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Assessment of the contributions of different flat roof types to achieving sustainable development

Salvador Guzmán-Sánchez[a], Daniel Jato-Espino[b,*], Ignacio Lombillo[c], Jose Manuel Diaz-Sarachaga[b]

[a] University of Cantabria, Civil Engineering School, 39005, Santander, Spain
[b] GITECO Research Group, University of Cantabria, Civil Engineering School, 39005, Santander, Spain
[c] Dept. of Structural and Mechanical Engineering, University of Cantabria, Civil Engineering School, 39005, Santander, Spain

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ABSTRACT

The sustainability of cities is being influenced by their roofs, which cover a high proportion of built-up areas and whose design is crucial to control their economic, environmental and social impacts in a context of urban sprawl and Climate Change. For this reason, this research developed a Multi-Criteria Decision Analysis (MCDA) methodology combining the Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to support the selection of four representative flat roof types (self-protected, gravel finishing, floating flooring and green) according to their contribution to sustainability, based on their performance across a list of indicators aligned to the United Nations Sustainable Development Goals (SDGs). The analysis was carried out under three different climate scenarios (Mediterranean, Oceanic and Continental) and relied on the judgments provided by a panel of experts in the building sector to both refine and weight the proposed indicators. The results proved that green roofs were the most sustainable alternative for all the scenarios evaluated, by virtue of their insulation, recycling, cost, energy, water and ecosystem-related benefits. Consequently, this type of roof emerges as a multifunctional solution to be strongly considered in the design of planning strategies seeking urban regeneration.

1. Introduction

Roofs occupy about 20–25% of urban surfaces [1], whilst the buildings they cover account for 40% of total energy consumption worldwide [2] and 36% of European greenhouse gas emissions [3]. As such, roofs are key drivers for ensuring sustainable economic development, environmental protection and social welfare, especially in a context of urban sprawl and Climate Change whereby more than half of the world's population live in cities [4] whose resilience is being exceeded by the intensity of weather events [5].

One the one hand, urbanisation favours the presence of impervious surfaces and reduces evapotranspiration, exacerbating the Urban Heat Island effect [6] and the warming of cities [7]. The presence of impervious areas also has relevant impacts on water quality and quantity [8], whilst the car-dependent lifestyle derived from urban population growth favours air pollution [9]. On the other hand, global temperature is forecasted to rise in the future, particularly in urban areas as a result of anthropogenic development [10]. There is also evidence of an increase in extreme rainfall intensity in recent years, boosting the magnitude and frequency of flash floods [11].

The design of roofs impacts on these phenomena, influencing the resilience of cities to alterations in temperature, water-related processes, energy and air quality [12]. Furthermore, roofs can also contribute to economic growth, environmental safeguard and human wellbeing [13]. Therefore, the planning of these elements provides a multifaceted opportunity to help meeting some of the United Nations Sustainable Development Goals (SDGs) [14], which seek to protect the planet and ensure prosperity for all.

The literature review, which is addressed in section 2, revealed a knowledge gap in the selection of roofs according to the principles of sustainable development using indicators that contribute to achieving the SDGs. The representativeness of the roof types analysed and the evaluation of different climate and weighting scenarios were other aspects having room for improvement. Hence, this study emerged to jointly address all these issues by assessing four characteristic flat roofs across a list of sustainability indicators under three climate types, including a sensitivity analysis to guarantee the reliability of the results obtained when prioritising different roof-related facets. Consequently,

* Corresponding author.
E-mail address: jatod@unican.es (D. Jato-Espino).

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the main theoretical contribution of this investigation consisted of the development of an ad-hoc methodology to measure the performance of different roofs using multiple conflicting variables. Still, the proposed approach might also be easily adapted to the characteristics of other elements, such as vertical and indoor horizontal systems, providing a practical tool to appraise the design of buildings and support the adoption of urban planning strategies aligned with the SDGs.

2. Literature review

Several investigations have been conducted over the past two decades to support the selection of roofs using multiple criteria. Nassar et al. [15] developed a tool to evaluate asphalt, plastic and metallic roofs in terms of durability, insulation, permeability, maintenance, warranty, compatibility and serviceability. Abeysundara et al. [16] presented a lifecycle-based matrix to support the choice of sustainable materials for two roof types (asbestos sheet and clay tile) according to their affordability, embodied energy, environmental impacts, comfort, aesthetics, strength, durability and constructability. Similarly, AL-Nassar et al. [17] evaluated six wall-roof systems using a lifecycle impact index aligned with the triple bottom line of sustainability. Collier et al. [18] assessed the sustainability of three roofing technologies (reflective, vegetated and solar roofs) considering their costs, resource usage, environmental impacts and welfare benefits. Canto-Perello et al. [19] appraised three roofs formed of prefabricated concrete, steel and laminated wood structures in terms of costs, emissions, energy, fireproofing, use of local materials and aesthetics. Loikkanen et al. [20] analysed different energy solutions for a glass roof using their internal rate of return, energy efficiency, CO_2 emissions and attractiveness as decision criteria.

The literature also contains more specific research in terms of either the alternatives or criteria evaluated. Liu et al. [21] developed a decision-making model to support the adoption of energy-saving designs for residential buildings, demonstrating the potential of green roofs for this purpose. Gagliano et al. [22] compared the energy savings and environmental advantages provided by three alternatives (conventional, cool and green roof), based on dynamic simulations under temperate climate conditions. Kalibatas and Kovaitis [23] focused on the selection of waterproofing membranes for inverted flat roofs through additive weighting methods and game theory rules. Szafranko [24] applied an indicator-based methodology to evaluate two roof girders according to installation, structural and recyclability variables. Finally, several studies have appraised green roofs in comparison with other green infrastructure systems, such as bioretention cells, infiltration trenches or permeable pavements [25–27].

3. Methodology

The main steps of the proposed methodology are outlined in Fig. 1. From a conceptual point of view, the approach taken consisted of establishing a series of energetic, hydrologic, environmental, social, economic and structural indicators to assess the sustainability of several flat roof types under different climate scenarios. From a technical perspective, this was accomplished using Multi-Criteria Decision Analysis (MCDA) methods, which enabled assessing the performance of different roofs and ranking them across a list of weighted indicators refined based on the opinions collected from a panel of experts in the building sector.

3.1. Definition of the initial list of sustainability indicators

An indicator can be defined as a measure providing guidance about how to value a certain parameter [28]. In this case, an initial set of indicators as listed in Table 1 was proposed to assess the sustainability of different flat roof types according to the principles included in the Sustainable Development Goals (SDGs).

The Albedo coefficient (I_1) represents the portion of solar radiation reflected to the atmosphere [29]. Hence, the greater the Albedo of a roof, the less it is heated by insolation. Consequently, this indicator is related to the impacts of roofs on the warming of buildings, which might help improving the resilience against climate hazards considered in SDGs 1 and 13.

The second indicator (I_2) concerned the thermoregulatory potential of roofs and their capacity of attenuating local temperature. This factor might have a positive effect on the production of solar energy, since high temperatures reduce the performance of photovoltaic cells. Therefore, the indicator of solar power can contribute to meeting the targets of energy efficiency contemplated in SDG 7.

The materials forming the layers of roofs might help capturing atmospheric carbon, such that they act as a natural sink (I_3). This aspect is in line with some of the targets included in SDGs 3, 11 and 12, focused on reducing the presence of atmospheric hazards to protect human health, as well as controlling environmental contamination in cities.

The next two indicators (I_4 and I_5) consisted of the embodied carbon and energy associated with roofs, from the extraction of raw materials to the construction of the structure. Hence, these indicators, as well as that concerning the use of recycled materials (I_{11}), are related to SDGs 3, 7, 8, 11 and 12, which deal with the effects of resource efficiency on energy and environment.

Rainfall was added to the list of indicators through the benefits of roofs in terms of runoff (I_6), pollution (I_7) and temperature (I_8) reduction. These aspects can be translated into flood mitigation, rainfall purification and protection of flora and fauna against high runoff temperatures, which are concepts extremely linked to the water-related issues highlighted in SDGs 1, 3, 6, 11, 13, 14 and 15.

Biodiversity (I_9) and agricultural productivity (I_{10}) referred to the potential of roofs for supporting the presence of animal and plant species and the growth of crops, respectively. These indicators may aid to meet several targets seeking the achievement of sustainable food, communities and life in SDGs 2, 11 and 15.

Building insulation in thermal and acoustic terms was represented through I_{12} and I_{13}, which served to value the role played by different roofs when alleviating adverse external weather and noise conditions. Consequently, both indicators are associated with SDGs 7 and 11 in what concerns the safeguarding of the energy efficiency and adequate services of buildings.

Life cycle cost (I_{14}) was an indicator devoted to measure the economic expenses stemming from the construction, maintenance and eventual demolition of roofs, according to their expected lifetime. As such, this indicator is aligned with the principles of sustainable economic growth and urban development highlighted in SDGs 8 and 11.

The social dimension of sustainability was represented by an indicator concerning the contribution of roofs to improving the aesthetical perception of their surroundings (I_{15}). This aspect was expected to impact positively on the development of urban areas towards inclusive and pleasant places to live in, as expressed in the SDG 11.

Finally, the last two indicators accounted for functional characteristics of roofs, either in the form of the dead load transmitted to the structure below (I_{16}) or the protection of the waterproofing membrane (I_{17}). These factors can help achieving safe and controlled living and working environments, as specified in SDGs 8 and 11.

Some of these indicators depended on the climate conditions affecting roofs, such as precipitation, temperature and solar irradiance. To enable the accurate characterisation of different roofs across these weather-based indicators, a trio of scenarios was defined to represent some of the most characteristic types of climate in Europe.

3.2. Climate scenarios

Climate is a crucial factor in the assessment of roofs in terms of sustainable development. This study was undertaken under three different weather scenarios, coinciding with the three main types of