Modelling Outdoor Thermal Comfort and Energy Demand in Urban Canyons: Validation of a Novel Comprehensive Parametric Workflow

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Abstract

Within the frame of climate change, it is essential to understand the relation between local microclimate, building energy performance and outdoor comfort. In this sense, a key issue is the possibility to model the thermodynamic interdependency among these three fields, which are often treated separately, through dynamic simulation tools.

To this extent, this paper investigates the applicability of a novel simulation methodology developed within the Ladybug tools, where the Honeybee and Ladybug plug-ins for Grasshopper are used to link the outdoor thermal field to the indoor thermal behaviour of the buildings.

The model provides both the hourly dynamic thermal load of the buildings overlooking the canyon and several outdoor thermal parameters such as the *Mean Radiant Temperature* (MRT) and the *Universal Temperature Climate Index* (UTCI). In comparison to other existing approaches, the workflow proposed in this paper offers significant flexibility and the complete modelling of the indoor/outdoor thermal fields. This makes it possible to perform a parametric investigation of the effects of different design solutions on the indoor and outdoor environment, both for new and existing buildings.

The model is tested in an urban canyon located in Catania, Southern Italy, with the specific aim of validating one of its main modules: the outdoor comfort simulation. In particular, the results concerning MRT are compared to on-site measurements performed with a black-globe thermometer during a sunny day in summer. The validation of the module for outdoor MRT assessment is, at the time of writing, a missing study and this work is a step in this direction.

Introduction

The thermal properties of the envelope have a significant influence on the performance of a building, and in particular on the energy needs for space heating and cooling. For this reason, national and international regulations have introduced strict requirements regarding stationary and dynamic thermal transmittance for the envelope components of new and refurbished buildings.

However, several works in the literature have recently pointed out that a non-negligible interaction holds between the outer envelope of buildings and the thermal field perceived outdoors by pedestrians (Andreou and Axarli, 2012). This is especially true in the so-called *urban canyons*, with a high ratio between the area of the

façades and the area of the ground surface that is free from constructions. The morphology of the built environment can also reduce the local air velocity, which in turn amplifies the effects of the heat released from the façades to the outdoors. This effect is exacerbated in the summer when the solar radiation overheats buildings and streets, often leading to pronounced outdoor thermal discomfort for pedestrians.

Many studies have underlined the critical role played by the albedo of the outer finishing layer of buildings. Light colours, or any coating with high albedo, avoid the overheating of the outer surfaces, thus reducing the energy needs for space cooling and improving indoor thermal comfort in the summer. Moreover, a low outside surface temperature of the envelope reduces the heat released by convection and by long-wave radiation to the urban canyon. Local effects on pedestrians can originate from the application of high-albedo finishing layers to a single building (Evola et al., 2018), while positive effects in terms of *Urban Heat Island* (UHI) reduction can be observed only if this is applied at urban scale. However, recent studies have shown an unexpected drawback: the short-wave radiation that is not absorbed by the façades is reflected towards the ground, thus hitting the pedestrians and overheating the ground surface (Chokhachian et al., 2017). In many cases, this side effect counterbalances the positive effects commented above and generates a worsening of the outdoor thermal comfort conditions (Erell et al., 2014; Yang et al., 2015; Schrijvers et al., 2016). In this sense, some authors found out that an average albedo ($r \approx 0.4$) is the best compromise (Rosso et al., 2018).

The present paper describes a parametric workflow for the dynamic thermal simulation of an urban canyon, implemented in the Grasshopper platform and relying on its plug-ins Honeybee and Ladybug. The workflow can take into account the interaction of the envelope with both the indoor spaces and the outdoors; this allows assessing the consequences of a building design solution in terms of energy needs, but also in terms of outdoor thermal comfort perceived by pedestrians. After a validation stage based on a preliminary on-site measurement campaign in a real urban canyon in Catania, a sensitivity analysis shows the effects of different albedo values for the envelope on the thermal load of the buildings and on the outdoor comfort, measured through the MRT and the UTCI.

Case study and methodology

The selected urban canyon

The urban canyon selected to test the proposed parametric workflow is located in the centre of Catania, a densely populated city in Sicily (Southern Italy). Figure 1 shows the area addressed by this study, which belongs to a district next to the historic centre. The selected area has a side of about 375 m, and includes multi-storey residential buildings (from two to seven floors) built between the 1930s and the 1960s.

The whole area was considered in order to model the UHI effects on the local microclimate through the Urban Weather Generator (UWG), which is not discussed in this paper. Instead, the study illustrated in this paper refers to the urban canyon enclosed within the white box (Figure 1), which includes Via Ughetti and six apartment buildings. These buildings were modelled with a high level of detail, including balconies and window frames, in order to allow indoor and outdoor dynamic simulations through the Grasshopper plug-ins Honeybee and Ladybug (Figure 1).

Some simplifications to the geometry were introduced, by simplifying the pitched roofs and some elaborated façades. Moreover, in order to model the outside walls, the most recurring solution was retained. In fact, most of the buildings in this district have 60-cm thick walls made with basalt stones mixed to lime mortar and finished with two 20-mm layers of plaster. The average U-value of the walls is $1.9 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$; such walls are massive, with a surface mass above $1200 \text{ kg} \cdot \text{m}^{-2}$. The windows are single glazed and with wooden frames ($U_w = 4.8 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$), apart from few openings recently refurbished.

Figure 1: Selected urban area and its geometrical model

Measurement of the Mean Radiant Temperature

The Mean Radiant Temperature (MRT) allows measuring with a single number the intensity of the radiant heat exchange between the human body and the surroundings. In particular, the MRT corresponds to the uniform temperature of a fictitious environment where the body would exchange the same radiant heat power as in the real environment.

The MRT can be measured in-situ by employing a black globe-thermometer. This is a hollow metal sphere painted in black, with a diameter of 150 mm; when the black globe-thermometer is placed in the environment under investigation, the MRT can be correlated to the measured values of the globe temperature T_g , the air temperature T_a and the air velocity v_a (Kantor and Unger, 2011):

$$\text{MRT} = \sqrt[4]{(T_g + 273.15)^4 + 2.5 \cdot 10^8 \cdot v_a^{0.6} \cdot (T_g - T_a)} - 273.15 \quad (1)$$

This measurement technique was initially conceived for indoor applications. However, recent studies have shown that – despite a certain degree of approximation – the use of the black globe thermometer outdoors is sufficiently reliable if the measured data are averaged on a time basis of at least ten minutes, in order to average out the dynamic effects of the variable wind speed. On the other hand, if one needs to measure the outdoor MRT with a finer time resolution, it is necessary to adopt a more advanced measurement procedure based on three pairs of pyranometers plus three pairs of pyrgeometers, arranged along the three principal directions (Marino et al., 2017).

In this study, the monitoring campaign was performed on 30th August 2018 from 12:50 to 15:00. A TESTO 480 data logger was placed in Via Ughetti sufficiently close to the centre of the street (see Figure 2); the data logger was equipped with suitable probes to measure the following parameters (the uncertainty of the probes is reported in brackets):

- Outdoor dry-bulb air temperature (0.5 °C);
- Outdoor relative humidity (2 %);
- Outdoor CO₂ concentration (50 ppm);
- Black-globe temperature (1.5 °C);
- Air velocity along the street (0.03 m/s).

The probes were positioned at the height of around 1.1 m from the ground. All values were recorded every 30 s; however, suitable average values over longer periods were calculated during post-processing when necessary.

The relatively short duration of the campaign is justified by the need to perform a first preliminary check and calibration of the simulation model. Based on the outcomes and the lessons learned from this first experimental activity, longer and more detailed measurements are going to be performed, whose results will be shown in a following paper.

Figure 2: Position of the probes in the urban canyon

Calculation of the Mean Radiant Temperature

Dealing with the prediction of the MRT in an urban canyon is a complex task, due to the superposition of a long-wave and a short-wave radiant field. The first one is due to the thermal emission of the canyon surfaces towards the human body; the second one is due to the solar radiation directly hitting the human body or by the radiation reflected by the surfaces of the canyon.

To account for short-wave effects, the Ladybug Tools make use of an algorithm called *SolarCal*, recently developed at UC Berkeley (Arens et al., 2015). According to this, a first assessment of the MRT at any point in the canyon is made by accounting rigorously for the long-wave component, considering all surface temperatures and the view factors between the surfaces and the human body. Here, the view factors are calculated through a *ray-tracing* approach (Naboni et al., 2017). Then, the contribution of the short-wave radiation adds to the results of the first step (MRT_{LW}) as in Eq. (2). Here, ERF is the so-called *Effective Radiant Field*, i.e. the overall short-wave irradiance hitting the body:

$$MRT = MRT_{LW} + \frac{ERF}{h_r \cdot f_{eff}} \quad (2)$$

More details about the calculation of the ERF can be found in the literature (Arens et al., 2015; Mackey et al., 2017). The calculation is affected by some simplifying assumptions:

- the radiant heat transfer coefficient is constant and set to $h_r = 6.012 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$;

- the fraction of the body involved in the radiant heat transfer is constant and set to $f_{eff} = 0.725$ (standing person);
- the total solar irradiance hitting the ground is reflected proportionally to the ground albedo, and this reflected radiation hits the lower half of the human body;
- the solar irradiance reflected by the façades of the buildings, and then hitting the human body, is not taken into account.

Calculation of the UTCI

The Universal Temperature Climate Index (UTCI) is a widely accepted parameter used to measure the thermal stress experienced by people when outdoors. Its calculation rests on the model developed by Fiala to describe the complex physiological behaviour of a human body, including its thermoregulatory reactions to modifications in the outdoor conditions.

In particular, the UTCI is the value of the air temperature that, under suitably defined reference conditions, causes in the human body the same response as in the actual conditions, according to the Fiala model (Błażejczyk et al., 2013). The reference conditions consider a person walking at 4 km/h, with a metabolic rate corresponding to 2.3 met. Moreover, the reference wind speed is 0.3 m/s at 1.1 m, and the reference relative humidity is 50 %. Finally, the reference mean radiant temperature equals the dry bulb air temperature.

The value of the UTCI depends only on the air velocity, the mean radiant temperature, the relative humidity and the actual air temperature. The calculation is performed through a very complex polynomial expression with 210 coefficients (Błażejczyk et al., 2013). According to the UTCI value, it is possible to classify the thermal stress experienced by a pedestrian as detailed in Table 1.

Table 1: Correlation between thermal stress and UTCI

UTCI range	Stress category
$UTCI > 46 \text{ }^{\circ}\text{C}$	Extreme heat stress
$46 \text{ }^{\circ}\text{C} \geq UTCI > 38 \text{ }^{\circ}\text{C}$	Very strong heat stress
$38 \text{ }^{\circ}\text{C} \geq UTCI > 32 \text{ }^{\circ}\text{C}$	Strong heat stress
$32 \text{ }^{\circ}\text{C} \geq UTCI > 26 \text{ }^{\circ}\text{C}$	Moderate heat stress
$26 \text{ }^{\circ}\text{C} \geq UTCI > 9 \text{ }^{\circ}\text{C}$	No thermal stress
$9 \text{ }^{\circ}\text{C} \geq UTCI > 0 \text{ }^{\circ}\text{C}$	Slight cold stress
$0 \text{ }^{\circ}\text{C} \geq UTCI > -13 \text{ }^{\circ}\text{C}$	Moderate cold stress
$-13 \text{ }^{\circ}\text{C} \geq UTCI > -27 \text{ }^{\circ}\text{C}$	Strong cold stress
$-27 \text{ }^{\circ}\text{C} \geq UTCI > -40 \text{ }^{\circ}\text{C}$	Very strong cold stress
$UTCI \leq -40 \text{ }^{\circ}\text{C}$	Extreme cold stress

The simulation workflow

This paragraph describes the main steps of the workflow followed to obtain the MRT and UTCI maps in the Grasshopper environment. Firstly, it is necessary to create the geometrical model of the urban canyon. In particular, after defining the thermal zones of the selected buildings with the “Honeybee_Masses2Zones” component, it is essential to define the *ground thermal*

zone properly. This step allows considering into the model the surface temperature of every single area of the ground, that will directly influence the evaluation of the MRT inside the urban canyon.

The ground thermal zone is a volume delimited by the following three elements (Phase 1 in Fig. 3): side surfaces (whose height can be set to 50 cm), a lower surface (i.e. the base of the ground thermal zone) and the urban canyon surface (i.e. the street surface). Moreover, the ground floor surfaces of the buildings must also be included. Through the “Honeybee_Generate Test Points” component, the ground can be divided into a grid, setting the pitch to 1 m (`_gridSize`). Then, all the created surfaces will be jointed with “Brep Join” and “Cap Holes Ex” components and, eventually, the ground zone is formed through “Honeybee_Masses2Zones” and “Honeybee Create_EP_Ground” (see Phase 2 in Fig. 3). The latter allows setting the specific type of ground. In this case, the solar absorptance of asphalt was set to 0.8 (meaning that the albedo is $r = 0.2$).

After determining the thermal characteristics of external walls and windows, together with the schedules for the internal loads (lighting and occupancy) and the heating/cooling set point, it is possible to carry out the dynamic simulations by using OpenStudio 2.1.0 and EnergyPlus 8.5.0. Our simulations refer to 30th August at 13:00 and 14:00.

The next step consists in processing the outputs of the dynamic simulations to generate the MRT and UTCI map (Fig. 4). First, one needs to use the component called “Honeybee_Indoor View Factor Calculator” to calculate the view factors between each point of the grid, with a height of 1.1 m from the ground, and all surfaces that compose the urban canyon, including also the sky surface (ray-tracing approach). The view factors are required to compute the long-wave MRT through the following equation:

$$MRT_{LW} = \left(\sum_{i=1}^N F_i \cdot T_i^4 \right)^{1/4} \quad (3)$$

Here, F_i are the view factors between each point of the grid and the surrounding surfaces, and T_i is the temperature of these surfaces.

To this aim, the output of this component (`viewFactorMesh` and `viewFactorInfo`, see points 2 and 3 in Fig. 4) is used by “Honeybee_Outdoor Comfort Analysis Recipe” component, which also receives information about the outdoor surface temperatures (see point 4), in order to generate an output called `comRecipe` (point 5). The latter is a matrix containing all the essential variables for defining MRT (such as air temperature, wind speed, relative humidity, view factors, wearing absorptance, scattered solar radiation, direct solar radiation, horizontal global radiation), which is calculated according to Eq. (2). Finally, the “Honeybee Microclimate Map Analysis” component generates the MRT and UTCI matrixes for the period indicated through the input “Analysis_Period_or_HOY”.

Figure 3: Grasshopper components to create a Ground zone

Figure 4: Grasshopper components to obtain MRT and UTCI maps

Results and discussion

Measured parameters

This paragraph shows the main results of the measurement campaign carried out on 30th August 2018 in the selected urban canyon. In particular, from Figure 5 it is possible to observe that the relative humidity (RH) oscillates between 40 % and 55 %, which is very close to the reference relative humidity assumed for the UTCI calculation (50 %). The CO₂ concentration, even if affected by sudden variations, shows a decreasing trend from 380 ppm at 13:15 to 360 ppm at 15:00, associated with the reduced number of vehicles travelling during this period of the day. Moreover, the wind velocity component along the axis of the canyon shows a very irregular trend, which is a typical condition of urban canyons. The values can drop from 3.0 m/s to around 0.1 m/s in a few seconds.

The dry-bulb air temperature ranges from 29 °C to 31 °C during the first hour. Starting from 14:10, a sudden increase by around 2 °C is observed. However, in the same time, a steep increase in the black globe temperature is registered: this suggests that both probes, which were previously in the shade of a building, are now hit by direct solar radiation.

Figure 5: Time evolution of the measured parameters (top: relative humidity and CO₂ concentration; middle: wind velocity; bottom: air and globe temperature)

Figure 6: Experimental MRT values in the selected position

This is acceptable concerning the black globe measurements, but the measure of the dry-bulb temperature is altered by the probe overheating induced by the solar irradiance. Accordingly, the calculation of the MRT is limited to the period when both probes were shaded.

Now, based on the parameters measured by the probes, it is possible to calculate the experimental MRT through Eq. (1). This calculation can be performed at each time step (30 s); however, previous studies have shown that the black globe has non-negligible thermal inertia, which is not compatible with the sudden variations in the wind velocity outdoors. Hence, it is appropriate to calculate the MRT on a more extensive time basis (10 minutes), by adopting in Eq. (1) the average of the values measured over this time lapse. The results for both calculation methods are reported in Figure 6.

Outdoor MRT and workflow validation

In order for the simulation model to calculate the MRT accurately in the same position of the probes, it is essential to assign the correct albedo values to all the surfaces. Most of the buildings in the canyon show light colours, apart from building #6 (see Figure 7), which is painted in grey. This justifies the relatively high albedo chosen for the façades, as reported in Table 2. Moreover, according to the literature, the albedo of asphalt varies between 0.05 and 0.2, depending on its colour: the highest end of this range is here adopted (Table 2).

Table 2 also includes the view factors calculated by Ladybug Tools in relation to the long-wave radiant heat transfer from the surfaces to the point of measurement, placed at 1.1 m above the ground. These values suggest that the main contribution to the MRT comes from the ground surface. Being the ground sub-divided into a one-metre grid, the model calculates a different surface temperature for each sub-surface of the grid. Hence, a higher contribution to the MRT is expected from the zones close to the point of measurement. Additionally, the buildings other than #1 and #4 play a negligible role in the MRT calculation. The sky view factor is also relevant, as it is the view factor for the side “fictitious” surface, which amounts to 0.09. In the simulation, this side surface has the same temperature as the sky vault.

Figure 7: Identification of the surfaces in the urban canyon

Table 2: View factors from the point of measurement to the surfaces, and corresponding albedo values

Surface	View Fact.	r	Surface	View Fact.	r
#1	0.234	0.7	#5	0.015	0.5
#2	0.002	0.55	#6	$\approx 10^{-4}$	0.4
#3	$\approx 10^{-4}$	0.6	Ground	0.425	0.2
#4	0.090	0.6	Sky	0.143	-

Table 3: Measured surface temperatures and MRT, and comparison with the simulation outcomes

	13:00	14:00
Surface #1	33.0 °C	33.5 °C
Surface #5	30.6 °C	31.0 °C
Ground surface	33.6 °C	36.2 °C
MRT (measured)	37.0 °C	38.9 °C
MRT (simulated)	36.3 °C	39.4 °C
Δ MRT	- 0.7 °C	+ 0.5 °C

As a final point, since the validation process aims to check the reliability of the Ladybug Tools in the calculation of the outdoor MRT, it is necessary to exclude the influence of other parameters than the geometry of the canyon and the thermal properties of the materials. To this aim, the weather file was modified by imposing the same values of outdoor temperature and wind velocity as those measured in the urban canyon.

The main results of this first simulation are reported in Table 3, together with the comparison between measured and simulated MRT values. The results refer to two different hours of the day; in both cases, the probes were in the shade. It is first possible to observe that the outside surface of building #1 is constantly hotter than for building #5. This is coherent with the fact that the façade of building #1 faces South and is hit by the direct solar radiation. In geometrical opposition, the façade of building #1 faces North, and it only receives diffuse solar radiation. Moreover, the ground shows the highest temperature, due to its low albedo.

As far as the MRT is concerned, the results of the simulation show a promising agreement with the measured values. Indeed, the absolute value of the discrepancy is 0.7 °C at 13:00 and only 0.5 °C at 14:00. In the following section, further analyses will be carried out to understand whether a more suitable choice of the albedo for the façades and the ground can reduce this discrepancy.

Figure 8: MRT profiles along the width of the canyon

Figure 9: UTCI maps for three different hours on 30th August

The proposed workflow allows calculating the MRT variation along any section of the canyon. As an example, Figure 8 shows the MRT profile along the width of the canyon, between building #2 and building #5. The very high MRT values occurring at 14:00 between point A and point C, i.e. from 48 °C to 53 °C, are justified by the direct solar radiation hitting the façade of building #2, as well as every pedestrian walking here. Then again, point D and point E are in the shade, due to the shading effect of building #5: here, the MRT values at 14:00 lie between 34 °C and 35 °C.

Furthermore, Figure 8 suggests that the MRT at morning and in the late afternoon is quite uniform through the canyon and does not exceed 40 °C. At 10:00 all points except point E receive direct solar radiation; however, the intensity is weak, and it is not sufficient to produce considerable surface heating. On the other hand, at 17:00, the sun is low, and all the points are in the shade, which justifies the small MRT values.

Finally, one more potential output from the proposed parametric workflow is the UTCI map. Figure 9 reports three maps for the 30th of August, referring to three different moments of the day. The worst situation occurs at 14:00, when in a large portion of the canyon the UTCI ranges between 35 °C and 37 °C. This implies strong heat stress according to the UTCI categories (see Table 1). In the remaining parts of the canyon, i.e. in the shaded areas, the UTCI is between 30 °C and 32 °C, meaning moderate heat stress. The situation is slightly better at 17:00, when the UTCI does not exceed 34 °C: nevertheless, this implies strong heat stress. On the contrary, at 10:00, the UTCI is below 32 °C: this conditions leads to moderate heat stress.

Sensitivity analysis to the surface albedo

This section discusses the results of a sensitivity analysis aimed at identifying the impact of lower albedo values on the energy needs and the outdoor comfort conditions, measured through the MRT and the UTCI.

To this aim, three additional simulations are carried out, starting from the albedo values adopted in the validation stage, which is identified as “Case A” (see Table 4). In particular, in “Case B” the albedo of the buildings located in the Northern side of the canyon – with the façades facing South – is set to $r = 0.4$, while all the other surfaces keep the same albedo as in “Case A”. In “Case C”, the same change to the albedo is applied to the façades of the buildings located on the Southern side. Finally, in “Case D” the albedo of the ground is modified: $r = 0.05$ is proposed, since this is the lowest possible albedo for asphalt as reported in the literature.

The results of the sensitivity analysis are shown in Table 5 and Figure 10. The values of the thermal load for space heating and cooling are calculated by setting an ideal thermostatic control for indoor air temperature at 20 °C in winter and at 26 °C in summer and integrated over the entire season. The results reported in Table 5 are the average values for all the buildings belonging to the portion of the urban canyon (Figure 7).

Table 4: Albedo values for the proposed cases
 (“-” means that the same value as in Case A is applied)

Surface	Case A	Case B	Case C	Case D
#1	0.7	0.4	-	-
#2	0.55	0.4	-	-
#3	0.6	0.4	-	-
#4	0.6	-	0.4	-
#5	0.5	-	0.4	-
#6	0.4	-	0.4	-
Ground	0.2	-	-	0.05

Table 5: Mean energy needs for space heating and cooling (in kWh/m²) and relative variation compared to Case A

	Case A	Case B	Case C	Case D
Cooling	20.4	21.4 + 5.0 %	20.6 + 1.0%	20.4 =
Heating	11.8	11.4 - 3.5 %	11.6 - 1.8 %	11.8 =
TOTAL	32.2	32.8 + 1.8 %	32.3 =	32.2 =

Figure 10: Effect of the albedo on the outdoor thermal comfort

The sensitivity analysis suggests that a reduction in the albedo of the façades exposed to the direct solar radiation, as in Case B, brings about adverse effects. In particular, the outdoor MRT perceived in the point of measurement (see Figure 7) increases by 0.5 °C, even if this is less evident in terms of UTCI, which raises by 0.2 °C. Moreover, the mean energy needs for cooling increase by 5 % in the summer (see Table 5); however, in the winter the buildings benefit from the higher solar absorption rate, and the mean energy needs for heating decrease by 3.5 %. On an annual basis, the total energy needs increase by nearly 2 % if compared to Case A.

On the other hand, a lower albedo for the buildings facing North, as in Case C, has only very limited consequences. Indeed, the impact of the albedo on the thermal performance is minor for a façade hit by the only diffuse solar radiation. Hence, the variation of the energy needs compared to Case A is below 2 % on a seasonal basis, but it becomes negligible on an annual basis (Table 5). The changes induced on the MRT and UTCI values are negligible too.

The sensitivity analysis also suggests that decreasing the asphalt albedo from $r = 0.2$ to $r = 0.05$ has only minor consequences in terms of outdoor thermal comfort, as highlighted in Figure 10, where the results for Case D are very close to Case A. In fact, one might guess that the higher absorption rate should imply a higher ground surface temperature, hence a more intense longwave radiant heat transfer from the ground to the pedestrians. However, this effect is offset by a lower shortwave reflection from the ground, which makes in this case the UTCI and MRT values almost unchanged. Finally, the variation of the asphalt albedo does not affect the energy needs of the buildings.

Conclusion

The paper has introduced a parametric workflow that can simulate the thermal behaviour of several buildings at a district level, as well as their interaction with the outdoor space. The workflow is implemented on Grasshopper and relies on its plug-ins Honeybee and Ladybug. As a result, it allows calculating the dynamic thermal load of the buildings overlooking the canyon, and several parameters needed to assess the outdoor thermal comfort, such as the *Mean Radiant Temperature* (MRT) and the *Universal Temperature Climate Index* (UTCI).

The reliability of the workflow has been tested in an urban canyon located in Catania, Southern Italy, where the façades have a relatively high average albedo values ($r = 0.6$). In particular, the results concerning the MRT are compared to on-site measurements performed with a black globe thermometer during a sunny day in summer. The results of the validation are encouraging since the simulation shows good agreement with the measured values: indeed, the absolute value of the discrepancy is around 0.5 °C on a selected point.

After the validation stage, a sensitivity analysis has shown that a lower albedo ($r = 0.4$) for the South-facing façades induces an increase by up to 0.5 °C in the outdoor MRT perceived by pedestrians, which also induces a slight increase in the UTCI (+ 0.2 °C). This outcome does not agree with other similar studies in the literature, based either on experimental measurements or on the use of more advanced software tools such as Envimet. This suggests that the algorithm used by the Ladybug Tools to assess the outdoor MRT may have a certain degree of inaccuracy in the treatment of the shortwave solar radiation reflected by the façade towards the pedestrians. On the other hand, the workflow correctly suggests higher energy needs for cooling in the buildings belonging to the urban canyon because of a reduced albedo.

On the contrary, a lower albedo ($r = 0.4$) for the buildings facing North has negligible consequences in terms of outdoor thermal comfort and energy needs for heating and cooling, and similar results occur when decreasing the asphalt albedo from $r = 0.2$ to $r = 0.05$.

In comparison to other existing approaches, the workflow proposed in this paper offers greater flexibility and the complete modelling of the indoor/outdoor thermal fields on a single software platform. This makes it possible to perform a parametric investigation of the effects of different design solutions on the indoor and outdoor environment, both for new and existing buildings.

Future works will include into the parametric workflow a further module for morphing the weather file, thus taking into account the Urban Heat Island effect, based on the Dragonfly plug-in. Moreover, more detailed experimental measurements will be performed, while further analyses will try to solve possible suggested inaccuracies in the algorithm.

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