Cool Roofs in Hot Climates: A Conceptual Review of Modelling Methods and Limitations

Mohamed H. Elnabawi *, Aysha Alhumaidi, Bana Osman and Reem Alshehhi

Abstract: Cool roofs are a long-term alternative for the creation of a building’s thermal comfort as they can reduce the energy required for cooling demands and mitigate the urban heat island effect, thus benefiting both buildings and cities. Interest in cool roofing has recently escalated and numerous concepts, techniques, and experiences are represented in various studies conducted for hot climates; however, in reviewing the literature, it was found that most of this research is limited to the investigation of these benefits at either the building or city scale. Indeed, only six attempts were found that integrated both scales. To assist with design decisions, several studies have concluded there is an urgent need for a multi-level, interdisciplinary assessment framework, but as yet no such framework has been constructed. Following the literature review, in this study, a general framework is proposed which permits current modelling to progress beyond typical protocols, by including data linking a specific urban microclimate at the neighbourhood/city level with that of a building, thus connecting the microclimatic environment with objective assessment of energy efficiency. It is hoped that this framework will promote the development of exclusive cool roof applications for buildings and outdoor urban settings.

Keywords: cool roof; energy efficiency; hot climates; thermal performance; UHI mitigation

1. Introduction

Although planning approaches are focused on addressing population needs and land resources, they have also created the problem of degraded urban conditions. This accelerated urbanisation, being strongly linked to global warming, has sparked several well-known environmental threats which are very difficult to tackle, such as the degrading of the microclimate in urban areas and increased ambient urban air temperatures; the impact of this produces an urban heat island (UHI) [1–3]. A UHI appears when temperatures rise in dense urban spaces in comparison to the adjacent countryside, largely as a result of the relatively greater level of incident solar energy taken in by man-made materials. UHIs have a substantial effect on day and night-time temperatures, but also indirectly raise demand for air conditioning, deteriorate the quality of water and air, lower the lifespan of pavement, and intensify heatwaves. These greater air temperatures tend to lead to higher cooling demands and less efficient cooling systems in built environments, thus causing the demand for, and consumption of, energy to rise. According to the 2021 United Nations Climate Change Conference (COP26), these changes in the climate continue ‘to be perceived as the gravest threat to humanity’ and, with the present lack of successful action on climate change, the next ten years may incur the greatest damage to date on the global scale [4].

In response, recent research has made it possible to create technological solutions to mitigate the effects of UHIs [5–8]. By improving thermal losses and lowering equivalent benefits, mitigation strategies seek to balance the thermal budgets in cities. Among the top proposed techniques are those aimed at increasing the proportion of green spaces [9–12] and the use of albedo materials in urban areas [13,14]. Green spaces can turn solar radiation
into latent heat through evapotranspiration and, because of the high reflectivity of the high albedo materials, much of the solar radiation received on the outer surface is recast to the sky [12,15]. In several studies, these techniques have proven very effective in mitigating UHIs, enhancing urban thermal comfort, and reducing UHI stress [16–19].

As a building element, a roof is ideal for these techniques, as it is the building element that is most open to solar radiation [20], covering about 20% (15–24%) of some urban areas [21–23]; thus, it adds to around 50–60% of the cooling load of buildings in hot, dry, warm, and humid climate zones [24]. However, reflective surfaces appear to be more applicable to mass roof applications for several reasons, not least because the reflection of incident solar energy is the fastest way to reduce its impact; moreover, a coating that reflects sunlight can cast 90% of its energy back to the sky. The installation of such reflective coatings on building roofs is also easier and much cheaper in comparison to other passive strategies (e.g., a green roof), as they are used just like ordinary paint [25].

To produce a cool roof, a reflective coat is applied. This type of coating is a roofing material with a high capacity to reflect sunlight, or a high albedo, causing a great deal of solar radiation to be reflected. In addition, a significant amount of stored heat is not retained due to the material having a high thermal emittance. In regions with hot climates, these roofs may be an optimal solution to rising air temperatures and increased energy demand for cooling. For instance, on a hot, sunny, summer day, conventional materials for roofing can reach temperatures of 88 °C versus 49 °C for a cool roof [26], and they can also effect 15% energy savings in hot climates [24]. Bhatia et al. [27] considered maximum energy savings for a cool roof based on climate type, finding that the best savings were for warm, humid, and hot dry climatic zones. In another recent study, it was determined that increasing the roof albedo led to energy savings of 20–70% [28]. Indeed, the advantages of cool roofs go beyond the building level, since there is an additional key effect at the street and city scales [15,18].

Thus, the impacts of cool roofs are interrelated and many levels of assessment are required to avoid misinterpreting the advantages of cool roofing or failing to understand the interrelated implications at the building and city levels. Without this understanding, adverse effects can occur, such as increased mean radiant temperature (MRT) at the street scale, leading to uncomfortable local outside conditions [29–31]. Despite this complexity, most existing studies, if not all, have investigated the effect of cool materials at a single level. At the building level, this includes interior cooling load and/or thermal comfort [24,32,33]. Alternatively, authors have focused on the advantages of cool roofs at the city level, for example by enhancing outdoor cooling temperature and UHI mitigation, although these did not consider what the impact would be within a building [34,35].

Designers could therefore have a better understanding of the optimum technology and its feasibility for the building envelope [36], as well as its relation to the outdoor thermal effect both at the pedestrian level and for UHI mitigation. For example, there is a lack of research into hot, dry climates [37]. Alongside this, there has been a very limited focus on the combined effects of a cool roof on outdoor thermal comfort [38] and, indeed, none of the most recent review articles such as [24,39] have provided a general framework of assessment in this regard. This highlights the necessity for a multi-disciplinary framework which can promote the understanding of the outcomes of cool roof applications from various perspectives [40,41].

Regarding building design and urban planning, it is essential to determine how cool roofs can improve the urban environment while also conserving energy and improving thermal comfort conditions. With the variety of fields represented in the literature, a broad framework for evaluating and relating the advantages of cool roofs at different levels would be significant for decision-makers and planning practitioners. Thus, to promote knowledge of the comprehensive advantages of a cool roof, the objectives of this paper are twofold. First, there is an assessment of cool roof studies on buildings and urban communities published in the last two decades, including modelling methodology and tested parameters, especially for hot climates, and the processes and limitations of these studies. Second, the
aim is to develop a general framework for assessing cool roofs, and in so doing to determine
the necessity for a predictive tool in building design and urban planning that not only
considers direct effects in terms of energy savings and reduced carbon emissions, but also
an indirect reduction in ambient air temperature and UHI mitigation.

2. The Cool Roof Mechanism

The thermal and energy performance of a roof can be determined by two surface film
features. Solar reflectance and thermal emittance not only control the roof’s ability to lower
how much heat the building absorbs from the sun by casting back incoming sunlight, but
also enable the reemission of the outstanding absorbed fraction. This broadly explains why
cool roofs remain cooler compared to conventional roofs of a similar structure under the
same climate conditions.

Three parameters are used to measure cool roof efficiency. The first is solar reflectance
(SR), often known as albedo, which is the capacity of the surface of the material to cast
back infrared and ultraviolet light, i.e., visible and invisible solar radiation. White and
black surfaces have respective solar reflections of one and zero, with white surfaces having
greater solar reflectance and lower absorption and dark surfaces having the reverse. A
roof will absorb energy that it does not reflect, and this is where thermal emittance acts as
another indicator. The second parameter is thermal emittance (IE), which is the capacity of
the surface to discharge thermal radiation in the infrared (heat) range; in other words, it is
the roof’s ability to re-radiate absorbed heat. If this does not happen quickly, the heat is
trapped on the roof’s surface and more heat may pass to the building underneath. Thermal
emittance can range from 0–1, with lower surface temperatures causing higher emittance.

It is vital to remember that neither high reflectivity nor high emittance values in
themselves provide a cool roof. Therefore, the third parameter, the solar reflectance index
(SRI), is a helpful tool for assessing a roofing product’s general thermal characteristics.
The SRI is a further determined figure that may be referred to in codes, regulations, and
programmes outlining the requirements for cool roofing. With SRI, standard black, which
has a solar reflectance value of 0.05 and an emittance of 0.90, is valued at zero, while
standard white is 100 (reflectance 0.80 and emittance 0.90). Materials having high SRI
values are more appropriate for cool roofs and can even surpass 100. To calculate SRI values,
the SR and IE values are calculated as per the ASTM E 1980 standard [42]—Calculating
Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces. In 2017, an
almost identical European standard was published called EN 17190 [43] Flexible Sheets for
Waterproofing—Solar Reflectance Index.

Energy Equilibrium for Cool Roofs

The major difference between cool and standard roofs is surface reflectance (r), and
so the balance of their energy may be explained with the identical balancing equation
(Equation (1)). The following heat fluxes are of interest to the upper roof surface, which
is considered to be grey: incident solar short-wave radiation (I), long-wave radiation ex-
change with the sky (gradient), the exchange of convective heat with the external environ-
ment (qconvective), and the exchange of heat with the interior environment (qtransferred)
(Figure 1). Thus, the roof surface’s energy balance can be calculated using Equation (1) [44]:

\[
\frac{T_{so} - T_i}{R_{i-se}} = (1 - r) \cdot I - \left[ \sigma \cdot \varepsilon \cdot \left( T_{so}^4 - T_{sky}^4 \right) + h_c \cdot (T_{so} - T_o) \right]
\]

(1)

where, \( T_{so} \) is the outer surface temperature and \( T_i \) is the air temperature inside. The values
of \( r \) and the thermal emittance \( \varepsilon \) are dependent on the outer roof layer’s properties. Solar
irradiance \( I \), outside air temperature \( T_o \), sky temperature \( T_{sky} \), and the external convective
heat transfer coefficient \( h_c \) are linked to the building’s location. How much heat passes
through the roof from outside is mostly determined by the difference between temperatures
within a building and on its roof, by considering the thermal resistance (\( R_{i-se} \)) of the roof’s
layers [15,45].
3. Literature Review: Recent Applied Cool Roof Studies

At this point, a critical overview is required of the literature on cool roofs in relation to their potential benefits for buildings (e.g., for energy savings and inside thermal comfort) and urban communities (e.g., outdoor thermal performance and UHI mitigation). Due to technological improvements in the field, the selection criteria for these studies were twofold: that they were conducted within the past two decades in hot climates, and their methodology. On the latter, to estimate energy and thermal performance, the three main techniques are mathematical, experimental, or computer modelling [46,47]. The first method is rather complex, with slight alterations, such as outdoor air temperature changes, influencing the outcomes. The second method is impractical when multiple design scenarios are considered due to being time-consuming and uneconomical. However, computer modelling can mitigate the shortcomings of the other approaches [48] and its outcomes have greater feasibility, accuracy, and informativeness [46]. On this basis, only computer modelling studies were included in the review. From a search of science citation index (SCI) impact journals, a combination of multiple keywords was chosen, including cool roof, energy savings, indoor cooling effect, outdoor cooling effect, UHI, heat wave, hot, arid, and humid. Other relevant selection criteria were then applied, such as the validity of the scope and methodology, and whether there was a clear methodological strategy. This filtered sixty-four articles which seemed to be related to the study’s objectives.

For the last thirty years, high-albedo roofs have been proposed to mitigate the UHI effect and reduce energy demands and costs for cooling requirements, as well as to increase thermal comfort in unairconditioned buildings. However, most of the reviewed literature only focused on selected aspects, as presented in Figure 2, such as the building level, indoor cooling demand, and/or thermal comfort [32]; this is additionally true of other, more recent review studies by Rawat and Singh [24] and Abuseif and Gou [33]. Although studies on the city scale considered improvements to external cooling, they omitted consequences to the indoors [34,35]. In Ashtari’s review of ninety articles [39], only a study by Xu et al. [49] investigated the impact of cool roofs at both the building and city scales and addressed savings in cooling requirements and the mitigation of UHIs. Nevertheless, the research only contained an estimate of the decrease in yearly direct CO₂ emissions linked to energy savings as a gauge for moderating UHIs. Additionally, recent reviews by Santamouris et al. [18], Ashtari et al. [39], and Rawat and Singh [24] narrowly focused on the building or city level, without proposing a valid approach for practitioners implementing cool roofs in future smart cities. In the review of the literature by Haberl et al. [50],
there was an assessment of seventy-two articles, but the results are for typical US buildings and only targeted energy saving for cooling needs. Despite the insightfulness of their approach, such research is now not only out-of-date but also restricted to a particular place and climate. The same points apply to Santamouris’s review [19], as most of the investigated cases are in the US and little attention was given to the possible impact of the roofing strategies at the building level. The final review to consider here is Testa and Krarti’s cool roof energy savings study [51], which did not state the benefits and drawbacks of their work at the city scale, such as for UHI mitigation.

Figure 2. Overview of the level of investigation of selected cool roof studies, with their objectives and test parameters.

Due to the separation in the literature between buildings and urban communities in terms of assessing the implications of cool roofs, the following section presents the reviewed studies in three tables based on the investigatory scale undertaken, i.e., at the neighbourhood/city scale (Table 1), building level (Table 2), or both levels in one framework (Table 3).
Table 1. Overview of the potential of cool roofs at the city and global scales, based on the selected publications.

<table>
<thead>
<tr>
<th>Source</th>
<th>Location</th>
<th>Methodology</th>
<th>Albedo Value</th>
<th>Conclusion</th>
<th>Limitation</th>
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<tbody>
<tr>
<td>[52]</td>
<td>Athens, Greece Mediterranean dry summer climate</td>
<td>Numerical simulations ‘urbanised’ nonhydrostatic MM5 (version 3-6-1)</td>
<td>0.63 and 0.85</td>
<td>Temperature decreased by 1.5 °C for the albedo of 0.63 and 2.2 °C for the albedo of 0.85</td>
<td>Only counted air temperature at 2 m and no analysis of MRT or outdoor thermal comfort</td>
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<td>[53]</td>
<td>Different American cities, including the hot arid climate of Phoenix</td>
<td>WRF model version 3.2.1</td>
<td>0.25</td>
<td>Average decrease in post midday summer temperatures by 0.11–0.53 °C and 0.16 °C in Phoenix. Average decrease in summer afternoon temperatures by 0.16 °C in Phoenix</td>
<td>Based on an assumption which combined 25% cool roofs with 35% cool pavement, but applying cool material to the pavement might elevate MRT, causing outdoor discomfort conditions at street level</td>
</tr>
<tr>
<td>[54]</td>
<td>All roofs worldwide</td>
<td>GATOR–GCMOM model</td>
<td>Original albedo 0.12 and new albedo 0.65</td>
<td>Global conversion weighted global temperatures by ~0.02 K but to heat the Earth in total by ~0.07 K</td>
<td>Based on an unrealistic conversion and one albedo value for the whole globe, with no differentiation between different climate zones</td>
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<tr>
<td>[55]</td>
<td>Baltimore, Washington heat wave period in humid subtropical climate</td>
<td>WRF model in combination with the PUCM</td>
<td>0.7 and 0.9</td>
<td>Modifying the albedo value from 0.7 to 0.9 resulted in an additional 0.79 °C decrease in UHI surface and an extra 0.14 °C decrease in near-surface UHI</td>
<td>No consideration of buildings with different heights, which might cause outdoor discomfort conditions at some levels due to the elevated MRT and high shortwave radiation. Air temperature was estimated</td>
</tr>
<tr>
<td>[13]</td>
<td>Rome, Italy Mediterranean climate, with mild winters and warm to hot summers</td>
<td>WRF mesoscale model</td>
<td>Albedo raised to 0.65, 0.6, and 0.45 for roofs, walls, and roads, respectively</td>
<td>A rise in albedo reduced the urban area temperature by up to 4 °C in the day and a marginal rise (up to 1 °C) in certain places at night-time</td>
<td>The findings were mainly built on a combination of different surfaces including walls, roofs, and streets, so the direct impact of the roof was unclear, which may be the reason for the slight rise in air temperature at night</td>
</tr>
<tr>
<td>[56]</td>
<td>Jerusalem and Tel Aviv, Israel. Dry summer subtropical</td>
<td>Experimental study using the PUCM and the WRF model</td>
<td>0.2, 0.5 and 0.8</td>
<td>The effect of differing albedo levels on 2-m surface temperature was roughly 0.4 °C and the effect of altering soil moisture was 0.1 °C</td>
<td>No examination of the effect on pedestrian thermal sensation. The study mentioned limitations such as the anthropomorphic heating effect on surface temperature being inaccurate because of the application of a fixed diurnal profile. Tall buildings present in each modelling area but excluded from the modelling</td>
</tr>
<tr>
<td>[35]</td>
<td>Phoenix in the arid and hot southwest of the USA New York City at the humid northeast coast</td>
<td>Sensitivity study with ENVI-met microclimate modelling and the WRF model</td>
<td>Cool roof albedo 0.85 Super cool roof albedo 0.96</td>
<td>Super cool roofs remained around 6 K under ambient air temperature when solar irradiation was high. Super cool roofs were cooler by 0.1–0.15 K than typically used cool roofs and green roofs during high solar radiation</td>
<td>No site measurements or validation for the two simulations and no strong justification of the variation in the outcomes of the two models used</td>
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Table 1. Cont.

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<td>[57]</td>
<td>Shanghai, China</td>
<td>WRF-Chem model paired with a one-layer urban canopy model</td>
<td>Cool roofs set to 0.5 and 0.7</td>
<td>Cool roofs can lower the 2-m temperature by almost 1.5 °C, which is positively correlated with the albedo coverage fraction. Changing albedo to 0.7 had the greatest cooling effect at around 20% more compared to the green roof with identical vegetation coverage.</td>
<td>Methodology based on short-term ozone pollution in a heat wave, and no analysis of the cooling effect on human thermal comfort.</td>
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<tr>
<td>[58]</td>
<td>Seoul, South Korea during the 2018 heat wave</td>
<td>WRF model simulations</td>
<td>Conventional roof albedo 0.2; white roof 0.7</td>
<td>During the day, maximum reductions were 1.0 °C at 2-m temperature and 0.5 m/s at 10 m for wind speed. The cool roof’s maximum temperature was 21% less compared to the conventional roof maximum temperature.</td>
<td>Although one of the objectives was to study the thermal environment, air temperature rather than MRT or the comfort index was used as the parameter.</td>
</tr>
<tr>
<td>[38]</td>
<td>Heatwave in Berlin</td>
<td>WRF model paired with the urban canopy model (WRF/UCM) and the RayMan model</td>
<td>Scenarios 1–3 albedo 0.163, 0.50, 0.85, respectively</td>
<td>Cool roofs caused more reduction in UTCI than green roofs, but both reduced high heat stress from 7 h to 5 h.</td>
<td>Only focused on the rational comfort index and adaptive thermal comfort approaches, and the simulation outcomes required more development for validation.</td>
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Table 2. Summary of the energy performance of cool roofs at the building scale in selected publications.

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<th>Source</th>
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<tr>
<td>[59]</td>
<td>27 global cities, including Cairo (hot/arid) and Abu Dhabi (hot/humid)</td>
<td>TRNSYS thermal simulation software and METEONORM database</td>
<td>Base case (SR = 0.2) Raised albedo case 1 (SR = 0.6) Raised albedo case 2 (SR = 0.85)</td>
<td>- Cairo energy saving improvements were 19% and 31%, and in Abu Dhabi 11% and 18% higher. - Comfort index enhancement by lowering discomfort time by 9–100%; peak temperatures in unairconditioned residences reduced by 1.2–3.3 °C.</td>
<td>The same single-storey, flat-roof house was the base case for 27 cities covering five different climatic regions, and the same comfort thermal range applied for all climates.</td>
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<td>[60]</td>
<td>Durban, South Africa, Kuala Lumpur, Malaysia, Lisbon, Portugal Miami, Florida, and Phoenix, Arizona, US, Shanghai, China</td>
<td>EDSL TAS version 9.0.9 w 12 coating materials Albedo 0.05–0.65</td>
<td>- With 0.65 albedo, the energy reduction ranged between 25–38% for Kuala Lumpur, Miami, Phoenix, and Durban. - With reflective coatings (reflectance 0.05–0.65), the energy saved in Shanghai was around 11%, and in Phoenix (identical reflectance values) this was 35% for electricity use in total. - CO₂ emissions 9.83–35.78% less based on climate type and 24.51–25.76% for hot arid Phoenix</td>
<td>No validation of simulation outcomes, and only one very simple retail building used as a base case.</td>
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<td>[61]</td>
<td>Townsville, Australia (tropical savanna)</td>
<td>Influence of the colour on roof heat gain quantified by building simulation (no program stated)</td>
<td>Albedo 0.34–0.74</td>
<td>The roof with a light colouring had 30% less total heat accumulation (air temperature variation)</td>
<td>Neither the building simulation software nor the validation approach were stated; no measurement of cool roof energy savings</td>
</tr>
<tr>
<td>[62]</td>
<td>Hong Kong (humid subtropical)</td>
<td>FOR-TRAN90, and on-site measurements</td>
<td>Albedo 0.2–0.52</td>
<td>Cooling load decrease of 9.3% for the white painted surface (albedo 0.52), 8.8% for off-white (albedo 0.50), 2.5% for brown (albedo 0.25), and 1.3% for green (albedo 0.2)</td>
<td>No accounting for indoor thermal comfort or any other parameters such as CO₂</td>
</tr>
<tr>
<td>[63]</td>
<td>Athens, Greece (Mediterranean dry summer)</td>
<td>Validated TRNSYS software</td>
<td>Grey concrete (SR = 0.2) and after ABOLIN cool roof barrier (SR = 0.89)</td>
<td>A decrease of 1.5–2°C in inside air temperature in summertime and about 0.5°C in wintertime. A 40% decrease in energy demand for cooling against a 10% rise in heating demand</td>
<td>Only counted energy savings and indoor air temperature, and no consideration of thermal comfort index or CO₂</td>
</tr>
<tr>
<td>[64]</td>
<td>Sicily, Italy (humid, subtropical)</td>
<td>TRNSYS</td>
<td>Broadband thermal emittance 0.88</td>
<td>Cool paint on a 700 m² roof reduced cooling demand by 54%</td>
<td>Outcomes limited to one storey office building and no CO₂ emissions were calculated</td>
</tr>
<tr>
<td>[15]</td>
<td>Catania, Italy Coastal (Mediterranean dry summer subtropical climates)</td>
<td>DesignBuilder</td>
<td>Cool roof solar reflectance 0.55</td>
<td>For uninsulated roofs, peak outer surface temperature was 49°C against 43°C for the cool roof. Inner surface temperatures: traditional roof peaked at 33°C and the cool roof at 31°C</td>
<td>The method quantified the relation between roof type and impact on UHI but this was only based on peak outer surface temperature; the simulation model was a single building without data validation</td>
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<td>[65]</td>
<td>Ahmedabad (hot/dry) Mumbai (warm/humid) New Delhi (composite) Bangalore (temperate) Shillong (cold)</td>
<td>EnergyPlus V7.1</td>
<td>Reflectivity varied from 20–90% with an increment of 10% per case</td>
<td>Cool roof reflectivity of 0.6 led to 2.91 kWh/m² in hot/arid climate and 2.01 kWh/m² in warm/humid</td>
<td>One simple schematic of the model for the simulation study; no data validation conducted; no indoor thermal comfort examined</td>
</tr>
<tr>
<td>[66]</td>
<td>Athens, Greece (Mediterranean climate)</td>
<td>DesignBuilder v.4.2 software</td>
<td>The cool paints used had emissivity 0.89, reflectance 0.89, thermal conductivity 0.87 W/(mK)</td>
<td>Daily mean decrease in inside air temperature under the cool roof ranging from 1.3–2.3°C and 1.6–1.9°C according to measurements and simulations, respectively. An estimated decrease of &gt; 30% in cooling load for summertime, but the heating cost for wintertime was 12%</td>
<td>No examination of indoor thermal comfort or CO₂</td>
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<td>[67]</td>
<td>Queensland, Australia (humid subtropical)</td>
<td>(IES-VE) package</td>
<td>Solar reflectance Before: 0.2 After: 0.875 Emissivity: Before: 0.25 After: 0.9</td>
<td>Reduction in underside roof surface temperature of 9°C. Decrease in internal temperature of 8°C. The reduction in yearly average demand at peak network time of 12.00–14.00 was 2.2 kW (18%)</td>
<td>Only one building model (a warehouse-sized shop); more studies are required to determine cost-effectiveness and return on investment</td>
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<tr>
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<tr>
<td>[68]</td>
<td>Jamaica</td>
<td>Experimental and computational study (EnergyPlus)</td>
<td>0.15 representing the roof without cool paint and 0.82 representing the roof with cool paint</td>
<td>Annual simulations found internal ceiling surface temperatures less on average by 3.2–5.5 °C and internal air temperatures by 0.75–1.2 °C. Cooling demand simulations found similar annual potential savings in three locations although estimated CO₂ emissions reduction varied depending on electricity generation fuels. Ageing of the cool roof impacts reductions in load savings by 22–26 kWh/m²/year.</td>
<td>No estimation of comfort index but instead used internal air temperature to represent indoor thermal comfort; same building modelled in different locations with no consideration for different urban contexts.</td>
</tr>
<tr>
<td>[32]</td>
<td>Los Angeles, United States (Mediterranean dry, subtropical)</td>
<td>EnergyPlus models</td>
<td>Albedo of 0.2 represents a typical roof with a dark surface; albedo of 0.5 represents a roof-top with a bright colour</td>
<td>Large-scale installation of cool roofs over the region could lead to savings of 24–41% in cooling energy bills. In unairconditioned buildings, a rise in albedo can cut uncomfortable hours in summer by up to 20%.</td>
<td>Adjusting the weather file based on an assumption is questionable.</td>
</tr>
<tr>
<td>[37]</td>
<td>Saudi Arabia (hot/arid, hot/humid, cold/dry, and mountainous)</td>
<td>eQuest 3.65 software, founded on the DOE-2.2 simulation engine</td>
<td>Solar radiation reflectance and emittance of infrared light, 0.85 and 0.9, respectively</td>
<td>Cool roofs with high reflectiveness can lower yearly cooling energy by 110.3–181.9 kWh/m². For a sufficiently insulated roof (R = 1.75), the cool roof reduced yearly cooling demand by 27.5 kWh/m² in the cold dry climate and to 44.5 kWh/m² in the hot dry.</td>
<td>Single-storey villa-type residence 100 m² with no assessment of thermal comfort or inside air temperature.</td>
</tr>
<tr>
<td>[69]</td>
<td>Saudi Arabia (hot/arid, hot/humid)</td>
<td>Numerical model incorporating COMSOL Multiphysics</td>
<td>Absorption coefficients (αs) had values from 0.05 for the cool roof to 0.8 for the black.</td>
<td>The transferred energy gain in July for the roof decreased from 214 to 139 Wd/m² and 122 Wd/m² with a concomitant decrease in the short-wave solar absorption coefficient from 0.88 (black roof) to 0.2 and 0.05, respectively. Conductive energy increase was lowered by 54% and 75% with a decrease in the short-wave solar absorption coefficient from 0.88 to 0.2 and 0.05, respectively.</td>
<td>Variation in thermal insulation quantity and the parallel short-wave solar absorption coefficient of a reflective roof applying the indoor conditions as per ASHRAE Standard 160, which was mainly developed for North America.</td>
</tr>
<tr>
<td>[70]</td>
<td>Shanghai area (subtropical climate)</td>
<td>Dynamic building thermal performance simulation software (THERB) validated using measured data</td>
<td>Solar radiation reflectivity common roof (0.2) and cool roof (0.7)</td>
<td>Green roof lowered cooling and heating loads on the top floor by 3.6% and 6.2%, respectively. Cool roof lowered cooling load by 3.6% and increases heating load by 10.4%.</td>
<td>Simple office building shape, no indoor thermal comfort analysis, and only one albedo case examined.</td>
</tr>
<tr>
<td>[71]</td>
<td>Five climate zones in China: Harbin (severe cold), Kunming (moderate), Nanjing (hot summer and cold winter), Beijing (cold), Guangzhou (hot summer and warm winter)</td>
<td>EnergyPlus</td>
<td>Shingle roof: albedo 0.25 and emissivity 0.9 Typical white roof: albedo 0.7 and emissivity 0.9 MFCR: albedo 0.97 and emissivity 0.93</td>
<td>Yearly electricity usage for cooling for the MFCR dropped 12.9% in Harbin (severe cold), 12.1% in Kunming (moderate), 10.3% in Nanjing (hot summer/cold winter), 8.6% in Beijing (cold), and 7.8% in Guangzhou (hot summer/warm winter). A drop in the indoor air temperature of &gt; 11.7 °C in the moderate zone, 11.6 °C in the cold zone, 11.5 °C in the hot summer/warm winter, 9.2 °C in the hot summer/cold winter, and 8.0 °C in the severe cold.</td>
<td>Very simple building model (12.5 m × 7.3 m); applied same building characteristics in different locations and climates; indoor thermal comfort not considered.</td>
</tr>
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### Table 2. Cont

<table>
<thead>
<tr>
<th>Source</th>
<th>Location and Climate</th>
<th>Methodology</th>
<th>Tested Roof</th>
<th>Energy/Thermal Comfort</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>[72]</td>
<td>Seville, Spain (dry summer subtropical)</td>
<td>Energy Plus software</td>
<td>Solar reflectivity ranged from 0.1–0.9</td>
<td>Annual total load improvement was close to 32% against a reference roof with solar absorptivity = 0.9 and a cool roof of solar absorptivity = 0.1</td>
<td>Focus on economic lifecycle and ageing which is only relevant to the study context</td>
</tr>
<tr>
<td>[26]</td>
<td>Mexico (warm)</td>
<td>A computational tool consisting of a numerical model utilising the finite volume method</td>
<td>Grey roof: solar absorptance 0.67 and thermal emittance 0.87 Terracotta roof: solar absorptance 0.70 and thermal emittance 0.88 White roof 1: solar absorptance 0.20 and thermal emittance 0.90 White roof 2: solar absorptance 0.16 and thermal emittance 0.89</td>
<td>Exterior surface temperatures of white-coloured roofs with no insulation were 11–16°C less than the grey roof with no insulation There was a decrease of 41–54% for the white roofs regarding daily heat gain Insulated white roofs lowered outside surface temperature by 17–21°C against the grey roof with insulation</td>
<td>Outcomes limited to a roof model with no mention of building type or building energy performance</td>
</tr>
<tr>
<td>[24]</td>
<td>Jodhpur, India (hot/dry)</td>
<td>Simulation but the software used not stated</td>
<td>U values: Base case 3.14 Case one 2.5 Case two 1.82 Case three 0.60</td>
<td>Comfort hours rose 12–17 against the conventional roof For coated roofs, TSI remained within the range of comfortable temperatures at 27.5°C, versus a base case</td>
<td>Simulated a very simple rectangular building with only two windows; did not consider other parameters such as saving cooling loads or annual emissions</td>
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### Table 3. List of studies examining the effect of cool roofs at the building and neighbourhood/city scale.

<table>
<thead>
<tr>
<th>Source</th>
<th>Location and Climate</th>
<th>Methodology</th>
<th>Albedo</th>
<th>Conclusion</th>
<th>Limitation</th>
</tr>
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<tbody>
<tr>
<td>[73]</td>
<td>Arizona, United States Semi-arid to arid climate</td>
<td>In-situ data collection with EnergyPlus modelling of building energy</td>
<td>Albedo of 0.30 and 0.72</td>
<td>CO² emissions reductions of 90.33 and 173.88 tonnes/year for the 50% cool roof and 100% cool roof, respectively Energy reductions of 1.3–1.9% and 2.6–3.8% in overall monthly energy usage from a 50% cool roof and 100% cool roof replacement, respectively</td>
<td>Only considered one parameter on urban scale; no consideration of cooling effect on ambient air temperature and outdoor thermal comfort</td>
</tr>
<tr>
<td>[74]</td>
<td>Hyderabad area of India Tropical climate, both wet and dry, almost hot semi-arid</td>
<td>Multi-episode mesoscale meteorological simulations utilising the PSU/NCAR MM5</td>
<td>Residential roof 0.30 Commercial roof 0.40 Road 0.25 Pavement/ driveway 0.20 Parking space 0.25</td>
<td>Energy reductions for cooling of 10–19% An air temperature decrease of 2°C when surface albedo is raised and vegetative cover used in combination</td>
<td>Did not quantify direct impact of cool roof on mitigating UHI or improving indoor and outdoor thermal perception</td>
</tr>
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Table 3. Cont.

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<tr>
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</table>
| [75]            | Catania, Italy                                | EnergyPlus                          | CR 1: cool paint with $R = 0.65$  
CR 2: cool white paint with $R = 0.80$ | CR2 best reductions between 15–25 °C in summertime  
Sensible heat flux generated by the roof was reduced with each of the green roofs (42–75%, dependent on the climate) and cool roofs (around 75%, $R = 0.65$; more with $R = 0.80$)  
At the building scale, the cool roof ($R = 0.8$) lowered cooling load by 18% against 10% for cool roof ($R = 0.65$) and green roofs | Only based on one office building to study the impact on the urban scale—this is still not an accurate approach as the microclimate and the urban configurations of a place need to be considered |
| [41]            | Bahrain                                       | DOE and ENVI-met                    | Lightweight concrete screed  
Albedo 0.38 emissivity 0.90  
Bituminous roofing felt  
Albedo 0.23 emissivity 0.87  
Tile-light  
Albedo 0.77 emissivity 0.94  
Tile-dark  
Albedo 0.30 emissivity 0.90  
Metal decking  
Albedo 0.71 emissivity 0.89 | Lightweight concrete screed  
Mean $T_s$ 52.2 °C Mean $T_a$ 41.3 °C  
Bituminous roofing felt  
Mean $T_s$ 49.5 °C Mean $T_a$ 41.3 °C  
Tile-light  
Mean $T_s$ 44.3 °C Mean $T_a$ 38.6 °C  
Tile-dark  
Mean $T_s$ 50.1 °C Mean $T_a$ 44.3 °C  
Metal Decking  
Mean $T_s$ 43 °C Mean $T_a$ 39.2 °C | Based on only five buildings which is a very limited urban configuration for representing the neighbourhood; no annual energy savings were estimated |
| [76]            | Ten typical Chinese cities                     | Model development,  
simulation validation, and numerical modelling with MATLAB  
Solar reflectance 77.04%–64.5%  
Thermal emittance 88.34%–11.27% | Super-cool roof enhanced sub-ambient temperature by 2 °C less than solar radiation of 950 W/m² in a hot humid climate  
Super-cool roof enhanced peak and average day roof temperatures by 24.8 °C (43.4%) and 10 °C (29%), respectively  
Yearly electricity reduction in hot cities averaged between 42.9–97.8 kWh/m² | Did not account for outdoor thermal perception; the built chambers for the experiment are very small (W0.7 m × L0.6 × H0.4) |
| [40]            | Bahrain                                       | DesignBuilder and ENVI-met           | 0.83 for reflectance  
0.91 for emissivity | 10% and 7.5% reduction in the cooling load  
−0.8 °C less outdoor air temperature at pedestrian level | The study only validated the indoor energy modelling and did not consider outdoor thermal comfort |
In terms of city scale, the high solar reflectance of a cool roof means that the surface of the roof is cooler under the sun, reducing the transfer of heat from the roof into the air, which in turn lowers the ambient temperature. Theoretically, this process also reduces direct and indirect air pollution. One of the first studies to investigate the primary and secondary impacts of cool roof strategies was conducted for the warm summer Mediterranean climate of Los Angeles, USA, by Rosenfeld et al. [77]. The authors reported that when less energy is used for cooling, air pollution is directly reduced, resulting in fewer power plant pollutants being produced; for example, CO\textsubscript{2} or NOx. In contrast, an indirect reduction in air pollution is due to the ozone-forming reaction, which accelerates the creation of smog at warmer temperatures; thus, the potential for smog is reduced with lower urban air temperatures. Following this study, several simulation studies assessed the possible effect of albedo-related moderation approaches on reducing ambient temperature. Table 1 presents relevant simulation studies on cool roof applications at the urban level and contrasts their climate, methods, and outcomes as related to heat waves, and hot regions. From such examples, it can be seen that cool roofs with both high reflectivity and emissivity do indeed have a significant influence on mitigating UHI and thus the usage of outside city spaces.

In general, the studies reviewed mainly employed urban modelling, with some also including experimental work or field measurements for validation. All tested similar hot climates or heat wave periods. However, each study used a different framework and method, and tested different parameters; none included all the parameters related to UHI (air temperature, MRT, radiation flux, and outdoor thermal comfort) on one framework or the interrelationship between UHI and building energy performance. For instance, some studies could not quantify the effect of cool roofs as they combined other surfaces such as car parks or roads [13,53], while other methods were based on unrealistic assumptions [53,54]. Moreover, most of this urban modelling was unvalidated, bringing into question the outcomes [35,54,56]. Overall, these studies lack a reliable framework for evaluating and analysing collected data, standardised modelling protocols, and data analysis methods.

At the building level, cool roof materials reduce the energy used for cooling and ventilation when the latter reaches a peak, as smaller amounts of heat transfer to the building from the cooler roof [18]. For this reason, numerous studies have explored the ability of a cool roof to improve thermal comfort in various types of building, as well as the energy use of such roofs. Indeed, studies exploring the potential effect of a cool roof on buildings are twice as numerous as those exploring its impacts on urban communities. Table 2 presents an overview of research into cool roofs applied at the building scale, contrasting their strategies and outcomes for hot and hot humid regions. According to a cool roof for hot projects report [78], it is recommended that a cool roof be selected on the basis of the place and climate, local code requirements, and aesthetic preferences. However, many studies have assessed the same building in different climate conditions [37,59,60,65,68,71]. Other studies have considered prototype case studies of buildings with a very simple one-storey shape which is unrepresentative of actual buildings [15,24,37,59,64,65,67,70]. In addition, many studies appear to have incorrectly validated their building modelling [15,60,61,65]. All the reviewed studies lack an attempt to relate the applications of cool roofs at the city level to UHI mitigation. To conclude this section, Table 2 presents a summary of the main related publications in terms of how cool roofs perform at the building scale regarding energy.

None of the reviewed studies summarised in Tables 1 and 2 included a multi-disciplinary framework that could reveal the relationship between the advantages of cool roofs for both buildings and urban communities. However, a few studies have examined cool roofs from two assessment perspectives. Table 3 presents six studies examining the effect of cool roofs at the building and neighbourhood/city scale. With these studies in mind, if the cool roof benefits are to be maximized [60], it is necessary to reflect on the actual urban situation and microclimate of a building as these factors have largely been missed in the reviewed studies. Examples include the modelling of the same building in different cities [75,76] or creating a
very small modelling size which is insufficient to quantify the mitigation effects on UHI [41]. As such, these studies do not fully account for the cool roof’s thermal and environmental performance in terms of buildings and urban communities. In this context, there is a need for an appropriate decision-making structure for building designers and urban planners, to permit and deepen understanding of the implications of cool roofs for both buildings and urban communities by clarifying the direct and indirect benefits and penalties; at the same time, the tool must be grounded in the theoretical assessment and design of low energy and thermally comfortable buildings and more habitable outdoor spaces.

4. Cool Roof Applications: Methods and Knowledge Gaps

It is clear now that cool roofs can mitigate the impact of UHIs at the urban scale, decrease the energy used for cooling, and enhance inside thermal comfort at the building scale. However, current typical ways of assessing cool roofs lack a holistic evaluation and thus do not facilitate an understanding of the link between the building and urban scales. At the building scale, all the reviewed studies lack a clear vision and understanding of the cool roof and its physical properties, such as the high albedo. This has caused the studies’ objectives to be very narrow in considering the cool roof as just another insulation material, ignoring its indirect advantages at the urban scale. These intensive, time-consuming and expensive studies did not aim their findings and recommendations at a single building but to mass scale or groups of buildings. On this basis, if a cool roof coating is applied on a group of buildings or an urban community, then the outcomes of these building-level studies are skewed because the weather conditions used in the building energy simulation will be different from when cool roofs are applied at the urban scale.

At the city scale, the situation is even worse due to the limited number of studies in this area compared to the building energy and thermal performance studies. This may be because urban scale simulations are much more complex; with very few appropriate modelling programs being available, such simulations are more complex and time-consuming compared to the multiple user-friendly building energy simulation (BES) programs. Urban microclimate simulation has some drawbacks in that it usually requires powerful workstations and investigators who are more knowledgeable about climatology and fluid dynamics; it is also less easy to turn energy-saving data into financial savings than when working at the level of the building. The benefits of lower ambient air temperatures are more indirect, especially if high-albedo surfaces are widely applied. Nevertheless, the studies reviewed in Table 1 shows how there is no comprehensive framework with the capability to evaluate and analyse the actual performance of a cool roof. This should also include the effect of the cool roof’s age on its ability to reflect sunlight, and its relationship to outdoor thermal comfort—indeed, just one study incorporated the outdoor thermal comfort index [38]. Other shortcomings are detailed in Table 1.

Although the efforts to include building and urban scales in one structure are very limited, they have tried to include various theoretical frameworks to promote how we comprehend interoperability at the building and city scales. To maximise the benefits of a cool roof, it is essential, in any framework, to factor in the building’s location/latitude and actual microclimate [60]; however, as explained in Section 3 existing typical approaches fail to explain the cool roof’s thermal and environmental performance fully in terms of buildings and urban communities.

Moreover, highly reflective cool surfaces project strong radiation around them, and this can distract and produce an irritating brightness, especially when the weather is clear and sunny [79]. Therefore, it is always recommended to perform analyses before applications, especially in urban neighbourhoods with various building heights and homogeneous building morphologies, or at projects which require clear vision, such as airports [39]. None of the research explored in this study endeavoured to provide such analyses.

Accordingly, three main gaps were identified regarding the employment of cool roofs at the urban level in comparison with the extensively investigated application at the building scale:
Few studies attempted to comprehend the holistic effect of cool roofs at the building and urban levels;

- There is no standardised methodology and data processing, as seen in comparisons that have assessed the same structure in various climate zones, or the discovery of inconsistencies in the tested parameters due to either their distinct methodology or different data gathering techniques;

- There is a paucity of theoretical frameworks founded on established theories to assist data collection and interpretation and promote integration between various evaluation levels, such as the building type, microclimate, urban configuration, and outdoor and indoor thermal comfort that varies from one place to another.

It is necessary to understand fully all the implications of applying cool roofs and to do so, a multidisciplinary approach is required, in combination with a tool that clearly explains how data on different levels can be interrelated, interpreted, and linked to the circumstances of a study.

**Prospects for Future Research**

Based on the reviewed literature, the materials used in urban construction have a key role in maintaining the urban thermal equilibrium. Therefore, cool roof applications in an urban context require the consideration of multiple factors, including factors such as meteorology, the urban framework, inside and outside thermal comfort, and efficient energy performance. Any attempt at a thorough assessment should include the project’s location and climate, energy-saving goals, the local code requirements for roof characteristics, or green building credits [78]. These are additional to the ranges for inside and outside thermal comfort—the latter in particular suffers from a lack of attention paid to the cool roof’s cooling effect on human outdoor thermal comfort [38]. These factors reinforce the need for a framework integrating several disciplines and levels of assessment, including the relationship between the implications of a cool roof at the building and urban levels, as shown in Figure 3. An understanding of this type of relationship could identify, for instance, how wide-scale use of mitigation strategies has indirect advantages for urban areas, such as the effectiveness of cooling systems being enhanced by cooler external air, a reduction in smog and greenhouse gas (GHG) emissions, and lower power plant emissions, thus enhancing overall environmental health. Additionally, cool roofs decrease heat gain and improve thermal comfort indoors, so decreasing cooling energy demand and subsequently reducing peak demand for electricity and thus electricity bills.

Founded on how the building and neighbourhood(city scales are interoperable, the proposed multi-disciplinary framework is comprised of two modelling programs, one dealing with the urban microclimate and the other with the building energy simulation (BES). This combination allows the interchange of the appropriate boundary conditions between the two models [80] (Figure 4). The framework functions on two scales, starting with the urban or city scale, which has two objectives: (1) examining the cool roof’s ability to mitigate the UHI effect (and so improving air temperature at pedestrian-level and enhancing outdoor thermal comfort); and, (2) creating microclimate output files for the main environmental parameters of the site around the building, including ambient air temperature, relative humidity, wind velocity, and solar radiation. The latter is used via a weather generator to create a more localised weather data file for actual and up-to-date microclimate conditions which act as input in dynamic energy simulations to improve understanding of the impacts at the building level. All the parameters in Figure 4 are thus considered, such as environmental parameters (air temperature, relative humidity, solar radiation, etc.) and outdoor thermal comfort indices (PMV, PET, etc.). At the building scale, energy savings, CO₂ emissions, indoor air temperature, and indoor thermal comfort are examined in relation to the typical outdoor meteorological phenomena of a precise site.
emissions, thus enhancing overall environmental health. Additionally, cool roofs decrease heat gain and improve thermal comfort indoors, so decreasing cooling energy demand and subsequently reducing peak demand for electricity and thus electricity bills.

**Figure 3.** Overall interrelation of the cool roof mechanism at the building and urban scales.

This coupling of two or even three programs so far looks to be a promising tool for designs for a building, cluster of buildings, or urban space, and it would be better for building designers, urban planners, and decision-makers to have a prediction tool, which permits several design alternatives to be evaluated and compared for effectiveness as buildings and outdoor urban spaces. A testing implement is particularly required which can facilitate improved comprehension of the links between the microclimate, buildings, and urban spaces. This implement should have the capacity to handle complex information related to building characteristics, the urban context, location, microclimate and time, as well as to present analytical outcomes to clarify the inter-relationships. In this context, urban microclimate modelling software such as WRF, ENVI-met [81], and Rayman [82] can offer comprehensive interpretations of the climatic conditions related to the urban and city scales, while at the building level, different building energy simulation tools, such as EnergyPlus, DesignBuilder, eQUEST and IES-Virtual Environment (IES-VE), can provide the data on energy and thermal building performance [83].
5. Conclusions

Quality design for the built environment ought to encompass outdoor and indoor spaces within comfortable thermal ranges, as well as low-energy buildings. In this regard, cool roof technology has proven very promising for improved thermal comfort, the conservation of energy, and better urban spaces. However, it has become much harder to facilitate the relationship between the different layers of assessment at the building and neighbourhood/city scale, as this relationship requires a multi-disciplinary approach. To investigate this theme, a literature review was conducted on cool roof studies conducted in the last two decades at the building and neighbourhood/city scales. The following conclusions can be drawn:

- Very few investigations attempted to understand the full implications of cool roofs at the building and urban scales;
- Most, if not all, the conducted studies at the building level had very narrow objectives in considering the cool roof as just another thermal insulation sheet and investigating its impact on energy consumption or indoor air temperature;
- There has been a failure to standardise methodology and data processing, for example by comparing the same building in different climate zones or discrepancies in the tested parameters, either due to variations in techniques or data collection strategies;
- There has been a failure to incorporate the theoretical frameworks of well-established theories to facilitate the integration of different levels of assessment and support data gathering and interpretation, such as building type, microclimate, urban configuration, and outdoor and indoor thermal comfort range as this differs from one place to another;
- There is a lack of application of the microclimate factor in the investigation of cool roofs, since most building energy simulation (BES) programs rely on pre-defined hourly weather profiles to calculate heating and cooling loads. This leads to high uncertainty in simulation data input and output when these profiles are obtained from weather stations, which are typically situated outside of cities and in low-density built-up areas unaffected by UHIs. As a result, assumptions on energy demands for indoor thermal comfort are skewed.
Therefore, most existing common approaches have failed to reveal or explain cool roof performance at different levels, including buildings and urban communities. However, there are some very interesting outcomes that are relevant to any successful study of such applications. The first of these relates to climate type in that the advantage of a cool roof which lowers cooling load in warmer months must be offset against the disadvantage of an increase in heating load in cooler ones, thus reducing total efficiency [51,59]. Secondly, according to Baniassadi et al. [32], the direct and indirect advantages of cool roofs are dependent on climate and building characteristics as well as building type [28]. Thirdly, different roof configurations also influence how a cool roof performs, such as the amount of ceiling insulation, the placing of ducts, and the configuration of the attic [50]. Another interesting factor is the effect of age on the energy performance of renovated cool roofs [72], as dust/dirt build-up on roofs can influence the surface’s capacity to recast sunlight, thus increasing solar heat storage [37]. Therefore, roofs must be periodically cleaned and repeat applications of reflective paint may also be required [84].

Accordingly, to achieve the full benefit of a cool roof, all these aspects should be considered in one framework designed largely for a specific climate and building type. In this context, the current study proposed a multi-disciplinary framework that contextualises both the building and urban aspects of a cool roof in hot regions. To create an effective decision-making framework for designers and urban planners and energy scientists, the framework integrates the potential benefits of a cool roof at both levels. Accordingly, the proposed framework is based on interoperability and data exchange between the urban microclimate simulation and building energy simulation. This coupling appears promising for building designers, urban planners, and decision-makers to promote their understanding of the connection between the urban environment, buildings, and microclimate. It will also enable modelling to progress beyond typical protocols that only consider a single or a range of parameters by expanding these to include a comprehensive evaluation. Such a tool should not only be able to process extensive data on the characteristics of buildings, urban environment, location, microclimate, and time, it should also be able to present analytical findings which can explain the inter-relationship of these aspects. This will permit several design alternatives to be evaluated and compared for effectiveness at the building and outdoor urban space scales.

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