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Selection of (Green) Roof Systems: A Sustainability-Based Multi-Criteria Analysis

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Abstract: A wide diffusion of green envelopes in cities can be an opportunity to improve urban environment conditions and reduce negative effects of climate change. The green roof system is a widespread solution adopted all over the world due to the relative simplicity of installation and the large private and social benefits provided. Despite this, some factors hinder the diffusion of the green roof system, not only economic factors (due to the higher installation costs compare to a traditional roof solution), but also technical factors connected to lack of knowledge. The present paper investigates the factors influencing designers in the choice of a building roof systems, comparing a traditional solution and a greening system. The involvement of architects, engineers, and researchers allows the selection of the most important factors. Results of the study identifies their priority, and through a sustainability-based multicriteria analysis, the role played by each one in the decision process. This approach provides interesting hints to identify effective strategies to support a wider diffusion of greening systems for urban resilience.

Keywords: green roof; multi-criteria analysis; Analytic Hierarchy Process; sustainability

1. Introduction

Green roofs are widely recognized as sustainable systems able to improve the building envelope performance. Several researches have investigated the economic benefits of green roofs. Wong et al. [1] compared the cost of traditional roof solutions with green roof solutions, demonstrating that when considering the whole life span of a roof, the costs for extensive green roofs are lower compared to traditional flat roofs. Bianchini and Hewage [2] demonstrated that green roofs are sustainable solutions on a long-term basis. Claus and Rousseau [3] found that subsidies and tax incentives are socially desirable and needed to convince potential private investors to install green roofs. Rosato et al. [4,5] studied the technological and economic features of the systems. Other authors [6,7] have shown that the most relevant benefit influencing the economic and environmental sustainability of green roofs is energy saving. Coma et al. [8] demonstrated that the passive cooling capacity of green roofs is able to reduce heating and cooling demands. Another economic benefit is roof protection—the layers of green roofs can increase the roof longevity from 20 to 40 years [9]. According to Peck et al. [10], green roofs, as green areas, can also increase the real estate value of a building from 6 to 15%. Green roofs can reduce sound exposure near and inside a building [11]; they are also recognized as water-sensitive urban design systems thanks to their capacity to improve the quality of urban water run-off [12].

A wide diffusion of green roofs in urban areas provides the opportunity to improve air quality, since plants naturally clean the air and sequester carbon [13]. Other environmental issues typical of urban areas can be addressed, such as urban heat island mitigation [14], i.e., a phenomenon causing higher temperatures in cities compared to the surrounding rural areas [15]. Tan and Sia [16] sampled roof temperatures and air quality parameters before and after green roof installation in Singapore, finding that acid gaseous pollutants, carbon mass levels, and ambient temperature drop significantly after the installation of green roofs. According to Bianchini and Hewage [17], social benefits of green roofs include air quality improvement, carbon reduction, reduction of flood risks, habitat creation, aesthetics, provision of recreational space, and urban heat island mitigation.

Green roofs are classified as intensive or extensive solutions [18]. The layers composing a green roof generically are vegetation, substrate, filter, drainage, protection and water retention, root protection, and waterproofing [19]. Extensive green roofs are lightweight, require low maintenance, and are low cost systems compared to intensive green roofs; intensive green roofs have thicker substrates and related weight, can be accessible, but initial costs and maintenance are higher. Also, semi-intensive green roofs should be mentioned, with deeper substrates compared to extensive solutions, allowing the use of several plant species [8].

Despite the benefits derived from the installation of a green roof system, the dissemination of this solution is hindered by several factors: professional (low knowledge of the technical system by the designers); technical (greater load on building structure, shape and slope of roof, property rights of the building's roof); and economic (initial investment and maintenance costs, depending on the system).

As the short review presented suggests, nowadays the choice of (greening) system should be based on a wide range of environmental, social, and economic aspects. Recent studies have shown that multi-criteria analysis can be used to select technological solutions for buildings systems [20,21]. In addition, Sangkakool et al. [21] show that a multi-criteria technique can be used to weight the factors that facilitate or hinder the wide spread of green roofs.

Through a panel composed by professionals and academics, this paper identifies which factors (in terms of criteria and sub-criteria) influence the choice between a traditional or a green roof solution, considering economic, environmental, social, and performance criteria. Indeed, sustainable design should consider the three pillars of a sustainable system, i.e., economic, environmental, and social aspects [22].

The study investigates if there is a gap between research and design practice, involving professionals, i.e., the ones presenting to a client different design options and related benefits and challenges, and academics conducting research on building systems and greening systems. By means of a sustainability-based multi-criteria analysis, the priority (or "weight") of each factor is evaluated. Multi-criteria analysis is an important tool to drive designers and decision makers within a multidimensional decision problem characterized by several solutions (alternatives); the optimization of choices can increase knowledge and control of the relevant aspects, providing useful hints for a wider diffusion of greening systems.

2. Methodology

In order to develop a sustainability-based multi-criteria analysis, the main factors involved in the choice of a (green) roof system are identified.

The study is structured in three parts:

(1) Identification of the factors influencing the choice between a traditional flat solution and a green roof system (Figure 1), to define the main criteria and sub-criteria considered;
(2) Application of a multi-criteria technique—the Analytic Hierarchy Process (AHP) [23]—in order to evaluate the priority of each selected criteria and sub-criteria;
(3) Final ranking of green roofs and traditional roofs according to the full set of criteria and sub-criteria.

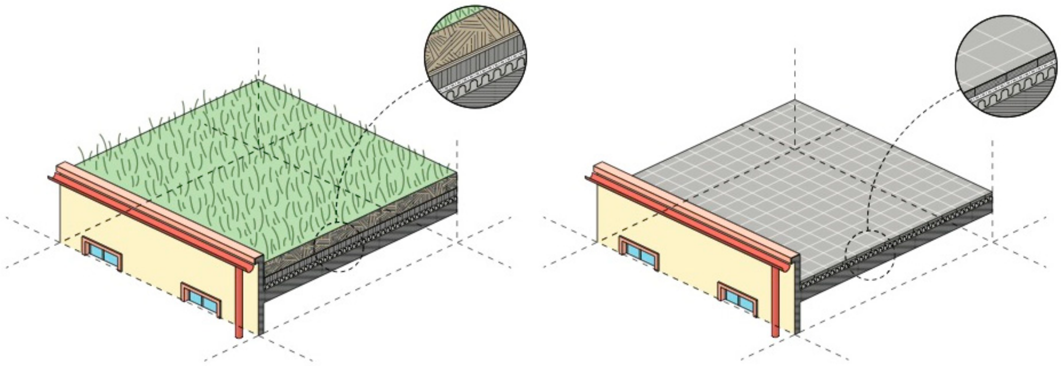

Figure 1. Left: Green roof (layers: slab, insulation material, waterproofing, drainage, filter, substrate, vegetation). **Right:** traditional roof (layers: slab, insulation material, waterproofing, roof covering).

The identification of criteria and sub-criteria and the application of the sustainability-based multi-criteria analysis is performed thanks to the involvement of a panel of experts. The panel is made of professionals (architects and engineers) in the design and construction of new buildings and retrofitting projects with experience in green roof systems, operating mainly at the local and national level in Italy, and with academics working in the field of architecture technology and economic evaluation (i.e., researchers and professors). The total number of participants is 30 (Table 1).

Table 1. Composition of panel.

Panel	Number of Components
Group a: Academics *	15
Group b: Professionals **	15

* 6 specialized in economic evaluation of projects and 9 in technology. ** designers, architects, engineers.

2.1. Selection of Criteria

Each member of the panel was involved in a cross-group discussion (brainstorming technique, led by a moderator). The discussion started with the question: *"In the planning phase of an intervention that involves the construction of a flat roof for a new building (for example an office building), which are the criteria that you consider when choosing between a "traditional" or "green" roof solution*?" The participants freely proposed criteria, and at least in a first phase, all the indications (even the outlandish, paradoxical or with little relevance to the proposed topic) were considered. This created a "flow of knowledge" that allowed the identification of a wide range of aspects of the decision process. In a second phase, the most important topics were highlighted in order to define a framework for a group of criteria. In addition, it is preliminarily specified to each member that both the "traditional" and "green" roofing solutions are, based on the characteristics of the building and the local regulatory provisions, technically and legally feasible; it is also specified to refer, for both solutions, to a flat roof accessible directly from the stairwell of the building (freely accessible).

In order to better orient the discussion, four main groups of criteria are identified, namely:

(1) Economic
(2) Environmental
(3) Social
(4) Performance

Afterwards, for each of the four groups of criteria, the panel members indicate the most relevant sub-criteria for the choice between a green roof and traditional flat roof; each member individually completed a document to avoid the influence of other members in the identification of the sub-criteria. A targeted revision of the sub-criteria produced is implemented to avoid repetitions or mistakes (e.g., same criteria named differently or included in the wrong group). The different skills and expertise of the members of the panel allowed identification of 17 sub-criteria within the group of four main criteria (Table 2). A similar approach was shown to be effective by Nadoushani et al. [22].

Table 2. The 4 groups of criteria and the 17 sub-criteria.

Economic	Environmental	Social	Performance
Installation cost	Air quality and heat island reduction	Building aesthetic	Roof longevity
Maintenance and disposal costs	Runoff reduction	Urban aesthetic and biodiversity	Acoustic noise reduction
Tax incentives	Embodied energy and carbon emission	Suitability to location	Weight of system
Real estate benefit	Resource sustainability	Health	Insulation properties
Energy savings (heating, cooling)			

The greatest number of sub-criteria indicated belong to the "Economic" area (five), while four sub-criteria were indicated for each of the other groups ("Environmental", "Social", and "Performance").

2.2. Economic Criteria

2.2.1. Installation Costs

Installation costs is the price paid to the construction company in charge of the work; it is the sum of the costs of all materials (including transportation), labor, and rental of the equipment needed for the installation. These costs also include those related to the preparation of the construction site (e.g., scaffolding). The cost of a traditional flat roof varies from 80 to 100 €/m^2 depending on the type of roof covering and insulation layer, while a green roof range from 139 (extensive) to 249 €/m^2 (intensive) [7].

2.2.2. Maintenance Costs

Maintenance costs include all the costs related to the maintenance to be faced within the life span of a system—20 years for a traditional roof [24], and 40–45 years for a green roof [25,26]; at the end of this period, a total renovation is envisaged. For the traditional covering, maintenance concerns the repair or the replacement of elements of the roof covering, and in the case of water infiltration in the underlying layers, of the other layers involved (waterproofing sheath, layer of insulation, vapor barrier); interventions are usually limited to small portions of the roof surface with sporadic frequency if the roof has been correctly executed.

With regard to the green roof, maintenance needs depend on the green roof type; for extensive green roofs, maintenance includes mowing, eradication of weeds, soil fertilization, and cleaning of ducts for collecting and removing rainwater (once per year). For the intensive or semi-intensive type, maintenance can have more frequent infra-annual intervals (four-monthly) and also plant pruning and treatment against pests, replacement of plants, and maintenance of irrigation systems (replacement of about 10% of PVC pipes per year, as well as irrigation water). The annual unitary cost for extensive green roof maintenance is approximately 2.0 €/m^2 per year, while an intensive or semi-intensive green roof is approximately 7.0 €/m^2 per year [7]. At the end of the life-span the disposal cost of the roof (demolition, landfill etc.) must be considered; for a traditional roof it is about 25–35 €/m^2, while for a green roof it can vary from 38 €/m^2 (extensive green roof) to 48 €/m^2 (for intensive green roof) [7].

2.2.3. Tax Incentives

Several local, regional, and state administrations provide economic incentives to encourage the installation of high-performative covering systems in terms of thermal insulation characteristics (summer and winter); in Italy, these incentives concern interventions aimed at improving the energy performance of existing buildings and new constructions (Law number 10/1991). According to the Law number 145/2018, a tax deduction over a period of 10 years of 65% of the costs of installation (material used, construction, etc.) and design can be obtained with the installation of an insulated roof. This incentive would affect both traditional and green roof solutions. In addition, green roofs allow a further deduction of 36% of the cost incurred for planting plants, for a maximum deduction of €5000.

2.2.4. Real Estate Benefits

Greening systems increase the property value of a building, due to aesthetic factors connected with the presence of greenery and to the creation of accessible green areas on the top of buildings. The real estate value increases thanks to a green roof: it can vary from a minimum of 3.6% [27] to a maximum of 20.0% [28] for an accessible and recreational green roof. According to Bianchini and Hewage [2], the increase depends on the green roof type, at 2–5% for extensive green roofs and 5–8% for intensive.

2.2.5. Energy Savings

Green roofs, thanks to shading, evapotranspiration, wind barriers, and insulation capacity, reduce the energy demand for air conditioning and heating [8]. The energy saving depends on the green roof stratigraphy (with a substrate thickness of 6–20 cm for extensive, 10–25 cm for semi intensive, and >25 cm for intensive green roofs) and plant species. Green roof stratigraphy improves outdoor thermal comfort during summer, owing to cooling capacities [8]; the presence of water in the substrate also cools the building structure [29], with a further benefit in terms of saving electricity for air conditioning. In a case study of an office building located in Genoa (Italy), Perini and Rosasco [7] quantified the annual benefit of an extensive and an intensive green roof solution compared to a traditional insulated roof solution: results showed an annual economic benefit for heating of 0.19 €/m^2/year for an extensive green roof and 0.28 €/m^2/year for an intensive green roof, while for cooling, respectively, a benefit of 1.62 €/m^2/year and 2.69 €/m^2/year.

2.3. Environmental Criteria

2.3.1. Air Quality and Urban Heat Island Reduction

The criterion considers two environmental benefits typical of green envelopes: air quality improvement and urban heat island mitigation. The first is connected to the fine dust collecting capacity of plants [30], carbon sequestration, and capture of other pollutants typical of urban environments [13]. Speak et al. [31] measured that a green roof (325 m^2) located in the urban area of Manchester (England) is able to remove annually 2.3% of PM10 present in the surrounding environment. Currie and Bass [32] estimated that a green roof can remove between 7.2×10^{-3} kg/m^2 and 8.5×10^{-3} kg/m^2 of pollutants. A study conducted by Michigan State University [33,34] measured that a green roof with plants of the species Sedum has the capacity to retain 378 g CO_2/m^2. Traditional roofs with dark surfaces absorb large amounts of solar radiation, causing an increase in the temperature of the surrounding [35]. Vegetated areas absorb 70 to 90% of solar energy, cooling building surfaces. Indeed, green roofs can contribute to urban heat island mitigation [16,34,36].

2.3.2. Runoff Reduction

Green roofs can reduce water runoff, a relevant benefit, especially in urban areas [37]. The ability to retain water depends on the depth and composition of the substrate, climatic conditions, and the amount of precipitation [38]; vegetation also contributes to the retention of rainwater [39]; part of the water is retained by the leaves and part is eliminated by the evapotranspiration process [40]. The reduction of the peaks of water volume going to the water collection and removal systems during intense weather events allows a cost saving and an improvement in the quality of the wastewater. The retention capacity of a green roof is measured on the basis of the difference (%) between the volume of water falling on the surface of the green roof and the volume of water removed (adsorbed and evaporated by plants and substrate); the measure is usually expressed in annual terms. It varies from a minimum of 40 to a maximum of 80% [37], with percentages around 52% for Mediterranean areas [41].

2.3.3. Embodied Energy and Carbon Emission

The embodied energy of building materials and construction over the life cycle varies depending on several factors. Although data are not always available and a standardized measurement framework for estimation and comparison should be developed, studies show that low embodied energy buildings require the use of locally-available, renewable, and recyclable materials [42]. Therefore, the embodied energy of traditional roof systems and green roofs depends on the specific characteristics and materials used. Langstone [43] proposes a method to evaluate green roofs in terms of profit, people, and plants, which considers embodied and recurrent carbon footprint at various stages of the project's life cycle. Results show that green roofs can represent a viable option when considering a holistic approach. In addition, plants of green roofs use atmospheric CO_2 during the process of photosynthesis [13]. Green roofs lower ambient CO_2 concentrations above and near the roof [44].

2.3.4. Resource Sustainability

The requirements considered for the evaluation of materials and technologies in terms of sustainability have to rely not only on the analysis of the performance for accomplishing functional and architectonical characteristics; the requirements also concern the answer to the global needs of the whole community, with respect to the sustainable use of resources, the control of the productive process, and the valorization of ecosystem services. A traditional roof system can have a different impact mainly depending on material choice and durability. Green roofs consume more resources for plants maintenance, but also provide several ecosystem services [6,8]. The environmental sustainability of green roofs is evaluated by several authors by means of life cycle assessment. Coma et al. [6] show that the operation phase plays an important role, since green roofs, on one hand, often have a higher impact for construction and disposal, and on the other hand, thanks to the energy saving derived from higher building envelope performances, these systems have less environmental impacts in comparison to white reflective roofs or typical ballasted roofs.

2.4. Social

2.4.1. Building Aesthetic

Green roofs provide several ecosystem services. Among these, aesthetic value can be mentioned; a very important aspect is also represented by the social space at rooftop level that intensive green roofs provide [45]. Some aesthetic factors of green roofs are subjectively appreciated by people (residents, neighbors, etc.), such as the visibility of the roof, the type of plants placed, and the dimensions and shape of the roof [22]. Improvement in building aesthetic may also result in real estate value increase (property value) [7].

2.4.2. Urban Aesthetic

Urban environment aesthetic can be improved by the presence of green roofs, which can be appreciated as a green area (park, public garden), especially when they are also accessible by non-building owners [18]. Their presence has a positive influence on people's quality of life and well-being [45]. The benefits also derive from the presence of animal and plant species (biodiversity) [46] that live in these green spaces and the possibility of being able to observe them closely. In particular, green roofs are appreciated because they are:

- green spaces located at high altitude with panoramic views of the surrounding urban environment;
- spaces where plants and plant species are cultivated, even edible plants, and it is possible to observe animal species (e.g., birds);
- social gathering and meeting spaces (especially in the presence of cafes, restaurants, etc.).

2.4.3. Suitability to Urban Location

In order to select a material or system for the building envelope, the integration with the surrounding urban context is considered, with particular reference to landscape (integration into the surrounding natural and built landscape), technological (type, color, and characteristics of the materials used), and cultural (local building tradition) features. This criterion is particularly relevant when the roof is visible from the surrounding streets and fits into a building context characterized by a recurring typological and technological solution, as a result of a local architectural and technological tradition; for example, this is the case for buildings located in historic city centers, where the inclusion of a roofing solution made with different technologies and materials than traditional ones (e.g., a green roof) can alter the image of the surrounding landscape and be a foreign element to tradition and local culture. It is worth mentioning that in the present study a green roof is assumed to be feasible according to the local regulatory provisions, which often limit the use of such systems in historical centres. The criterion is assessed by the panel in a subjective way, as it involves aesthetic and landscape features.

2.4.4. Health

Urban greening is widely recognized for increasing the liveability of cities, with consequences on human health, social relations, working capacity, and productivity of citizens [47]. Vegetation in cities is able to collect fine dust and improve air quality [13,30], a relevant aspect to consider in order to reduce respiratory disorders [48]. Accessible green roofs could create space for physical activities, preventing sedentary lifestyles and related diseases (e.g., obesity). Heath improvement due to green areas is also related to physiological reasons; according to Wilson [49], the contact with nature is essential for humans, as metabolisms need nutrients and oxygen.

2.5. *Performance*

2.5.1. Roof Longevity

Roof longevity refers to the protection exerted by external layers of the roofing system on insulation and waterproofing. The protection action is against ultraviolet (UV) rays, thermal shock, and damages that may occur during punctual maintenance operations. The protection action allows an extension of the life span of the roofing systems. The life span of a conventional roof is about 20 years [50], while for a green roof the life span is around 40–55 years [25,50,51].

2.5.2. Acoustic Noise Reduction

In environments with high levels of noise pollution (65 dB by day and 60 dB at night), the presence of a roof that reduces the internal sound level increases the well-being of residents. In both traditional and green roofs, acoustic insulation is provided by specific materials (Figure 1) according to the local regulations. In the case of green roofs, sound insulation is improved by plants and substrates; plants act on high frequencies, while substrates act on low frequencies [52,53]. Field monitoring shows that a 12 cm layer of substrate reduces sound by 40 dB, while 20 cm of substrate reduces sound by 46 dB [54]. Other studies demonstrate an acoustic insulation by green roofs of approximately 38–40 dB [55]. It is worth mentioning that this performance affects the indoor space below the roof only.

2.5.3. Weight of System

Green roof stratigraphy has a higher weight compared to traditional ones, requiring larger and more expensive horizontal and vertical building structures. The weight of an extensive green roof ranges from 50 to 150 kg/m^2, while for an intensive roof the weight is >350 kg/m^2 [56]; for the same thickness and material of the insulating layer, the traditional roof weighs 80–120 kg/m^2. On the basis of a bill of quantities it has been estimated that for the building structure (horizontal and vertical) there is a cost increase of about 10%.

2.5.4. Insulation Properties

Minimum requirements in terms of insulation properties of building envelopes are determined by regional and local regulations. In this study, the same insulation layer is assumed for traditional and green roofs. Green roofs provide additional insulation, depending on substrate thickness and characteristics, plant species, and the other layers involved. The thermal properties of green roofs (U value) are not constant and vary depending on climate conditions and moisture content [8].

3. Multi-Criteria Analysis—The Analytic Hierarchy Process (AHP)

Following the identification of criteria and sub-criteria by the panel of experts, in the second phase the relative importance of each one is evaluated with a multi-criteria approach. This approach allows complex decision problems to be solved to achieve a predetermined goal; the possible alternatives (as roof systems) are analyzed by decision-makers according to a set of significant criteria and sub-criteria [57].

Among the various techniques of multi-criteria analysis, in this study the Analytic Hierarchy Process (AHP) devised by Saaty [23] is used. According to the AHP, the decision problem is broken down into hierarchical levels (Figure 2):

- First level: the goal to be achieved, i.e., identifying a better roof system solution;
- Second level: criteria, i.e., the significant factors considered for the selection of the better solution (i.e., Economic, Environmental, Social, Performance);
- Third level: sub-criteria (or groups of sub-criteria), which specify the upper criteria (i.e., the 17 sub-criteria);
- Fourth level: the alternative solutions that allow the goal to be reached (i.e., the two alternative roof solutions).

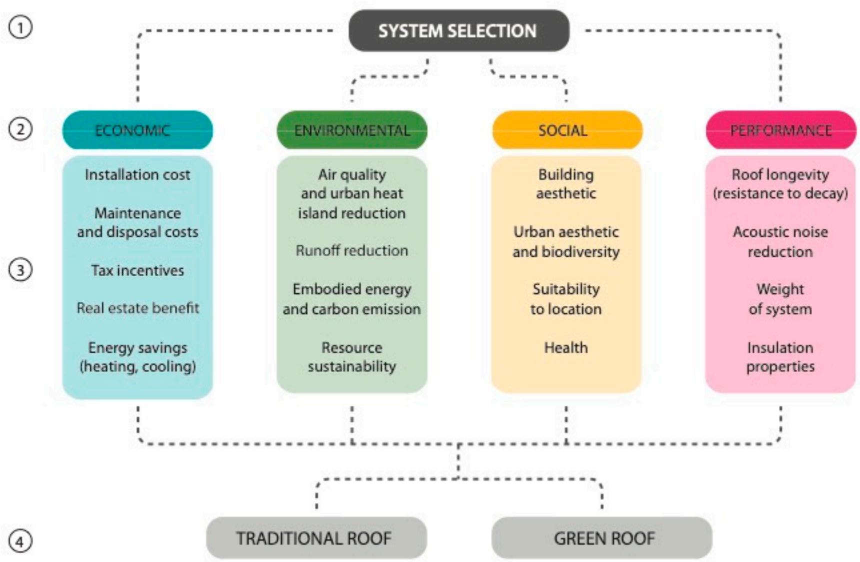

Figure 2. Hierarchy structure.

As in any decision process, the criteria and related sub-criteria are weighted depending on the importance attributed to the various aspects (cultural training, technical knowledge etc.); each alternative (green roof versus traditional roof) is then evaluated in relation to the impact it has on each sub-criterion. Through the pairwise comparison of the AHP technique, the priority of each criterion and sub-criterion are evaluated [58]. The pairwise comparison is based on a square matrix of order n × n (n is the number of compared elements located at the same level), also called "pairwise comparison matrix" (Table 3); concerning the weighting of the four groups of criteria, the comparison is achieved by attributing a score based on a 1–9 scale (Saaty's scale [23]), according to the priority of one criterion over the other and in relation to the higher-level element (e.g., for the four criteria and the goal).

Table 3. Example of comparison matrix for criteria priority.

	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Criterion 1	1	a_{12}	a_{13}	a_{14}
Criterion 2	a_{21}	1	a_{23}	a_{24}
Criterion 3	a_{31}	a_{32}	1	a_{34}
Criterion 4	a_{41}	a_{42}	a_{43}	1

Once the square matrix of the pairwise comparison is completed, the priority of each criterion is represented by the correspondent normalized component of the principal eigenvector derived by the matrix. According to normalization method, the sum of the priorities of all criteria (and sub-criteria within their criteria group) is equal to unit (1).

3.1. The Weighing of the Criteria and Sub-Criteria

For the purposes of determining the importance of the 4 criteria and the 17 sub-criteria selected, each member of the panel has completed the pairwise comparison matrices. Taking as a reference the hierarchical structure of the decision problem (Figure 2), the panel proceed from top to bottom (top-down); the 4 groups of criteria are compared to the goal (1 matrix 4 × 4) and then the sub-criteria are compared to the over-ordered criterion (four matrices). The compilation of the pairwise comparison matrices is done using the Expert Choice® software. The verification of the consistency of the prevalence scores (or equality) of criteria is performed through the Coherence Report (R.C.) for each matrix. The index is equal to the ratio between the Consistency Index (C.I.) of the matrix and the Random Index (R.I.), referring to the order of the matrix under consideration. The value of the C.I. must be ≤ 0.10; otherwise it is appropriate to reformulate the pairwise comparisons matrix. The final ranking is based on the comparison between the two alternatives (traditional roof versus green roof) with the 17 sub-criteria; according to the methodology, in order to express the priority, the scale with scores from 1 to 9 is used.

4. Results and Discussion

4.1. Criteria and Sub-Criteria Priority

Following the compilation of the pairwise matrices for the 4 groups of criteria and sub-criteria (17), the priority of each one is determined (Table 4, second column). The most relevant group of criteria for the selection of a roof system is "Performance" (priority 0.369), followed by "Environmental" (priority 0.230), and "Economic" (priority 0.206); the group considered less important is "Social" (priority 0.194). What emerges is a focus on the ecosystem services provided by greening systems at the building scale, demonstrating the ever-greater sensitivity that designers and researchers have towards these issues. On the other hand, the "Economic" and "Social" aspects are less important; for the former, the result can be explained by the fact that the economic aspect is secondary to technical ones and to the environmental impact; for the latter, it can be related to the scale of a single roof and the reduced social benefits achievable. The two groups of panels assigned different priority to the "Economic" and "Social" aspects—Academics gave more importance to "Economic" aspects (0.287 vs. 0.126), while Professionals attributed more importance to "Social" aspects (0.255 vs. 0.134) (Figure 3).

Table 4. Priorities of criteria and sub-criteria.

Groups of Criteria	Priority	Sub-Criteria	Priority within the Group *	Ranking within the Group *	Global Priority **	Global Ranking **
Economic	0.206	Installation costs	0.229	2	0.047	10
		Maintenance costs	0.309	1	0.064	6
		Tax incentives	0.171	3	0.035	13
		Real estate benefit	0.148	4	0.031	15
		Energy savings	0.143	5	0.029	17
Environmental	0.230	Air quality	0.322	1	0.074	5
		Runoff	0.228	3	0.053	8
		Embody energy and carbon emission	0.176	4	0.041	11
		Recycle materials	0,273	2	0.063	7
Social	0.194	Building aesthetic	0,156	4	0.030	16
		Urban aesthetic	0,160	3	0.031	14
		Sustainability location	0.205	2	0.040	12
		Health effects	0.480	1	0,093	4
Performance	0.369	Roof protection	0.275	2	0.101	2
		Acoustic noise reduction	0.137	4	0.051	9
		Weight of system	0.262	3	0.097	3
		Thermal insulation properties	0.326	1	0.120	1

* Sub-criteria priority within its groups. ** Global sub-criteria priority resulting from the multiplication of the local priority for the priority of the group of criteria.

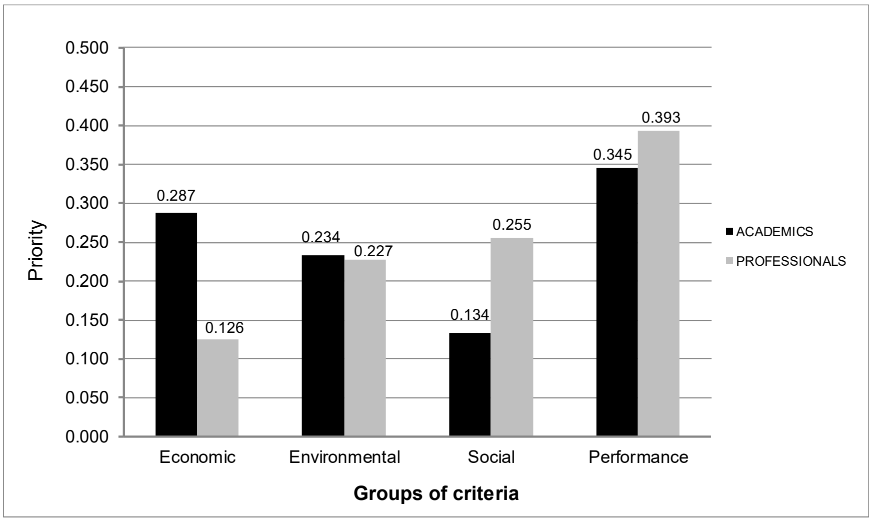

Figure 3. Priorities assigned to groups of criteria by Academics and Professionals.

A small difference emerges for the "Performance" criteria (0.393 vs. 0.345), while for "Environmental" criteria the values are substantially equivalent (0.234 vs. 0.227).

The priorities assigned to the sub-criteria differ more markedly. Within the "Economic" criteria, the greatest importance is attributed to "Maintenance costs" (0.309), followed by "Installation costs" (0.209) and "Tax incentives" (0.171) (Table 4, fourth column); almost equal importance is attributed to the criteria relating to the "Real estate benefits" (0.148) and to the "Energy savings" (0.143). This trend highlights a focus on construction and installation costs, which can be relevant for green roofs (especially for intensive systems).

Looking at the results obtained by the two sub-panels, compared to Academics, Professionals attribute a slight greater importance to the economic aspects linked to "Energy savings" (0.154 vs. 0.132) and to "Real estate benefits" (0.169 vs. 0.128); less importance is given to "Installation costs" (0.213 vs. 0.244), "Maintenance costs" (0.301 vs. 0.318), and "Tax incentives" (0.163 vs. 0.178) (Figure 4).

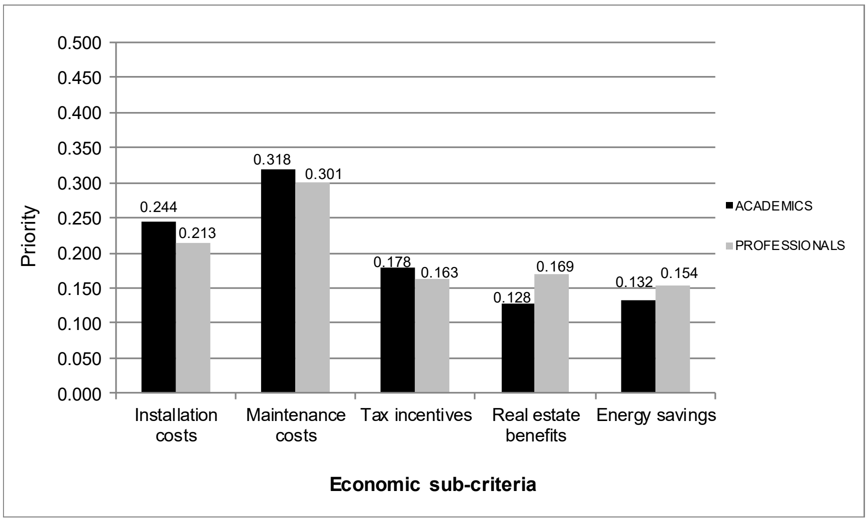

Figure 4. Priorities assigned to "Economic" sub-criteria by Academics and Professionals.

Among the "Environmental" sub-criteria, "Air quality" (0.322) is the most relevant, followed by "Recycle materials" (0.273), "Runoff" (0.228), and "Embody energy and carbon emission" (0.176) (Table 4, fourth column). For the Academics, the most important sub-criterion is "Runoff", while for Professionals it is "Air quality" (Figure 5).

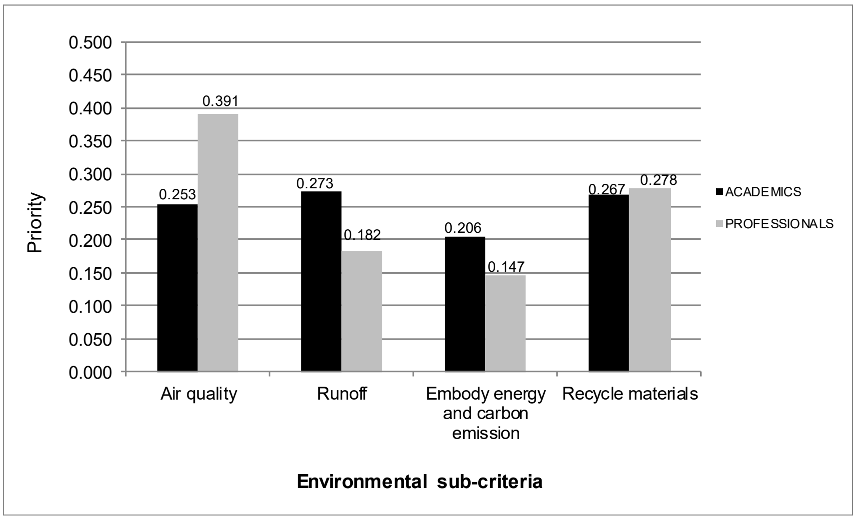

Figure 5. Priorities assigned to "Environmental" sub-criteria by Academics and Professionals.

With regards to the "Social" sub-criteria, according to the panel, "Health effects" have a great importance (priority 0.480); this result underlines a sensitivity towards the benefits of greening systems. "Sustainability location" (0.205), "Urban aesthetic" (0.160), and "Building aesthetic" (0.156) follow (Table 4, fourth column). Professionals attribute greater importance than Academics (0.480 vs. 0.322) to the sub-criterion "Health effects" , while Academics attribute a greater importance (0.299 vs. 0.156) to "Building aesthetic" (Figure 6).

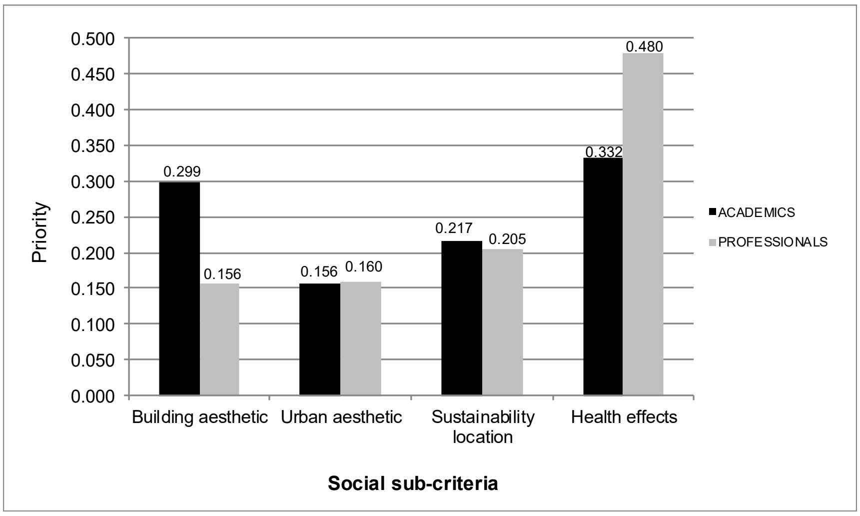

Figure 6. Priorities assigned to "Social" sub-criteria by Academics and Professionals.

The most important sub-criteria relating to the "Performance" are "Thermal insulation properties" (0.326) and "Roof protection" (0.275), followed by "Weight of system" (0.262) and the "Acoustic noise reduction" (0.137) (Table 4, fourth column).

Results show that the thermal properties of green roofs—highlighted by the literature—are well-known by the panel members. According to the Professionals, also "Weight of system" is an important sub-criterion (compared to the Academics, 0.262 vs. 0.147) (Figure 7). This result can be related to the experience of Professionals in the design and installation phase, as in an existing building, the feasibility of a green roof is strongly influenced by the load-bearing characteristics of the building structure.

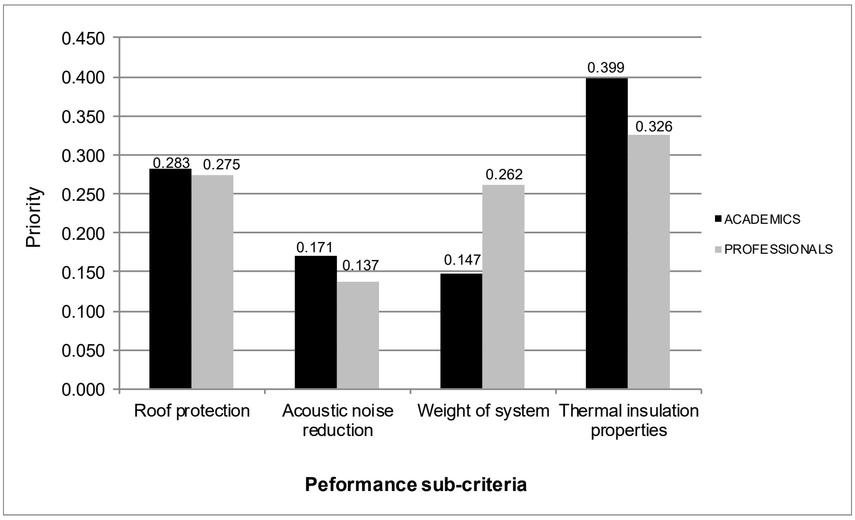

Figure 7. Priorities assigned to "Performance" sub-criteria by Academics and Professionals.

Three sub-criteria with the highest global ranking belong to the "Performance" group of criteria: "Thermal insulation properties", "Roof protection", and "Weight of system" (Table 4, fourth column). This result highlights that for the selection of a roof, thermal performances and roof protection are recognized as relevant benefits, while the weight of a green roof can be an obstacle; on the other hand, "Energy savings" is the criterion with less importance (although directly related to thermal performances), followed by "Building aesthetic" and "Real estate benefit". These results highlight a gap between research and practice, since several papers show that energy saving plays a key role in determining the economic sustainability of a green roof [9,25,42].

4.2. Final Ranking

Through the AHP technique, the two different roof solutions are compared to each sub-criterion; the results of the final ranking show that the green roof is the preferred solution for both Academics and Professionals (Table 5). The panel group of Professionals expresses a lower appreciation of green roofs compared to the Academics (0.583 vs. 0.602; −15%).

Table 5. Final ranking from Analytic Hierarchy Process (AHP) of two roof solutions.

Panel Group	Traditional Roof	Green Roof	Difference
Academics	0.398	0.602	0.204
Professionals	0.417	0.583	0.166

For the panel group of Academics, the traditional roof and the green roof obtain very similar scores for "Economic" criteria (0.502 vs. 0.498), while the green system prevails for all the other groups of criteria (Figure 8); the differences for the "Social" criteria (0.738 vs. 0.262) and the "Performance" (0.656 vs. 0.344) are evident. It is worth mentioning that the results for the "Economic" criteria can be related to the balance between higher installation and maintenance costs and economic benefits (real estate value, tax incentives, and energy savings).

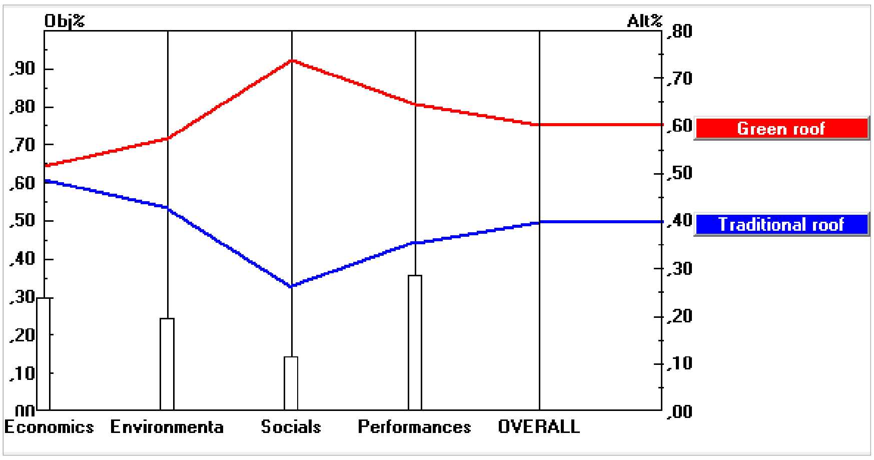

Figure 8. Academics group. Results obtained from the Multi-Criteria Analysis (MCA) reported with respect to the groups of criteria (Obj%; ranges 0.00–0.90) and the scale of the final priority of the two roof alternative solutions (Alt%; ranges 0.00–0.80).

The results of the panel group of Professionals show a marked difference for the "Economic" criteria, with a higher score obtained by the traditional roof compared to the green one (0.583 vs. 0.417) (Figure 9). This result is related to the relevance of installation and maintenance costs of green roofs and a reduced consideration of economic benefits (real estate benefit, etc.).

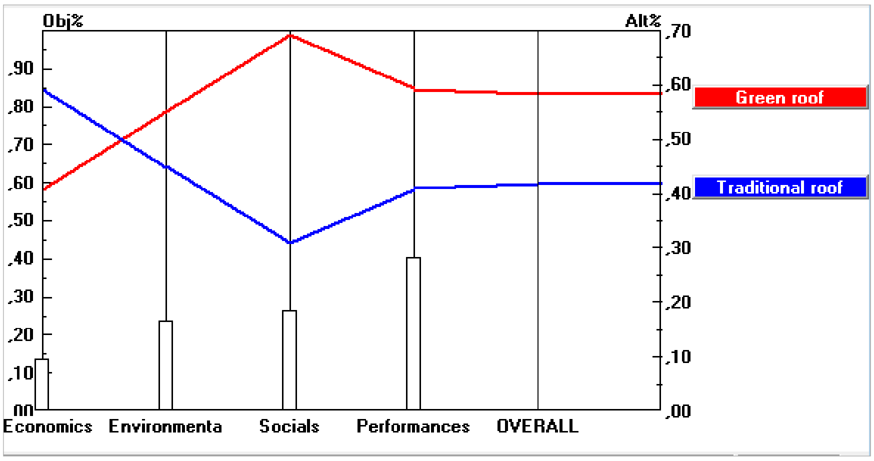

Figure 9. Professionals group. Results obtained from the Multi-Criteria Analysis (MCA) reported with respect to the groups of criteria (Obj%; ranges 0.00–0.90) and the scale of the final priority of the two roof alternative solutions (Alt%; ranges 0.00–0.70).

A relevant difference among Professionals and Academics is also related to the "Environmental" criteria—according to the group of Professionals—, the score difference between the two solutions is 0.06 (0.530 vs. 0.470) (Figure 9), while for Academics it is 0.14 (more than double) (Figure 8).

Results highlight that the economic benefits of green roofs are not effectively communicated and that the economic benefits in the medium-long term are less relevant according to Professionals.

5. Conclusions

This study investigates which factors are considered by a panel of experts in the fields of design and architecture for the selection of a building roof solution. The sustainability-based multicriteria analysis is an effective tool to identify the role played by each criterion in the decision process. The panel of experts involved evaluated, through a hierarchical structuring and pairwise comparisons, the priorities of each criterion and sub-criterion and identified the green roof as the best option.

As shown by other studies [21], designers are increasingly oriented towards the use of architectural and technological solutions for buildings with high environmental and functional performances in order to guarantee optimal indoor comfort conditions and compliance with local and national regulations and to reduce the environmental impact of buildings.

The most significant criteria for the selection of a green roof vs. a traditional roof are the ones related to performance, thermal insulation properties, roof protection, and weight of the system. Both panel groups, composed of Academics and Professionals, show that the environmental and social benefits of green roofs play a key role, with air quality and health criteria following thermal insulation properties, roof protection, and weight of the system in the global ranking. The panel groups assign different weights to the economic criteria. According to the experts working in academia (Academics), green roofs are economically convenient; although installation and maintenance costs are relevant, the economic benefits (tax incentives, energy savings, real estate benefits) can be higher. Conversely, according to the panel group of designers (Professionals), the benefits do not overcome the costs, although thermal insulation properties are ranked as the most relevant criterion. This result shows that for a wider diffusion of greening systems, the economic benefits, highlighted by several studies [3,17,27], should be better communicated, especially to professionals working in the field, designers, building companies, and others.

Future research could be focused on investigating if and how different locations, types of clients, building use, etc., affect the decision process.

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