Optimizing urban canyon design for energy efficiency and thermal comfort: Integrating material properties and canyon configuration features using a DoE approach

Chiara Chiatti [a,b] , Claudia Fabiani [a,b] , Elie Bou-Zeid [c] , Anna Laura Pisello [a,b],*

[a] Department of Engineering, University of Perugia, Via G. Duranti 97, Perugia 06125, Italy
[b] EAPLAB at CIRIAF - Interuniversity Research Center on Pollution and Environment "M. Felli", University of Perugia, Via G. Duranti 63, Perugia 06125, Italy
[c] Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ 08544, USA

ARTICLE INFO

ABSTRACT

Urban canyon configuration significantly affects local microclimate, with direct implications for building energy demands and outdoor thermal comfort. While certain aspects of urban configuration are fixed during early planning, others, such as surface material selection, remain adaptable, even in existing urban contexts. This study proposes a method to develop design guidelines that optimize urban layouts for both energy efficiency and thermal comfort across both winter and summer seasons. Using the Princeton Urban Canopy Model (PUCM), 384 unique canyon configurations are simulated under both seasonal conditions. A comprehensive Design of Experiment (DoE) approach and Analysis of Variance (ANOVA) identify how canyon geometry, orientation, and surface materials interactively influence key outcomes. Results show how the optimal material layout for urban canyons varies by orientation, with traditional cool materials best for North-South canyons and thermochromics improving energy efficiency, while East–West canyons require a more strategic material selection due to trapped radiation. In the best-performing configuration, thermochromic roofs reduced summer heat flux into buildings by up to 30 kW/m^2 ($\sim$ −3%), while photoluminescent walls helped maintain summer apparent temperatures below 38.6 °C. As the aspect ratio increases, cool and photoluminescent materials become more effective, reducing entering heat flux to 109 kW/m^2 in summer and maximizing it to 1040 kW/m^2 in winter, while optimizing thermal comfort.

1. Introduction

Urban heat island (UHI) is a well-documented phenomenon characterized by elevated temperatures in urban areas compared to their rural surroundings, primarily driven by human-induced alterations of natural surfaces (Erell, Pearlmutter, & Williamson, 2012). The mechanisms underlying UHI are complex and multifaceted, involving a combination of factors like land surface albedo, vegetation coverage, urban morphology, anthropogenic heat emissions, and atmospheric interactions. These elements influence surface air temperatures, leading to important environmental and socio-economic consequences. Among the latter, ecological disruptions lead to changes in vegetation growth, air quality, and alteration in precipitation patterns, posing significant risks to human health through increased heat-related illnesses and fatalities (Huang, Li, Zhao, Zhai, 2022). At the same time, the prolonged exposure to high temperatures translates into a higher building energy demand, especially during the hot season, with the consequent increased energy consumption and greenhouse gas emissions (Ciancio et al., 2020). Crucially, the local UHI signal is now superimposed on a pervasive global warming trend: baseline outdoor temperatures are projected to rise in most world regions, further amplifying heat stress and energy needs even in rural settings (Viganò, Rugani, Marengo, & Picco, 2024). With more than half of the global population living in urban areas – a number projected to swell by an additional billion before 2050 (Huang, Li, Liu, & Seto, 2019) – it is imperative to understand the intricacies of UHI, particularly amidst rapid urbanization in developing unprecedented global climate shifts. Recent studies indicate that the compounded effects of global warming and the urban heat island (UHI) phenomenon may undermine the energy neutrality of zero-energy buildings (ZEBs), potentially converting them into net energy consumers under projected mid-century climate scenarios (Zhao et al., 2025). For this reason, over the past few years, the research community has emphasized the importance of integrating urban environmental criteria, quantification tools, and workflows into urban design practices (Natanian & Auer, 2020).

The magnitude of UHI is dictated by a combination of anthropogenic factors. Field monitoring and simulation data have demonstrated how altering albedo and vegetation cover with artificial finishings significantly impacts land surface temperature (Calhoun et al., 2024). In particular, global-scale research by Clinton and Gong (Clinton & Gong, 2013) identifies building density, vegetation coverage, and built-up land as the primary determinants of UHI levels. Additionally, factors like urban morphology and local air circulation have been revealed to contribute significantly to the complex mechanisms of urban thermal behavior. Climate-model projections consistently show a decline in heating loads but a sharp rise in cooling loads across diverse climatic zones, ultimately increasing annual energy use in warm–humid and hot–dry cities (Bazazzadeh, Nadolny, & Safaei, 2021). While numerous studies have investigated these UHI critical determinants, a major challenge remains the fragmented approach in assessing urban performance, without effectively managing the huge number of parameters affecting the urban scale (Mauree et al., 2019). Existing models tend to focus on a single performance aspect (e.g., energy demand or thermal comfort) and often neglect other critical indicators (Shmelev & Shmeleva, 2018). This limits the overall comprehensiveness and effectiveness of the findings, thereby preventing a holistic understanding of the environmental performance of urban canyons.

Urban environments are inherently complex thermodynamic systems, where heat transfer occurs through conduction, convection and radiation. To address such complexity, significant strides have been taken toward developing parametrization schemes that capture key hydrological and atmospheric interactions at different scales (Li & Bou-Zeid, 2014). The motivation behind such endeavors lies in the potential to evaluate the impact of different urban features, including the adoption of UHI mitigation strategies, starting from the initial design phase. Domains that are typically considered are urban climate, building energy demand, outdoor thermal comfort, and energy systems (Mauree et al., 2019), but models dealing with a specific topic do not easily communicate among each other, leading to complex and time-consuming processes. Among the existing few exceptions, urban climate and outdoor thermal comfort have been combined, introducing a simplified scheme of the human body into the Princeton Urban Canopy Model (PUCM). The first was developed by Pigliautile, Pisello, and Bou-Zeid (2020) and it is based on a simplified human energy balance that represents the energy fluxes exchanged between pedestrians and the environment. The code quantifies outdoor thermal comfort by computing human skin and apparent temperature, which are among the most complete indicators according to the literature (Coccolo, Kämpf, Scartezzini, & Pearlmutter, 2016). A more realistic representation of pedestrian thermal comfort in urban environments was introduced by Huang, Song, Wang, Chan (2022) that integrated an Urban Canopy Model (that is very similar to PUCM) with a multi-node human thermoregulation model. Their study demonstrated how street-level human thermal stress can be accurately assessed by considering the interaction between local meteorological conditions and pedestrian heat exchange processes. The PUCM was developed by Wang, Bou-Zeid, and Smith (2013) and solves the energy budget of a parameterized urban canopy layer, simulating the heterogeneity of built surfaces with sub-facets for different materials and detailed representations of hydrological processes. The PUCM relies on the concept of land surface energy budget (Oke, 1982). This theory divides the absorbed and released energy of a land surface into the net all-wave radiation, sensible and latent heat, and heat storage. As these energy components transfer between the land surface, sub-surface and near-surface atmosphere, their variations lead to temperature changes within the urban environment (Takebayashi & Moriyama, 2007). For instance, Yang and Bou-Zeid (2018) combined weather station data from 12 U.S. cities and high-resolution simulations demonstrating that UHI intensifies during extreme-cold periods, especially at night, because of the anthropogenic heat released from building heating and, more in general, because of anthropogenic actions that alter urban surface cover. Recent additions to the PUCM code allow to assess the impact of newly developed advanced materials for urban applications (Chiatti, Fabiani, Huang, Bou-Zeid & Pisello, 2024; Fabiani, Pisello, Bou-Zeid, Yang, & Cotana, 2019).

Building on these advancements, this work proposes a novel methodology to optimize urban canyon configurations by integrating multiple variables and performance criteria. Following a comprehensive review of the primary factors involved in urban planning and influencing the final urban energy and environmental performance (Section 2), we develop and apply a workflow that enables the identification of optimal canyon layouts by simultaneously considering multiple design variables and response metrics (Section 3). Our objective is to propose a comprehensive design process that exploits the potential of the PUCM to evaluate the influence of canyon geometry and material properties on both outdoor thermal comfort and buildings' energy consumption, even from the earliest stage of the design process. A Design of Experiment (DoE) approach is employed, using a full-factorial approach that systematically explores all possible combinations of factor levels. In this context, a "factor" is a design variable, while a "level" denotes the specific value or setting of that variable. This method, commonly employed in both research and industrial contexts to plan, execute, and analyze experiments efficiently (Pazzaglia et al., 2023), enables the evaluation of main effects and interaction effects among variables, providing deeper insight than traditional sensitivity analysis. The impact of each factor is quantified by measuring the change in response attributed to variations in its level. Our experiment entails the design of an urban canyon where the combined effect of different factors, i.e., characteristics in terms of geometry aspects and surface finishings, optimizes the canyon's response for both buildings' energy consumption and outdoor comfort for citizens, during summer and winter periods. The here-proposed methodology is demonstrated through a case-study canyon situated in Princeton (NJ), leveraging its microclimate boundary conditions and experimentally obtained data to validate the effectiveness of the integrated assessment framework. Although demonstrated through a case-study, the proposed methodology is inherently adaptable to different climates and locations. The PUCM allows straightforward reapplication to other regions simply by updating the input meteorological data. While the optimization results are inevitably site-specific, the proposed workflow itself is generalizable and scalable.

This study is driven by two main research questions:

- How can alternative approaches like DoE guide the integration of passive cooling strategies – ranging from conventional to innovative materials – within existing or newly developed urban contexts?
- How do urban canyon configurations and surface material selections influence the microclimate, building energy use, and outdoor thermal comfort across seasonal conditions?

In summary, while prior research has explored various aspects of urban heat mitigation, this study proposes a novel multi-objective optimization framework for urban canyon design that focuses on its performance as a thermodynamic system. The aim is to understand how the combination of geometric parameters and surface materials collectively influences the total energy fluxes and thermal comfort within the canyon. The DoE approach allows to systematically explore all combinations of the selected variables, quantifying not only the main effects but also interactions among variables. Furthermore, the DoE multi-aspect optimization, across both summer and winter scenarios, seeks to identify the best design solutions suitable for common and practical urban heat mitigation pathways.

2. Literature review

A comprehensive understanding of the UHI dynamics is essential for effective urban planning and climate mitigation strategies. The conscious design of urban development in the coming decades has the potential to significantly influence climate change, while simultaneously enhancing quality of life in cities (Echenagucia, Capozzoli, Cascone, & Sassone, 2015). Consequently, urban designers are placing greater emphasis on various aspects of early-stage urban canyon design, such as street width and orientation, building characteristics, and surface materials, which can contribute to create a climate-responsive and healthier built environment (Mirzabeigi & Razkenari, 2022). The following subsections delineate the primary urban design aspects that impact the canyon's overall performance in terms of both energy efficiency and human comfort.

2.1. The impact of canyon's geometry, orientation and urban context

Urban canyons are narrow streets flanked by tall buildings on both sides, commonly found in densely populated cities where vertical construction and compact street layouts are necessary. Their geometry is primarily defined by the building height-to-street ratio (h:w) and the sky view factor (SVF), i.e., the visible portion of the sky from a point. These two parameters are closely related: a higher h:w ratio corresponds to a lower SVF. They significantly influence several key environmental aspects, including solar radiation, wind flow, air temperature, and humidity levels (Deng et al., 2023). In general, tall, narrow canyons provide shading that can help mitigate the UHI effect and reduce cooling demands (Muniz-Gäal, Pezzuto, de Carvalho, & Mota, 2020; Wang, Xu, Ng, & Raasch, 2018), though excessive shading may limit daylight affecting indoor comfort and street-level activities (Sakakibara, 1996). Their geometry can also alter wind patterns, either amplifying wind speed and noise or reducing air circulation, especially when perpendicular to prevailing winds (Huang et al., 2021). Conversely, wider canyons allow more direct solar radiation to reach street level, improving natural daylight penetration. While this can enhance air circulation and air quality, it may also result in higher temperatures due to increased solar heat gain Chen et al. (2021). Depending on sky coverage, a higher SVF in urban canyons promotes radiative cooling and helps dissipate trapped heat, especially during hot summer months (Schrijvers, Jonker, de Roode, & Kenjereš, 2020).

While each geometry feature has individual effects, the optimal canyon configuration is highly context-dependent and influenced by local climate conditions (Deng & Wong, 2020). For example, in hot arid regions, a high h:w ratio is often recommended: research suggests that an aspect ratio of 2.0 or even higher can be beneficial where minimizing direct sunlight at street level is crucial for thermal comfort (Abdelhafez, Altaf, Alshenaifi, Hamdy, & Ragab, 2022; Aboelata, 2020). An East-West orientation can minimize solar exposure during peak hours, reducing cooling loads and improving thermal comfort by limiting direct sunlight penetration into buildings (Taleghani, Swan, Johansson, & Ji, 2021). This orientation also enhances cross-ventilation, which can help cool down the canyon during warmer months since winds tend to flow in zonal (East-West or West-East) directions. In colder climates, instead, a ratio of 0.5 is suggested to increase solar heat gain, which is desirable for naturally heating buildings and reducing the energy demand Sahnoune and Benhassine (2023). In this scenario, a North-South orientation can maximize sunlight exposure throughout the day, with positive effects on heating loads and passive solar design strategies, particularly during winter (Marriage, 2021).

Beyond climate, different urban contexts require specific canyon features to optimize energy efficiency and human comfort. Dense urban areas, where land is scarce and buildings are closely spaced, benefit from balanced h:w ratios (between 0.8 and 1.5), to ensure both shade and light in temperate zones while mitigating excessive wind speeds (Hang & Chen, 2022). Residential neighborhoods may prefer wider streets and lower h:w ratios to enhance daylight access and create more open, less oppressive environments (Cui, Jiang, Zhang, & Wang, 2022). In mixed-use areas, instead, the optimal canyon geometry must accommodate diverse needs, such as commercial activities at street level and residential or office spaces above. Adaptive geometries with variable h:w ratios, staggered building heights, and setbacks can create dynamic microclimates that meet diverse requirements (Kannamma & Sundaram, 2015).

2.2. The impact of canyon's materials and their properties

As demonstrated by Loeffler, Österreicher, and Stoeglehner (2021), urban morphology incorporating adequate passive design measures can significantly influence the energy performance of future urban canyons. Nature-based solutions such as vegetation and water features effectively reduce ambient temperatures through evapotranspiration, shading, and evaporative cooling (Santamouris & Vasilakopoulou, 2023; Wang et al., 2023; Wong, Tan, Kolokotsa, & Takebayashi, 2021). Their effectiveness depends on water-sensitive urban design and low-impact development practices, which promote infiltration and reduce runoff. Permeable and evapotranspiration-promoting materials, such as biologically active surfaces and water-retentive pavements, can help mitigate both UHI and flooding (Xie, Akin, & Shi, 2019). Nevertheless, applying advanced finishings with appropriate optical and thermal properties for urban envelopes has often proven more cost-effective and feasible to reduce surface temperatures and building energy consumption (Manni et al., 2022). Albedo and emissivity – ideally considered in their spectral distribution – are critical to managing surface energy balance and influencing microclimate and energy demand Mungule and Iyer (2022). Albedo measures the reflectivity of a surface: it is the ratio of reflected radiation to incident radiation. Emissivity, on the other hand, measures a material capability of releasing the absorbed heat. Low-albedo finishings (dark-colored surfaces, like asphalt) absorb more solar radiation, while low-emissivity tends to retain heat longer. A comprehensive analysis of 14 studies examining the effects of albedo modifications on urban climates demonstrates that incorporating highly reflective materials into roofs and pavements can mitigate ambient temperature increases (Santamouris & Fiorito, 2021). For every 0.1 increase in albedo, the estimated afternoon outdoor air temperature reduction is approximately 0.09 °C, varying significantly with the scale of implementation of the high albedo material, and also with local climate, landscape features, and urban design (Yang & Bou-Zeid, 2019). To effectively implement such strategies, a systematic evaluation framework, considering the effectiveness of heat mitigation technologies across different urban scales, investment levels, and local climate zones (LCZs) is more than crucial (Zhao et al., 2023).

While urban context, canyon's geometry and orientation are often fixed in early planning stages, surface material choices can be adjusted. For this reason, recent research has focused on developing innovative materials and technologies to mitigate urban overheating. The first generation of "cool materials" featured light-colored coatings with high reflectivity and emissivity, but were limited by glare and winter energy penalties (Rosso et al., 2017). Subsequent materials improved solar reflectance in the near-infrared spectrum, with cool-colored alternatives based on titanium dioxide or calcium carbonate (Ramos et al., 2021). To overcome earlier drawbacks, adaptive materials such as thermochromic and photoluminescent coatings, have emerged within the latest generation of cool solutions (Feng et al., 2023). Thermochromism endows materials with the capability of undergoing color transitions in response to temperature fluctuations. When used as building coatings, they function as cool roofs during warm periods, switching to a darker color in colder seasons to absorb more solar radiation (Fabiani, Castaldo, & Pisello, 2020). Conversely, photoluminescent materials emit energy as light after absorbing radiation from either artificial or natural (solar) sources (Chiatti, Kousis, Fabiani, & Pisello, 2022b). The efficiency of this phenomenon, quantified by the ratio of emitted

to absorbed energy (quantum yield) is a key parameter for material characterization. Light-emitting materials offer UHI mitigation potential through a dual mechanism: rejecting the incident solar radiation by both reflectance and emission and contributing to lighting energy-saving, depending on the persistence of the phenomenon (Chiatti, Kousis, Fabiani, & Pisello, 2022a; Levinson, Chen, Ferrari, Berdahl, & Slack, 2017). However, recognizing the complexity of urban heat, integrated and feasible mitigation strategies emphasize that no single solution is universally superior. Instead, the work by Zhao et al. (2023) highlights the necessity of multi-measure solution sets, adaptable across diverse urban contexts and climatic zones.

Regardless of the specific advanced material, three consistent findings emerge: (i) integrated solutions perform better than isolated ones (Yenneti et al., 2020); (ii) distributed, small-scale interventions often outperform large single features (Gunawardena, Wells, & Kershaw, 2017); (iii) broader urban planning strategies, such as mixed land use and sprawl containment, enhance the effectiveness of mitigation efforts (Singh, Singh, & Shishir, 2023).

3. Methodology

As introduced in Section 1, this work delves into a novel methodological approach to outline the optimal configuration an urban canyon should have to maximize energy and comfort benefits. The impact of several design factors, related to both urban geometry and materials, is assessed while exploiting the PUCM. In addition, a full factorial DoE model is employed to statistically analyze all canyon layouts. This allows us to finally predict the optimal solution that best addresses both winter and summer boundary conditions. An urban canyon located in Princeton (NJ) is here considered as a case-study framework, but the same methodology is suitable for any urban model and any climate data worldwide.

3.1. Investigated materials

This study examines various materials for building envelopes to assess their impact on the overall energy balance within an urban canyon. The selected materials represent the evolution of passive cooling strategies for the built environment, ranging from conventional dark and cool materials to pioneering options with adaptive behaviors.

Traditional dark materials, such as asphalt, clay and dark stone finishings, are characterized by low albedo (α = 0.05–0.45) due to their dark color. While this property can be beneficial for building passive heating in colder climate, the widespread use of dark materials in urban areas exacerbates local temperature increases during hot periods (Jandaghian & Akbari, 2018). Conversely, high-albedo materials are considered an effective strategy to mitigate urban overheating and enhance thermal comfort in cities. Traditional cool materials, like white or light-colored finishings, possess high albedo (α = 0.70–0.95) and thermal emissivity (ε = 0.75–0.95), enabling to effectively reflect solar radiation and release absorbed heat Akbari and Levinson (2008). Among the latest advanced solutions with adaptive behaviors to counteract the drawbacks of traditional cool materials in winter, thermochromic materials can reversibly adjust their optical properties in response to ambient temperature variations. These coating typically exhibit a light color when heated and a dark color when cooled. In this work, we refer to the thermochromic materials developed and investigated by Fabiani et al. (2020), which are mixtures made of 50wt% toluene-xylene based solvent, 30wt% petroleum-derived resins, and 20wt% thermochromic pigments, applied twice over a white polyurethane membrane. These thermochromic pigments transition from black to nearly almost color at 20 °C, moving from a low-albedo value of 0.15 to 0.55. Another class of dynamic materials suitable for urban applications includes photoluminescent prototypes, i.e., materials that emit visible light after absorbing energy from UV–VIS radiation. Recent studies have highlighted the potential of photoluminescence in mitigating the UHI phenomenon, through the dual

rejection of incoming solar radiation by both reflection and emission (Chiatti et al., 2022a). Among various photoluminescent colors, red emission has shown the highest potential for reducing urban surface temperatures (Chiatti, Fabiani, Huang et al., 2024). For this reason, red-emitting pigments previously investigated by Fabiani, Gambucci, Chiatti, Zampini, Latterini, and Pisello (2022) have been selected as reference material for this study. They are commercially available europium-doped calcium sulfide pigments (CaS:Eu) that can be dispersed in various mixtures (e.g., plastics, glass, paints, etc.) to create materials that glow in the dark. In their inactive state, the pigments appear white, turning bright red after exposure to solar or artificial radiation. This study examines their application as coatings for urban building envelopes.

In summary (Table 1), the present work examines four types of materials to evaluate and compare their impact within various urban canyon configurations: a traditional dark (DM) or cool (CM) solution, a thermochromic finishing (TC) and a photoluminescent red-emitting coating (PL). Their analytical models and integration into the PUCM are detailed in Section 3.2. It is important to highlight that the final aim of this study is not to assess the standalone performance of single passive cooling materials for building-scale applications. This work prioritizes the combined effect of selected urban surface materials and canyon's geometric properties. The inherent dependence of materials' behavior on changing environmental parameters is implemented within the physical models of the PUCM. Furthermore, the main goal is to integrate such passive cooling solutions into a broader DoE framework to evaluate their holistic impact on the overall thermal and energy performance of the urban canyon, viewed as a system, rather than a material-centric analysis of individual responses.

3.2. UCM description and setup

The PUCM simulates the energy balance of an idealized single-layer urban canopy consisting of two facing walls, ground, and roofs (Wang et al., 2013). The model can capture the diversity of built surfaces by incorporating sub-facets representing various materials, along with detailed depictions of hydrological processes. It considers energy exchanges between the facets and the air above, reproducing heat fluxes and temperatures of each urban surface, according to the following energy budget equation for an infinitesimally thin interface:

$$R_{net} = H + LE + G \tag{1}$$

where R_{net} is the net radiation calculated using a two-reflection model; H and LE are respectively the sensible and latent heat fluxes; and G is the conductive heat flux into the urban surface. The PUCM has undergone extensive validation across a wide range of climate scenarios, both through field measurements collected in different cities worldwide and in offline configurations driven by high-resolution meteorological data (5 to 30-minute averaged data from weather stations above the canopy) (Ramamurthy et al., 2014; Ramamurthy, Sun, Rule, & Bou-Zeid, 2015; Ryu, Bou-Zeid, Wang, & Smith, 2016; Wang et al., 2013). Originally developed and tested using empirical data from the Princeton campus, the PUCM provides a site-specific and physically-grounded urban canopy framework. Early validation efforts included the deployment of a dense sensor network comprising surface temperature sensors, radiometers, soil moisture probes, and micrometeorological towers, enabling the capture of energy and water budget components across representative urban surfaces. Comparisons between model outputs and observations demonstrated good agreement for sensible heat fluxes, surface temperatures, and radiative exchanges, confirming the model's ability to realistically reproduce the urban surface energy balance. In addition to whole-model validation, individual components of the PUCM have been refined and tested, such as roof surface albedo and emissivity parameters calibrated against measured upwelling radiation, and the representation of vegetation, tree shading, and urban greening, which have been shown to significantly influence urban microclimate

Table 1
Summary of the materials investigated in this study and their main features and peculiarities.

Material	Description	Albedo (α)	Peculiarities
Dark materials (DMs)	Dark-colored materials like asphalt, clay and dark stone finishings.	0.05–0.45	They absorb solar radiation, beneficial for passive heating in cold climates but contribute to urban overheating during the hot season.
Cool materials (CMs)	Whitish or light-colored materials or finishings.	0.50-0.95 initially	They reflect solar radiation while dissipating heat, promoting surface temperature reduction. Penalties during the winter period.
Thermochromic materials (TCs)	Finishings that change color based on temperature, transitioning from black to almost transparent.	0.15 above 20 °C/0.50 below 20 °C	They combine the performance of dark and cool materials, according to the temperature of exposure. No winter penalties like for traditional CMs.
Photoluminescent materials (PLs)	Finishings with CaS:Eu pigments that appear white in their inactive state and become red in their active phase.	0.70	They emit a persistent red light after artificial or solar radiation exposure, enhancing the material's reflectivity while contributing to lighting.

and thermal comfort (Fabiani et al., 2019; Talebpour, Welty, & Bou-Zeid, 2021; Wang et al., 2013). More recent developments have further extended the PUCM to account for novel passive cooling materials, with thermo-optical properties derived from experimentally validated laboratory characterizations and subsequently applied to urban-scale scenarios (Chiatti, Fabiani, Huang et al., 2024; Fabiani et al., 2019). The PUCM "offline mode", when it uses atmospheric observations as input, provides flexibility in its application with minimal computational demands. It was thus adopted in this study. This feature enables more comprehensive analyses of problems with large parameter spaces, facilitating the study of urban microclimatic responses to building surface changes.

Furthermore, Pigliautile et al. (2020) coupled a schematic representation of the human body with the PUCM, considering a simplified energy balance expressed as the sum of the energy fluxes exchanged between a pedestrian in the middle of the street canyon and the environment:

$$R_{body} + C + K + E = 0 \qquad (2)$$

where R_{body} is the radiative exchange between the body and the surroundings; C and K are respectively the convective and conductive energy fluxes, while E is the latent heat loss due to evapotranspiration at the skin surface. The code also quantifies outdoor thermal comfort by computing the apparent temperature (AT), which adjusts the air temperature based on environmental parameters influencing thermal perception (e.g., relative humidity, radiation). The adopted equation is (Steadman, 1984):

$$AT = T_a + \frac{0.348 \cdot e}{100} - 0.7ws + \frac{0.7 \cdot R_{net}}{ws + 10} - 4.25 \qquad (3)$$

where T_a is the dry bulb temperature in °C; ws is the wind speed, and e is the water vapor pressure.

Based on the above, the current study shows how the PUCM can be used to assess the impact of various building materials before their actual implementation in an urban canyon. The numerical modules of the selected typology of urban skins (Section 3.1) were developed in previous works. Traditionally, the parametrization of materials with static and constant properties (e.g., DMs or CMs) is based on using their primary main thermo-optical values, such as albedo and thermal emissivity, as input for the PUCM. TCs and PLs, instead, exhibit dynamic behavior, changing their optical properties over time in response to variations in local boundary conditions.

While numerical simulations of well-established envelope typologies, like cool and green roofs, have already been validated against experimental data support (Li & Bou-Zeid, 2014; Li, Bou-Zeid, & Oppenheimer, 2014), more innovative materials have only recently been integrated into the PUCM environment. For these novel materials, in-lab characterization is typically conducted to determine the thermo-optical properties required as input for PUCM simulations, which are then verified against laboratory data. In particular, Fabiani et al. (2019) provided experimental validation of PUCM for thermochromic coatings – the same materials considered in the present study – under controlled conditions, thereby ensuring robustness of the model for simulating their thermo-optical transitions. Similarly, the PUCM formulation describing photoluminescent materials has already been presented in previous works, where it was shown to be valid on the basis of laboratory evidence (Chiatti, Fabiani, Bou-Zeid & Pisello, 2024; Chiatti, Fabiani, Huang et al., 2024). Although large-scale field experimental validation of these early-stage technologies is still limited, their performance at the building scale can be reliably assessed numerically using validated models. Accordingly, this study does not propose new mechanistic models for TC or PL materials. Instead, it builds on the existing, experimentally validated modeling framework and code to evaluate their potential when applied to building envelopes, thereby enabling trade-off analysis and supporting evidence-based decision-making in urban design.

Fabiani et al. (2019) modeled the evolution of thermochromic materials albedo as a function of surface temperature, developing the following equation:

$$\alpha(T) = \alpha_{dark} + \frac{\alpha_{cool} - \alpha_{dark}}{2}(1 - erf(t_{norm})) \qquad (4)$$

where $\alpha(T)$ is the albedo at temperature T; $\alpha_{dark} = 0.15$ is the albedo for temperatures below the thermochromic transition temperature ($TT = 20$ °C); $\alpha_{cool} = 0.15$ is the albedo for temperatures higher than TT; $erf(t_{norm})$ is the error function; and t_{norm} is the normalized time, defined as:

$$t_{norm} = count(t)\frac{2\pi}{t_{TT}} \qquad (5)$$

where t_{TT} is the thermochromic transition time interval, set to 1200 s and $count(t)$ is a counting function that tracks the time elapsed from the

beginning of a given thermochromic transition, defined as:

$$count(t) = \begin{cases} t_{TT} & \text{if } T(t-1) < TT \text{ and } count(t-1) > t_{TT} \\ count(t-1) - dt & \text{if } T(t-1) < TT \text{ and } count(t-1) \leq t_{TT} \\ 0 & \text{if } T(t-1) \geq TT \text{ and } count(t-1) < t_{T0} \\ count(t-1) + dt & \text{if } T(t-1) \geq TT \text{ and } count(t-1) \geq t_{T0} \end{cases}$$

(6)

where t_{T0} is equal to 0, and dt is the time interval of the simulation.

On the other hand, Chiatti, Fabiani, Bou-Zeid et al. (2024), Chiatti, Fabiani, Huang et al. (2024) implemented a model in the PUCM for photoluminescent materials that quantifies the amount of shortwave radiation emitted by phosphorescence (PP) as follows:

$$PP = \left(\frac{1}{\lambda_{PL}} \int_{\lambda=300}^{\lambda_A} QY(\lambda) \cdot a(\lambda) \cdot \lambda \cdot \varphi(\lambda) \cdot d\lambda\right) \cdot A \cdot SR_{down} - \tau \cdot \frac{dPP}{dt}$$

(7)

where λ_{PL} and λ_A are the wavelengths corresponding to the peak of emission and absorption, respectively; $QY(\lambda)$ is the spectral quantum yield; $a(\lambda)$ is the material's solar absorption; $\varphi(\lambda)$ is the spectral distribution of solar radiation according to the standard spectrum AM 1.5 g; A is the surface area; SR_{down} is the incident shortwave solar radiation; and τ is the lifetime decay constant of the photoluminescent emission. Among different afterglow colors, red emission has demonstrated the highest cooling potential. For this reason, this study focuses on a red photoluminescent material with the following experimentally obtained properties: a peak of emission $\lambda_{PL} = 645$ nm, a peak of absorption $\lambda_A = 465$ nm, a quantum yield $QY = 0.62$, an absorption coefficient $a = 0.34$ and a decay characteristic time constant $\tau = 0.63$.

Each material (DM, CM, TC, and PL) is applied either on the roof, walls and ground portion of the canyon, whose main descriptive features are based on and adapted from the work by Ryu et al. (2016) (Table 2). Changes in envelopes' reflectivity – whether caused by thermochromic transitions or photoluminescent emission – are directly integrated into the energy balance calculation (Eq. (1)), influencing absorbed solar radiation, longwave exchanges, and consequently the surface thermal regime. This approach guarantees consistency with the underlying physics, since surface temperatures emerge as the outcome of the coupled radiative-convective-conductive processes rather than being imposed or simplified. For wall surfaces, no windows are conceived at this stage of the study. This choice is intentional, as it allows for a focused analysis of the urban canyon's thermal performance that isolates the impact of passive cooling materials and key geometric parameters. While it is acknowledged that windows represent a fundamental component of the thermal-energy behavior of buildings and that, under conventional building energy simulation practices, a realistic window-to-wall ratio is generally required, the absence of windows here is consistent with the specific objectives of the work. The aim is not to provide a full, realistic building energy simulation, but rather to compare the relative performance of different envelope material solutions in shaping the canyon's thermal response. Moreover, the work can be also intended as a contribution for buildings' retrofit strategies, where modifications on opaque surfaces are often more feasible. Related to this, it should be noted that thermal insulation assumed for building walls and roof is relatively low, as set for previous studies (Ryu et al., 2016; Wang et al., 2013). Of course, for higher levels of insulation, the impact of envelope surface properties on building energy consumption would be reduced, but the outdoor comfort would not be significantly affected. However, considering a low-insulation scenario reflects the condition of many existing building that are potential targets for retrofit interventions.

Simulations are performed for the average summer and winter day in 2011, with air temperature (T_a), downwelling solar radiation (SR_{down}), and wind speed (u_w) profiles shown in Fig. 1. These profiles are determined by averaging weather parameters from early June to the end of August for summer and from early December to the end of

Table 2

Input parameters used in the PUCM for materials' thermophysical properties and canyon geometry settings, according to the previous work by Ryu et al. (2016).

Thermophysical properties	Symbol	Value
Roof emissivity	ε_R	0.95
Wall emissivity	ε_W	0.95
Ground emissivity	ε_G	0.93
Roof thermal conductivity	κ_R	0.94 W/(mK)
Wall thermal conductivity	κ_W	1.06 W/(mK)
Ground thermal conductivity	κ_G	2.00 W/(mK)
Roof heat capacity	c_R	1.40 MJ/(m²K)
Wall heat capacity	c_W	1.40 MJ/(m²K)
Ground heat capacity	c_G	1.30 MJ/(m²K)
Geometrical properties	**Symbol**	**Value**
Roof thickness	d_R	0.30 m
Wall thickness	d_W	0.30 m
Roof elevation (different h:w ratios)	h_R	9.1/18.2/36.4 m
Roof width	W_R	21.4 m
Canyon width	W	18.2 m
Other parameters	**Symbol**	**Value**
Fraction of asphalt/concrete on the ground	f_G	0.65/0.35
Roof roughness length for momentum	Z_{mR}	0.15 m
Canyon roughness length for momentum	Z_{mc}	1.46 m
Ground roughness length for momentum	Z_{mG}	0.15 m
Roof roughness length for heat	Z_{hR}	0.05 m
Canyon roughness length for heat	Z_{hc}	0.146 m
Ground roughness length for heat	Z_{hG}	0.05 m

February for winter. As detailed by Wang et al. (2013), weather data for driving the UCM (giving it the atmospheric conditions and inputs that prevail above the canopy), are taken from measurements on a tower deployed over an elevated roof on Princeton University campus. The tower has an eddy covariance system with a Campbell Scientific three-dimensional sonic anemometer (CSAT3), an open-path infrared gas analyzer (LI-7500 from Licor Biogeosciences), a mean temperature and relative humidity probe (HMP45C from Vaisala), a wind monitor (05103 R.M. Young from Campbell), and a four-component radiometer (NR01 from Hukseflux). Data are collected with a Campbell Scientific CR3000 data logger at various frequencies, but the files prepared to run the UCM in the present study are averaged over 30-min periods. The data mimic the variables a coupled atmospheric model would have given to the UCM. The 30-min data are then interpolated to fit the simulation time interval of 10 s, but the forcing data do not capture any dynamical scales below 30-min.

3.3. Design of experiment approach

Simulation runs are designed exploiting Design Expert 13 (Anon, 2023) and following a full factorial method. As previously introduced, the full factorial approach allows to analyze the effects of multiple factors (independent variables) on a response variable. Each factor can be assigned multiple levels, and all possible combinations of factor levels are tested, allowing for a comprehensive evaluation of both individual effects (main effects) and interactions between factors, via ANOVA analysis. The aim of the study is to assess the impact of different combinations of finishings for urban envelopes, canyon geometry, and orientation (factors) on responses related to both buildings' energy consumption and outdoor thermal comfort. Five factors are screened for the analysis, as outlined in Table 3: the surface type where the finishing is applied (roof R, walls W, or ground G), the aspect ratio (h:w) of the canyon, and the orientation of the canyon (NS or EW). By "ground", we refer to the portion of the canyon pavement designated only for pedestrians and where materials are supposed to be applied, which constitutes 35% of the total pavement surface. This section is made of concrete, while the remaining pavement is composed of asphalt.

As introduced in Section 3.1, four options of envelopes' coatings are considered for roof, walls and ground: DMs, CMs, TCs and PLs.
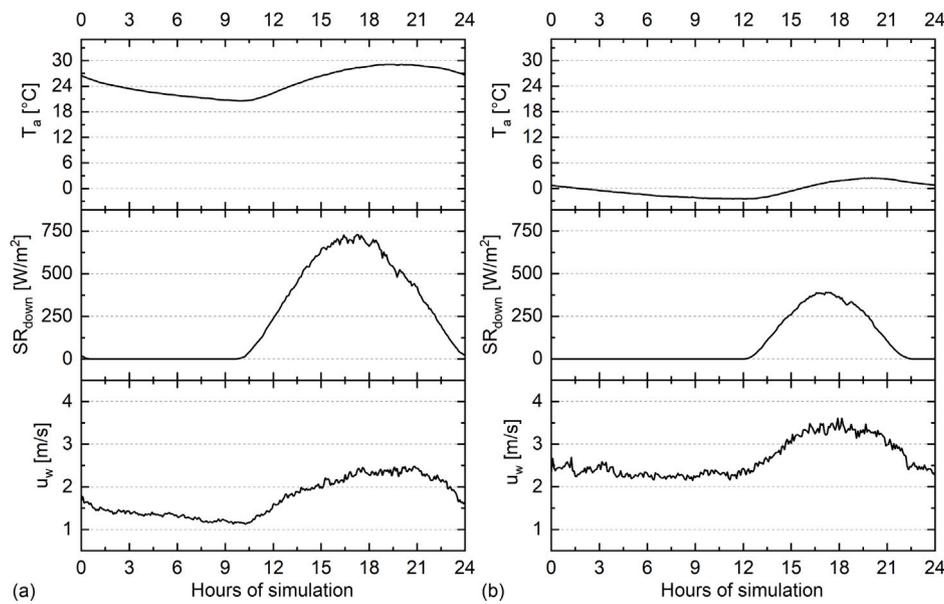
Fig. 1. Air temperature (T_a), downwelling solar radiation (SR_{down}) and wind speed (u_w) profiles of the simulated average (a) summer and (b) winter day, according to Princeton (NJ) weather data.

Table 3
Factors and levels set in the full factorial DoE model.

Factor	Name	Levels			
		L1	L2	L3	L4
A	Material on the roof	DM	CM	TC	PL
B	Material on the wall	DM	CM	TC	PL
C	Material on the ground	DM	CM	TC	PL
D	Canyon aspect ratio	0.5	1	2	
E	Canyon orientation	NS	ES		

The aspect ratio of the canyon is kept at three levels as 0.5, 1.0 and 2.0 to represent low, medium and high-density urban environments. The orientation of the canyon, instead, can vary between two levels, i.e., North-South (NS) and East–West (EW). With five factors having 4, 4, 4, 3, and 2 levels respectively (see Table 3), a list of 384 combinations is provided by Design Expert software (calculated as $4 \times 4 \times 4 \times 3 \times 2 = 384$ and reported in table S1). Each simulation is repeated for the average winter and summer day, resulting in a total of 768 runs to create a full factorial DoE model. Fig. 2 visually recapitulates the four types of materials investigated and the DoE factors with their levels. As anticipated, the experiment is oriented to define the optimal urban canyon configuration considering buildings' energy consumption and outdoor thermal comfort aspects. In doing so, specific parameters are selected as responses for the DoE model, namely the amount of heat flux entering/exiting the building interior from the roof and the walls during the day ($\dot{Q}_{in}$) and the peak of apparent temperature (AT) experienced by the simulated pedestrian inside the canyon. The first response is calculated by the PUCM solving the energy budget equation of each building surface (walls and roof); no dedicated building energy module is currently implemented within the model. For each response (Y), an equation that mathematically describes the factorial design is generated by the software, according to the formula:

$$Y = b_0 + \sum_{i=1}^{n} b_i X_i + \sum_{1<i<j}^{n} b_{ij} X_i X_j \tag{8}$$

where b_0 is the global mean, which serves as a baseline response; b_i represents the influence of each i-factor on the response; and b_{ij} indicates how the combined presence of factors i and j affects Y.

Therefore, the optimal urban canyon design is predicted by considering multiple criteria on the model prediction of $\dot{Q}_{in}$ and AT to find the canyon design that:

- Minimizes the heat flux entering the building in summer and simultaneously maximizes it in winter.
- Minimizes the peak of apparent temperature perceived by the pedestrian inside the canyon in summer and simultaneously maximizes it in winter.

In Design Expert, during the optimization process, the weight assigned to each criterion determines how strongly it influences the overall desirability function. Different weights mean that the software will prioritize satisfying that particular criterion when searching for the optimal settings. In this study, equal importance has been assigned to both aspects – each weighted at 50% – but this strategy can be easily adjusted to reflect specific contextual goals. Fig. 3 schematically summarizes the interaction between the DoE presented here and the previously introduced PUCM, with particular emphasis on the role of materials' properties on the surface energy budget and how the PUCM results affect the DoE optimized output according to the selected criteria.

4. Results

This study employed a comprehensive DoE approach, encompassing 384 unique scenarios repeated simulated under both summer and winter conditions using the PUCM, for a total of 768 runs. Table S1 specifies the settings of each scenario, encompassing variations in canyon geometry, orientation and materials implementation. This exhaustive method ensured the examination of both the individual main effect of each factor on the response variables (heat flux entering the building $\dot{Q}_{in}$ and apparent temperature AT) and the effects of interactions, i.e., how the impact of a factor on a response depended on the settings of another factor (up to 3-level interaction). Table S2 and S3 summarize the results of the ANOVA test for each response variable. The heat flux entering the building ($\dot{Q}_{in}$) was significantly influenced by all factors involved in the study (p-value < 0.05), suggesting a strong interplay between material choices and canyon geometry in determining building energy performance. Interestingly, the apparent temperature perceived by pedestrians inside the canyon (AT) was
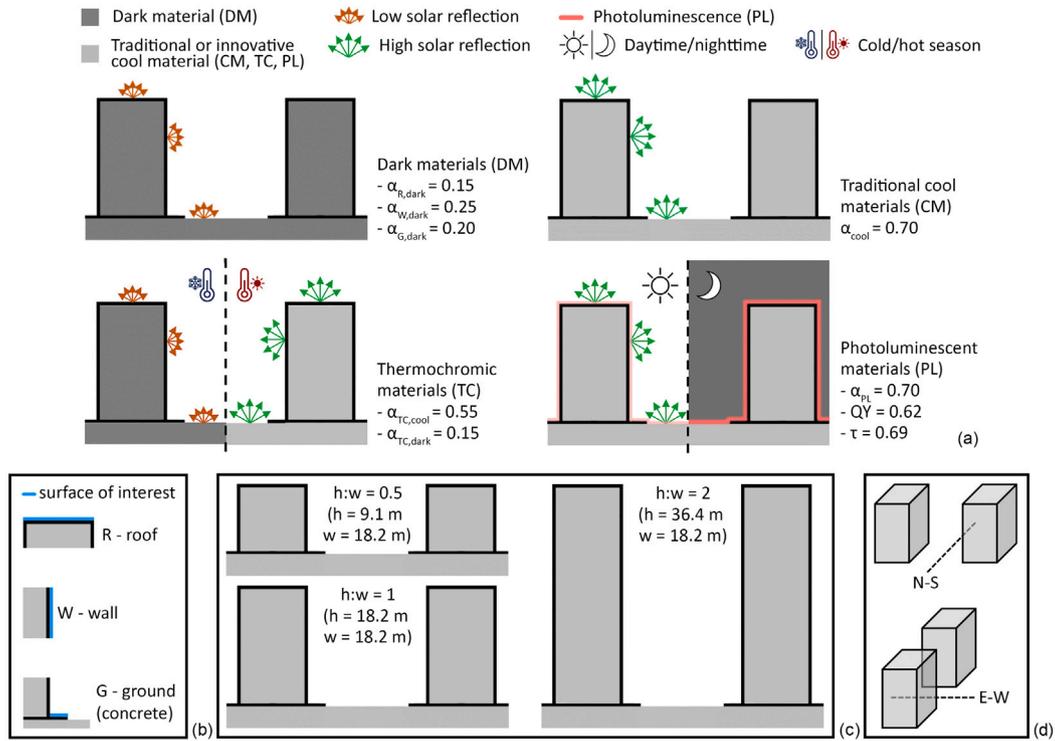
Fig. 2. (a) Investigated material options and their main optical properties. (b-d) DoE model factors: (b) surface of material application, (c) canyon's aspect ratio (h: w) and (d) canyon's orientation.
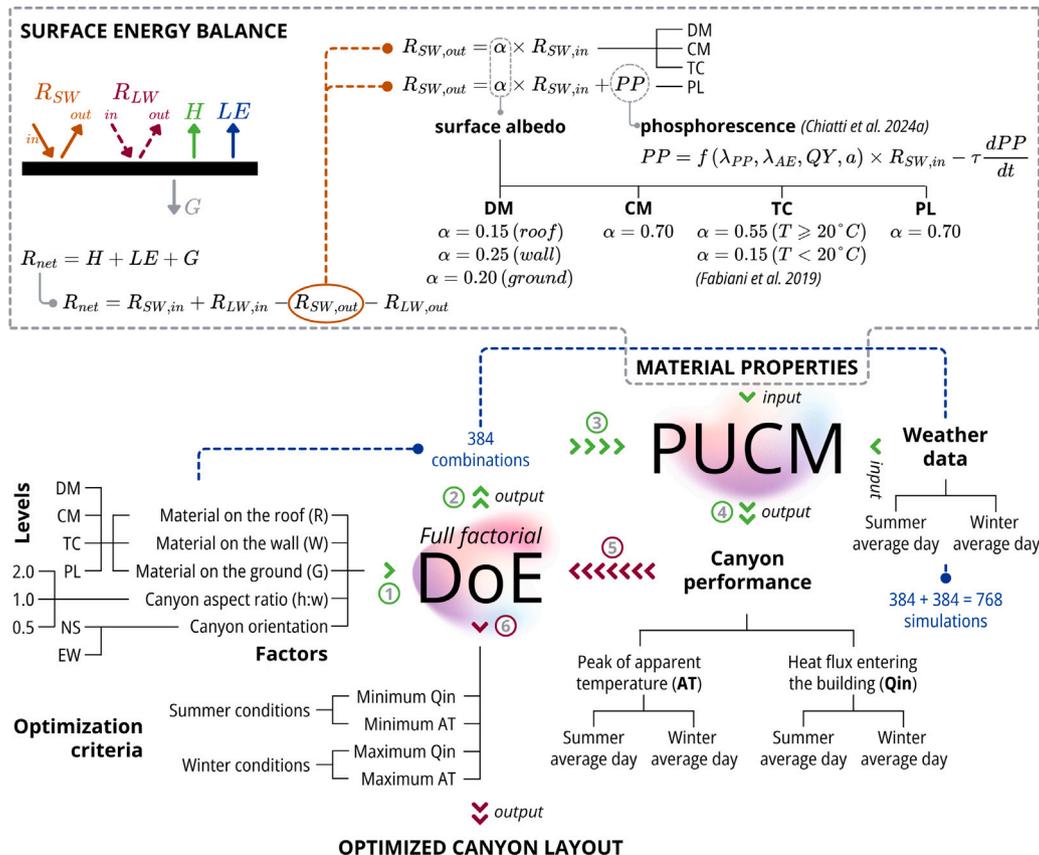

Fig. 3. Schematic representation of the here presented DoE-PUCM combined methodology.

not significantly affected by the roof finishing (p-value > 0.05). This observation aligns with the PUCM structure, where the roof surface does not directly interact with the air within the canyon.

Given this, the following paragraphs analyze optimal canyon configurations for maximizing benefits in three key areas: (i) building energy saving, considering the heat flux entering the indoors toward the minimization of cooling/heating costs; (ii) outdoor thermal comfort, considering the apparent temperature perceived by pedestrian inside the canyon; (iii) combined equal-weight optimization, offering a balance between both building energy savings and outdoor thermal comfort. Optimal configurations are visually presented in radar diagrams (Figs. 4–7), where each axis is a factor of the DoE model with its levels. Colored dots on the axes represent the optimal choice for that specific factor to achieve the desired outcome: blue for energy saving, red for thermal comfort and green for the balanced optimization. For example, as shown in Fig. 4a, a NS-oriented canyon with an aspect ratio of 1.0 would achieve maximum energy efficiency with thermochromic materials (TC) on the roof (R) and ground (G), and traditional cool materials (CM) on the walls (W).

4.1. The role of urban materials

To understand how envelopes' finishings affect the energy and thermal comfort performance of urban canyons, the aspect ratio was first fixed to 1 (h=w=18.2 m). NS and EW orientations were analyzed separately as shown in Fig. 4a and 4b, together with the main numerical outcomes.

For NS-oriented canyons (Fig. 4a), the optimal material distribution across all the considered targets consistently excluded dark materials. To maximize outdoor thermal comfort, traditional CMs were recommended everywhere on all surfaces. However, replacing TCs on the roof and ground proved optimal for minimizing energy consumption. The combined optimization strategy, balancing both ($\dot{Q}_{in}$) and AT, recommended CMs for the ground and building walls, and TCs on the roof. This configuration for combined optimization achieved AT peaks of 38.61 °C in summer and −4.60 °C in winter (respectively, 3.39 °C and 1.77 °C warmer than the only-comfort optimization). This indicates a trade-off where incorporating energy efficiency criterion improved summer thermal comfort but worsened winter comfort. Simultaneously, this combined optimization minimized the heat flux entering the building during the simulated summer day (4.03 kW/m^2) and the heat loss during the simulated winter day (1149.85 kW/m^2). This aligns with the adaptive nature of TCs, which adjust their optical properties as a function of temperature, avoiding the extra-cooling penalty of common CMs during winter. Notably, this configuration achieved a heat gain of + 30 kW/m^2 inside the building during winter compared to the only-comfort optimized scenario (CMs on all the canyon's surfaces).

For an EW-oriented canyon (Fig. 4b), instead, the inclusion of DMs was favored for optimizing outdoor thermal comfort. The optimal material configuration suggested DMs on the ground to reduce reflected solar radiation onto pedestrians, coupled with PLs on the walls. This is consistent with the capability of PLs of absorbing and re-emitting light, potentially reducing glare compared to whitish CMs. Focusing solely on building energy use, the optimal configuration involved TCs on the roof, CMs on the walls and PLs on the ground minimizing summer heat gain (−39.73 kW/m^2). However, this negatively impacted thermal comfort, increasing AT summer peak by 2.47 °C and decreasing the winter peak by 1.14 °C. As a result, the balance between outdoor thermal comfort and building energy use for an EW-oriented canyon required thermochromic materials on the roof, photoluminescent materials on the walls and dark materials on the ground, for a final range of AT spanning from −1.78 °C and + 43.51 °C and a heat flux entering the building in summer minimized at 17.61 kW/m^2 and a heat flux leaving the building in winter minimized at 1157.72 kW/m^2.

Fig. 4c provides a comparative overview of how the optimal material configurations depend on canyon orientation. For minimizing

building energy consumption, a NS-oriented canyon performed best, utilizing TCs on both the roof and ground, and CMs on the walls. When prioritizing pedestrian thermal comfort, either solely or in the balanced optimization, an EW-oriented canyon with DMs on the ground and building roof, combined with PLs on the walls, emerged as the preferred solution. This approach effectively reduced the amount of radiation trapped within the canyon, while benefitting from the light-emission of photoluminescence.

4.2. The role of canyon geometry

This section examines the influence of canyon geometry, specifically the h:w ratio, on the optimal material selection for urban canyons. Three different aspect ratios were analyzed, as depicted in Figs. 5 (NS orientation) and 6 (EW orientation).

For NS-oriented canyons (Fig. 5), traditional or innovative cool materials remained the preferred choice for both energy savings and thermal comfort, regardless of the aspect ratio. In EW-oriented configurations (Fig. 6), instead, managing the radiation trapped within the canyon is crucial for pedestrians' comfort. This is especially pronounced at low-to-medium aspect ratios, where DMs were favored to minimize reflected radiation. For instance, in a canyon with an aspect ratio of 0.5 (Fig. 6a), while a combination of TCs on the roof and PLs on walls and ground optimized building energy consumption, prioritizing pedestrian comfort required DMs placed on all surfaces. This DM-focused configuration resulted in a more comfortable AT, ranging from −1.53 °C and 47.10 °C, respectively 1.40 °C and 3.98 °C below winter and summer peaks of the energy-optimized scenario. However, this comfort improvement came at the expense of energy performance, with a heat flux penalty of 187.0 kW/m^2 entering the building during the simulated summer day. To further improve such result, i.e., optimizing both AT and $\dot{Q}_{in}$, the implementation of TCs on the roof achieved an 87.05 kW/m^2 reduction in the heat flux entering the building, without compromising the optimized thermal comfort.

Moving toward higher aspect ratios, textcolorredimplementing cool or photoluminescent materials instead of DMs guaranteed a general reduction in both AT peaks and $\dot{Q}_{in}$ entering/exiting the building. In particular, the application of PLs on building walls proved particularly effective in optimizing canyon responses, regardless of a NS- or EW-orientation. While for a low/medium aspect ratio optimizing buildings' energy use was mainly due to the implementation of TCs on the roof and CMs on the walls ($\dot{Q}_{in}$ ranging from 1.73 kW/m^2 in summer to −1171.21 kW/m^2 in winter conditions), for a h:w=2.0 the extensive application of PLs on a larger wall surface translated into the optimization of energy consumption and outdoor thermal comfort.

As a matter of fact, the optimal NS-oriented canyon configuration for maximizing both energy savings and pedestrian thermal comfort featured a h:w ratio of 2.0 with CMs applied to all urban surfaces (Fig. 5c). This design yielded AT peaks of 35.22 °C for the simulated summer day and −4.75 °C for the simulated winter day, with a heat flux ($\dot{Q}_{in}$) of 109.24 kW/m^2 entering the building in summer and 1040.10 kW/m^2 exiting in winter. In comparison, the optimal configuration for an EW-oriented canyon also required a height-to-width ratio of 2.0, but with a different material layout TCs on the roof, PLs on the walls, and CMs on the ground (Fig. 6c). While this EW-oriented configuration resulted in slightly higher AT in both summer and winter compared to the NS-oriented canyon (+ 5.66 °C and + 2.41 °C, respectively), it reduced the heat flux entering/exiting the building by 15.62 kW/m^2 in summer and 6.01 kW/m^2 in winter, demonstrating a more balanced trade-off between comfort and energy efficiency.

4.3. Final optimized urban canyon design

Fig. 7 presents the results of DoE optimization for the canyon configuration that best enhanced the investigated responses, i.e., energy use and/or outdoor thermal comfort. As previously discussed, a high-rise
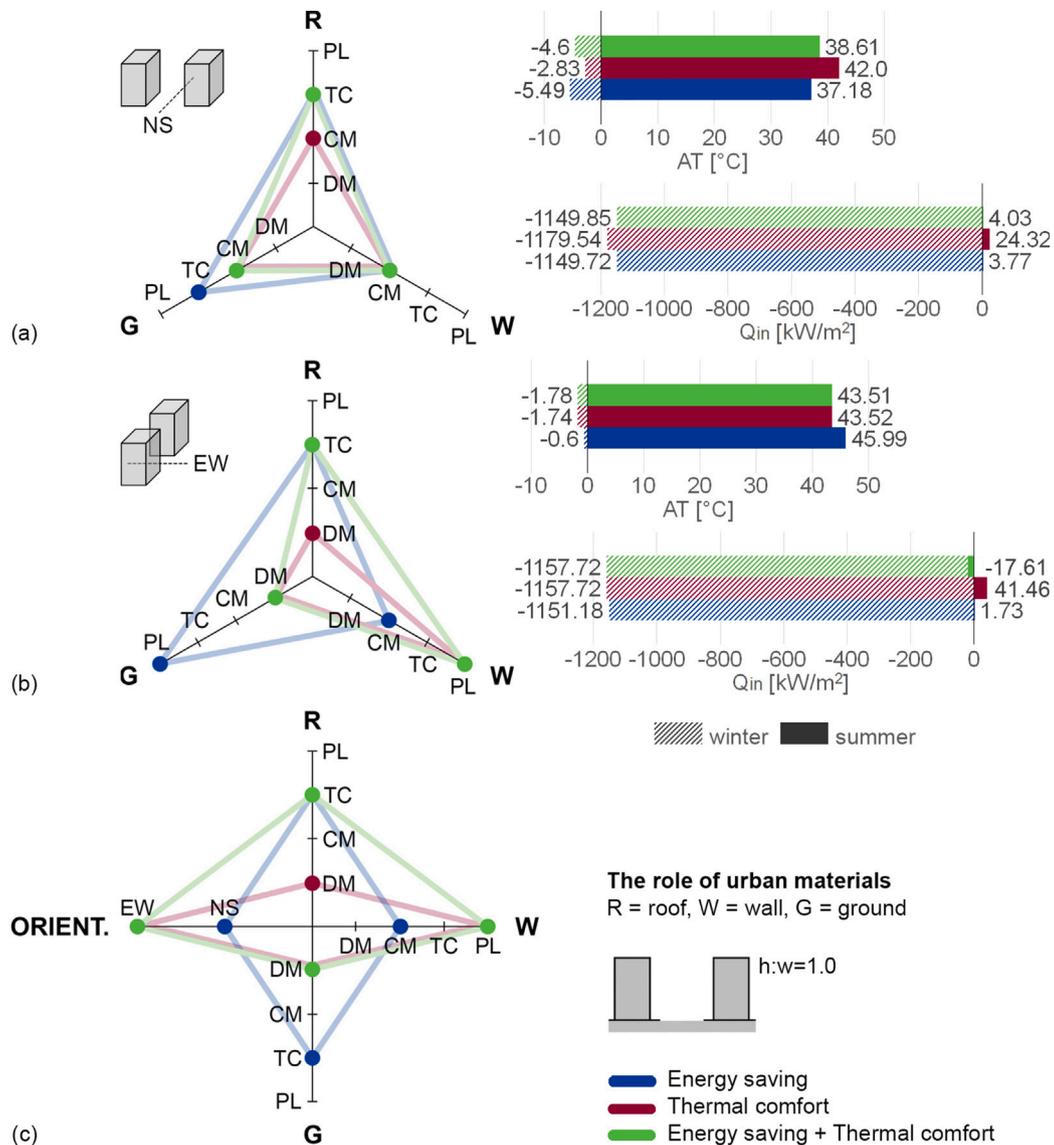
Fig. 4. Optimal materials' application and corresponding responses in terms of energy saving, thermal comfort and both, for a (a) NS-oriented and (b) EW-oriented canyon with an aspect ratio h:w = 1. (c) Optimal materials' distribution for the same canyon with free orientation.

canyon configuration (h:w=2.0) proved advantageous for both NS and EW orientations. For NS-oriented canyons, a taller layout minimized energy consumption, thanks to the less amount of solar radiation entering the canyon and negatively impacting surface and air temperature. Applying CMs on the roof, PLs on the walls and TCs on the ground was the most effective strategy for optimizing building energy use. This configuration resulted in a heat flux penalty of 78.46 kW/m² entering the building during the simulated summer day and 1049.01 kW/m² exiting the building during the simulated winter day. While this configuration effectively managed summer *AT* for pedestrians, reaching a peak of 32.89 °C, in winter conditions *AT* drastically dropped to −6.15 °C. For this reason, when prioritizing outdoor thermal comfort, an EW-oriented canyon configuration at h:w=2.0 is preferred. Although this resulted in a higher summer *AT* peak at 40.88 °C, it but also raised the winter peak to −2.34 °C, i.e., 3.81 °C above the minimum *AT* observed in the NS-oriented energy-optimized canyon. Optimizing solely for *AT* led to a configuration with DMs on building roof, PLs on the walls and CMs on the ground, for a final $\dot{Q}_{in}$ = 122.78 kW/m² entering the building during the summer day and $\dot{Q}_{in}$ = −1034.09 kW/m² exiting the building in the winter day. Finally, when optimizing for both energy saving and outdoor thermal comfort, the proposed urban canyon design

mirrored the comfort-focused EW-oriented configuration. However, TCs were applied on the roof instead of DMs, translating into minimal changes in terms of apparent temperature but a significant reduction to the heat flux entering the building during the simulated summer day by 30 kW/m². This highlights the potential of TCs to achieve a more balanced trade-off between energy efficiency and thermal comfort in urban canyons.

To provide a more comprehensive assessment of thermal comfort in these configurations, the Universal Thermal Climate Index (UTCI) was derived using the environmental parameters corresponding to the peak *AT* given by the DoE optimization (Table 4). UTCI was computed using the Python package developed by Tartarini and Schiavon (Tartarini & Schiavon, 2020), which offers a reliable implementation of the UTCI model. Previous research showed a very high correlation between *AT* and UTCI, indicating that about 95% of the variance in *AT* can be explained by UTCI and vice versa (Blazejczyk, Epstein, Jendritzky, Staiger, & Tinz, 2011; Morabito et al., 2014). Our results are consistent with this correlation and further demonstrate that thermal comfort optimization leads to significant improvements in UTCI, particularly during winter conditions. Specifically, for the average winter day, the energy-optimized canyon configuration resulted in a UTCI of −0.60 °C,
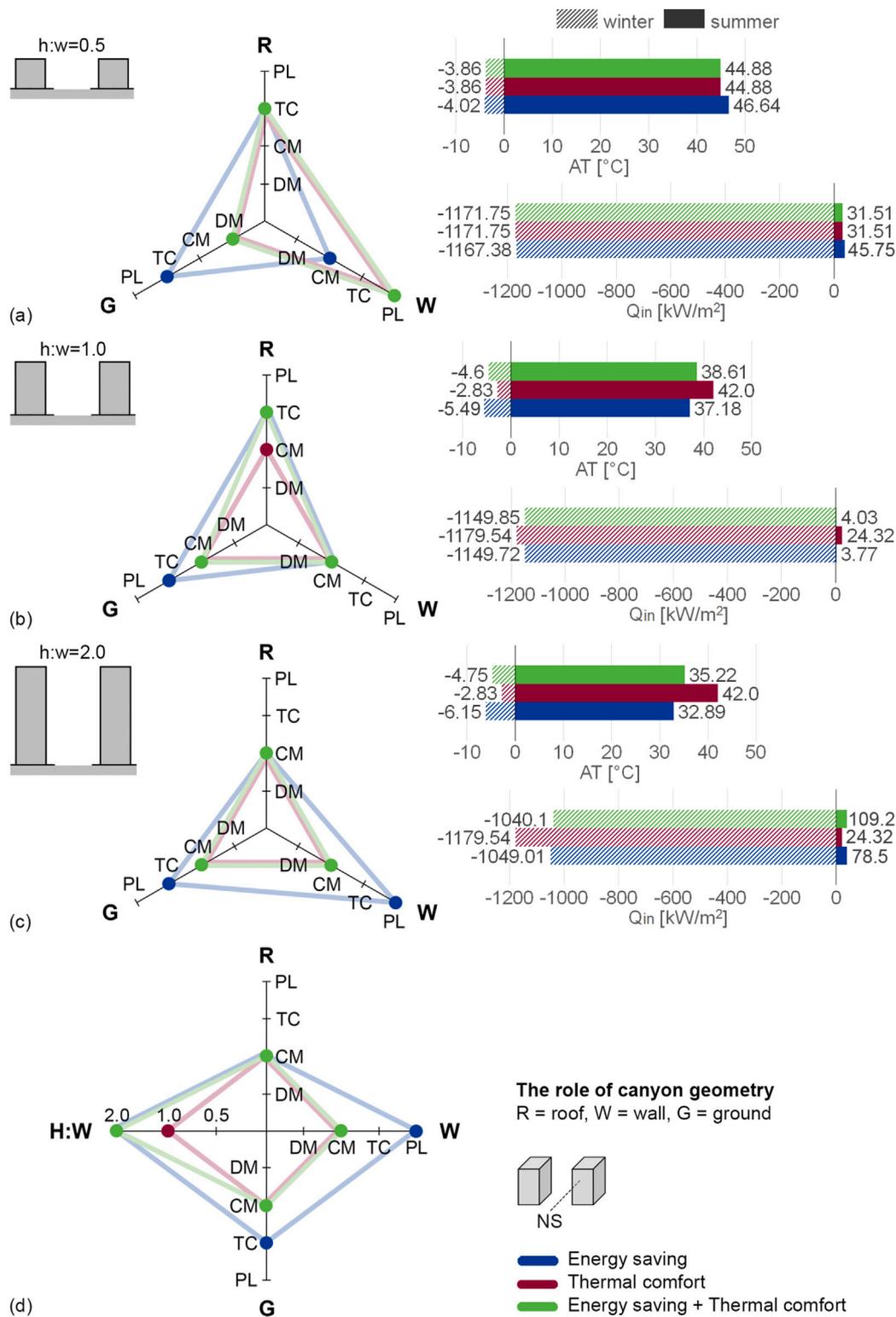
Fig. 5. Optimal materials' application and corresponding responses in terms of energy saving, thermal comfort and both, for a NS-oriented canyon, with different aspect ratios: (a) 0.5, (b) 1.0, (c) 2.0. (d) Optimal materials' distribution for free aspect ratios and NS orientation.

which corresponds to a "moderate cold stress". In contrast, the thermal comfort-optimized and combined configurations achieved a UTCI of 3.10 °C, falling within the "slight cold stress" range, thereby indicating better outdoor thermal conditions. In the summer scenario, all three optimization strategies led to UTCI values within the "moderate heat stress category", with the thermal comfort and combined approaches slightly outperforming the energy-saving configuration.

5. Discussion of the results

This study considers an urban canyon located in Princeton (NJ), characterized by a temperate climate, with warm, humid summers and cold, snowy winters. While Princeton serves as case-study city, the proposed methodology – which is the main core of this work – is readily adaptable to any urban setting and climate worldwide. Such
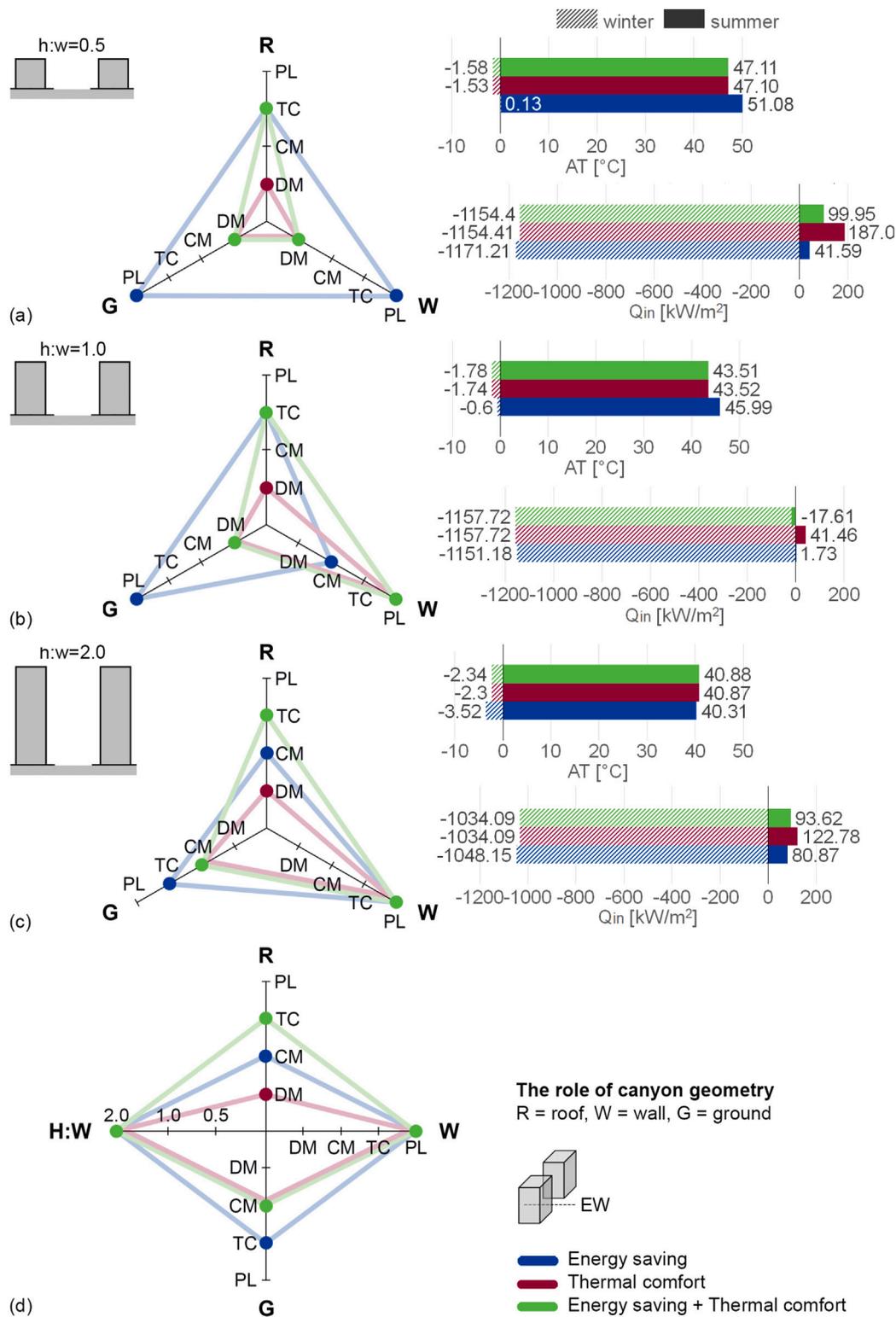
Fig. 6. Optimal materials' application and corresponding responses in terms of energy saving, thermal comfort and both, for a EW-oriented canyon, with different aspect ratios: (a) 0.5, (b) 1.0, (c) 2.0. (d) Optimal materials' distribution for free aspect ratios and EW orientation.

adaptability is a significant advantage over studies limited to specific locations or climate conditions. Moreover, although the PUCM model is here employed, other simulation platforms – such as WRF or ENVI-met – could also be used to assess urban canyon responses, demonstrating the broader applicability of the approach. The novelty of this research lies in its application of a DoE methodology, commonly used in industrial process optimization, to evaluate the influence of various

urban canyon characteristics on both energy consumption and thermal comfort. This DoE-PUCM combined approach, a novel contribution to the field, enables the final identification of a configuration that maximizes overall benefits, a more systematic and efficient approach than traditional trial-and-error methods.

Focusing on the role of urban materials, for low-to medium aspect ratio (h:w≤1) with a NS orientation, results highlight the combined
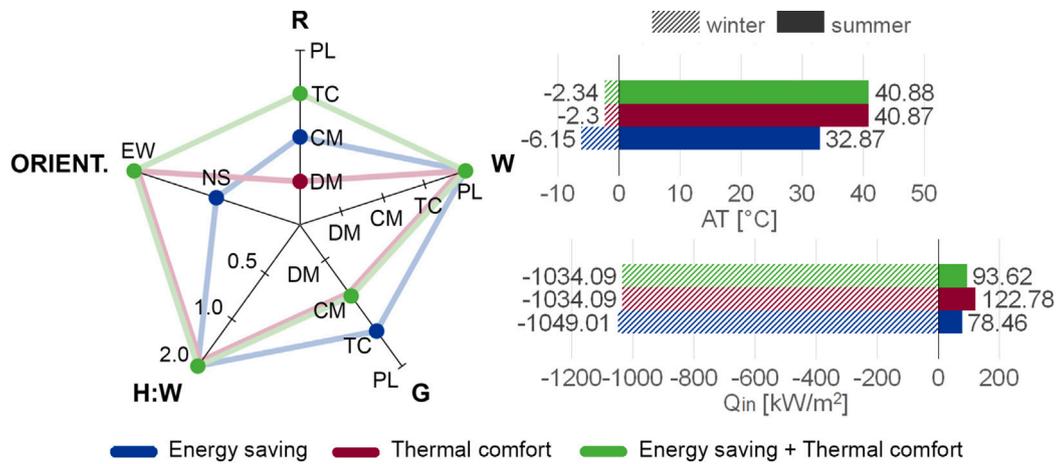
Fig. 7. Optimal canyon design and corresponding responses in terms of energy saving, thermal comfort and both, considering all the DoE model factors as variables.

Table 4
Calculated UTCI for the canyon configurations optimized in terms of energy saving, thermal comfort and both, considering all the DoE model factors as variables.

Optimization criteria	UTCI Summer scenario	UTCI Winter scenario
Energy saving	30.40 °C	−0.60 °C
Thermal comfort	34.80 °C	3.10 °C
Energy saving + Thermal comfort	34.80 °C	3.10 °C

benefits of traditional cool materials (CMs) and thermochromic materials (TCs). CMs effectively mitigate pedestrian discomfort by reflecting solar radiation, thus controlling apparent temperature (AT) during the summer months. This aligns with existing literature emphasizing the cooling potential of CMs (Tichý et al., 2023). However, TCs applied on roofs offer superior building energy efficiency by adapting to seasonal temperature changes across variations (−20.55 kW/m^2 entering the building in summer and −29.82 kW/m^2 exiting the building in winter conditions, when h:w=1). This temperature-adaptive behavior of TCs minimizes the risk of overcooling in winter, a known limitation of CMs, highlighting the advantage of TCs in achieving year-round energy efficiency.

In contrast, for EW-oriented canyons, the optimal material strategy for outdoor thermal comfort involves dark materials (DMs) on the ground and roof. This divergence from the NS-oriented configuration stems from the use of apparent temperature as trigger for thermal comfort optimization. As defined in Eq. (3), AT is sensitive to multiple environmental parameters, including the net radiation inside the canyon. EW-oriented canyons receive more solar radiation throughout the day because of the Sun's path, resulting in less wall shaded and prolonged exposure to direct sunlight compared to NS-oriented walls. Consequently, the model suggests that DMs, which absorb rather than reflect solar radiation, improve pedestrian comfort in EW-oriented canyons, despite a potential decrease in building energy efficiency. These findings are consistent with those reported by Pigliautile et al. (2020), where AT was also considered as a driving parameter for outdoor thermal comfort. On the other hand, the use of photoluminescent materials (PLs) on building walls further contributes to pedestrian comfort by absorbing and re-emitting light, a strategy supported by previous research on the benefits of PLs in urban environments (Marchini, Chiatti, Fabiani, & Pisello, 2023).

Quantitative comparisons between different optimized options explicitly demonstrate the extent to which prioritizing one objective affects the other. For instance, in NS-oriented canyons, the configuration optimized for combined performance (TCs on the roof, traditional

CMs on the ground and walls) achieved a summer AT peak of 38.61 °C, which is 3.39 °C higher than the thermal comfort-optimized case, but reduced summer heat flux entering the building by 4.03 kW/m^2. In winter, the same configuration raised AT by 1.77 °C while improving indoor heat gain by 30 kW/m^2. Similarly, for EW-oriented canyons, the comfort-optimized case (DMs on ground and roof, PL on walls) increased summer AT comfort by reducing peak temperatures by 2.47 °C with respect to the energy-optimized configuration (TC roof, CM walls, PL ground), but with a trade-off of 22.12 kW/m^2 more heat entering the building in summer.

Increasing the aspect ratio reduces per se the exposure to solar radiation, enhancing the effectiveness of cool materials, even in EW-oriented canyons. Results show that when h:w=2.0 the optimal material layout for both energy savings and thermal comfort includes TCs on the roof, PLs on the walls, and CMs on the ground. This setup balances between heat flux reduction and outdoor comfort improvement, yielding AT peaks of 40.88 °C in summer and −2.34 °C in winter, closely matching the configuration optimized solely for comfort. Replacing DMs with TCs on the roof reduces the heat flux entering the building by 29.82 kW/m^2 during the average summer day, improving energy efficiency while maintaining thermal comfort.

It is important to emphasize that these findings are specific to the case study location, i.e., an urban canyon in Princeton (NJ). Optimized configurations will likely vary under different climate conditions and urban contexts. Additionally, while material properties were derived from recent experimental studies (as detailed in Section 3.1) and meteorological data were collected on-site at Princeton University, other PUCM input parameters were based on values provided by Ryu et al. (2016). Modifying parameters such as thermal conductivity or building envelope thickness would alter key responses, including the heat flux entering and exiting the buildings. Therefore, these results are context-dependent and should be adapted for other locations and conditions, by adjusting the input variables of the method. This highlights a potential area for future research: sensitivity analysis exploring the impact of varying such input variables.

6. Conclusions

This study utilized a full factorial Design of Experiment (DoE) to investigate the interplay between urban canyon geometry and materials and their effects on building energy consumption and outdoor thermal comfort. By examining five factors with varying levels, a comprehensive analysis was conducted through 768 simulations, employing the Princeton Urban Canopy Model (PUCM) under both summer and winter conditions. The latter were defined as the average summer and winter day of Princeton town climate, but the same approach can be exploited

for any canyon's feature and any city or climate worldwide. Indeed, the PUCM framework is readily adaptable to any location by simply updating the input meteorological data, making the proposed workflow applicable across diverse geographic and climatic contexts. Here, four different materials were considered for possible application on urban surfaces (building roof, walls and canyon ground): (i) dark materials, with a low albedo, (ii) traditional cool materials, with high albedo and emissivity values, (iii) thermochromic materials, that dynamically adjust their optical properties based on superficial temperature, and (iv) photoluminescent materials, for their radiation absorption and consequent long lasting light-emission capability. The aim of the work was to define the canyon configuration in terms of materials choice and canyon geometry that best optimize its performance for building energy saving and/or outdoor thermal comfort. Findings proved the significant impact of the investigated factors focusing on parameters like (i) the heat flux entering/exiting the building through roof and walls, and (ii) the apparent temperature experienced by pedestrians inside the canyon. Here is a breakdown of key findings:

- The optimal material layout varies significantly with canyon orientation:

    - For North-South oriented canyons, traditional cool materials are ideal for improving pedestrian thermal comfort, while thermochromics on roof offer better energy efficiency adapting to seasonal temperature changes. In our case-study, this configuration provided for a reduction of heat flux entering the building in summer to 4.03 kW/m^2 ($\sim -83\%$ compared to the only comfort-optimized scenario), and a minimized winter loss of 1149.85 kW/m^2 ($\sim -3\%$ compared to the only comfort-optimized scenario).
    - For East–West oriented canyons, particular attention should be focused on the net radiation trapped within the canyon, which requires a strategic selection of materials, not excluding low-albedo ones. In our case-study, combining dark materials on the ground and photoluminescent walls yielded a summer AT of 43.51 °C and limited heat gain entering the building to 17.61 kW/m^2 ($\sim -57\%$ compared to the only comfort-optimized scenario).

- As the aspect ratio increases, the effectiveness of cool and photoluminescent materials in optimizing both thermal comfort and energy consumption becomes more pronounced. In our case-study, for a high-rise canyon (h:w=2.0), applying photoluminescent materials on the walls and thermochromics on the roof increased summer heat flux entering the building to 109.24 kW/m^2 but decreased winter heat loss to 1040.10 kW/m^2 ($\sim -12\%$ compared to the only comfort-optimized scenario), while keeping summer AT at 35.22 °C and winter AT at -4.75 °C.
- Photoluminescent materials helped in improving comfort, particularly in east–west oriented and high-rise canyons. These materials also can reduce glare, although that is not assessed in the present study.

These results are not universally applicable design outcomes, but they strictly depend on the input parameters of both PUCM and DoE. Optimized configurations are likely to differ based on variations in climate and building characteristics. To address this, future work will explore incorporating multiple climate conditions as an additional factor in the optimization process, while also accounting for material aging and degradation and consequent changes in their thermo-optical properties. Furthermore, the time resolution of the simulations could be improved for greater accuracy. This will be feasible thanks to the computational efficiency of the combined PUCM-DoE methodology. Indeed, the PUCM is a MATLAB-based tool whose computational demand largely depends on the complexity of the urban configuration and the simulation period. In our case, a single simulation of an average day typically runs in under a minute, ensuring feasibility for large-scale parametric analyses. Additionally, the full factorial DoE setup using Design Expert software is computationally lightweight, enabling rapid scenario generation. On the other hand, the use of different urban models, potentially on larger scales, could be investigated. By tailoring material choices to these diverse factors, urban planners can significantly improve the energy efficiency and livability of cities, creating more comfortable environments for both pedestrians and building occupants.

CRediT authorship contribution statement

Chiara Chiatti: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Claudia Fabiani:** Writing – review & editing, Visualization, Methodology, Conceptualization. **Elie Bou-Zeid:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Conceptualization. **Anna Laura Pisello:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.scs.2025.106987.

Data availability

Data will be made available on request.

References

Abdelhafez, M. H. H., Altaf, F., Alshenaifi, M., Hamdy, O., & Ragab, A. (2022). Achieving effective thermal performance of street canyons in various climatic zones. *Sustainability*, *14*, 10780. http://dx.doi.org/10.3390/su141710780.

Aboelata, A. (2020). Vegetation in different street orientations of aspect ratio (h/w 1:1) to mitigate UHI and reduce buildings' energy in arid climate. *Building and Environment*, *172*, Article 106712. http://dx.doi.org/10.1016/j.buildenv.2020.106712.

Akbari, H., & Levinson, R. (2008). Evolution of cool-roof standards in the US. *Advances in Building Energy Research*, *2*, 1–32. http://dx.doi.org/10.3763/aber.2008.0201.

Anon (2023). Design-expert. https://www.statease.com/software/design-expert/. (Accessed 27 December 2023).

Bazazzadeh, H., Nadolny, A., & Safaei, S. S. H. (2021). Climate change and building energy consumption: A review of the impact of weather parameters influenced by climate change on household heating and cooling demands of buildings. *European Journal of Sustainable Development*, *10*(2), http://dx.doi.org/10.14207/ejsd.2021.v10n2p1.

Blazejczyk, K., Epstein, Y., Jendritzky, G., Staiger, H., & Tinz, B. (2011). Comparison of UTCI to selected thermal indices. *International Journal of Biometeorology*, *56*(3), 515–535. http://dx.doi.org/10.1007/s00484-011-0453-2.

Calhoun, Z. D., Willard, F., Ge, C., Rodriguez, C., Bergin, M., & Carlson, D. (2024). Estimating the effects of vegetation and increased albedo on the urban heat island effect with spatial causal inference. *Scientific Reports*, *14*, 540. http://dx.doi.org/10.1038/s41598-023-50981-w.

Chen, L., Hang, J., Chen, G., Liu, S., Lin, Y., Mattsson, M., et al. (2021). Numerical investigations of wind and thermal environment in 2D scaled street canyons with various aspect ratios and solar wall heating. *Building and Environment*, *190*, Article 107525. http://dx.doi.org/10.1016/j.buildenv.2020.107525.

Chiatti, C., Fabiani, C., Bou-Zeid, E., & Pisello, A. (2024). Evaluating the potential of persistent luminescence in counteracting urban overheating. *Journal of Physics: Conference Series*, *2685*, Article 012029. http://dx.doi.org/10.1088/1742-6596/2685/1/012029.

Chiatti, C., Fabiani, C., Huang, X., Bou-Zeid, E., & Pisello, A. L. (2024). Exploring the potential of phosphorescence for mitigating urban overheating: First time representation in an Urban Canopy Model. *Applied Energy*, *362*, Article 122984. http://dx.doi.org/10.1016/j.apenergy.2024.122984, URL: https://linkinghub.elsevier.com/retrieve/pii/S0306261924003672.

Chiatti, C., Kousis, I., Fabiani, C., & Pisello, A. L. (2022a). Effect of optimized photoluminescence on luminous and passive cooling potential: A new combined experimental and numerical approach applied to yellow-emitting glass tiles. *Renewable Energy*, *196*, 28–39. http://dx.doi.org/10.1016/j.renene.2022.06.027.

Chiatti, C., Kousis, I., Fabiani, C., & Pisello, A. (2022b). Luminescence for the built environment: from lighting to urban heat island mitigation purposes. http://dx.doi.org/10.1016/B978-0-323-85539-6.00005-6.

Ciancio, V., Salata, F., Falasca, S., Curci, G., Golasi, I., & de Wilde, P. (2020). Energy demands of buildings in the framework of climate change: An investigation across Europe. *Sustainable Cities and Society*, *60*, Article 102213. http://dx.doi.org/10.1016/j.scs.2020.102213.

Clinton, N., & Gong, P. (2013). MODIS detected surface urban heat islands and sinks: Global locations and controls. *Remote Sensing of Environment*, *134*, 294–304. http://dx.doi.org/10.1016/j.rse.2013.03.008.

Coccolo, S., Kämpf, J., Scartezzini, J.-L., & Pearlmutter, D. (2016). Outdoor human comfort and thermal stress: A comprehensive review on models and standards. *Urban Climate*, *18*, 33–57. http://dx.doi.org/10.1016/j.uclim.2016.08.004.

Cui, P., Jiang, J., Zhang, J., & Wang, L. (2022). Effect of street form on uhi and energy consumption based on vegetation and street aspect ratio: Taking Harbin as an example. *SSRN Electronic Journal*, http://dx.doi.org/10.2139/ssrn.4282775.

Deng, X., Cao, Q., Wang, L., Wang, W., Wang, S., Wang, S., et al. (2023). Characterizing urban densification and quantifying its effects on urban thermal environments and human thermal comfort. *Landscape and Urban Planning*, *237*, Article 104803. http://dx.doi.org/10.1016/j.landurbplan.2023.104803.

Deng, J.-Y., & Wong, N. H. (2020). Impact of urban canyon geometries on outdoor thermal comfort in central business districts. *Sustainable Cities and Society*, *53*, Article 101966. http://dx.doi.org/10.1016/j.scs.2019.101966.

Echenagucia, T. M., Capozzoli, A., Cascone, Y., & Sassone, M. (2015). The early design stage of a building envelope: Multi-objective search through heating, cooling and lighting energy performance analysis. *Applied Energy*, *154*, 577–591. http://dx.doi.org/10.1016/j.apenergy.2015.04.090.

Erell, E., Pearlmutter, D., & Williamson, T. (2012). *Urban microclimate*. Routledge, http://dx.doi.org/10.4324/9781849775397.

Fabiani, C., Castaldo, V., & Pisello, A. (2020). Thermochromic materials for indoor thermal comfort improvement: Finite difference modeling and validation in a real case-study building. *Applied Energy*, *262*, Article 114147. http://dx.doi.org/10.1016/j.apenergy.2019.114147.

Fabiani, C., Gambucci, M., Chiatti, C., Zampini, G., Latterini, L., & Pisello, A. L. (2022). Towards field implementation of photoluminescence in the built environment for passive cooling and lighting energy efficiency. *Applied Energy*, *324*, Article 119687. http://dx.doi.org/10.1016/j.apenergy.2022.119687.

Fabiani, C., Pisello, A., Bou-Zeid, E., Yang, J., & Cotana, F. (2019). Adaptive measures for mitigating urban heat islands: The potential of thermochromic materials to control roofing energy balance. *Applied Energy*, *247*, 155–170. http://dx.doi.org/10.1016/j.apenergy.2019.04.020.

Feng, J., Gao, K., Khan, H., Ulpiani, G., Vasilakopoulou, K., Yun, G. Y., et al. (2023). Overheating of cities: Magnitude, characteristics, impact, mitigation and adaptation, and future challenges. *Annual Review of Environment and Resources*, *48*, 651–679. http://dx.doi.org/10.1146/annurev-environ-112321-093021.

Gunawardena, K., Wells, M., & Kershaw, T. (2017). Utilising green and bluespace to mitigate urban heat island intensity. *Science of the Total Environment*, *584–585*, 1040–1055. http://dx.doi.org/10.1016/j.scitotenv.2017.01.158.

Hang, J., & Chen, G. (2022). Experimental study of urban microclimate on scaled street canyons with various aspect ratios. *Urban Climate*, *46*, Article 101299. http://dx.doi.org/10.1016/j.uclim.2022.101299.

Huang, Y., Lei, C., Liu, C.-H., Perez, P., Forehead, H., Kong, S., et al. (2021). A review of strategies for mitigating roadside air pollution in urban street canyons. *Environmental Pollution*, *280*, Article 116971. http://dx.doi.org/10.1016/j.envpol.2021.116971.

Huang, K., Li, X., Liu, X., & Seto, K. C. (2019). Projecting global urban land expansion and heat island intensification through 2050. *Environmental Research Letters*, *14*, Article 114037. http://dx.doi.org/10.1088/1748-9326/ab4b71.

Huang, H., Li, Y., Zhao, Y., & Zhai, W. (2022). Analysis of the impact of urban summer high temperatures and outdoor activity duration on residents' emotional health: Taking hostility as an example. *Frontiers in Public Health*, *10*, http://dx.doi.org/10.3389/fpubh.2022.955077.

Huang, X., Song, J., Wang, C., & Chan, P. W. (2022). Realistic representation of city street-level human thermal stress via a new urban climate-human coupling system. *Renewable and Sustainable Energy Reviews*, *169*, Article 112919. http://dx.doi.org/10.1016/j.rser.2022.112919.

Jandaghian, Z., & Akbari, H. (2018). The effect of increasing surface albedo on urban climate and air quality: A detailed study for Sacramento, Houston, and Chicago. *Climate*, *6*, http://dx.doi.org/10.3390/cli6020019.

Kannamma, D., & Sundaram, D. A. M. (2015). Significance of microclimatic study in urban canyons towards ambient urban space design. *Journal of Today's Ideas - Tomorrow's Technologies*, *3*, 95–109. http://dx.doi.org/10.15415/jotitt.2015.31007.

Levinson, R., Chen, S., Ferrari, C., Berdahl, P., & Slack, J. (2017). Methods and instrumentation to measure the effective solar reflectance of fluorescent cool surfaces. *Energy and Buildings*, *152*, 752–765. http://dx.doi.org/10.1016/j.enbuild.2016.11.007.

Li, D., & Bou-Zeid, E. (2014). Quality and sensitivity of high-resolution numerical simulation of urban heat islands. *Environmental Research Letters*, *9*, Article 055001. http://dx.doi.org/10.1088/1748-9326/9/5/055001.

Li, D., Bou-Zeid, E., & Oppenheimer, M. (2014). The effectiveness of cool and green roofs as urban heat island mitigation strategies. *Environmental Research Letters*, *9*(5), http://dx.doi.org/10.1088/1748-9326/9/5/055002.

Loeffler, R., Österreicher, D., & Stoeglehner, G. (2021). The energy implications of urban morphology from an urban planning perspective – A case study for a new urban development area in the city of Vienna. *Energy and Buildings*, *252*, Article 111453. http://dx.doi.org/10.1016/j.enbuild.2021.111453.

Manni, M., Kousis, I., Lobaccaro, G., Fiorito, F., Cannavale, A., & Santamouris, M. (2022). Urban overheating mitigation through facades: the role of new and innovative cool coatings. In *Rethinking building skins* (pp. 61–87). Elsevier, http://dx.doi.org/10.1016/B978-0-12-822477-9.00013-9.

Marchini, F., Chiatti, C., Fabiani, C., & Pisello, A. (2023). Development of an innovative translucent–photoluminescent coating for smart windows applications: An experimental and numerical investigation. *Renewable and Sustainable Energy Reviews*, *184*, Article 113530. http://dx.doi.org/10.1016/j.rser.2023.113530.

Marriage, G. (2021). Sunshine, daylight, healthy living and sustainability. In *Modern apartment design* (pp. 57–68). London: Routledge, http://dx.doi.org/10.4324/9781003123873-5.

Mauree, D., Naboni, E., Coccolo, S., Perera, A., Nik, V. M., & Scartezzini, J.-L. (2019). A review of assessment methods for the urban environment and its energy sustainability to guarantee climate adaptation of future cities. *Renewable and Sustainable Energy Reviews*, *112*, 733–746. http://dx.doi.org/10.1016/j.rser.2019.06.005.

Mirzabeigi, S., & Razkenari, M. (2022). Design optimization of urban typologies: A framework for evaluating building energy performance and outdoor thermal comfort. *Sustainable Cities and Society*, *76*, Article 103515. http://dx.doi.org/10.1016/j.scs.2021.103515.

Morabito, M., Crisci, A., Messeri, A., Capecchi, V., Modesti, P. A., Gensini, G. F., et al. (2014). Environmental temperature and thermal indices: what is the most effective predictor of heat-related mortality in different geographical contexts? *The Scientific World Journal*, Article 961750. http://dx.doi.org/10.1155/2014/961750.

Mungule, M., & Iyer, K. K. R. (2022). A review on role of pavement materials on urban heat island effects. (pp. 229–237). http://dx.doi.org/10.1007/978-981-16-5543-2_19.

Muniz-Gäal, L. P., Pezzuto, C. C., de Carvalho, M. F. H., & Mota, L. T. M. (2020). Urban geometry and the microclimate of street canyons in tropical climate. *Building and Environment*, *169*, Article 106547. http://dx.doi.org/10.1016/j.buildenv.2019.106547.

Natanian, J., & Auer, T. (2020). Beyond nearly zero energy urban design: A holistic microclimatic energy and environmental quality evaluation workflow. *Sustainable Cities and Society*, *56*, Article 102094. http://dx.doi.org/10.1016/j.scs.2020.102094.

Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*, *108*, 1–24. http://dx.doi.org/10.1002/qj.49710845502.

Pazzaglia, A., Gelosia, M., Giannoni, T., Fabbrizi, G., Nicolini, A., & Castellani, B. (2023). Wood waste valorization: Ethanol based organosolv as a promising recycling process. *Waste Management*, *170*, 75–81. http://dx.doi.org/10.1016/j.wasman.2023.08.003.

Pigliautile, I., Pisello, A., & Bou-Zeid, E. (2020). Humans in the city: Representing outdoor thermal comfort in urban canopy models. *Renewable and Sustainable Energy Reviews*, *133*, Article 110103. http://dx.doi.org/10.1016/j.rser.2020.110103.

Ramamurthy, P., Bou-Zeid, E., Smith, J. A., Wang, Z., Baeck, M. L., Saliendra, N. Z., et al. (2014). Influence of subfacet heterogeneity and material properties on the urban surface energy budget. *Journal of Applied Meteorology and Climatology*, *53*, 2114–2129. http://dx.doi.org/10.1175/JAMC-D-13-0286.1.

Ramamurthy, P., Sun, T., Rule, K., & Bou-Zeid, E. (2015). The joint influence of albedo and insulation on roof performance: A modeling study. *Energy and Buildings*, *102*, 317–327. http://dx.doi.org/10.1016/j.enbuild.2015.06.005.

Ramos, N. M. M., Maia, J., Souza, A. R., Almeida, R. M. S. F., & Silva, L. (2021). Impact of incorporating NIR reflective pigments in finishing coatings of ETICS. *Infrastructures*, *6*, 79. http://dx.doi.org/10.3390/infrastructures6060079.

Rosso, F., Pisello, A., Castaldo, V., Fabiani, C., Cotana, F., Ferrero, M., et al. (2017). New cool concrete for building envelopes and urban paving: Optics-energy and thermal assessment in dynamic conditions. *Energy and Buildings*, *151*, 381–392. http://dx.doi.org/10.1016/j.enbuild.2017.06.051.

Ryu, Y.-H., Bou-Zeid, E., Wang, Z.-H., & Smith, J. (2016). Realistic representation of trees in an urban canopy model. *Boundary-Layer Meteorology*, *159*, 193–220. http://dx.doi.org/10.1007/s10546-015-0120-y.

Sahnoune, S., & Benhassine, N. (2023). Winter thermal comfort of a typical courtyard geometry in a semi-arid climate. *Journal of Green Building*, *18*, 95–117. http://dx.doi.org/10.3992/jgb.18.1.95.

Sakakibara, Y. (1996). A numerical study of the effect of urban geometry upon the surface energy budget. *Atmospheric Environment*, *30*, 487–496. http://dx.doi.org/10.1016/1352-2310(94)00150-2.

Santamouris, M., & Fiorito, F. (2021). On the impact of modified urban albedo on ambient temperature and heat related mortality. *Solar Energy*, *216*, 493–507. http://dx.doi.org/10.1016/j.solener.2021.01.031.

Santamouris, M., & Vasilakopoulou, K. (2023). Recent progress on urban heat mitigation technologies. *Science Talks*, *5*, Article 100105. http://dx.doi.org/10.1016/j.sctalk.2022.100105.

Schrijvers, P., Jonker, H., de Roode, S., & Kenjereš, S. (2020). On the daytime microclimatic conditions inside an idealized 2D urban canyon. *Building and Environment*, *167*, Article 106427. http://dx.doi.org/10.1016/j.buildenv.2019.106427.

Shmelev, S. E., & Shmeleva, I. A. (2018). Global urban sustainability assessment: A multidimensional approach. *Sustainable Development*, *26*, 904–920. http://dx.doi.org/10.1002/sd.1887.

Singh, A. S., Singh, A. G., & Shishir, A. . (2023). Identifying crucial aspects in formulating urban flood mitigation strategies. *International Journal for Research in Applied Science and Engineering Technology*, *11*, 3483–3486. http://dx.doi.org/10.22214/ijraset.2023.50997.

Steadman, R. G. (1984). A universal scale of apparent temperature. *Journal of Climate and Applied Meteorology*, *23*, 1674–1687. http://dx.doi.org/10.1175/1520-0450(1984)023<1674:AUSOAT>2.0.CO;2.

Takebayashi, H., & Moriyama, M. (2007). Surface heat budget on green roof and high reflection roof for mitigation of urban heat island. *Building and Environment*, *42*, 2971–2979. http://dx.doi.org/10.1016/j.buildenv.2006.06.017.

Talebpour, M., Welty, C., & Bou-Zeid, E. (2021). Development and testing of a fully-coupled subsurface-land surface-atmosphere hydrometeorological model: High-resolution application in urban terrains. *Urban Climate*, *40*, Article 100985. http://dx.doi.org/10.1016/j.uclim.2021.100985.

Taleghani, M., Swan, W., Johansson, E., & Ji, Y. (2021). Urban cooling: Which façade orientation has the most impact on a microclimate? *Sustainable Cities and Society*, *64*, Article 102547. http://dx.doi.org/10.1016/j.scs.2020.102547.

Tartarini, F., & Schiavon, S. (2020). pythermalcomfort: A Python package for thermal comfort research. *SoftwareX*, *12*, http://dx.doi.org/10.1016/j.softx.2020.100578.

Tichý, D., Kapounek, Štěpán., Voldán, M., Manara, J., Lladós-Flores, A., Fernandez, J. J., et al. (2023). *Report on the collection and production of candidate passive radiative cooling materials, and identification of figures of merit to evaluate their cooling performance*: *Technical Report,* Project 21GRD03 PaRaMetriC, Work Package 1, Activity 1.2.4.

Viganò, G. S. M., Rugani, R., Marengo, M., & Picco, M. (2024). Assessing the impact of climate change on building energy performance: A future-oriented analysis on the UK. *Architecture*, *4*(4), 1201–1224. http://dx.doi.org/10.3390/architecture4040062.

Wang, Z.-H., Bou-Zeid, E., & Smith, J. A. (2013). A coupled energy transport and hydrological model for urban canopies evaluated using a wireless sensor network. *Quarterly Journal of the Royal Meteorological Society*, *139*, 1643–1657. http://dx.doi.org/10.1002/qj.2032.

Wang, X., Rahman, M. A., Mokroš, M., Rötzer, T., Pattnaik, N., Pang, Y., et al. (2023). The influence of vertical canopy structure on the cooling and humidifying urban microclimate during hot summer days. *Landscape and Urban Planning*, *238*, Article 104841. http://dx.doi.org/10.1016/j.landurbplan.2023.104841.

Wang, W., Xu, Y., Ng, E., & Raasch, S. (2018). Evaluation of satellite-derived building height extraction by CFD simulations: A case study of neighborhood-scale ventilation in Hong Kong. *Landscape and Urban Planning*, *170*, 90–102. http://dx.doi.org/10.1016/j.landurbplan.2017.11.008.

Wong, N. H., Tan, C. L., Kolokotsa, D. D., & Takebayashi, H. (2021). Greenery as a mitigation and adaptation strategy to urban heat. *Nature Reviews Earth & Environment*, *2*, 166–181. http://dx.doi.org/10.1038/s43017-020-00129-5.

Xie, N., Akin, M., & Shi, X. (2019). Permeable concrete pavements: A review of environmental benefits and durability. *Journal of Cleaner Production*, *210*, 1605–1621. http://dx.doi.org/10.1016/j.jclepro.2018.11.134.

Yang, J., & Bou-Zeid, E. (2018). Should cities embrace their heat islands as shields from extreme cold? *Journal of Applied Meteorology and Climatology*, *57*, 1309–1320. http://dx.doi.org/10.1175/JAMC-D-17-0265.1.

Yang, J., & Bou-Zeid, E. (2019). Scale dependence of the benefits and efficiency of green and cool roofs. *Landscape and Urban Planning*, *185*, 127–140. http://dx.doi.org/10.1016/j.landurbplan.2019.02.004.

Yenneti, K., Ding, L., Prasad, D., Ulpiani, G., Paolini, R., Haddad, S., et al. (2020). Urban overheating and cooling potential in Australia: An evidence-based review. *Climate*, *8*, 126. http://dx.doi.org/10.3390/cli8110126.

Zhao, Y., Ding, X., Fan, Y., Zhao, Y., Ge, J., & Carmeliet, J. (2025). Global warming likely compromises the annual performance of zero-energy buildings while the urban heat island effect exacerbates the impact. *Sustainable Cities and Society*, *126*, http://dx.doi.org/10.1016/j.scs.2025.106385.

Zhao, Y., Sen, S., Susca, T., Iaria, J., Kubilay, A., Gunawardena, K., et al. (2023). Beating urban heat: Multimeasure-centric solution sets and a complementary framework for decision-making. *Renewable and Sustainable Energy Reviews*, *186*, http://dx.doi.org/10.1016/j.rser.2023.113668.