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Urban albedo: developing a canyon albedo calculator

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Authors

Marialena Nikolopoulou, Alkis Kotopouleas, Giridharan Renganathan, Richard Watkins and Muhammed Yeninarcilar (University of Kent), Maria Kolokotroni and Agnese Salvati (Brunel University London), Bala Vaidhyanathan and Aashu Anshuman (Loughborough University)

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(*i*) The Kent School of Architecture and Planning at the University of Kent focused on the experimental part of the work, developing the 1:10 scale physical model of the case study, and conducted the RADIANCE simulations;

(*ii*) The Institute of Energy Futures at Brunel University London focused on the modelling of urban albedo through ENVImet and EnergyPlus simulations;

(*iii*) The Department of Materials at Loughborough University focused on materials degradation testing using a weathering chamber.

The three universities collaborated in the development of a model for urban albedo computation.

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Editing and layout

Ken Butcher

Head of Research

Anastasia Mylona

Head of Knowledge

Eileen Bell

Technical Director

Hywel Davies

Contents

Executive summary

Urban albedo, the capacity of urban surfaces to reflect solar radiation, is one of the most important contributors to changes in outdoor temperature, intensifying the urban heat island phenomenon. As a result, it has significant implications for the urban microclimate, affecting thermal comfort conditions as well as building performance and energy consumption, all of which become more pronounced under climate change.

Urban albedo is affected by various parameters, such as the geometry of the urban configuration, the materials and the geographic location. However, most modelling studies approximate the urban albedo by using surface albedo, which can lead to significant errors in the modelling process. The research project 'Urban albedo computation in high latitude locations: An experimental approach' was primarily motivated by the need to provide accurate albedo estimates for urban configurations, which are lacking in most urban heat island models used to mitigate albedo's effects. The project proposed a novel experimental study for the computation of urban albedo in high latitude locations, using London as a representative urban environment in the UK and employing laboratory and field measurements and computational methods to construct an albedo calculation tool.

More specifically, using a 1:10 scale physical model of a residential area in Islington, identified as representative of the urban settings of London, incorporating variations in block geometry, canyon geometry and surface materials, the project developed new knowledge and insights, along with guidance and design strategies to enable thorough incorporation of albedo in the urban mosaic to support design studies and planning. More specifically we highlight the following key findings:

— The substantial impact of the urban fabric and the position of materials on urban albedo, demonstrating the dominant effect of horizontal ground surfaces. The impact of vertical surfaces on the radiation exchange within the street canyon becomes more significant with increasing building height. The work also revealed the highly dynamic nature of canyon albedo, which presented diurnal and seasonal variations, and a consistent rainfall-induced reduction of albedo.

— The detrimental impact of increasing surface reflectance in urban canyons on outdoor thermal comfort, due to increased inter-reflections between surfaces leading to higher mean radiant temperatures. It also showed that increasing the road reflectance also increases the incident diffuse radiation on adjacent buildings, producing a small increase in indoor operative temperatures.

— The impact of ageing on surface reflectance of construction materials, demonstrating little to no variation for gloss, while the mean surface roughness reduced with ageing.

— Formulating design strategies to improve the urban thermal environment by using reflective materials in urban canyons without compromising outdoor thermal comfort or indoor thermal environments.

— The development of the albedo calculator, an empirical model, designed for latitude 51° N/S, to predict changes in albedo in relation to changes in urban fabric and solar altitude.

1 Background to the research project

Urban albedo, the capacity of urban areas to reflect radiation back to the sky, is intrinsically associated with the urban heat island (UHI) phenomenon where temperatures in urban areas are higher than surrounding rural areas. For London, where the UHI has been systematically investigated for summer and winter (Kolokotroni and Giridharan, 2008; Giridharan and Kolokotroni, 2009), the Greater London Authority has identified urban albedo as one of the most significant parameters for mitigating the UHI (Greater London Authority, 2006).

The urban albedo of an environment is the proportion of the solar radiation reflected by the various surfaces (reflection coefficient), defined as the ratio of incoming to outgoing radiation; an albedo of 0 absorbs 100% of the incoming radiation and has no reflection, while an albedo of 1 reflects 100% of the incoming radiation back to the environment. In an urban setting the incoming radiation undergoes multiple reflections as indicated in Figure 1.

At every incidence of the radiation, part of the radiation is absorbed by the incident surface while another portion is reflected back into the environment. It is assumed this radiation is completely absorbed in an urban canyon after 50 reflections (Aida and Gotoh, 1982). The factors that contribute to this photometric process are (Kondo *et al.*, 2001; Yang and Li, 2015): (1) building block geometry, (2) reflectance of the roof, (3) canyon geometry, (4) reflectance of the ground, (5) reflectance of walls, (6) solar altitude, (7) solar azimuth, (8) urban vegetation, (9) soil moisture.

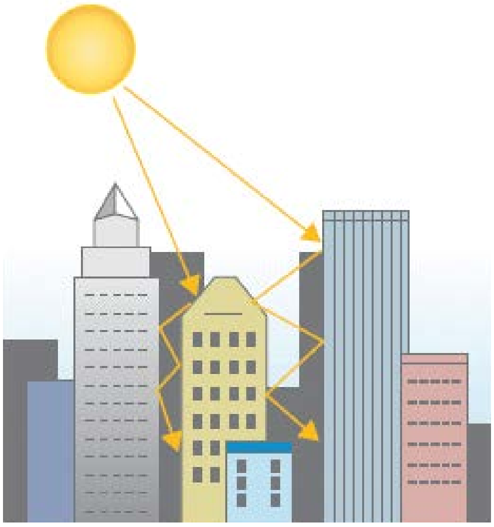


Figure 1 Multiple reflections of solar radiation in an urban environment (adapted from Tandon (online); reproduced under CC Attribution-NonCommercial License)

The albedo of street canyons which shape urban settings is a major determinant of the reflective power of urban surfaces. At the street canyon level, albedo is a significant contributor to changes in outdoor ambient temperature (Oke, 1988) with implications for building cooling energy demand (Kolokotroni *et al.*, 2007) as well as for outdoor thermal comfort (Steemers *et al.*, 1998) and human health (Santamouris and Fiorito, 2021).

Increasing surface reflectance has been identified as an effective way of lowering ambient temperatures (Erell *et al.*, 2011). However, the effectiveness of reflective materials in urban canyons may be reduced due to the interaction between solar reflections and urban geometry. Streets and urban spaces have a reduced openness to the sky due to the proximity of buildings. Therefore, the radiation reflected from the ground and the façades undergoes multiple reflections between vertical and horizontal surfaces, instead of being reflected directly towards the sky. This phenomenon is known as radiation trapping and causes an increase in the net radiation absorbed by the urban surfaces. For this reason, increasing the surface reflectance of roads and façades may also lead to unwanted negative effects on street level microclimate and indoor operative temperature, due to the trapping of solar reflections within the urban geometry. This means that increasing urban albedo may have contrasting outcomes at the urban and the micro scales and precautions should be taken before adopting this UHI mitigation strategy at large scale.

Nowadays, urban development professionals and designers source urban albedo values from the literature to incorporate in building energy and thermal simulations. However, the multiplicity and variability of the factors involved in the radiation exchange within urban settings suggest that a fixed albedo value for a certain location may not be representative, particularly for cities with substantial surface variations.

Moreover, despite the wealth of studies on the performance of urban materials, the effect of surface reflectance of urban materials has been investigated in predominantly isolated experiments where the impact of the urban geometrical complexities was ignored, while the few studies that employed scale models investigated theoretical buildings (Steemers *et al.*, 1998) and were limited to a single material.

Using London as a representative urban environment in the UK, this project aimed to:

- investigate experimentally the impact of common urban materials on canyon albedo
- investigate the impact of surface reflectance on microclimate and thermal comfort
- investigate the impact of ageing on materials' surface characteristics that could affect surface reflectance
- develop an albedo calculator, an empirical model to predict changes in urban albedo in relation to changes in urban fabric and solar altitude.

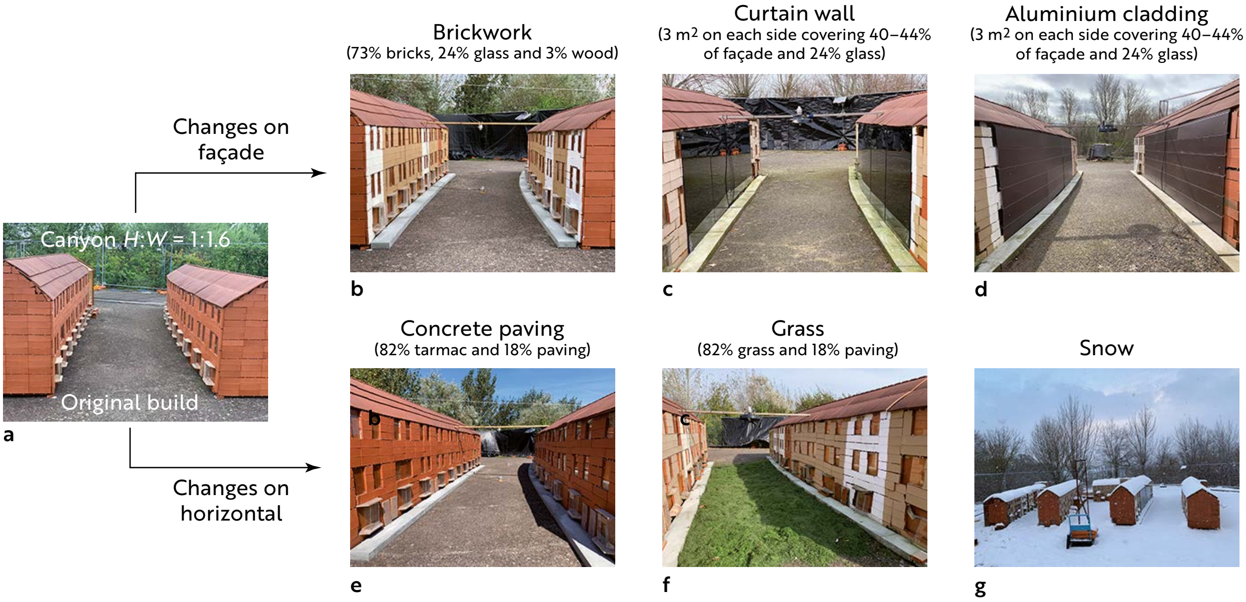
2 The experimental model

The study developed a 1:10 scaled model of a residential area in Islington, London (Figure 2). The case study was selected through surveys in Greater London which involved 80 locations formerly studied for UHI (Kolokotroni and Giridharan, 2008; Kolokotroni *et al.*, 2007). The latitude difference between London (51.5074 °N) and Canterbury (51.2802 °N) is negligible, therefore the model was built for logistical purposes in the University of Kent campus at Canterbury. The model used an area of 5 m radius, since a 50 m radius is considered a suitable area to capture urban climate variations in a London setting (Watkins *et al.*, 2007). Using data collected during 3D scanning surveys of the real site, the modelled façades were developed to reproduce accurately the proportionality of materials at the case study area. The original model was made of about 5400 red brick slips, 490 cut-to-size clear float glass pieces 4 mm thick and with a *U*-value of 5.8 $W/m^2{\cdot}K$, and 600 clay roof tiles used for the roofs, while doors were assembled using plywood.

Figure 2 Left: the case study area in Islington, London; Middle: the 1:10 scaled model developed with real building materials; Right: pyranometers taking incident and reflected radiation measurements at canyon eaves level using IR filters and shade

Detailed measurements of incoming and reflected radiation were taken 24/7 at one second intervals in the middle of the modelled street canyons, at eaves level, by means of back-to-back pyranometers. Another pair of back-to-back pyranometers was suspended at 2.25 m (i.e. 1 m above the tallest building) capturing incident and reflected radiation for the entire model. The view of the downward-looking pyranometers was restricted to the area under investigation by means of shades, while the entire model area was bordered with black tarpaulins to eliminate noise radiation from the surrounding environment.

The findings presented in this document focused on a street canyon, where material changes were made on both horizontal (street-level) and vertical (façades) surfaces to evaluate their impact on urban canyon albedo (Figure 3). The canyon was NE–SW oriented and included 22 terraced three-storey building blocks with height-to-width ratio of 1:1.6.


Brickwork (73% bricks, 24% glass and 3% wood)

Curtain wall (3 m² on each side covering 40–44% of façade and 24% glass)

Aluminium cladding (3 m² on each side covering 40–44% of façade and 24% glass)

Concrete paving (82% tarmac and 18% paving)

Grass (82% grass and 18% paving)

Snow

Figure 3 Experimental phases of modelled street canyon with street-level and façade material tests.

3 Canyon albedo profiles

3.1 The effect of horizontal and vertical surfaces on canyon albedo

Four different street-level surfaces were investigated: tarmac; combination of tarmac and concrete paving; combination of grass and concrete paving; and snow (Figure 3a and 3e–g). The tests were done at different times in the year, thus the impact of each phase was comparatively assessed against the canyon's albedo just before each material change so that the effects of material ageing and varying solar angles were eliminated. The introduction of concrete paving to the tarmac ground was seen to increase the canyon's ability to reflect radiation back to the sky by 9% (from 0.11 to 0.12). Measurements taken with the paving in place during different seasons revealed significant variations in canyon albedo (0.12 in summer, 0.09 in autumn and 0.04 in winter), highlighting the effect of seasonality. The substitution of tarmac with grass increased the canyon's reflective power by 70% (from 0.09 to 0.16), while the greatest increase — of the order of 1000% — was seen when the horizontal was white in snow[1], raising the mean canyon albedo from 0.04 to 0.43.

An early intervention on the vertical surfaces was the colouring of brickwork façades with masonry paint, using hues similar to those at the actual site. Façade colours increased canyon albedo by 10% (from 0.11 to 0.12); however, it was the combined effect of façade colour and paving that had the highest impact, resulting in an average albedo increase of 20% (to 0.13).

The investigation of the effect of vertical surfaces on canyon albedo included the testing of three commonly used façade types: brickwork; aluminium cladding[2]; and curtain wall[3]. In the 'brickwork' application (Figure 3b) façades were 73% bricks (coloured to resemble the brick colours in the actual site), 24% glass and 3% wood. In the 'curtain wall' and 'aluminium cladding'

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[1] Snowfall occurred at a time when the canyon's SE- and NW-facing façades were curtain wall and brickwork respectively and the canyon average albedo was 0.04.

[2] Extruded aluminium weatherboard system powder-coated in RAL 7016

[3] 4 mm toughened glass (U-value = 5.8 W/m^2·K) backed with a blackout film

applications (Figures 3c, 3d), for logistical efficiency, the test materials were installed uniformly on either side of the canyon, spanning symmetrically from the middle where the pyranometers were located, covering 40–44% of the façades' surface area.

Figure 4 shows the variation of mean canyon albedo with incident radiation and sun altitude for the three façade applications. Brickwork and aluminium cladding façades were constantly leading to higher canyon albedo under all sky conditions and across the measured solar irradiance and sun altitude ranges, resulting in an average canyon albedo of 0.11 and 0.09 respectively. On the other hand, the canyon's reflective power decreased sharply to an average of 0.06 with curtain wall façades (Table 1).

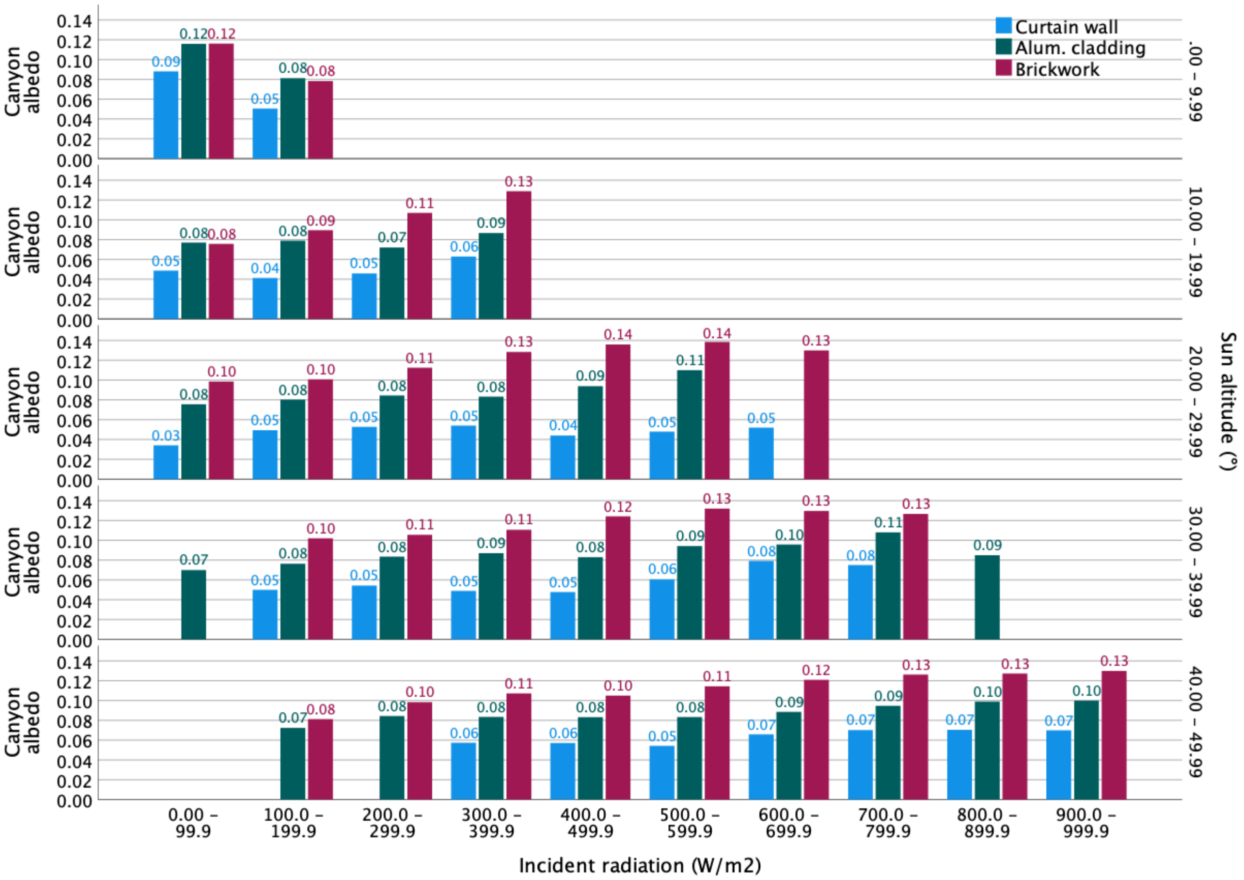

Figure 4 Variation of average canyon albedo by solar irradiance and sun altitude during brickwork, aluminium cladding and curtain wall façade applications

The results also revealed the highly dynamic and complex nature of canyon albedo. In all applications the diurnal albedo presented a U-shaped profile, with albedo rising sharply at dawn, dropping soon after and presenting little variation during daytime, peaking again just before dusk (Figure 9). The observed pattern was the combined effect of orientation and sun altitude, which alternate the contribution of the horizontal and vertical surfaces to the canyon's reflective power during the day. The peaks are largely the result of the low sun angle during sunrise and sunset when material specularity comes into play. With the sun being higher during the day, however, the street receives more direct radiation, therefore the contribution of street level materials on canyon albedo increases. The considerably lower surface reflectance of tarmac contributes to lower canyon albedo, which presents little fluctuation throughout the daytime until the evening when albedo peaks again as a result of the low sun angle.

Moreover, the results also showed that, controlling for sun altitude, canyon albedo increases with solar irradiance (Figure 3), highlighting its variability under different sky conditions. The magnitude of increase with irradiance was greatest with brickwork façades and least with curtain wall because of the high transmission of glass. The findings were also informative about the effect of solar angle on the radiation exchange within the canyon, indicating that a certain level of radiation intensity may result in varying canyon albedo values depending on the angle of incidence, with lower sun angles associated with higher albedo. For the specific canyon orientation, this highlighted the dominant role of façades when the sun was low and of the horizontal surface at high sun angles.

3.2 The impact of orientation and aspect ratio

To investigate the impact of orientation, measurements were also taken with the aluminium cladding and curtain wall systems applied on one side of the street canyon only while the opposite façade was brickwork. The applications of aluminium cladding on the SE- and NW-facing façades showed little differentiation and a similar diurnal albedo profile, both resulting in a mean canyon albedo of 0.10. In contrast, significant differentiation (50%) was observed between the respective SE- and NW-facing curtain wall applications, which led to a mean canyon albedo of 0.08 and 0.04 respectively (Table 1). This is because the sunlight striking first the SE-facing façade — the part of the canyon receiving direct sunlight for most of daytime — was largely transmitted due to the particularly low surface reflectance of glass (Table 2), therefore eliminating interreflections within the canyon. The difference between the two applications was seen to increase with irradiance because of the greater increase of brickwork's reflectance at higher irradiation levels, thus presenting its higher values at midday. These findings suggest that the effect of orientation depends largely on the surface reflectance of the material where sunlight strikes first.

Table 1 Descriptive values of canyon albedo for brickwork, aluminium cladding and curtain wall façade applications.

Configuration	**Count of 5-minute averages (*N*)**	**Precipitation**	**Canyon albedo**			
			Mean	**Min.**	**Max.**	**Std. dev.**
Curtain wall on both façades	2019	No rainfall during daytime	0.06	0.01	0.76	0.05
	633	Rainfall during daytime	0.04	0.01	0.15	0.02
Curtain wall on NW-facing façade	639	No rainfall during daytime	0.08	0.01	0.71	0.06
	314	Rainfall during daytime	0.07	0.01	0.63	0.09
Curtain wall on SE-facing façade	224	No rainfall during daytime	0.04	0.01	0.23	0.02
	780	Rainfall during daytime	0.04	0.01	0.50	0.04
Aluminium cladding on both façades	1513	No rainfall during daytime	0.09	0.01	0.54	0.04
	162	Rainfall during daytime	0.07	0.03	0.24	0.04
Aluminium cladding on NW-facing façade	420	No rainfall during daytime	0.10	0.01	0.39	0.03
	1275	Rainfall during daytime	0.09	0.01	0.63	0.05
Aluminium cladding on SE-facing façade	822	No rainfall during daytime	0.10	0.02	0.46	0.04
	148	Rainfall during daytime	0.08	0.02	0.20	0.02
Brickwork on both façades	2390	No rainfall during daytime	0.11	0.01	0.69	0.06
	1028	Rainfall during daytime	0.07	0.01	0.53	0.05

RADIANCE simulations

The effects of orientation and aspect ratio were further investigated with simulations with RADIANCE, the powerful ray tracing programme[4]. A 3D model was developed using the 3D point cloud data collected during the scan surveys of the actual case study site and the physical model. The model was calibrated using the geometrical, solar irradiance and material surface reflectance data from the 1:10 scaled physical model. Using the measured surface reflectance values of the façade materials (Table 2) and a reflectance of 0.11 for the street, the mean daily canyon albedo was simulated for different canyon orientations under clear sky conditions.

The results revealed a constant canyon albedo of 0.12 (for NE–SW, NW–SE, W–E, SW–NE, SE–NW and E–W) that would change to 0.10 only for N–S and S–N orientation, where the influence of the horizontal street surface on canyon albedo increases, reducing the canyon albedo because of its

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[4] https://www.radiance-online.org (accessed 4.07.22)

lower surface reflectance. This confirms that the effect of orientation on canyon albedo is a combined effect of orientation and surface reflectance of the materials struck first by sunlight.

This was further highlighted from another set of simulations which used the actual orientation of the canyon, keeping street reflectance constant at 0.11, while testing three façade surface reflectance scenarios: (*a*) 0.6 for façades on both sides of the street; (*b*) 0.2 for the SE-facing and 0.6 for the NW-facing façade; and (*c*) 0.6 for the SE-facing and 0.2 for the NW-facing façade. The results showed a mean canyon albedo of 0.13 in scenario (*a*), 0.11 in scenario (*b*) and 0.09 in scenario (*c*) indicating that canyon albedo was lowest when the façade receiving direct sunlight for most of the daytime (i.e. the SE-facing façade) had lower surface reflectance.

Simulations were also employed to evaluate the effect of height-to-width (*H*:*W*) ratio changes on canyon albedo, which would be difficult to implement in the experimental model. The results showed that increasing building height, while keeping street width unchanged, leads to lower canyon albedo for low façade surface reflectance only (i.e. 0.2–0.4; Figure 5), whereas for high façade surface reflectance values (0.6 and 0.7; Figure 5) canyon albedo presents an increasing trend. This is because the contribution of the horizontal street surface to canyon albedo decreases with increased building height, while that of the façades becomes more significant. Comparing the views from the pyranometer reading the reflected radiation from the canyon at eaves level (Figure 6), at 13:00 for instance, between *H*:*W* of 1:2 and 1:1, it can be seen that for an *H*:*W* ratio of 1:2 radiation is received by both the left façade and street while when the building height is doubled (*H*:*W* = 1:1) the contribution of the street recedes and most of the reflected radiation comes from the left façade. The results indicate that the impact of vertical surfaces on the radiation exchange within the street canyon becomes more significant with increasing building height.

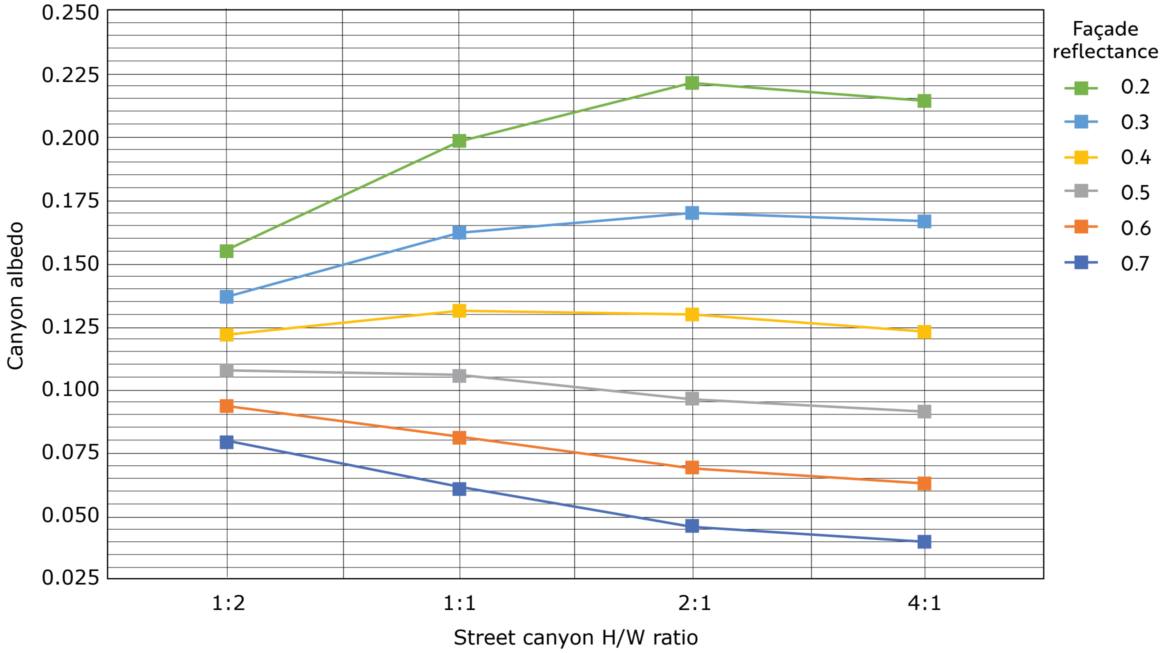
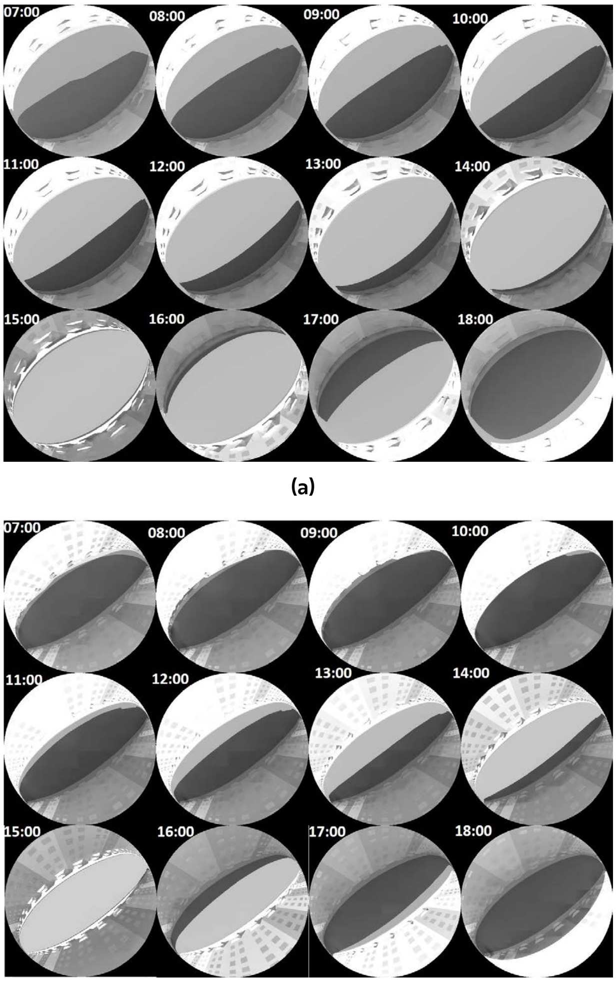


Figure 5 Simulated variation of canyon albedo at different height-to-width ratios and varying façade reflectance (street reflectance constant at 0.11)



(a)

(b)

Figure 6 View from the downward-looking pyranometer (which measures reflected radiation), in RADIANCE, at eaves level for height-to-width ratio of (a) 1:2 and (b) 1:1

3.3 The effect of rainfall

Throughout the experimental phases, the ability of the canyon to reflect radiation back to the sky was seen to vary considerably between dry and rainy conditions. Statistically, this was confirmed by the correlation between the mean daily albedo and the daily (24 hours) amount of rainfall ($r = -0.25$; $p < 0.01$), with the direction of the correlation indicating lower albedo with higher levels of rainfall.

In the original build (Figure 3a) for instance, the canyon's average albedo was reduced from 0.11 on dry days to 0.08 on rainy days, indicating a 27% reduction. Rainfall was also seen to negate the albedo increase observed with the introduction of paving and façade colour, leading to an albedo reduction of 33% (from 0.12 to 0.08) when the model was in its paved-only phase and 20% (from 0.13 to 0.11) when in its paved and coloured phase. The façade material applications revealed rainfall-induced albedo reductions of a similar order: 36%, 33% and 22% during the brickwork, curtain wall and aluminium cladding applications respectively (Figure 7). Although the percentage reduction was of a similar magnitude, the absolute decrease of albedo with brickwork façades (0.04) was twice the respective decrease with aluminium cladding (0.02) and curtain wall (0.02) façades, indicating that façade materials of lower permeability and surface roughness restore faster the reflectance capacity they present in dry conditions. This was particularly noticeable for the curtain wall application, where the albedo drop due to rain occurred mostly at very low irradiance levels (Figure 7).

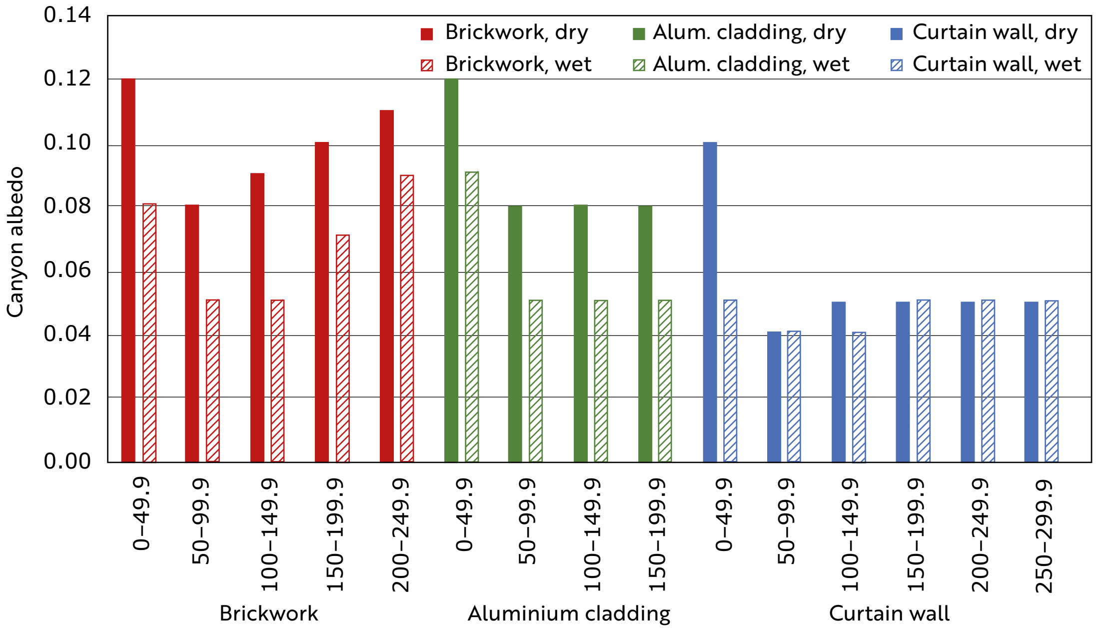


Figure 7 Variation of canyon albedo with measured solar irradiance in dry and wet conditions during the different façade material applications

3.4 Infrared albedo

The study investigated infrared (IR) albedo because this part of the electromagnetic spectrum is primarily responsible for heat transfer and therefore for heat trapped within street canyons. Using a handheld albedometer and dome-shaped IR filters developed in the University of Kent, spot measurements of both the IR and full spectrum albedo of the materials used in the physical model were taken (Figure 8). The full spectrum reflectance of bricks was found to vary widely between 0.31 for red bricks to 0.73 for white bricks, highlighting that colour is a more significant determinant of surface reflectance than the material type itself (Table 2). The aluminium cladding had lower surface reflectance than brickwork while the glass used in the curtain wall application had the lowest reflectance (0.06). In the infrared region, brighter surfaces demonstrated higher reflectance, with tarmac (0.15) and glass (0.04) presenting the lowest values.

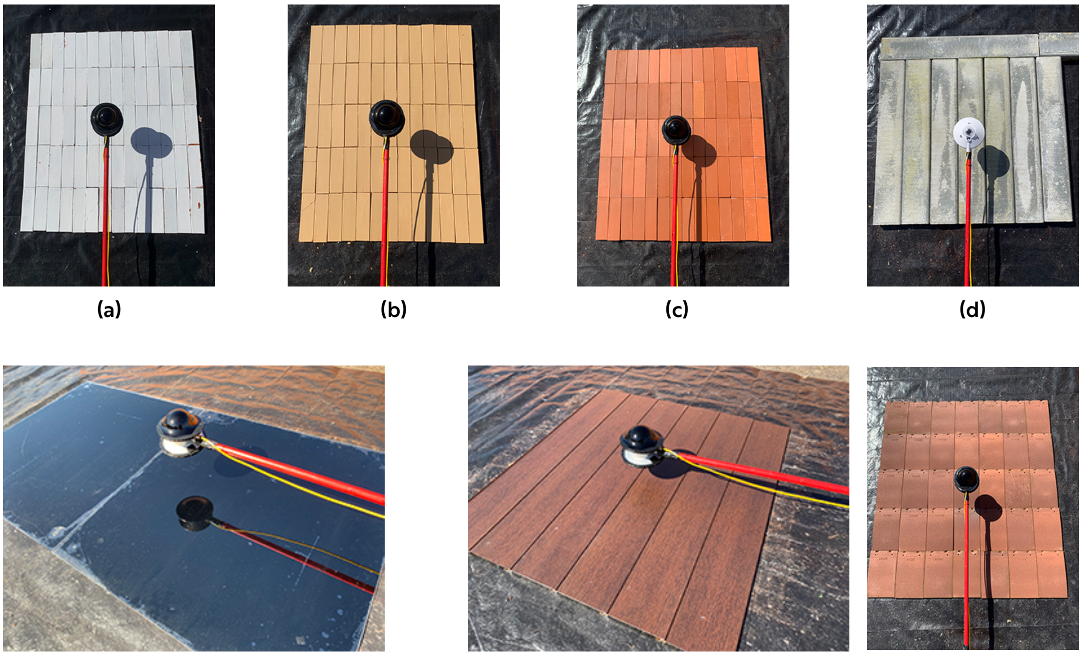


Figure 8 Spot measurements of surface reflectance and surface infrared reflectance of materials used in the physical model (a) white bricks; (b) buff lime bricks; (c) red bricks; (d) concrete paving; (e) glass; (f) aluminium cladding; and (g) clay roof tiles.

Similar IR filters were used to measure the canyon IR albedo during the façade material applications. The diurnal IR albedo also presented a U-shaped pattern and in all three façade applications IR albedo was higher than the full spectrum albedo (Figure 9). The canyon's IR albedo was on average 0.20, 0.14 and 0.11 with brickwork, aluminium cladding and curtain wall façades, with brickwork contributing to 82% and 43% higher albedo than aluminium cladding and curtain wall, therefore making curtain wall systems less preferable applications in terms of avoiding thermal energy trapped within street canyons.

Table 2 Measured surface albedo and surface IR albedo of materials used in the physical model

	White bricks	Magnolia bricks	Buff lime bricks	Red bricks	Concrete paving	Glass	Alum. cladding	Roof tiles	Plywood	Tarmac
Albedo	0.73	0.65	0.42	0.31	0.27	0.06	0.22	0.21	0.40	0.12
Infrared albedo	0.72	0.67	0.62	0.42	0.29	0.04	0.28	0.30	0.53	0.15

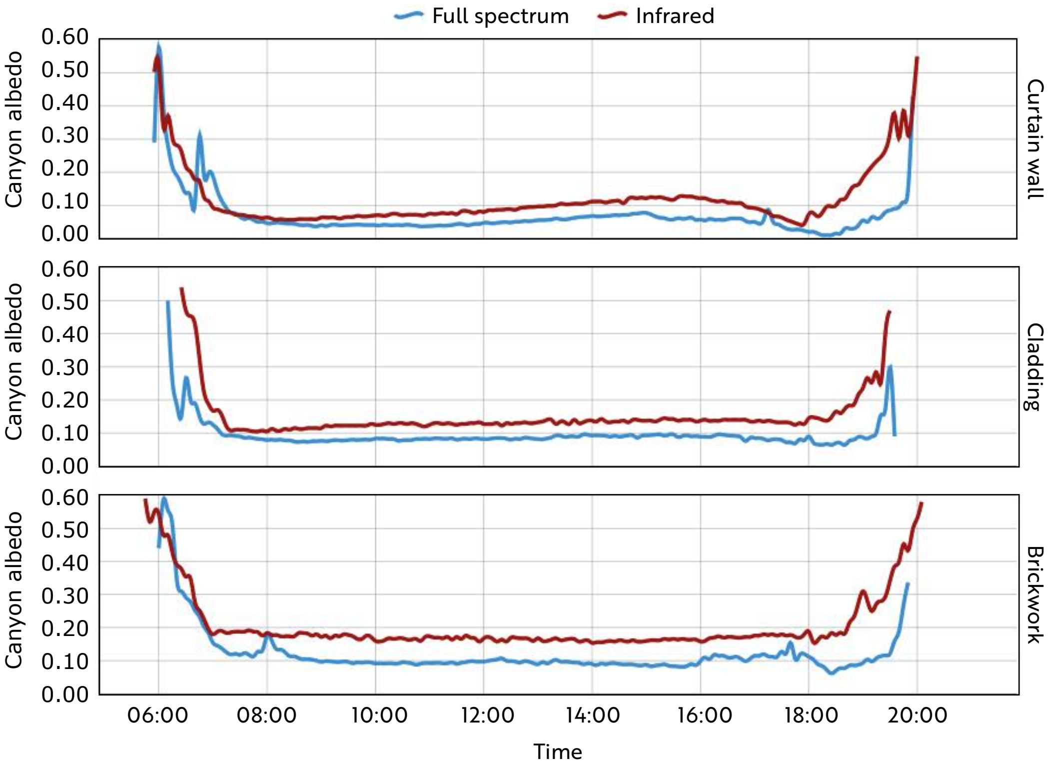


Figure 9 Mean diurnal variation of full spectrum and infrared canyon albedo with brickwork, aluminium cladding and curtain wall façades

4 Simulations on the effectiveness of reflective materials in urban canyons

The modelling part of the urban albedo project investigated the impact of changing the surface reflectance of the road and the façades on the urban canyon albedo (UCA), street-level microclimate and outdoor thermal comfort, considering the urban canyon geometry of the London case study area.

The interconnections between surface albedo, urban canyon albedo, outdoor thermal comfort and building indoor thermal environment are illustrated in Figure 10. These have been investigated in the Urban Albedo project by means of simulations to assess the actual potential of reflective materials in urban settings in London. The computational tools used were ENVImet 4.4.6[5], which was calibrated using measurements from the real case-study and scale model, and EnergyPlus[6] for the impact on the building indoor thermal environment. The main findings are summarised in the next sections.

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[5] https://energyplus.net (accessed 4.07.22)

[6] https://www.envi-met.com/simplify-your-workflow-with-envi-met-4-4-6 (accessed 4.07.22)

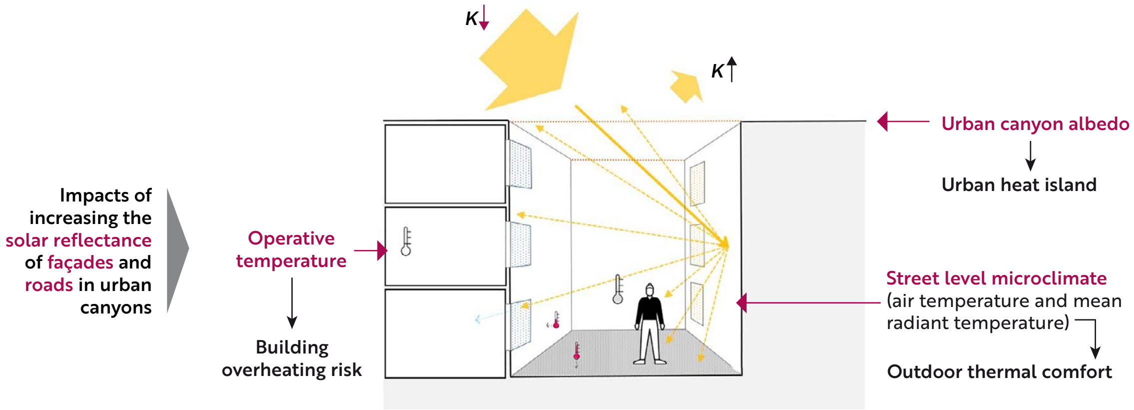

Figure 10 Interconnections between surface solar reflectance, urban canyon albedo, outdoor thermal comfort and building indoor thermal environment in urban canyons.

4.1 Impact of horizontal and vertical surfaces on canyon albedo

Various reflective scenarios were investigated. Figure 11 shows the current distribution of solar reflectances in the case study area, along with the different scenarios, which include changes to the reflectance to the façades, the street and their combined effect. Using the microclimate model ENVImet 4.4.6, the impact of the various reflective scenarios on Urban Canyon Albedo (UCA) was investigated, namely their potential to increase reflected radiation towards the sky. The results are summarised in the bar graph on the right side in Figure 11.

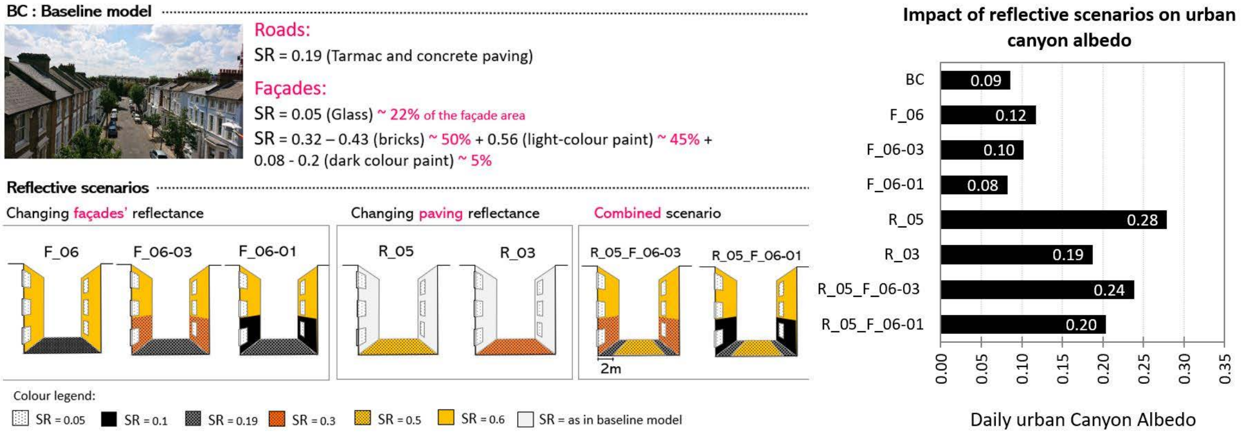

Figure 11 Current solar reflectance distribution (top), reflective scenarios (bottom) and impact on UCA (right)

The results showed that increasing the street reflectance is much more effective on UCA than increasing the reflectance of the façades. In fact, the increase or decrease of the façades' reflectance has a very limited impact on UCA, which can be explained by the fact that vertical surfaces receive less radiation than horizontal surfaces. Furthermore, the radiation reflected by the façades is more likely to be trapped within the canyon geometry. These results are valid for the particular canyon geometry analysed, characterised by a street width of 16 m and building height of 10 m at the eaves and 12 m at the ridge level, resulting in a canyon aspect ratio (H/W) between 0.63 and 0.75. In deeper urban canyons, the relative contribution of the road reflectance on UCA is reduced while that of the façades is increased, as was also demonstrated through the RADIANCE simulations presented earlier.

4.2 Impact of reflective materials on outdoor thermal comfort

The impact of the reflective scenarios on the street level outdoor thermal comfort was analysed using the physiological equivalent temperature (PET). The PET index gives the equivalent temperature of a typical indoor setting (without wind and solar radiation) that would lead to the same heat balance for the human body as in the outdoor environment (Höppe, 1999). The impact of reflective scenarios on the PET in the case study area is illustrated in Figure 12. The figure shows that some of the scenarios have a detrimental impact on outdoor thermal comfort (i.e. increase in PET). Specifically, this happens for the scenarios with increased reflectance of the street, because of the significant increase in mean radiant temperature (MRT) as a result of increase in reflected radiation at street level. Conversely, increasing the reflectance of façades produces a small reduction in MRT, resulting in a very limited improvement in PET. The scenario that allows PET temperatures to be improved is the one where the reflectivity of the bottom part of the façades is reduced, as it reduces the interreflections between surfaces at the street level. However, this scenario is also the one with the lowest impact on UCA, meaning that it does not contribute to mitigate the UHI intensity. The last scenario analysed (Figure 12, bottom) has a lower reflectivity of the bottom part of the façades and a higher reflectivity of the street, except for the 2m footpaths. This combination produces a significant increase in UCA (Figure 11) and it also reduces the negative impact on PET in the pavement area, where pedestrians walk. For this reason, this is deemed the best strategy to increase urban albedo while avoiding negative impacts on outdoor thermal comfort.

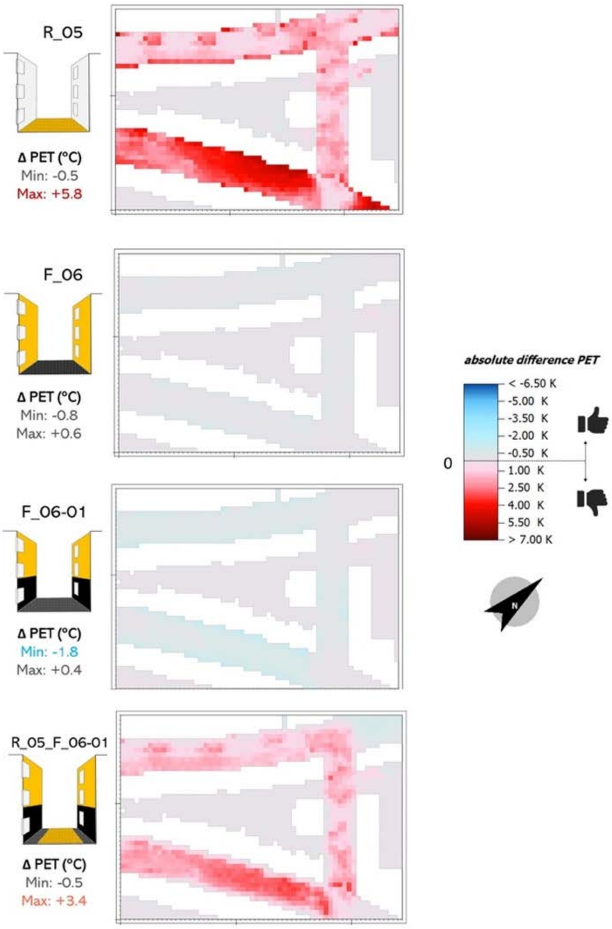

Figure 12 Impact of the reflective scenarios on the street-level physiological equivalent temperature (PET) on 25th July 2019 at 13:00; the buildings of the case study area are shown in white

4.3 Impact of reflective materials on the indoor operative temperature in urban canyons

The impact of reflective scenarios on the building indoor environment is assessed in terms of changes in indoor operative temperature. Increasing the reflectance of the street or the façades has a two-fold effect, namely an increase in the incident radiation on the façade (resulting from the increase of reflected radiation from the environment) and a change in the external surface temperature. The outcome of these effects on the operative temperature of the typical terraced house and canyon geometry of the case study area are illustrated in the graphs in Figure 13, for a typical hot summer day in July.

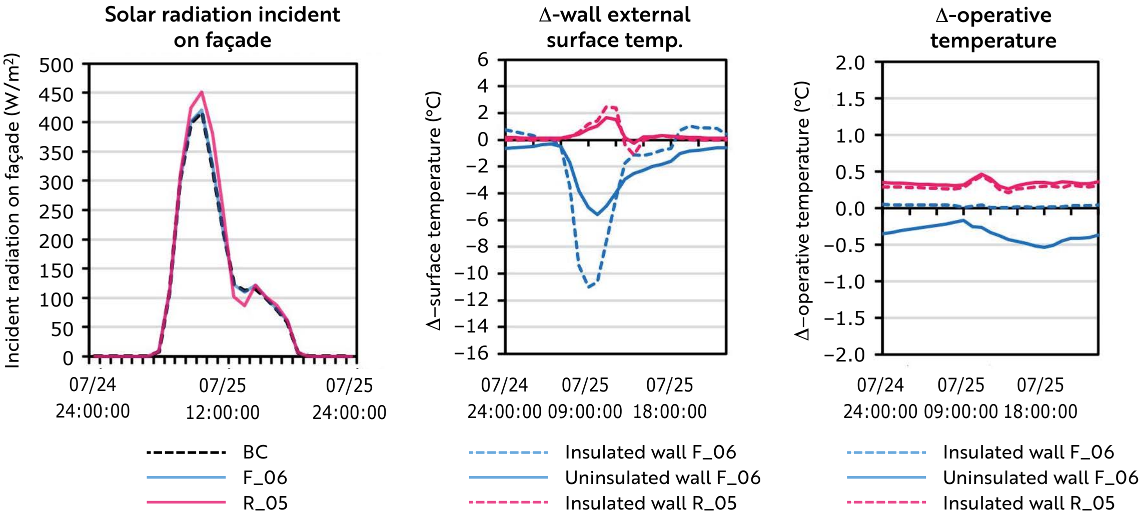

Figure 13 Impact of increasing the reflectance of the road (R_05) or the façades (F_06) on the incident radiation on the façade, external surface temperature and building indoor operative temperature, considering two types of wall constructions

Increasing the street reflectance from 0.19 to 0.5 leads to a significant increase in the incident radiation on the façade, leading to an increase in indoor operative temperature up to 0.5 °C, mainly due to the increase in solar gains. Increasing the façade reflectance (F_06) allows external the surface temperature to be reduced significantly, but the impact on the indoor operative temperature is limited to about 0.5 °C in the uninsulated wall construction type, and nil in the insulated one. The beneficial effect indoors of cool materials is lost in insulated walls because the heat transfer through the envelope is reduced.

5 Impact of weathering on material surface properties

Material surface properties are affected by exposure to the weather elements and UV radiation, all of which can cause significant degradation. To simulate the ageing effect of the full spectrum of natural sunlight on the surface properties which could affect the albedo, artificial ageing techniques are usually designed to reproduce the damage caused by sunlight and rain. They are often able to achieve the level of damage that would take several years under natural conditions in mere weeks or months in a laboratory.

An artificial weathering chamber was thus employed to simulate the ageing effect of the full spectrum of natural sunlight, following ASTM Active Standard G155 (ASTM, 2013) for non-metallic materials. The full list of bricks and tiles (Ibstock bricks) tested is as follows:

- Aldridge Multi Rustic
- Argyll Buff
- Berkshire Orange
- Bracken Brown Rustic
- Calderstone Claret
- Cheddar Golden
- Coral Sandstone
- Himley Ash Grey
- Himley Ebony Black
- Holbrook Sandfaced Brown

- Leccesse Beige Limestone
- Leccesse Grey Limestone
- Manorial Mixture
- Marlborough Stock
- Ravenhead Red Smooth
- Staffordshire Slate Blue
- Surrey Cream Multi
- Surrey Russet
- Tradesman Buff Multi
- Weston Red Multi
- White Ostuni Limestone

The samples were aged for a maximum period of 1200 hours, which could correspond to approximately five years of natural weathering for the type of materials tested, and were collected for characterisation and comparison against the original samples at 400-hour intervals. The surface of these samples can be broadly divided into two major types. Figure 14 contains images of two samples, the Ravenhead Red Smooth and the Himley Ebony Black brick, taken using a scanning electron microscope (SEM). Most sample surfaces included in this study resemble that of Himley Ebony Black.

The key surface properties that have an impact on a material's albedo which were measured included surface roughness, colour, and gloss of the samples.

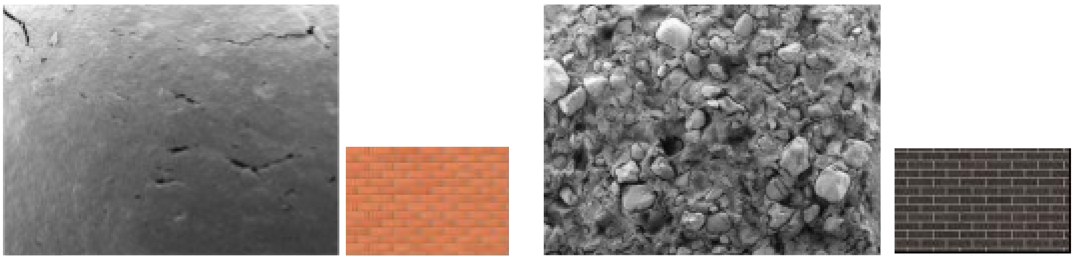

Figure 14 Scanning electron microscope micrographs of two brick samples: Ravenhead Red Smooth (left); Himley Ebony Black (right)

Gloss is calculated by projecting a beam of light at a fixed angle and measuring the intensity of the reflected light at the same angle on the opposite side of the normal to the surface. Measurements taken using a glossmeter showed little to no variation in gloss across the samples even after 1200 hours of ageing.

Using a colorimeter the colour of the samples was characterised. The L^* value, which represents the lightness of the colour of a material, showed a mixed trend depending on the value of the initial lightness of the material; samples with originally high L^* exhibited an increase in L^*, whereas samples with originally low L^* value showed a downward trend.

Surface roughness measurements were conducted using a Bruker Alicona InfiniteFocus instrument and the focus variation technique[7]. The mean roughness of the samples showed a downward trend with increasing periods of ageing (Figure 15).

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[7] https://www.alicona.com/en/our-technology/focus-variation (accessed 11.07.22)

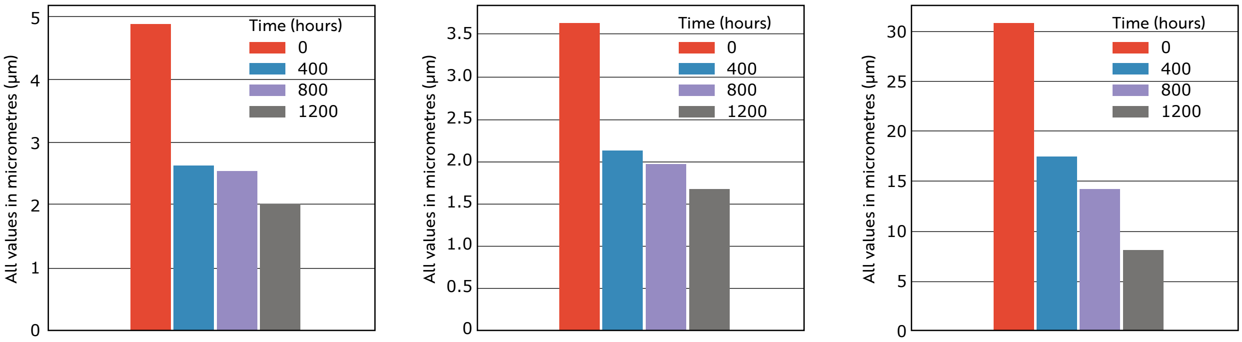

Figure 15 Examples of variation in mean surface roughness of three different brick types after 400, 800 and 1200 hours of artificial weathering: Argyll Buff (left); Ravenhead Red Smooth (middle); and Himley Ash Grey (right)

6 Urban Canyon Albedo Calculator

Using the findings from the experimental investigation of canyon albedo in the scaled model, an empirical model was developed to calculate changes in the albedo of urban street canyons in relation to urban fabric and solar altitude. The calculator was built in GitLab[8], an open-source web-based DevOps lifecycle tool and programmed in Javascript. The user interface was developed in React[9], an open-source front-end JavaScript library for building user interfaces or UI components.

The calculator enables the calculation of hourly or mean daily albedo of a 2D street canyon, at eaves level, any time of the year, under sunny or cloudy sky conditions. It uses a cell system, where each cell has a fixed length of 4 m (typical architectural space grid for residential buildings) parallel to the street. The length of the street canyon is therefore defined by the user and equals the total number of cells multiplied by the fixed cell length. Beyond the street width, which is also user-defined, each cell can be assigned a different height thus allowing for varying building façades heights on either side of the street.

Other user inputs include façade orientation, time of the day and month, sky conditions (sunny or cloudy) and materials. The street canyon under investigation is assumed to be perfectly straight, therefore once the user defines a façade orientation the façade on the other side of the street is automatically assigned with the opposite orientation (e.g. SW and NE). The selection of the time of the day/month triggers the use of hardcoded beam and diffuse irradiances for vertical and horizontal surfaces. The calculator is currently designed for latitude 51 °N/S and uses the beam and diffuse irradiances given in CIBSE Guide A (2015) for this latitude. The view factors, the purely geometrical dependent fractions of radiation leaving a surface and directly impinging another, are calculated dynamically (Howell, 2010).

Façade and street-level materials are user-specified to take into account interreflections between vertical and horizontal surfaces. Each cell can have a unique material composition while the materials on all surfaces, horizontal and vertical, are assumed to be homogeneously distributed. Therefore, the user inputs the fraction coverage of each of the materials selected. For a building façade made of 70% red bricks and 30% glass for instance, the user inputs a fraction of 0.7 for red bricks and 0.3 for glass. The material library can be easily populated with other surface reflectance databases of urban materials. The process is presented graphically with the steps explained in Figure 16.

The calculator was designed with flexibility and extensibility in mind to allow future inputs and alterations. For instance, it can be easily adjusted to use beam and diffuse irradiances applicable to different latitudes while it could also be programmed to use a rainfall factor to adjust the calculated albedo for rainy days, in accordance with the significant reduction of a canyon's ability to reflect radiation in rainy weather observed in the experiment.

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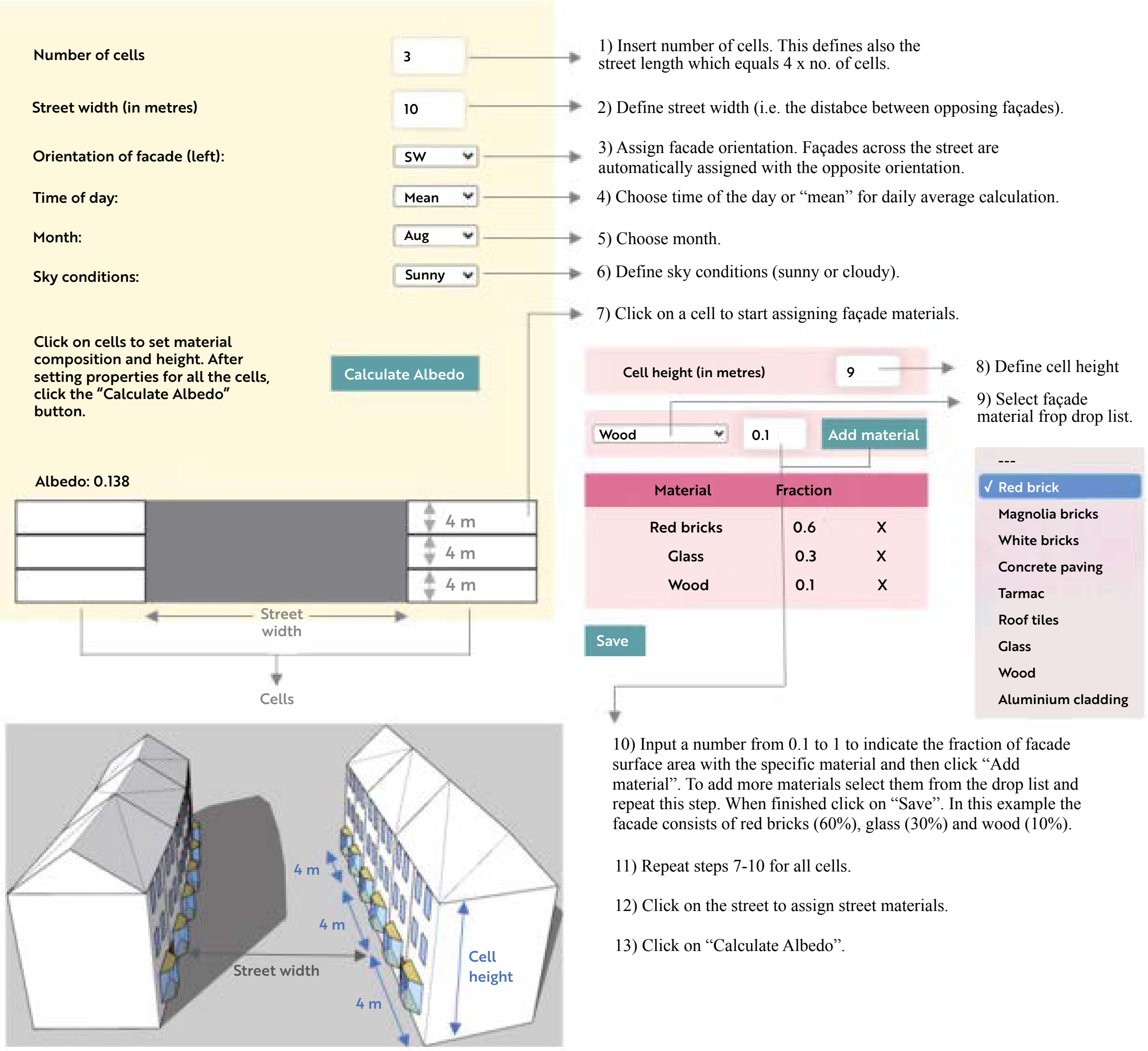
[8] https://gitlab.com (accessed 11.07.22)

[9] https://reactjs.org (accessed 11.07.22)

The tool is intended to serve architectural and urban planning educational purposes. It is free to use and available at https://ua-calc.vercel.app.



Number of cells: 3

Street width (in metres): 10

Orientation of facade (left): SW

Time of day: Mean

Month: Aug

Sky conditions: Sunny

Click on cells to set material composition and height. After setting properties for all the cells, click the "Calculate Albedo" button.

Albedo: 0.138

Cell height (in metres): 9

Material	Fraction	
Red bricks	0.6	X
Glass	0.3	X
Wood	0.1	X

1) Insert number of cells. This defines also the street length which equals 4 x no. of cells.

2) Define street width (i.e. the distabce between opposing façades).

3) Assign facade orientation. Façades across the street are automatically assigned with the opposite orientation.

4) Choose time of the day or "mean" for daily average calculation.

5) Choose month.

6) Define sky conditions (sunny or cloudy).

7) Click on a cell to start assigning façade materials.

8) Define cell height

9) Select façade material frop drop list.

10) Input a number from 0.1 to 1 to indicate the fraction of facade surface area with the specific material and then click "Add material". To add more materials select them from the drop list and repeat this step. When finished click on "Save". In this example the facade consists of red bricks (60%), glass (30%) and wood (10%).

11) Repeat steps 7-10 for all cells.

12) Click on the street to assign street materials.

13) Click on "Calculate Albedo".

Figure 16 Urban canyon albedo calculator user interface and steps explained

7 Conclusions

This project was the first of its kind to have developed a 1:10 scaled physical model of a real residential area in London to investigate experimentally the impact of urban fabric on canyon albedo. Different material applications were tested at street level and building façade level while the canyon's reflective power was also assessed in the infrared range and in wet conditions.

Concrete paving was seen to lead to a 9% rise in canyon albedo while the substitution of tarmac with grass led to a 70% increase indicating the large potential for vegetation to lower the energy absorbed in street canyons. The façade material tests demonstrated that curtain wall contributes to a significantly lower canyon albedo throughout the day compared to aluminium cladding and brickwork façades, including in the infrared range, highlighting therefore that curtain wall systems are less favourable for strategies aiming to mitigate the urban heat island (UHI).

The results also demonstrated the varying nature of canyon albedo with irradiance, sun altitude and orientation as well as the high impact of rainfall on the ability of surfaces to reflect; it was seen to reduce albedo up to 36%. With canyon albedo varying significantly between different sky conditions as well as between dry and wet conditions, variable albedo values which take into account seasonality and rainfall for a given location would be more appropriate for simulations instead of a fixed all-year-round albedo value.

The findings from the advanced simulations highlight the need to carefully assess the multiple consequences of reflective materials in urban canyons. While increasing the street reflectance has a positive impact on the canyon albedo and the UHI intensity, it also has a detrimental impact on outdoor thermal comfort and indoor thermal conditions. The negative impact can be avoided by applying the reflective material at a certain distance from the façades and the pavement, to prevent an increase of reflected radiation where pedestrians walk and towards the building indoor environments.

Highlighting the dynamic and complex nature of the radiation exchange within urban canyons, ultimately, the project developed a series of design guidelines on the influence of design decisions for materials and geometry, their impact on urban albedo and implications for urban design and planning. These can be used as rules of thumb to enable a more informed use of high and low reflectance materials to improve the urban microclimate and thermal comfort in London and other cities of similar latitude and canyon geometry configurations.

Finally, the empirical model developed, the Urban Canyon Albedo Calculator has been developed in an open source environment, and with simple inputs can be used to predict changes in urban albedo in relation to changes in urban fabric and solar altitude.

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Annex: Published outputs from the project

Journal publications

Kotopouleas A, Renganathan G, Nikolopoulou M, Watkins R and Yeninarcilar M (2021) 'Experimental investigation of the impact of urban fabric on canyon albedo using a 1:10 scaled physical model' *Solar Energy* **230** 449–461 (available at https://doi.org/10.1016/j.solener.2021.09.074) (accessed 11.07.22)

Salvati A, Kolokotroni M, Kotopouleas A, Watkins R, Renganathan G and Nikolopoulou M (2022) 'Impact of reflective materials on urban canyon albedo, outdoor and indoor microclimates' *Building and Environment* **207** (available at https://doi.org/10.1016/j.buildenv.2021.108459) (accessed 11.07.22)

Salvati A, Palme M, Chiesa G and Kolokotroni M (2020) 'Built form, urban climate and building energy modelling: case-studies in Rome and Antofagasta' *Journal of Building Performance Simulation* **13** (2) 209–225 (available at https://doi.org/10.1080/19401493.2019.1707876) (accessed 11.07.22)

Book chapter

Kolokotroni M and Salvati A (2021) 'Comfort and Energy Implications of Urban Microclimate in High Latitudes' pp 79–104 in Palme M and Salvati A (eds) *Urban Microclimate Modelling for Comfort and Energy Studies* (Springer) (details at https://doi.org/10.1007/978-3-030-65421-4) (accessed 11.07.22)

Conference publications

Nikolopoulou M, Kotopouleas A, Renganathan G and Watkins R (2020) 'Developing an Urban Albedo Calculator for London: the experimental campaign supporting the development of the tool' *Proc. CIBSE ASHRAE Technical Symposium, Glasgow, UK, 14–15 September 2020* (available at https://www.cibse.org/knowledge-research/knowledge-portal/developing-an-urban-albedo-calculator-for-london?id=a0q3Y00000IMuE8QAL)

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Salvati A and Kolokotroni M (2020) 'Impact of urban albedo on microclimate and thermal comfort over a heat wave event in London' pp 566–578 in Roaf S, Nicol F and Finlayson W (eds) *Proc. 11th Windsor Conference: Resilient Comfort, Windsor, 16–19 April 2020* (available at https://windsorconference.com/wp-content/uploads/2020/05/WC2020_Proceedings_final_compressed.pdf) (accessed 11.07.22)

Salvati A, Kolokotroni M, Kotopouleas A, Watkins R, Renganathan G and Nikolopoulou M (2020) 'Impact of Urban Albedo on Microclimate: Computational Investigation in London' in Rodríguez-Álvarez J and Gonçalves JC (eds) *Proc. 35th PLEA Conf. on Passive and Low Energy Architecture, A Coruña, 1–3 September 2020* (Vol. 1) 677–682 (available at http://hdl.handle.net/2183/26695) (accessed 11.07.22)

Yeninarcilar M, Nikolopoulou M, Kotopouleas A, Watkins R and Renganathan G (2020) 'Investigating the Impact of Urban Texture on Urban Albedo: Case Study of London' in Rodríguez-Álvarez J and Gonçalves JC (eds) *Proc. 35th PLEA Conf. on Passive and Low Energy Architecture, A Coruña, 1–3 September 2020* (Vol. 1) 806–811 (available at http://hdl.handle.net/2183/26695) (accessed 11.07.22)

Computer model

Urban Canyon Albedo Calculator (https://ua-calc.vercel.app) (accessed 11.07.22)