embodied energy and embodied carbon.

3.4. Selecting Façade Building Materials Based on Performance and Origin

The selection of façade materials that meet the performance and green properties requirements has been evaluated in other studies. Farahzadi et al. [37] compared using conventional and alternative environmentally friendly building materials regarding energy consumption and carbon dioxide production in a typical residential building. Optimizing building energy consumption and environmental impacts have been studied [38,39] using LCA, simulation, and building information modeling (BIM). Balali et al. [14] identified six smart materials' weightings and relative importance for façades based on technical, economic, social, environmental, and energy consumption criteria using SPSS software and AHP method to select the most sustainable smart material for building façades. Moussavi et al. [12] classified the most sustainable alternative between five façade material systems based on AHP regarding environmental impacts, life cycle cost, performance, and social benefits. Mostavi et al. [40] identified the optimum design based on the life cycle cost, environmental impacts, and occupant satisfaction considering a database of 65 different materials in an office building. Leo et al. [41] analyzed eight buildings' thermal performance constructed with eco-friendly, durable, and cost-effective structures regarding surface and indoor air temperatures and thermal comfort. Gomaa et al. [20] identified the energy consumption, embodied carbon, and thermal comfort when replacing a conventional material with an environmentally friendly one for an external wall using simulations.

Although the reviewed studies could enhance the design of sustainable building facades using better green building materials, limitations lessen their application effectiveness. Firstly, considering selecting façade materials based on green properties, researchers mainly focus on utilizing LCA. Secondly, researchers rely primarily on the performance of façade selected materials in terms of energy efficiency. On the other hand, green performance and origin of building materials have been considered based on limited disciplines. Moreover, various previous relevant optimization approaches do not reflect the whole picture. Thus, incorporating multiple disciplines' performance and origin assessment attributes is essential to accomplishing a green building envelope.

3.5. Comparison of Green Building Rating Systems

A comparison is carried out between four green building rating systems (LEED [42], BREEAM [43], GPRS [44], and Estidama [45]) to identify the highest consideration of categories' credits. Considering the total points, the first consideration for LEED, BREEAM, and Estidama is the Energy category with 30%, 21%, and 25%, respectively. Moreover, GPRS grants the highest weightings for Water Efficiency with 30% then Energy Efficiency with 25%. As for the materials' category, LEED awards 12% approximately of the total weightings in the third level of interest, and the fourth level for BREEAM, GPRS, and Estidama with 9%, 10%, 16%, respectively.

Materials' related categories in the four green rating systems' technical manuals have been studied to determine the sub-criteria for selecting green building façade materials. Moreover, identifying the possible credits for each sub-criteria compatible with façades to derive the relative weights. Table 2 illustrates the proposed matched sub-criteria and credits of green building façade materials derived from the four green rating systems' manuals. It can be noticed that green building materials' main attributes (green performance and green origin) comprise various categories (the proposed evaluation criteria of green materials will be identified later in Section 5.1).

Green origin criterion of façade building materials is mainly comprised of the materials' category (namely, for LEED: "Materials and resources", for BREEAM: "Materials", for GPRS: "Materials and resources", and for Estidama: "Stewarding Materials").

However, the green performance criterion is comprised mostly of the categories of indoor environmental quality and energy categories (namely, for LEED: "Indoor Environmental Quality", "Energy and Atmosphere", for BREEAM: "Health and Wellbeing", "Energy", for GPRS: "Indoor Environmental Quality", "Energy Efficiency", and for Estidama: "Livable Indoors", "Resourceful Energy").

Table 2. Sub-criteria credits based on selected green rating systems.

Main Category	LEED	Relevant Criteria *	BREEAM	Relevant Criteria *	GPRS	Relevant Criteria *	Estidama	Relevant Criteria *
Materials	Building Life Cycle Impact Reduction (5)	O2a (5 Points)	Environmental impacts from construction products (Building life cycle assessment LCA) (7)	O2a (7 Points)	Life Cycle Cost analysis of materials in the project (LCC) (1)	O4a (1 Point)	Non-Polluting Materials (3)	O2a (3 Points)
	Building Product Disclosure and Optimization (Environmental Product Declarations) (2)	O3b (1 point)	Environmental impacts from construction products (Environmental Product Declarations EPD) (1)	O3b (1 Point)			Reused or Certified Timber (2)	O3b (2 Points)
		O2b (1 point)						
		O1c (1 Point)	Material efficiency (1)	O1c (1 Point) O2b (1 point)	Use of salvaged materials (3)	O1c (3 Points)	Material Reuse (1)	O1c (1 Point)
	Building Product Disclosure and Optimization (Sourcing of Raw Materials) (2)	O1d (1 Point)			Use of readily renewable materials (3)	O1d (3 Points)	Rapidly Renewable Materials (1)	O1d (1 Point)
		O1b (1 Point)			Use of recycled materials (4)	O1b (4 Points)	Recycled Materials (6)	O1c (6 Points)
		O1a (2 Points)	Responsible sourcing of construction products (4)	O1a (1 Point)	Regionally procured materials (3)	O1a (3 Points)	Regional Materials (2)	O1a (2 Points)
		O2d (2 Points)					Non-Polluting Materials (3)	O2d (2 Points)
			Designing for durability and resilience (1)	O1e (1 Point)	Use of higher durability materials (1)	O1e (1 Point)	Design for Durability (1)	O1e (1 Point)
				P1a (1 Point)		P1a (1 Point)		P1a (1 Point)
			Material efficiency (1)	P4a (1 Point)			Design for Materials Reduction (1)	P4a (1 Point)
	Construction and Demolition Waste Management (2)	P2b (2 Points)					Improved Construction Waste Management (2)	P2b (2 Points)
IEQ	Enhanced Indoor Air Quality Strategies (2)	P2a (2 Points)	Indoor air quality (4)	P2a (4 Points)	Optimized Ventilation (5)	P2a (5 Points)	Ventilation Quality (3)	P2a (3 Points)
	Low-Emitting Materials (3)	O2c (3 Points)			Controlling emissions from building materials (5)	O2c (5 Points)	Material Emissions: Paints & Coatings (1)	O2c (1 Point)
	Thermal Comfort (1)	P3b (1 Point)	Thermal comfort (3)	P3b (3 Points)	Thermal Comfort (2)	P3b (2 Points)	Thermal Comfort & Controls: Occupant Control (2)	P3b (2 Points)
	Acoustic Performance (1)	P3c (1 Point)	Acoustic performance (4)	P3c (4 Points)	Acoustic Comfort (1)	P3c (1 Point)	Indoor Noise Pollution (1)	P3c (1 Point)
Energy	Optimize energy performance (18)	P1c (1 Point)	Low carbon design (3)	P1c (1 Point)	Passive External Heat Gain/loss Reduction (7)	P3a (7 Points)	Cool Building Strategies (5)	P3a (5 Points) P1c (1 Point)
		P5a (6 Points)	Reduction of energy use and carbon emissions (13)	P5a (3 Points)	Optimized balance of Energy and Performance (4)	P1c (1 Point)	Improved Energy Performance (15)	P5a (8 Points)
					Energy efficiency Improvement (10)	P5a (6 Points)		
Integrated Process	Integrative process (1)	O4a (1 Point)					Life Cycle Costing (4)	O4a (4 Points)
Management			Project brief and design (4)	O3a (1 Point)				
			Life cycle cost and service life planning (4)	O4a (4 Points)				

* refers to the proposed evaluation criteria, which will be discussed in Table 3.

4. Methodology

In developing systematic decision criteria, Figure 2 illustrates the steps involved in the research. Firstly, a literature review (Section 3) on the assessment criteria for selecting green building materials was discussed by previous studies. Additionally, identifying the criteria relevant to the concepts of green origin and performance of materials for the green building rating systems. The research is based on determining and assessing the criteria for selecting green building façade materials. Since there is no academic standardization procedure to measure these criteria, this paper has been linked to green certification protocols as a reference guide for measuring their importance. Furthermore, green building certification systems encourage using environmentally friendly materials in sustainable projects [46].

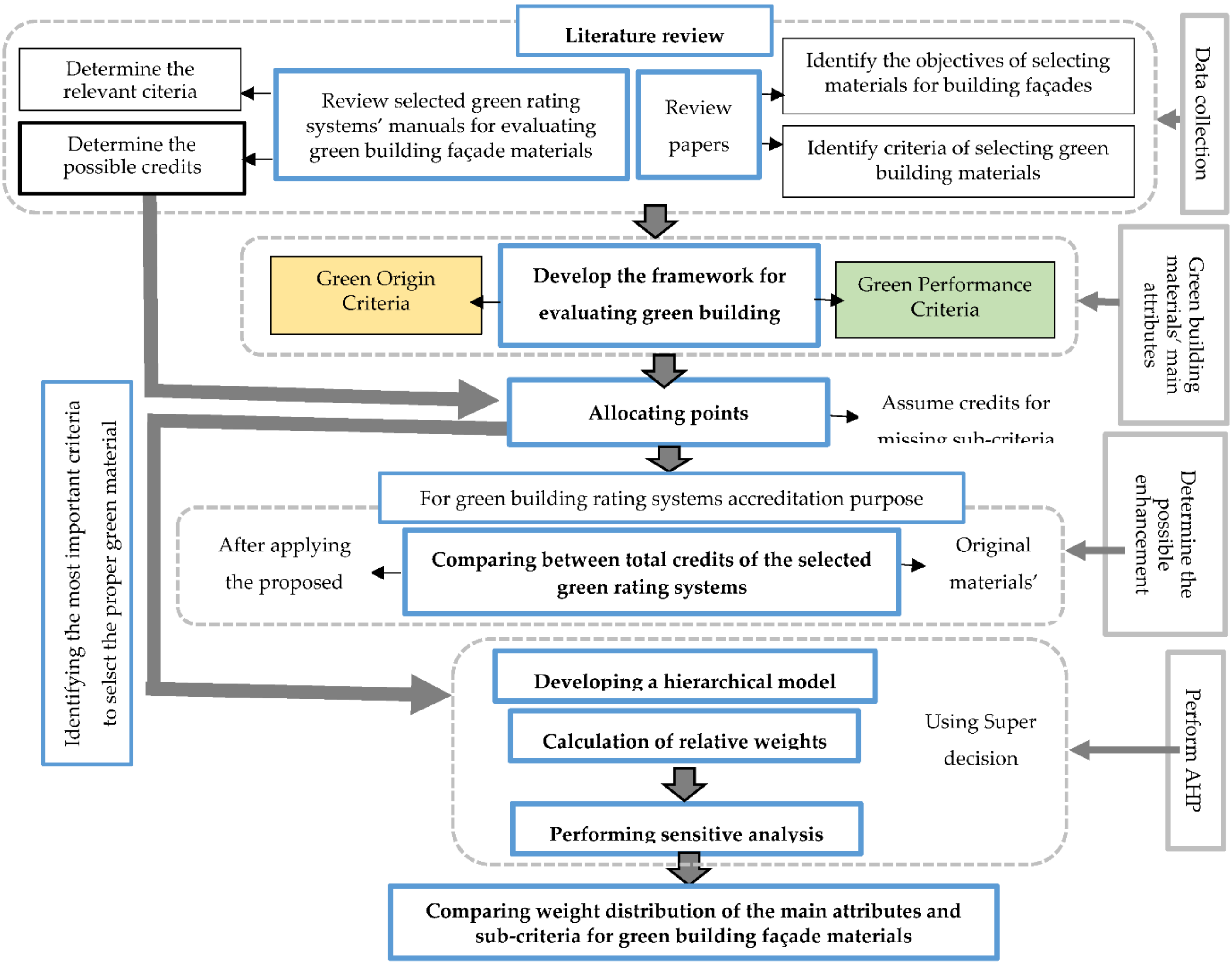

Figure 2. Research methodology.

Four green building rating systems have been chosen to define the matched criteria and credit points for materials-related categories. The selected rating systems are LEED v4.1 (New Construction and Major Renovation), BREEAM UK (New Construction 2018), Green Pyramid Rating System (GPRS v1 is developed for Egypt), The Pearl Rating System for Estidama v1 (Estidama is developed for the gulf region).

The next step is developing the evaluation criteria for green building façade materials that merge green origin and performance concepts to fulfill sustainability measures (Environment, Social, and Economic). Moreover, allocating scores to the proposed criteria is achieved by considering the materials' credits of the green rating systems as a reference. Additionally, a comparison is carried out to identify the difference between the original materials' credits and the proposed material evaluation for obtaining green building rating systems accreditation. Then, AHP is performed using super decision software to determine the highest and the lowest priority evaluation criteria. Finally, final weightings are compared, which assists decision-making in selecting the proper green material for a sustainable building façade.

5. Results and Discussion

5.1. Green Building Materials' Evaluation Criteria

Based on the study of materials-related categories in four green building rating systems, in addition to results obtained from previous studies, five main criteria can be defined to assess both the origin and performance of façade green building materials (Table 3).

The main criteria have been selected based on sustainability assessment measures (Environment, Social, and Economic). The authors also believe that selecting the optimum green material for façades requires the material to be resource-efficient and energy-efficient. This assumption is based on utilizing green materials to reduce energy consumption and conserve natural resources. Therefore, the green material depends on different variables to be a resource-efficient material. As to accomplish the goal of energy conservation, energy-savings are considered either during the material's life cycle or the operational energy (due to the different heat transfer of each façade material), which affects the greenness aim.

Table 3. Proposed assessment criteria for green building materials and their description.

Main Criteria	Green Materials' Attributes	Sub-Criteria	Description	Unit
1- Resource efficiency	Green origin (O)	- Regional materials (O1a) - Recycled content (O1b) - Reusable or recyclable (O1c) - Renewable sources (O1c) - Durable (O1e)	The goal is to reduce material use, waste, and energy consumption by selecting regional, recycled, reusable, renewable, and durable materials, promoting resource-efficient building materials.	-
	Green performance (P)	- Life expectancy (P1a)	The selected building materials are expected to have a long-life expectancy as it affects the façade systems' serviceability by reducing exposed materials' short time until degradation and minimizing maintenance costs.	years
		- Weather, moisture, fire-resistant (P1b)	Selecting green materials capable of complying with climatic conditions to be weather, moisture, and fire-resistant is favorable.	-
		- Compatibility with climate zone (P1c)	The goal is to select green materials compatible with climatic regions (as one of the buildings' passive design measures), affecting thermal characteristics and material thickness.	-
2- Environmental impacts	Green origin (O)	- Involve minimum levels of negative impacts (O2a)	The aim is to have lower environmental impacts of the built environment that can be performed using life cycle assessment LCA from cradle to cradle.	Physical units for each impact category
		- Low Embodied carbon (O2b)	Selecting material with lower embodied carbon is desirable, affecting global warming potential GWP [13].	$kgCO_{2eq}/m^2$
		- Low-Emitting Materials (low VOC emissions) (O2c)	Selecting materials with none or lower volatile organic compound (VOC) emissions is desirable for an environmentally friendly building.	-
		- Low or non-toxic content (O2d)	Selecting low or non-toxic content is recommended to ensure human health.	-
	Green performance (P)	- Promoting the performance of Indoor Air Quality (P2a)	It reflects the performance of green building materials after installation during the operation stage to identify indoor air quality performance.	-
		- Efficient waste disposal (P2b)	The target is to reduce construction and demolition waste to minimize the environmental impacts of construction, demolition, and diverted construction waste to material reuse or recycle.	Weight or volume
		- Healthfully maintained (P2c)	The goal is to select materials that do not release any toxic contents in the maintenance process.	-

Table 3. *Cont.*

Main Criteria	Green Materials' Attributes	Sub-Criteria	Description	Unit
3- Social impacts	Green origin (O)	- Aesthetics (O3a)	The aesthetic criterion is relative from one person to another, depending on the designer's preference based on the quality of the material finish [12].	Points
		- Certified materials (O3b)	The material with a verified document (Environmental Product Declarations) makes it easier to select the material with less environmental impact within sustainable buildings [47]. Thus, it increases the awareness of using documented materials [48].	-
	Green performance (P)	- Thermal performance (thermal resistance) (P3a)	Identifying the good thermal resistance is based on the type of materials, the thickness that affects heating and cooling load requirements. Thus, thermal resistance contributes to occupants' thermal comfort.	m^2.k/w
		- Effect on occupant thermal comfort (P3b)	Selecting proper building materials affects having acceptable thermal comfort levels, which is an essential building characteristic. Additionally, it affects energy consumption levels [49]. The satisfaction of buildings' occupants regarding health and comfort has a social sustainability impact [50,51].	Index
		- Effect on Acoustics (P3c)	Reducing indoor noise can be effective using proper external building materials [52], affecting occupants' satisfaction levels.	The average noise level (Leq)
		- Ease of implementation (P3d)	It reflects the selected green materials to be easy to handle and have the required expertise and skill for labor for installation.	-
4- Economic impacts	Green origin (O)	- Affordability from cradle to cradle-Life Cycle Cost (O4a)	The goal is to optimize the cost-effectiveness of alternative building materials from cradle to cradle, including reasonable capital, transport, operation, labor, installation, maintenance, and replacement cost [53].	Monetary units based on the currency in a country
		- Low Embodied Energy cost (O4b)	It reflects the cost of energy utilized during all building materials' processes.	Monetary units(i.e., \$/m^2)
	Green performance (P)	- Optimize the use of materials during the design (P4a)	The goal is to optimize materials in building design utilizing lightweight materials and materials with standard dimensions and designing for material reuse. Achieving material usage reduction while designing optimization procedures has an economic impact (economic profit) [46].	Monetary units
5- Energy efficiency	Green origin (O)	- Energy efficiency during their life cycle (Embodied Energy) (O5a)	Low energy is demanded during the production processes of building material on-site construction, demolition, and disposal [14].	MJ/m^2
	Green performance (P)	- Effect on energy consumption (P5a)	The impact of external envelope materials on the operating energy through heating and cooling affects the design of energy-efficient building facades.	kWh/m^2

5.2. Attributing Scores to Green Materials' Assessment Criteria

To facilitate comparisons of the evaluation criteria, attributing scores to each sub-criteria of the proposed framework is based on the equivalent credits presented in green building rating systems' manuals, as depicted in Table 2. Figure 3 represents the credits of sub-criteria conducted by green rating systems and the proposed average credits. The proposed assessment credits are calculated based on the average credit of the total four green rating systems' points (which will be used later in Section 5.4) to represent decision-makers' judgments.

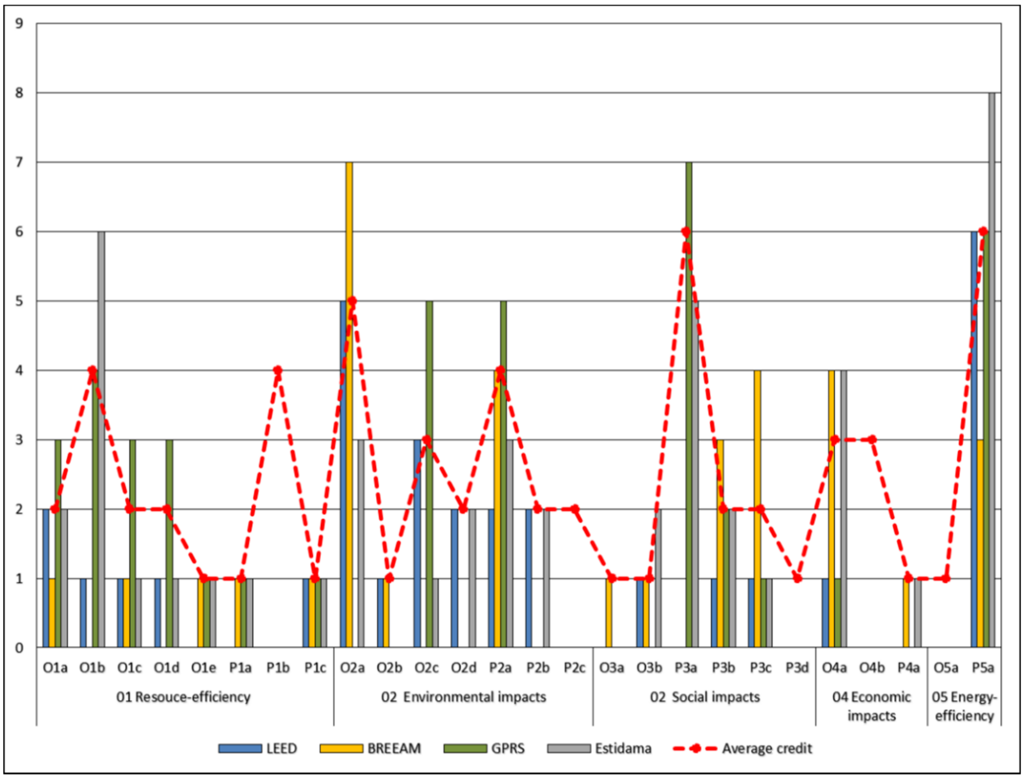

Figure 3. Sub-criteria ranking for green building rating systems and the proposed framework.

The highest average credit points among all assessed sub-criteria in four green building rating systems are for the effect on energy consumption and thermal performance, as shown in Figure 3, followed by involving minimum levels of adverse impacts. The same distribution is parallel to LEED and Estidama credits; however, the second-highest order for Estidama is for the sub-criteria of "recycled content". As for BREEAM, the highest credit is for involving minimum levels of adverse impacts. Moreover, GPRS awards the highest credit for thermal performance.

The selected green rating systems do not directly cover five sub-criteria credits; therefore, they are assumed based on the most relevant sub-criteria credit. The assumed sub-criteria can be derived as follows;

(1) 'Weather, moisture, fire-resistant' (P1b) is estimated to equal the credit point of 'Compatibility with climate zone' (P1c). This estimation is based on the green rating systems methodology, which award points to projects integrating passive design measures. One of these measures is that the building has to be adapted to climate change. Thus, sub-criteria credits of P1b and P1c are equals.
(2) 'Healthfully maintained' (P2c) is estimated to equal the credit point of 'Low or non-toxic content' (O2d) as it has a relevant aim.
(3) 'Ease of implementation' (P3d) is estimated to equal the credit point of 'Optimize the use of materials during the design' (P4a) as it is the most relative target based on optimized material design and selection to be easy to handle.
(4) 'Low Embodied Energy cost' (O4b) is estimated to equal the credit point of 'Affordability from cradle to cradle' (O4a) based on having a related intent.
(5) 'Energy efficiency during their life cycle (Embodied Energy)' (O5a) is estimated to equal the credit point of 'Low Embodied carbon (O2b)'. The basis of this assumption is the methodology that there is a relationship between embodied energy and carbon footprint [54].

Furthermore, the assessment methodology of energy efficiency in the green rating systems is based on the percentage of energy consumption reduction in the proposed building. Otherwise, LEED analyzes the efficiency measures in terms of energy cost and CO_2 emissions. Various studies identified the different percentages of optimized energy consumption using alternative building materials for external walls. For example, Zuhaib et al. [55] achieved a 65% reduction of final energy consumption using scenarios of envelope systems and materials in low-energy residential buildings compared to a reference case. Another study by Fonseca et al. [28] achieved 39% energy savings using active and passive building refurbishment measures. A further reduction in energy consumption was achieved by El-Darwish et al. [31], of 33%, using some of the building's envelope features for retrofitting. Therefore, aiming to have a standard assessment measure for all green building rating systems, the sub-criteria of the effect on Energy consumption (P5a) is calculated based on an average reduction of 30%.

5.3. Analysis Results for Green Materials' Credits of Green Building Rating Systems

Analyzing the selected green building rating systems' materials aspects based on the proposed assessment criteria (Tables 2 and 3) is concluded in Table 4. Therefore, Table 4 compares the total credits of green materials' main attributes (green origin and performance) among the four rating systems. Moreover, it represents each rating system's original total points for the materials' category-without adding assumption points-and the total final points for all categories.

Table 4. Comparison between GBMs credits for the proposed assessment criteria among Green Building rating systems.

	Green Origin of Building Materials (a)	**Green Performance of Building Materials (b)**	**Original Total Credit Points (d)**	**Original Points for Materials' Category (c)**	**The Original Percentage for Materials' Category (c/d*100)**	**Proposed Percentage of Using GBMs ((a + b)/d)**
LEED	18	13	110	13	12	28
BREEAM	17	17	149	14	9	23
GPRS	20	23	200	20	10	22
Estidama	23	24	177	28	16	27
Proposed average credits	31	32	-			

As shown in Table 4, higher credits are given to green origins for LEED certification than green performance. However, GPRS and Estidama award more green performance points than green origin, and BREEAM awards the same credits for both main attributes. Additionally, selecting green materials for building façades–regarding the proposed evaluation criteria points-helps decision-making obtain more points for accreditation than the original points of materials' category. This maximization is based on the selection of green materials that combine their green origin and performance criteria. More than double percentage weightings are achieved for the proposed criteria's total percentage compared with the original percentage of the materials' category.

Analyzing the preferable sub-criteria among green rating systems-regarding the proposed framework's highest points (Table 2)-has revealed that the green origin concept is identified from the sub-criteria involving minimum levels of adverse impacts for LEED and BREEAM. Moreover, GPRS mainly focuses on low-emitting materials. Furthermore, Estidama awards the highest points to the sub-criteria of recycled content. As for the green performance concept, LEED and Estidama award the highest credit to the effect on energy consumption sub-criteria. Otherwise, BREEAM awards more points similarly to the sub-criteria of promoting indoor air quality performance and the effect on acoustics. As for GPRS, the sub-criterion of thermal performance has the highest credit.

5.4. Formulation of the Proposed Criteria Using AHP

Super Decisions software v.3.2 [56] is used to solve the decision-making problem based on AHP. The steps of a typical AHP procedure are ranged as follows [57];

1. Developing a hierarchical model: The hierarchy consists of clusters arranged in levels to analyze the decision. The first level is the primary goal connected to five main criteria. Each criterion's cluster has a group of sub-criteria which are connected to two alternatives (attributes): green origin (O) and green performance (P) (Figure 4).
2. Deriving relative weights for the criteria: In this step, a pairwise comparison matrix is made for each criterion based on the primary goal.

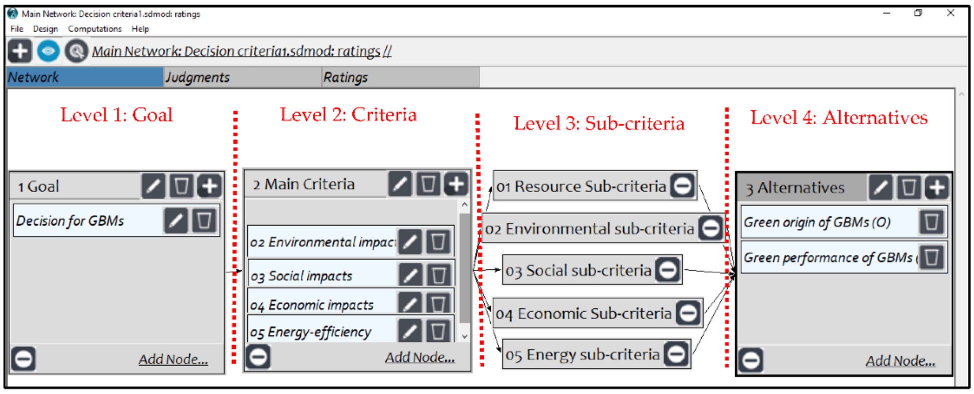

Figure 4. A snapshot of the hierarchical model in Super Decisions software.

Therefore, weights are calculated based on the values of the proposed credits. Table 5 represents each criterion's proposed points using the average credits of four standard green rating systems as a reference with the assumption of five sub-criteria (mentioned in Section 5.2). AHP ranks the fundamental evaluation scale from 1 to 9 (Table 6) [57], where 1 represents equal or weakly more important and 9 illustrates extremely important (was developed initially by Saaty [58]).

Table 5. The proposed credits for main and sub-criteria.

Main Criteria	Sub-Criteria							
	O1a	O1b	O1c	O1d	O1e	P1a	P1b	P1c
1- Resource efficiency	2	4	2	2	1	1	4 *	1
Sum [a]	11					6		
Sum [b]	17							

Main Criteria	Sub-Criteria						
	O2a	O2b	O2c	O2d	P2a	P2b	P2c
2-Environmental impacts	5	1	3	2	4	2	2 *
Sum [a]	11				8		
Sum [b]	19						

Main Criteria	Sub-Criteria					
	O3a	O3b	P3a	P3b	P3c	P3d
3- Social impacts	1	1	6	2	2	1 *
Sum [a]	2		11			
Sum [b]	13					

Main Criteria	Sub-Criteria		
	O4a	O4b	P4a
4- Economic impacts	3	3 *	1
Sum [a]	6		1
Sum [b]	7		

Main Criteria	Sub-Criteria	
	O5a	P5a
5- Energy efficiency	1 *	6
Sum [a]	1	6
Sum [b]	7	

* refers to assumed credit, [a] refers to the total points for green origin and performance, and [b] refers to the main criteria' total points.

The judgment matrix originated based on each pair's relative importance in each cluster, including the main criteria and sub-criteria involved in the decision (see Appendix A for the pairwise comparison of the main criteria and Appendix B for the judgment matrix for social impacts' sub-criteria). For example (considering the social impacts), the sub-criteria credit point P3b equals P3c, which means the importance ratio is 1. Additionally, P3a has the highest point–between sub-criteria of the social impacts–than other sub-criteria, while O3a, O3b, and P3d have the lowest points. Thus, the importance ratio equals 9, which is assigned as an input for this comparison.

Table 6. AHP pairwise comparison scale.

Judgment	Importance Value
Equal important	1
Moderately more important	2
	3
Strongly more important	4
	5
Very strongly more important	6
	7
Extreme important	8
	9

After entering the values of the importance ratio for each main and sub-criteria pair, the inconsistency rate is checked by the software. It is considered to be less than 10%, which validates that the assumptions are acceptable. Therefore, the inconsistency index of each pair of main criteria (10 comparisons) is 0.04219. After that, each sub-criteria pair is compared based on the main criteria (68 comparisons). Therefore, the inconsistency ratio–derived from the software–ranged between 0.01387 for resource-efficiency sub-criteria, 0.04033 for environmental impacts sub-criteria, 0.01952 for social impacts sub-criteria, and zero for economic impacts and energy efficiency.

3. Deriving local priorities for the alternatives: It is calculated based on the importance comparison between each alternative (green origin and green performance) regarding each sub-criteria (26 sub-criteria). Appendix C represents an example of the local priorities based on the sub-criteria O3a. As shown in this figure and based on the points in Table 5, O3a has the lowest point between sub-criteria, and the total points for green performance (for the main criteria social impacts) have the highest value. Therefore, green performance is ranked 9 as extremely more important than green origin regarding the sub-criteria O3a.
4. Deriving overall priorities (model synthesis): The weights are combined to synthesize the ratings and calculate the overall economic impact priorities. Therefore, the final ranking criteria of green building materials indicate three different levels (Table 7) as follows:

a. Ranking of main criteria (represents the priority of each main criteria):

Analyzing the main criteria's weights revealed that the environmental impacts criterion has the highest weight among main criteria with 0.47. However, both the economic impacts and energy efficiency criteria have the lowest weights with 0.04. As expected, the economic impacts–as the main criteria- has the least weight of priority. For instance, Illankoon et al. [59] mentioned a lack of evaluation for most green building rating systems' economic aspects.

b. Ranking of local criteria (represents the priority of sub-criteria based on main criteria):

Resource efficiency (with eight sub-criteria): The preferable sub-criterion for green origin is recycled content, similarly to the weighting of the preferable sub-criteria for green performance weather, moisture, fire-resistant with 0.30.

Environmental impacts (with seven sub-criteria): The preferable sub-criterion for green origin involves minimum levels of adverse impacts, and the preferable sub-criterion for green performance is promoting the performance of Indoor Air Quality with 0.41, 0.23, respectively.

Table 7. Overall rating of the assessment criteria.

Main Criteria		Sub-criteria	Local weight [a] %	Global weight [c]	weight [b] %
1- Resource efficiency	Green Origin (O)	Regional materials (O1a)	10	3.1	32
		Recycled content (O1b)	30	9.7	
		Reusable or recyclable (O1c)	10	3.1	
		Renewable sources (O1d)	10	3.1	
		Durable (O1e)	4	1.2	
	Green Performance (P)	Life expectancy (P1a)	4	1.2	
		Weather, moisture, fire-resistant (P1b)	30	9.7	
		Compatibility with climate zone (P1c)	4	1.2	
2- Environmental impacts	Green Origin (O)	Involve minimum levels of adverse impacts (O2a)	41	19.3	47
		Low Embodied carbon (O2b)	3	1.4	
		Low-Emitting Materials (O2c)	14	6.5	
		Low or non-toxic content (O2d)	7	3.1	
	Green Performance (P)	Promoting the performance of Indoor Air Quality (P2a)	23	11	
		Efficient waste disposal (P2b)	6	2.9	
		Healthfully maintained (P2c)	6	2.9	
3- Social impacts	Green Origin (O)	Aesthetics (O3a)	5	0.6	13
		Certified materials (O3b)	5	0.6	
	Green Performance (P)	Thermal performance (P3a)	60	7.9	
		Effect on occupant thermal comfort (P3b)	13	1.7	
		Effect on Acoustics (P3c)	13	1.7	
		Ease of implementation (P3d)	5	0.6	
4- Economic impacts	(O)	Life Cycle Cost. (O4a)	44	1.7	4
		Low Embodied Energy cost (O4b)	44	1.7	
	(P)	Optimize the use of materials during the design (P4a)	11	0.4	
5- Energy efficiency	(O)	Energy efficiency during their life cycle (Embodied Energy) (O5a)	10	0.4	4
	(P)	Effect on Energy consumption (P5a)	90	3.4	

[a] is the priority of sub-criterion derived from super decisions software regarding main criteria*100, [b] is the percentage of main criteria priority weight, and [c] is derived from multiple the local weight of the sub-criterion [a] by the priority of main criteria [b]/100.

Social impacts (with six sub-criteria): Both sub-criteria for green origin aesthetics and certified materials are equal to 0.05. Moreover, the preferable sub-criterion for green performance is the thermal performance with 0.60.

Economic impacts (with three sub-criteria): Both sub-criteria for green origin Life Cycle Cost and low Embodied Energy cost are equal with 0.44, while the sub-criterion for green performance optimizing the use of materials during the design has 0.11.

Energy efficiency (with two sub-criteria): The green performance sub-criterion affecting the energy consumption has a significantly higher weight than the green origin sub-criterion of energy efficiency during their life cycle, with 0.90 and 0.10, respectively.

c. Ranking of global criteria (represents the final priority of each sub-criteria)

Considering the global weight of sub-criteria, involving minimum levels of adverse impacts is the highest importance sub-criterion based on the final green origin scores with 0.193. Additionally, promoting Indoor Air Quality's performance has the highest weight, with 0.110, influencing green performance.

Moreover, there is no significant difference between the final weightings–obtained from the software–of green origin and green performance with an overall score of 0.53 and

0.47, respectively. This result is evident due to the close of total points among green rating systems (Table 4).

5. Perform sensitivity analysis: (will be discussed later in Section 5.5).
6. Making the final decision: The results representing the highest and the lowest priority evaluation criteria of green buildings, decision-makers could identify the proper green material for each project.

5.5. Sensitivity Analysis

Performing sensitivity analysis is essential for identifying which criteria motivated the initial results and the robust final decision [47].

Regarding the overall ranking (Table 7), Figure 5a illustrates that the green performance of green building materials is influenced by the main criteria of social impacts and energy efficiency more than other criteria. In contrast, the green origin is motivated more by economic impacts. As for environmental impacts and resource efficiency, they are relatively close concerning the green origin criterion. Moreover, considering global weight from Figure 5b, environmental impacts criteria significantly affect green origin and performance. After that, resource efficiency has a significant influence on both main attributes. Moreover, the green performance of social impacts is close to resource efficiency.

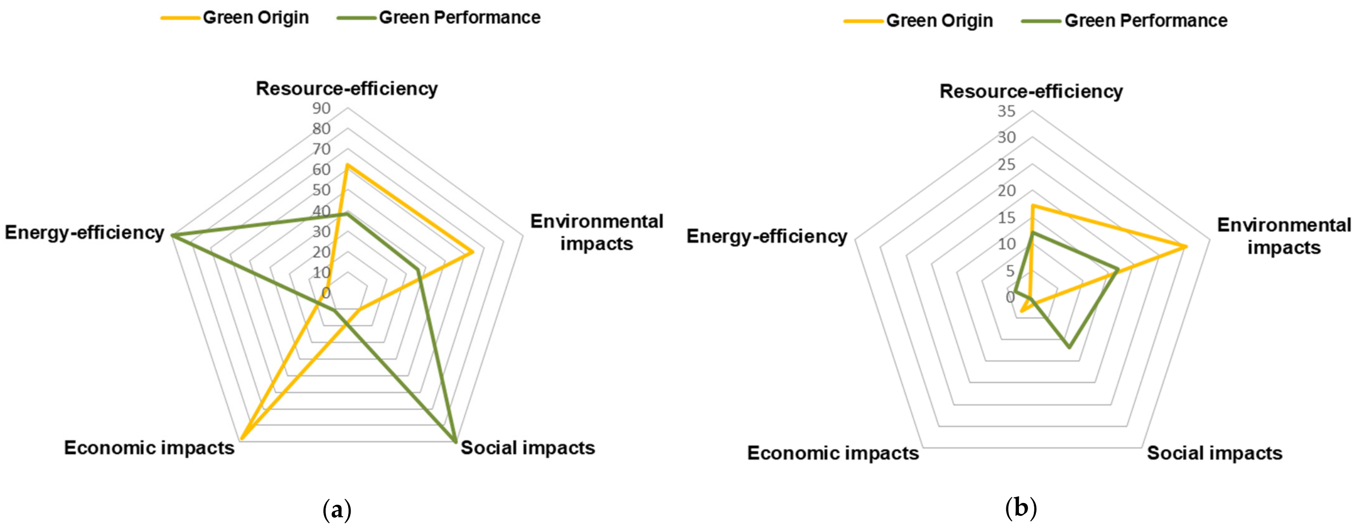

Figure 5. Sensitivity analysis concerning (**a**) local weights, (**b**) global weight.

Super decision software could identify the sensitivity of results by specifying the criteria effect if the weights are different (Figure 6). There is a minor difference between the total of green origin and green performance; thus, determining each criterion's effect is essential. From Figure 6c,e, social impacts and energy efficiency significantly influence green performance than green origin. As for Environmental impacts (Figure 6b), there is almost no difference between both main attributes. Moreover, resource efficiency (Figure 6a) and economic impacts (Figure 6d) have more influence on green origin than green performance.

5.6. Comparing the Previous Studies' Results

In this section, a comparison of the obtained findings with the relevant previous studies outcomes has been made to analyze the most important criteria for evaluating green building materials. Various studies represent different criteria based on the top ranking of green materials selection. Aiming to determine the most sustainable system for building façades, Moussavi et al. [12] recognized embodied energy and carbon emission, followed by material costs, as the top criteria. Khoshnava et al. [2] considered the affordability of green building materials as the top ranking. In contrast, resource efficiency focused on natural, renewable materials is the second top criterion based on sustainability measures (environment, social, and economic).

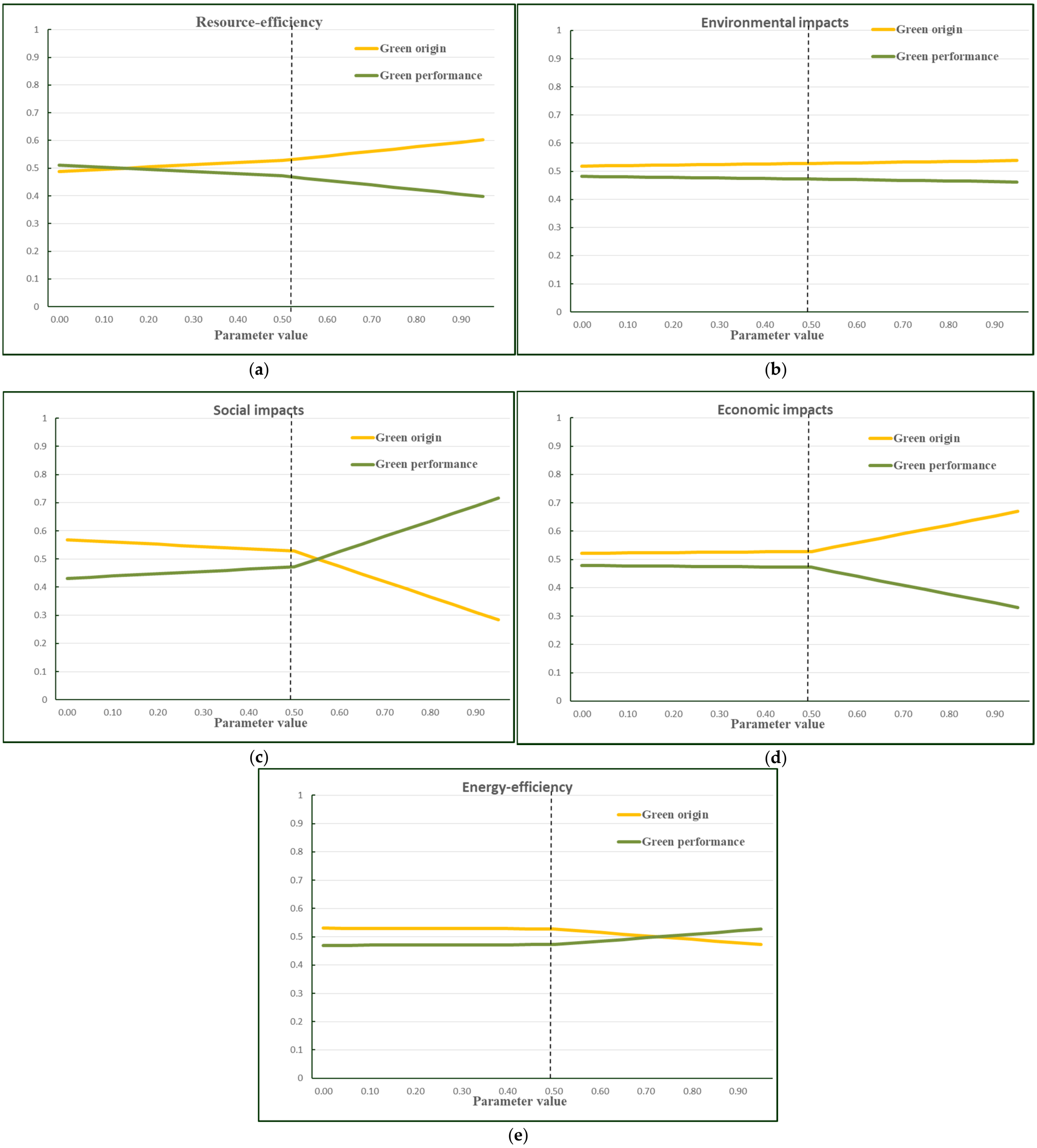

Figure 6. Sensitivity analysis for (**a**) Resource efficiency, (**b**) Environmental impacts, (**c**) Social impacts, (**d**) Economic impacts, and (**e**) Energy efficiency.

Moreover, decreasing energy consumption is the most remarkable selection criteria, according to Balali et al. [14], aiming to identify the most sustainable building façades' smart material. Furthermore, the availability and cost of green materials were highlighted as the most important criteria for evaluating green materials based on LEED, according to Castro-Lacouture et al. [60]. The environmental impacts, economic and the R-value are equally crucial as assessment criteria for selecting the optimum external building wall system, according to Prateep et al. [9].

As for this study's findings, environmental impacts involving minimum levels of adverse impacts and promoting Indoor Air Quality performance are the most critical criteria that merge green origin and performance, considering four green rating systems as a reference. The second top ranking is resource efficiency with recycled content and weather, moisture, and fire-resistant sub-criteria. The research recognized 14 sub-criteria for the green origin and 12 sub-criteria for green performance, distributed to five main criteria. These criteria are based on achieving sustainability measures to select the proper green material for building façades.

In the authors' opinion, the proposed framework weights of importance could be adapted based on each case study's requirement (climate zone, building type, etc.). Hence, it could require certain assumptions to determine the highest priority criterion that would be the basis of the selection process.

6. Conclusions

This study identifies the assessment criteria incorporating green origin and performance of green building façade materials based on sustainability aspects. Therefore, a literature review of the green material selection approaches is conducted to optimize the building façades' materials selection process. The researchers lean towards assessing green façade materials based on limited disciplines that reflect green performance and green origin concepts of façade materials. The authors highlight the importance of selecting the proper green materials for façades that require merging green origin and green performance, considering green building rating systems as a reference.

Therefore, five main criteria and 26 sub-criteria are identified throughout the study, which could be valuable for selecting building façade material for accreditation purposes or following sustainability standards in new or refurbished buildings. Four green rating systems were used to determine the relevant criteria and credits of using green materials to have more realistic numbers based on experts' opinions. Applying the proposed evaluation criteria for selecting green materials for building façades helps earn more credits for green rating systems' accreditation than the original credits for materials. Therefore, more than double the percentage of total credits is achieved for the analyzed green rating systems based on the proposed criteria. The green certification protocols are varied towards focusing more on earning points for green origin or performance criteria. The highest importance is given to green origin criteria than green performance for LEED; however, earning points for both main attributes in BREEAM are the same. As for GPRS and Estidama, more points are awarded to green performance than the green origin.

Furthermore, averaging each sub-criteria score of the four rating systems to develop the proposed evaluation criteria credits. Moreover, the average scores are used for criteria prioritization using the AHP process. It is preferable to select materials for façade buildings based on their green origin and performance, in the authors' opinion based on the results of AHP. However, for decision-makers who cannot consider the whole criteria for new or renovated buildings, the most priority criteria can be selected based on the final scores of the AHP method. It can be concluded that involving minimum levels of adverse impacts is the preferable selection sub-criteria for green origin. Promoting indoor air quality performance is the most favorable selection for green performance with 19%, 11%, respectively, for global weight. Regarding sensitivity analysis results derived from the software, social impacts and energy efficiency significantly influence green performance than green origin. Moreover, resource efficiency and economic impacts have more influence on green origin than green performance.

There are possible limitations of using AHP in determining the relationships among criteria and sub-criteria (especially for evaluating alternative green building materials in a case study). The decision is complex since several criteria are not based on numerical analysis. Therefore, other techniques (e.g., ANP) could be adopted in future work. Additionally, this study's findings can be further extended by evaluating the green origin and the green performance of different green materials and assessing their effect on the performance of the whole building. Moreover, they could assist in developing criteria for selecting green materials for other building elements (i.e., flooring and roofs) that comply with merging between green origin and performance.

Author Contributions: M.M.G.M.: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing—original draft, Visualization. Z.M.T.E.S.: Conceptualization, Validation, Writing—review & editing, Supervision. A.A.M.A.: Writing—review & editing, Supervision. M.G.I.: Resources, Supervision. All authors have read and agreed to the published version of the manuscript.

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Appendix A

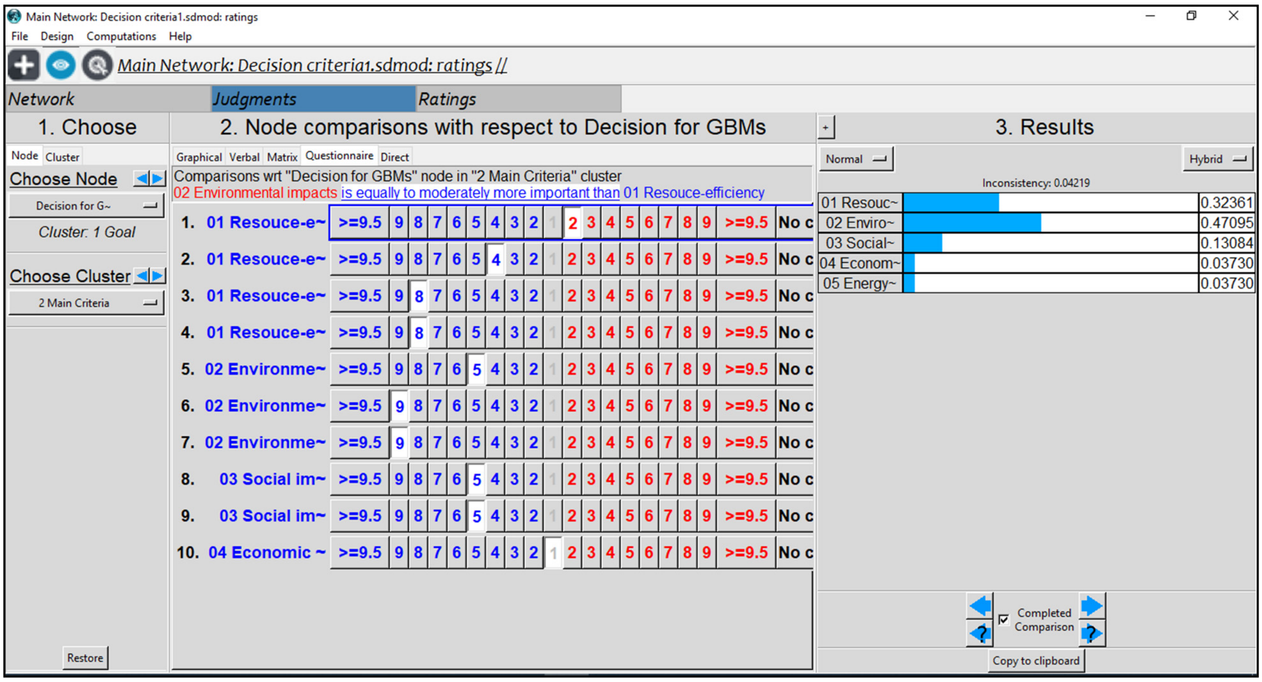

Figure A1. A sample of the pairwise comparison matrix for the main criteria.

Appendix B

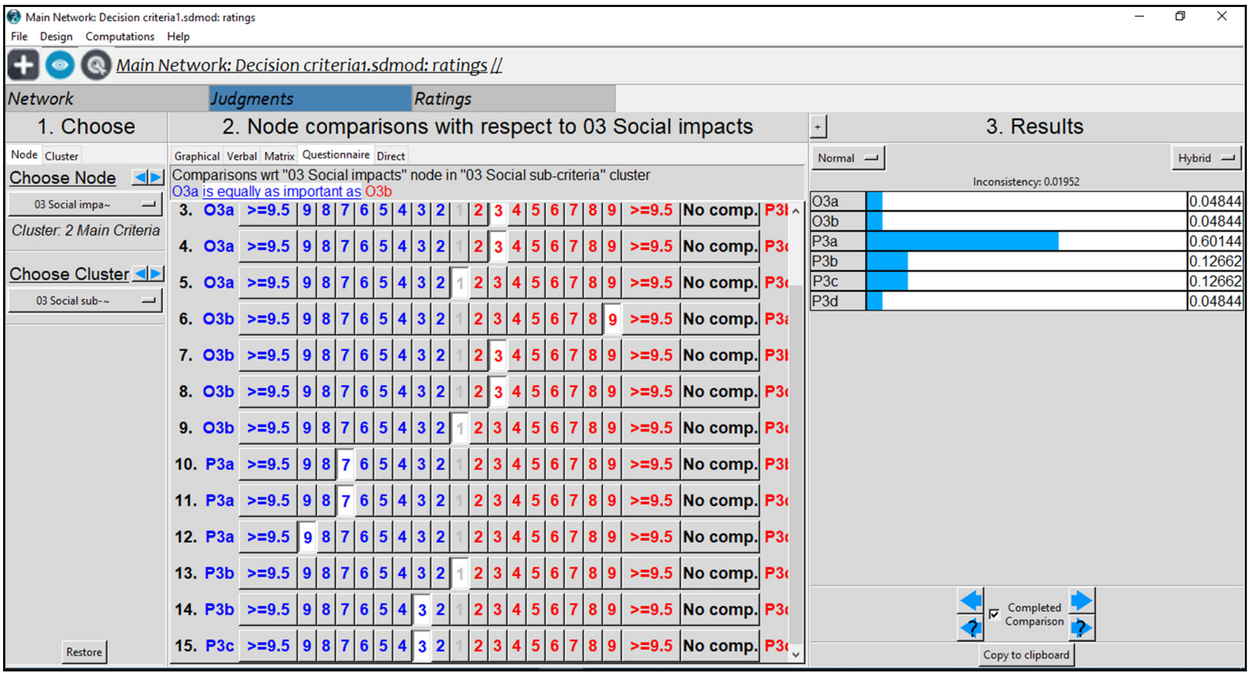

Figure A2. A sample of the pairwise comparison matrix for social impacts sub-criteria.

Appendix C

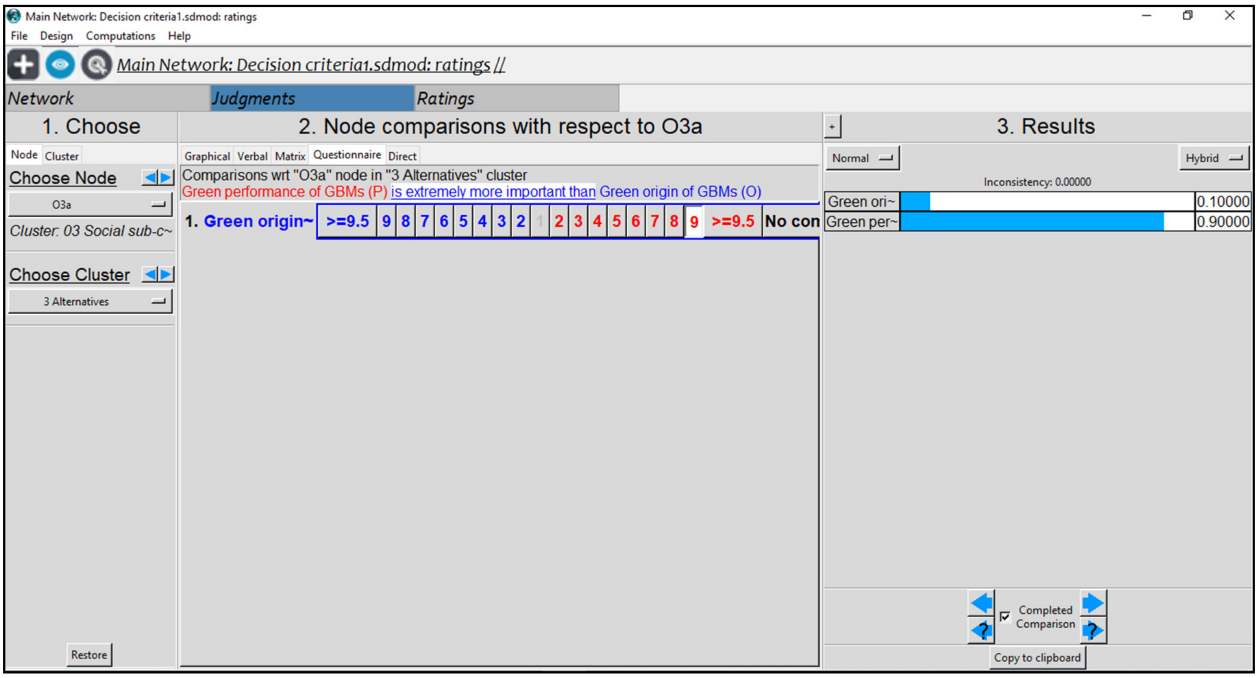

Figure A3. A sample of local preferences for each alternative with respect to sub-criteria.

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