Impact of retro-reflective materials as urban coating: a theoretical study through simulations

Mattia Manni1,2, Gabriele Lobaccaro3, Francesco Goia3, Andrea Nicolini1,2
1Interuniversity Research Center on Pollution and Environment “Mauro Felli”, Perugia, Italy
2Department of Engineering, University of Perugia, Perugia, Italy
3Department of Architecture and Technology, Faculty of Architecture and Design, Norwegian University of Science and Technology NTNU, Trondheim, Norway

Abstract
The use of retro-reflective materials has been recently proposed as a strategy to mitigate the urban overheating by increasing the solar irradiation reflected out of the urban environment. The hereby study focuses on the definition of a methodology to estimate the impact of retro-reflective coatings through a comparison with other surface treatments such as traditional and high-reflective materials. The case study is an urban canyon located in Milan (Italy). Firstly, the impact given by the geometry and the canyon’s orientation was investigated. Secondly, traditional, diffuse high-reflective and retro-reflective materials were applied to the façade and to the street. The outcomes demonstrated how the retro-reflective layer could perform better than the high-reflective when applied to the street in wide canyons, increasing by four times the solar irradiation reflected towards the sky dome. Conversely, the retro-reflective façade turns out to be more performant in narrow urban canyon models.

Introduction
Urban densification can be seen as one strategy to achieve sustainable objectives from an economic, social and environmental point of view. It is often associated with the reduction of heating and cooling energy use and with the improvement of the air quality. In the last two decades, many studies have revealed that the energy use in standing-alone buildings is lower than the amount calculated for the same building if included in a built context. This is due to the mutual solar inter-building reflections, which trap the solar irradiation within the canyon boundaries. On the other hand, evidence from different researches proved that outdoor air temperature values can be lowered by around 5°C in urbanized areas by applying high-albedo materials. This effect is known as the urban heat island (UHI) effect. The hereby study focuses on the definition of research questions and goals. The methodology section describes the workflow developed and used for the analyses, the case study, and the involved parameters. In results and discussion sections the outcomes are presented and commented; finally, a conclusion section summarizes the main findings of the study.

Background
The application of RR layers in the building sector has been only recently explored. In their studies, Nilsen and Lu (Nilsen and Lu, 2004) firstly introduced the use of RR coatings in buildings as a valid and efficient alternative to the traditional materials. In the review article carried out by J. Yuan (Yuan, Emura and Farnham, 2016), RR materials were compared to the HR ones discussing the advantages guaranteed by their application to urban elements (i.e. building’s façade, street ground). Nevertheless, the lack of performance standards represents the main barrier to the application of RR materials as urban coatings. During the last decade, several research activities (Sakai, Emura and Igawa, 2019) have been conducted to assess the potentials of RR materials. It is structured in a background section about the state-of-the-art of RR materials and the definition of research questions and goals. The methodology section describes the workflow developed and used for the analyses, the case study, and the involved parameters. In results and discussion sections the outcomes are presented and commented; finally, a conclusion section summarizes the main findings of the study.
2008; Rossi et al., 2014; Akbari and Touchaei, 2014; Rossi et al., 2015; Qin et al., 2016) have focused on the characterization of RR materials, ranging from the definition of an assessing protocol to the evaluation of their specific RR properties. Commercial films (prism-array structured), capsule-lens, and bead-embedded layers were analyzed and compared after they have been tested in miniature models of UCs or districts to demonstrate their effectiveness in mitigating UHI (Sakai et al., 2008; Rossi et al., 2014). The measurement facility employed in (Rossi et al., 2015) to test the efficiency of RR materials was equipped with 19 photodiodes (with a 10° wide step, from 0° to 180°), which estimate the reflected fractions in different directions. The outcomes from different samples demonstrated how a RR behaviour can be usually observed when the solar irradiation hits the material mainly perpendicularly, while an HR behaviour is shown in the case of mostly parallel sunrays’ direction.

Despite the proven advantages of the different RR technologies, there are still some aspects, which need to be addressed to fully enable the potentialities of these systems. Indeed, the RR materials could present some side effects such as (i) the increment of heating energy requirements in winter, since less solar irradiation is absorbed by the façades; and (ii) the higher lighting pollution level due to the reduction of urban surfaces able to absorb the city lights. To overcome these issues, two materials, which could be classified as selective RR materials, have been proposed by Sakai and Iyota (Sakai and Iyota, 2017), while a new inverse approach has been recently proposed (Manni et al., 2018) to identify optimal selective angular properties of RR surfaces (both horizontal and vertical).

In this scenario, the study presented in this paper aims at giving an original contribution to the evaluation process of RR materials by proposing a methodology to preliminary assess their mitigation potential in different UC environments.

Methodology

The methodology is based on a cluster of solar analyses which separately assess the contributions from direct and diffuse solar irradiation. It is applied to carry out a comparison among traditional, HR, and RR materials. Because of the numerical modeling approach, based on Radiance, this paper also investigates the suitability of ray tracing simulation to predict the potentials of the application of RR materials to increase the amount of solar irradiation reflected beyond the canyon. Some representative UC configurations are considered, where RR coatings are applied to street and building’s façade.

Workflow and parameters

As reported in Figure 1, the research is structured in two stages. Stage 1 aims at defining the UC models characterized by the highest and the lowest amounts of solar irradiation reflected towards the sky dome in order to provide two geometry configurations where different material patterns can be assessed in Stage 2. The main input parameters are the orientation of the UC, the aspect height-to-width ratio (H/W), and the geographical and climate information. The output considered during the selection process of the UC geometry configurations is the amount of solar irradiation reflected beyond the canyon by all the surfaces (Irrout).

The solar analyses for Milan latitude were carried out by changing the UC orientation (north-south, east-west, and northwest-southeast) and the H/W (from 0.5 to 1.0, and to 2.0) to explore low, medium, and high urban density patterns. In total, 9 different geometry configurations were investigated (Figure 2). The length of the building fabrics is set to avoid any uncontrolled boundary effects.
in the middle of the canyon during the calculation. This is obtained by multiplying the canyon’s width by six. Therefore, the building blocks vary through the study according to the H/W aspect ratio. For an H/W equal to 1.0, the building blocks are 6 m of height (H) x 6 m of width (W) x 36 m of length (L). In case of H/W equal to 2.0, the building fabrics’ height is doubled up to 12 m, whereas in the last geometry configuration – H/W of 0.5 – the streets’ width is increased from 6 m to 12 m while the height of the building is kept constant up to 6 m (Figure 3).

The base case defined during Stage 2 shows traditional diffuse materials from standard Radiance library applied to the street (asphalt, \( \rho = 0.2 \)) and to the building’s façades (brown painting, \( \rho = 0.35 \)).

As far as the cool treatments are concerned, the wording ‘high-reflective materials’ identifies a cluster of materials characterized by a solar reflectance higher than 0.90, while the wording ‘retro-reflective materials’ is referred to a group of coatings able to totally reflect back towards the skydome the solar irradiation impinging on the surface.

Two scenarios were assessed for HR and RR materials depending on their field of application (street or façade). Therefore, the investigated materials patterns are the ones reported in Table 1. In cool scenarios, conventional materials are always applied to those surfaces where HR or RR treatments are not exploited (i.e. to street surface in HR-F scenario).

**Table 1: Overview of the material patterns investigated during Stage 2.**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Applied Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>base case</td>
<td>brown painting asphalt brown painting</td>
</tr>
<tr>
<td>HR-P</td>
<td>brown painting HR brown painting</td>
</tr>
<tr>
<td>HR-F</td>
<td>HR asphalt brown painting</td>
</tr>
<tr>
<td>RR-P</td>
<td>brown painting RR brown painting</td>
</tr>
<tr>
<td>RR-F</td>
<td>RR asphalt brown painting</td>
</tr>
</tbody>
</table>

**Simulation tool and data processing**

The UC investigated in this study was parametrically modelled in Grasshopper environment and it was visualized in Rhinoceros to generate different geometry configurations by modifying the algorithm’s input values (i.e. H/W ratio, orientation).

The Diva for Rhino plug-in, based on Radiance engine, was chosen to conduct solar analyses using the .epw weather data climate of Milan (Italy). A grid of test points facing the street was generated by offsetting the ground surface by a distance equal to the building’s height. A cells’ size of one meter by one meter was also considered (Figure 4).
The **Radiance** simulation parameters were set as shown in Table 2. The outputs are referred to the solar irradiation incident on the test points throughout the year, which has been evaluated both yearly and seasonally. The I_{Rout} is estimated as the specific solar irradiation per square meter impinging the one-meter-wide strip surface located at the middle of the canyon (it permits to avoid boundary effects). The extension of the strip ranges from 6 m² (H/W of 1.0) to 12 m² (H/W of 0.5).

The ambient bounces (ab) value, that counts the number of the solar reflections before the sunray hits the analyzed surface, was set equal to 5 to estimate global solar irradiance composed by diffuse, direct and up to fifth-reflection contribution (I_{Rout}). This last setting guarantees the ideal compromise between computational time and accuracy of the results when it comes to multiple reflections (Pesenti, Masera and Fiorito, 2018). The values of 0 and 1 for ab were used to calculate the solar incident irradiation component due to direct (I_{Rinc,dir}) and diffuse solar irradiation (I_{Rinc,dif}). In particular, a weather file customized in *Elements* environment has been generated with null values for the direct sunlight. It has been used in the assessment of the diffuse fraction.

The analyses were conducted with an hourly time-step throughout the whole year. The yearly duration was organized according to the four seasons: spring (March, April, May), summer (June, July, August), fall, (September, October, November) and winter (December, January, February).

Custom **Radiance** materials properties were set considering the parameters of colour (RGB values), specularity (fraction of incident light that is reflected; varying from 0.0 for a perfectly diffusive surface to 1.0 for a perfect mirror), and roughness (surface irregularities quantified by the deviation from its ideal direction of the normal vector of a surface; the value varies from 0.0, which corresponds to a perfectly smooth surface, to 1.0 that corresponds to a perfectly irregular surface).

Since models of RR materials are not available, the proposed approach is based on the manipulation of weather data file and materials’ properties. Three independent simulations were carried out to define the three retro-reflected contributions – direct (Figure 5 a) and diffuse (Figure 5 b) solar irradiation retro-reflected from the RR surface, and global solar irradiation reflected out of the UC from the non-RR surfaces (Figure 5 c) – and arithmetically add them. In particular, a material able to completely absorb the solar radiation impinging on the surface (null ρ value) was used instead of the RR materials to calculate the solar irradiation reflected beyond the UC by non-RR surfaces.

<table>
<thead>
<tr>
<th>Ambient bounces</th>
<th>Ambient divisions</th>
<th>Ambient super samples</th>
<th>Ambient resolution</th>
<th>Ambient accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>0/1/5</td>
<td>1,000</td>
<td>20</td>
<td>300</td>
<td>0.1</td>
</tr>
</tbody>
</table>

**Table 2:** Set of ‘rtrace’ parameters employed for conducting solar radiation analyses with Diva-for-Rhino.

This simplification leads to underestimating the I_{Rout} since a minimum fraction of the solar irradiance absorbed by the surface with null ρ value would be actually retro-reflected towards the street or the façade, and then eventually further reflected beyond the canyon.

**Results**

**Definition of the UC configurations**

The estimated solar irradiation reflected by the UC underline how the orientation input parameter provides a negligible variation (lower than 3%) in canyon’s configurations with the same H/W (Figure 6). Conversely, the H/W influences the I_{Rout}; its least, 85 kWh/m², is shown in the narrowest geometry configuration (H/W equal to 2.0), while the maximum, 160 kWh/m², corresponds to the widest (H/W equal to 0.5). These two extremes were chosen as the H/W values proper of the best and the worst UC configurations.

When it comes to the orientation, the west-east was coupled to the 0.5 H/W value (the resulting model was named ‘W-E_0.5’) and the north-south to the 2.0 H/W (the resulting model was named ‘N-S_2.0’). They were considered as the most and the least advantageous orientations, respectively, since they are characterized by the greatest and the lowest difference in terms of collected solar irradiation among the façades (Vallati, Mauri and Colucci, 2018).
In the second part of Stage 1, the solar reflectance parameter was investigated. The W-E_0.5 and the N-S_2.0 models were considered as case studies along with an intermediate one (named as ‘NW-SE_1.0’) that is oriented northwest-southeast and whose H/W is equal to 1.0. Increasing the ρ value, the Irr\text{out} raises similarly in all the models. In particular, varying the solar reflectance from 0.2 to 0.4 doubles the estimated Irr\text{out}, while the variation is lower when incrementing from 0.4 to 0.6 (Figure 7).

The chosen homogenous solar reflectance (ρ = 0.2) does not influence the relationship among the different geometry configurations in terms of solar irradiation leaving the UC (i.e. varying the ρ value, the Irr\text{out} estimated for the N-S_2.0 is always lower than the amount calculated for the W-E_0.5).

**Impact of cool materials on the best-configuration**

The scenario with traditional diffuse materials applied to the street and to the façade of the W-E_0.5 model shows an amount of annual Irr\text{out} equal to 200 kWh/m\textsuperscript{2} (Figure 8). The seasonal contributions amount to 85 kWh/m\textsuperscript{2} and 20 kWh/m\textsuperscript{2} in summer and in winter, respectively.

When HR are considered as street’s surface treatment, the irradiation reflected out of the UC is increased by more than 240% (690 kWh/m\textsuperscript{2}), while the seasonal ΔIrr\text{out} is more than 280% in summer and around 160% in winter (Figure 8). The exploitation of HR on building’s façade (HR-F) causes a lower variation in the estimated Irr\text{out}, that achieves 320 kWh/m\textsuperscript{2} (ΔIrr\text{out} of 55%). The seasonal amounts of solar energy leaving the canyon are 120 kWh/m\textsuperscript{2} for the summer and 35 kWh/m\textsuperscript{2} for the winter (Figure 8).

Applying RR materials instead of HR allows reducing the amount of solar irradiation that remains trapped within the UC by improving the Irr\text{out}. The model with the RR street (RR-P) presents the greatest Irr\text{out}. The yearly, summer, and winter values equal to 995 kWh/m\textsuperscript{2}, 475 kWh/m\textsuperscript{2}, and 70 kWh/m\textsuperscript{2}, while the ΔIrr\text{out} ranges from 390% to 455%, and to 255% (Figure 8). As far as the scenario with the RR façade (RR-F) is concerned, the UC reflects towards the sky dome 460 kWh/m\textsuperscript{2} per year (ΔIrr\text{out} of 130%), while the Irr\text{out} equals 140 kWh/m\textsuperscript{2} in summer and 75 kWh/m\textsuperscript{2} in winter (Figure 8).

**Impact of cool materials on the worst-configuration**

When traditional materials are applied to the N-S_2.0 canyon model, the yearly amount of solar irradiation reflected beyond the UC is 150 kWh/m\textsuperscript{2} (Figure 9). The summer and winter seasons contribute for 65 kWh/m\textsuperscript{2} and 15 kWh/m\textsuperscript{2}, respectively.

Enhancing the solar reflectance of the street through HR materials (HR-P) increases the Irr\text{out} up to 240 kWh/m\textsuperscript{2} – 100 kWh/m\textsuperscript{2} in summer and 25 kWh/m\textsuperscript{2} in winter (ΔIrr\text{out} constantly equals 60%). Conversely, the HR layer applied to the façade is able to increment the Irr\text{out} by more than 90% annually (285 kWh/m\textsuperscript{2}), while the seasonal contributions amount to 120 kWh/m\textsuperscript{2} in the summer and 30 kWh/m\textsuperscript{2} in the winter.

The scenario with RR applied to the street (RR-P) shows 490 kWh/m\textsuperscript{2} per year of specific solar irradiation leaving the UC (ΔIrr\text{out} of 225%). The seasonal amounts are 210 kWh/m\textsuperscript{2} in summer (ΔIrr\text{out} of around 230%) and 50 kWh/m\textsuperscript{2} in winter (ΔIrr\text{out} of 220%). In the case study with the RR façade (RR-F), the greatest amounts of Irr\text{out} for the N-S_2.0 model is observed: the annual Irr\text{out} equals 575 kWh/m\textsuperscript{2} (ΔIrr\text{out} is 285%), and it ranges from
275 kWh/m² to 60 kWh/m², in summer and winter, respectively (ΔIrr\% varies from 330% to 310%).

Discussion

Potentials for the street application of RR materials

The yearly solar analyses conducted in Milan demonstrate that applying RR to the street instead of HR is always advantageous to lower the solar energy trapped within the UC. Indeed, the RR coating significantly reduces the shortwave radiative exchanges among the street and the two façades by reflecting the solar irradiation incident on the street towards the sky dome. The efficiency of the RR technology strongly depends on the amount of specific solar irradiation impinging the treated surface: when applied to wide canyon environments, they usually perform better than when exploited in narrow configurations characterized by a shadowed street surface (Figure 8 and Figure 9). The same behaviour can be observed in HR surface treatments.

When it comes to the seasonal assessment of the RR materials' efficiency in N-S_2.0 model, it can be observed how the ΔIrr\% in summer is almost the same as in winter. Conversely, in the W-E_0.5, it is greater in the warm than in the cold season (Figure 10). Furthermore, the Irr\% values for winter are negatively affected by RR materials (and HR as well) which are responsible for the reduction of solar energy gains in buildings and the consequent raising of the heating energy demand.

<table>
<thead>
<tr>
<th>Material Pattern</th>
<th>ΔIrr% Summer</th>
<th>ΔIrr% Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR-P</td>
<td>200%</td>
<td>50%</td>
</tr>
<tr>
<td>RR-F</td>
<td>250%</td>
<td>250%</td>
</tr>
<tr>
<td>HR-F</td>
<td>250%</td>
<td>250%</td>
</tr>
<tr>
<td>RR-PRR-F</td>
<td>300%</td>
<td>300%</td>
</tr>
</tbody>
</table>

*Figure 10: Amount of seasonal values of Irr\% and ΔIrr\% estimated for each material pattern of the (a) best- and the (b) worst configuration.*

The following practical guidelines about the application of RR layer to the street surface have been carried out from the results:

- RR materials applied to the street are more effective than HR during summer when they completely reflect the incident solar irradiation out of the UC;
- In winter, the RR materials are responsible for the low solar energy gains within the UC.

Potentials for façade application of RR materials

The analyses conducted on the models enhanced with a RR façade defined the narrow canyon as the best façade application of RR materials. In the N-S_2.0 model, both the scenarios exploiting cool materials on the façade (HR-F and RR-F) turn out to be more advantageous than the configurations with HR or RR paving. Indeed, the yearly ΔIrr\% increases from 60% (HR-P) to more than 90% (HR-F) and from 225% (RR-P) to 285% (RR-F) (Figure 8 and Figure 9).

The seasonal evaluation of the solar irradiation in W-E_0.5 model shows RR materials increasing the Irr\% more in winter (when it is not necessary) than during summer (Figure 10). This trend is less evident in the HR configuration than in the RR, which can be considered, for this reason, as the worst among the investigated RR applications. When it comes to the N-S_2.0 model, the ΔIrr\% does not vary passing from the summer to the winter and it equals 315% (RR-F) (Figure 10). Similarly, the ΔIrr\% is constantly equal to 90% in the HR scenario.

The hereby practical guidelines about the exploitation of RR materials in the most irradiated façade summarize the outcomes from this study:

- RR materials applied to the façade are less performant in wide UCs (low H/W) than in narrow ones where façade surface is longer exposed to direct solar irradiation;
- RR materials are as advantageous as HR in terms of reduction of the solar energy trapped within wide UCs during summer;
- As demonstrated for the street application, RR materials are responsible for the reduction of winter’s solar energy gains.

Conclusions and future developments

This study describes an approach for evaluating the impact of RR materials in relation to the increment of solar irradiation reflected out of the UC. The main findings can be summarized as follows:

- The UC configuration having traditional coatings on the surfaces with the greatest Irr\% (200 kWh/m²) is the W-E_0.5 model (main axis oriented eastwards and H/W equal to 0.5);
- The amount of solar direct irradiation impinging on the treated surface influences the performance of the RR materials;
- The façade application of the RR technology should be considered only for narrow canyons;
- RR materials applied to the street always perform better than HR during summer;
- All the investigated configurations can increase the Irr\% during summer while reducing solar gains during winter.
The outcomes highlighted how the investigated RR materials cannot be considered advantageous throughout the year when exploited in the building sector. Although they increase the $I_{\text{Rr}}$ more than HR in summer, they also contribute to reducing solar gains in winter. Thus, it is necessary to implement a selective behaviour—based on the angle of incidence of the sun rays—in the RR technology to activate its RR features only during the warm season.

The enhancement of the numerical model can represent an important step in the future developments of the present workflow allowing a better evaluation of the RR materials’ performances and permitting handling parameters which cannot be fully replicated in the present modelling approach (i.e., angular dependency of the coating’s reflectance value, directivity of the solar beam). Furthermore, its application to the assessment of angular-selective RR materials in different climatic contexts and scenarios would be fundamental as well.

References


