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Will Cities Survive?

Data-Driven Design for Climate Adaptation:
Validating Ladybug Tools for street-scale microclimate design

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ABSTRACT: Small, street-scale microclimatic design offers significant advantages in adapting to extreme temperatures expected due to climate change by improving the thermal comfort of outdoor urban space. This can improve health and wellbeing of city inhabitants, reduce energy demands and improve individual adaptive capacity to extreme temperatures. Designing, however, for outdoor thermal comfort is complex due to the dynamic nature of microclimate. Environmental simulation offers a tool to connect microclimate science to design but if used in design, is more likely to be applied to site analysis or evaluation of a project. This paper compares measured versus simulated surface temperatures to validate a workflow which relies on the parametric environmental analysis plugin for Rhino: Ladybug Tools to analyse the effect of a shading canopy on the thermal environment within a street canyon. Ground and Canopy surface temperature show a 0.868 and 0.901 r^2 value, respectively, indicating good prediction capability from Ladybug Tools. Ladybug Tools interface with 3D modelling software Rhinoceros, fast simulation time and parametric capabilities facilitate a feedback process between microclimate science and design helping to embed microclimate into design practice.
KEYWORDS: Outdoor thermal comfort, microclimate simulation, Ladybug Tools, shade canopy

1. INTRODUCTION

Outdoor urban space is as important to the survival of cities as the buildings it surrounds, providing not just connecting space but also a place for leisure, refuge, social and political life. In a post Covid world, urban outdoor space has taken on even greater value and new functions; entertainment, sport, education and important life celebrations, have moved (or returned) to the streets and city squares.

Rising temperatures due to climate change alongside the Urban Heat Island significantly affect the usability of this space and thus the liveability of cities[1]. On a large-scale, climate adaptation measures may not succeed in counter-acting the predicted rise in urban air temperatures[2]. However, improving the microclimate and thermal comfort of outdoor urban space at the street scale can offer multiple advantages that can contribute to the overall resilience of a city to climate change. Comfortable microclimates improve health and wellbeing and reduce energy demands by encouraging people to spend more time outdoors.[3,4] Thermally comfortable outdoor space can also support a level of individual adaptation at the pedestrian scale by providing cool 'refuges' that allow citizens to find relief during extreme heat events.

To design thermally comfortable outdoor space is complex, with multiple variables from physical surrounds, climate and the individual characteristics of users interacting to produce continually changing thermal sensations over time and across space. Designing for such a complex characteristic requires climate-responsive, data-driven design, grounded in a qualitative and quantitative understanding of how design decisions influence the microclimate of the space and the thermal experience of the user. Environmental simulation can provide a platform to designers to connect microclimate science & research to practice by allowing them to visualise site conditions and analyse and test the effects of projects on thermal comfort. If applied in the early stages of design, it becomes a tool to develop data driven design projects for climate adaptation.

Much of the existing software for outdoor microclimate analysis, however, does not lend itself well to the design process, either requiring a prohibitive amount of time for preparation and analysis of the model or significantly restricting the scale and geometry that can be tested.[5,6] This paper presents the validation of a microclimate model that uses design tools and easily accessible methods of data collection to analyse and visualise a microclimate mitigation design strategy on urban surface temperatures. A built design project of a shade parasol is used to study the effect of shading and materials on the thermal environment, providing a case study of one of the most simple yet effective methods of microclimate mitigation at a scale relevant to designers.

2. CONTEXT

2.1 Solar Radiation and Shading

The shade parasol offers a valuable case study because the moderation of solar radiation in the urban environment can have significant impact on thermal comfort.[7] Shade reduces direct heat gain by users as well as surrounding urban surfaces, directly improving thermal comfort both outdoors and indoors and reducing building energy use.[8,9] As a design strategy, shade canopies can offer extreme flexibility in terms of design and installation and target the microclimate variable most sensitive to design intervention (solar radiation). They provide small-scale rapid adaptation strategies that can be easily implemented in pre-existing urban areas and easily adapted to the local space. As such they represent one of the most common strategies used to improve outdoor thermal comfort.

2.2 Microclimate Simulation

The model uses Ladybug Tools (LBT)[10] a plugin for Grasshopper of Rhinoceros 3D[11], that is already widely used in design offices. Recent studies have found acceptable similarity between EnviMet (considered most accurate for outdoor microclimate modelling) or field measurements and LBT in assessing thermal comfort at the neighbourhood scale.[12,13] The greatest advantage it offers over other microclimate modelling software is the parametric capabilities: once validated, the model can be used to test multiple design parameters such as canopy dimensions, or material properties; as well placed in different street forms and climates, without re-modelling. Being parametric, the set up allows for the designer to adjust the type of analysis needed for the project. Thus, radiation studies, energy modelling or Computational Fluid Dynamics analysis may be run separately, and different outputs collected and visualised, from irradiance values to UTCI index. With this flexibility, the simulation time can be extremely rapid in comparison to other microclimate simulation software creating a feedback process between design and effect that allows the designer to gain a strong understanding of the microclimatic impact of their design. There is also very little restriction on the 3D geometry modelling allowing for the analysis of small-scale projects and fine detail. As such the tool facilitates an important iteration/evaluation process in the initial stages of design.

The downside of such flexibility can result in unreliable results if the designer does not understand the data needed, the parameters they are changing, or what kind of analysis is necessary. There is a balance to find in the use of Ladybug tools for microclimate simulation, however, the need for greater climate sensitivity in design versus complete accuracy weighs in favour of a rapid visualisation tool, that when supported by an active forum and detailed resources can offer a powerful design tool.

3. METHODOLOGY

Figure 1 illustrates the workflow to set up the microclimate model for calibration and illustrates the next steps for use as a design tool. The workflow was adapted from two example scripts used to simulate UTCI in a street canyon, and surface temperatures underneath a tree canopy.[14,15] Both environmental monitoring and modelling are combined in the workflow: the exact process followed is explained further in Section 4 using a shade parasol as case study.

Surface temperatures are the selected data for validation. While LB (radiation analysis) alone could be sufficient for understanding the microclimatic effect of shading strategies in the initial stages of design, this analysis focuses on simulating surface temperatures through HB because they are a relatively simple data type to collect and, they provide a common unit of information in understanding the effect of materials and shading on thermal comfort, as well as linking outdoor and indoor conditions. This is particularly relevant where materials such as photovoltaics, or 'cool materials' are used because their use results in significantly different surface temperatures when compared to ambient temperature. If modelled solely as a 'shade', the canopy would be assumed to follow the surrounding air temperature.

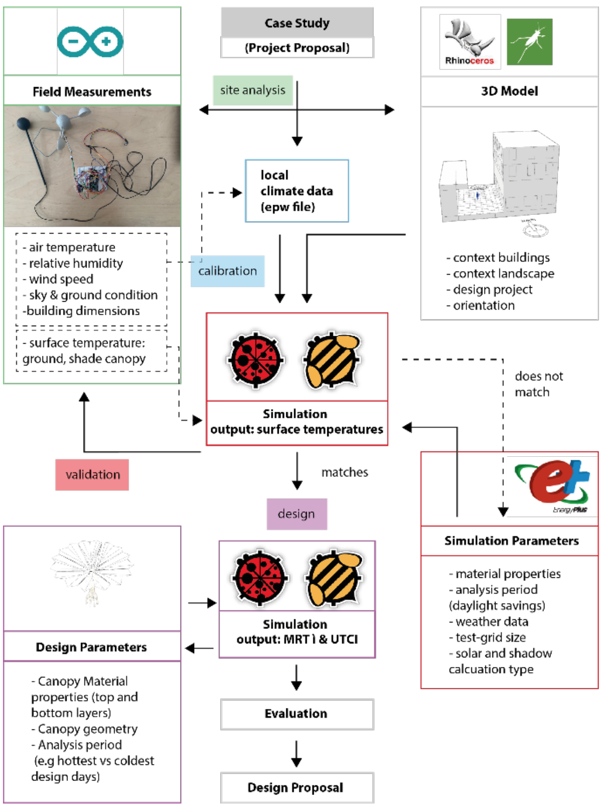

Figure 1| *Ladybug Tools Microclimate design workflow*

4. CASE STUDY

The case study is a redesign of the traditional beach umbrella, incorporating a foldable parasol integrated with thin film amorphous silicon photovoltaics. It measures 2.51m high with a 3.16m diameter and was developed by design firm Carlo Ratti Associati (CRA), for an installation in Milan to provide a 'cool' leisure space in one of the city's main parks during August.

Figure 2| *Canopy installation and sensor set up at test site*

The parasol was installed at CRA's factory (fig. 2), located in a mixed industrial/residential area northeast of Turin centre (lat: 45.1° N, 7.7° E). The site itself is a narrow 'canyon' bordered by a cement wall with an overhanging walkway on the western edge, and the factory on the eastern edge. The ground is a cement grid infilled with soil and sparse grass. The photovoltaics were not active during monitoring.

4.1 Monitoring

Data on ground temperature, the temperature of the underneath layer of the canopy and air temp, relative humidity and wind speed were collected to calibrate the model. Fig. 3 shows the location of sensors while the exact equipment and corresponding standards[16] are presented in Table 1. Standards for measuring outdoor thermal comfort don't exist, however, the sensors used comply or come close to compliance with those used for indoors. The anemometer was compared against a validated anemometer for verification since specifications were not provided.

Table 1 | Sensor specifications used in measuring outdoor microclimate variables.

Variable	Sensor	Range	Accuracy	ASHRAE 55
Air Temp °C	AHT20	-40 to +85	±0.3	±0.2
Rel. Humidity %	AHT20	0 to 100	±2	±5
Wind Speed m/s	WH-SP WS01	unknown*	unknown*	±0.05
Canopy Temp °C	Mlx90614	-40 to 125	±0.5	±1
Ground Temp °C	Tiny Tag Plus 2	-40 to +85	±0.01	±1

On the day of testing (17th September 2021) the weather conditions were clear and dry with no precipitation in the preceding days. From 10.00 to 18.00 hrs measurements were taken at five-minute intervals. Soil composition, cloud cover and shading patterns were also observed.

4.2 Modelling

Grasshopper is used to link 3D modelling of the site to LBT. The radiation analysis and energy modelling functions of LBT were used for the analysis: Ladybug (LB), to analyse climate data, create a shade map for comparison with field observations and visualise results; and Honeybee (HB), which creates an interface between the grasshopper/rhino platform and validated building energy modelling engine, EnergyPlus (EP)[17] to calculate surface temperatures of modelled thermal zones.

4.2.1 Climate Data

The local area weather file, in EnergyPlus weather format (EPW) can be downloaded through LB by connecting to a database of the world's currently available opensource weather data.[18] The collected site data alongside cloud cover observations were used to find the best matching 24-hour period in the EPW file. The epw air temp, RH and wind speed were replaced with the collected data and solar radiation values kept in order to calibrate the model to the specific local conditions of the site. EP also relies on the EPW file for the warmup period of the simulation, using weather data from the previous days until convergence is reached, from a minimum of 6 up to 25 days.

4.2.2 Geometry

Surrounding built form and ground geometry were modelled parametrically in Grasshopper, based on observations and measurements taken physically at the site and through GoogleEarth's 3D modelled buildings. A shading map generated by LB's 'Incident Radiation' component was compared to photos of modelled vs real geometry. The geometry to be evaluated for surface temperatures was converted to separate thermal zones with the outdoor exposed surfaces of the ground and canopy broken into small grids of 0.5m in order to capture the shading effects of small-scale geometry.

4.2.3 Materials

Construction materials were based on those defined in the EP constructions database or, for the case of the non-standard surfaces, derived from data collected on site, specific references found in literature or general theory when an exact reference could not be found (type and corresponding references indicated in Table 2 & 3). Two specific HB components: 'Opaque Material No Mass' and 'Vegetation Material' were used to represent ground and canopy. Default values embedded in the component were used where the value was unknown. The underside canopy layer is not included since a 1mm layer of PVC coated polyester would have very little effect on the thermal transmission of the PV layer and therefore negligible effect on surface temperature. This was confirmed in the simulation once calibrated.

Table 2| *Assigned Canopy material properties*

Properties	Amorphous silicone photovoltaic
R-value (W/m.K)	0.2[21]
Roughness	Very Smooth[o]
Thermal Absorptivity	0.2[19]
Solar Absorptivity	0.85[19]
Visible Absorptivity	0.85[19]

Table 3 | *Assigned ground material properties*

Properties	Grass & Moist Clay Soil
Plant Height (m)	0.05 [o]
Leaf Area Index	0.75[o]
Leaf Reflectivity	0.22[d]
Leaf Emissivity	0.95[d]
Soil Reflectivity	0.3[d]
Soil Emissivity	0.9[d]
Stomata resistance (s/m)	180 [d]
Thickness (m)	0.2 [o]
Conductivity (W/m-K)	3[20]
Density (kg/m^3)	2000[20]
Spec. Heat Capacity (J/kg-K)	1500[20]

o = observed *d = default* *# = reference*

4.2.4 Energy Loads

The buildings were assigned default construction and energy load schedules for a warehouse (bottom floor) and medium office (remaining floors) based on the EP database. Ground was converted to zero loads through the 'Make Ground' Honeybee component and the canopy also converted to zero energy loads through 'Plenum Zone' component.

4.2.5 Canopy Thermal Zone

To successfully run in EP, all thermal zones must be closed 'rooms' composed of planar surfaces. This results in an enclosed volume of air within the zone and limit on the minimum thickness of the zone. To work around these limitations the canopy was modelled as the roof of a thermal zone, consisting of walls with 95% surface area made up of 'windows' scheduled to remain open at all times (Fig. 3**)** In this way the canopy could be modelled without an air gap that could affect heat transfer and with the representative thickness of 3mm.

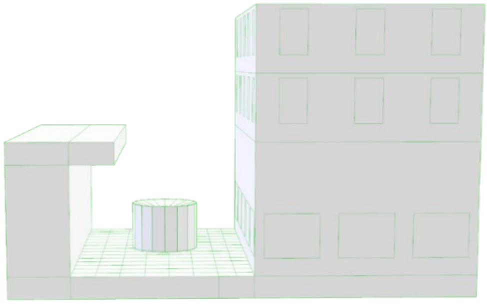

*Figure **3|** Canopy modelled as roof of enclosed room*

4.2.6 Simulation Parameters

The model was connected to EP with a 24-hour analysis period of 12 timesteps/hr (5-minute intervals) and polygon counting for shadow calculation method. All other parameters were left as default. Surface temperatures and surface energy flow were specified outputs. The run time is approximately 5 minutes on a laptop computer with intel core i7-1065G7 and 1.30Ghz CPU. Once validated and run with 1 timestep/hour simulation time can be further reduced significantly.

4.2.7 Visualisation

The outer surface temperatures were extracted for the entire model and visualised through 'HB colour faces' component on the Rhino 3D model. This can then be displayed as average outer surface temperatures or surface temperatures for every time step of the analysis period. Further analysis and visualisation were performed by selecting the grid face of the canopy and ground surface corresponding to the sensor locations on the site. The values for the 24-hour period were then extracted through Ladybug data analysis components and exported to a csv file to be analysed.

5. RESULTS

As the results in Figure 4 and Table 4 below indicate, simulated temperatures for both canopy and ground can be considered acceptable for the purposes of design comparison with an R^2 value of 0.86 for ground and 0.9 for canopy. Temperatures followed measured data closely up until 12H, where slightly higher peak temperatures were reached both by the simulated canopy and ground. As temperatures decrease around 15H, greater agreement is reached in ground temperatures while canopy temperatures remain up to 10K higher. The

Table 4| *Coefficient of determination statistical tests for measured vs simulated temperatures.*

	Ground	Canopy
R^2 Value	0.868	0.901

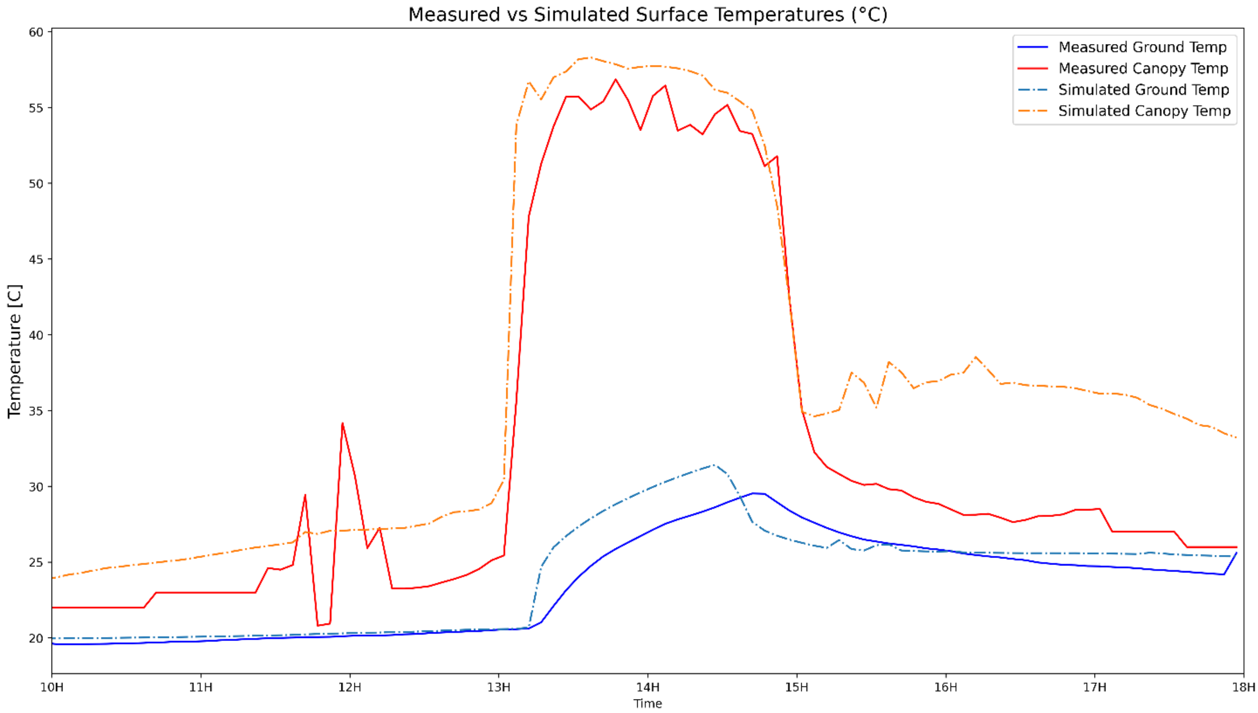

Figure 4**|** *Measured vs Simulated Surface Temperatures for Shade canopy case study using Ladybug Tools*

rapid gain in temperatures can be attributed to direct solar radiation reaching the sensor points both in the simulation and at the test site indicating the major role direct sun plays in surface temperatures. The differences between simulated and observed temperatures could be due to the inaccuracy of the material property inputs. The reliance on mostly EPW weather data, particularly the radiation values could also have affected accuracy of the simulation. To be further investigated, is the reason for the small peaks between 15H and 17H for both canopy and ground simulated temperatures and the increase in simulated canopy temperature in late afternoon (probably related to modelling the canopy as a room) Measured Canopy results show errors in the sensor set up encountered during the morning due to a faulty wire connection.

6. DISCUSSION

An effort was made to simplify the modelling and simulation process to maintain user friendliness, with as many inputs as possible left as default. Canopy geometry and materials carry the most complexity for the user and can significantly affect accuracy of results. EP provides many pre-defined materials and constructions based on standard buildings, however, when applying non-standard materials such as photovoltaics, custom properties need to be derived either from literature, measurements or theory. The use of the 'No Mass Opaque material' component allowed for the representation of a very thin material, requiring only five defined properties, simplifying the process of simulating canopy materials with unknown thermal properties. However, despite the more simplified inputs, this stage adds extra complications for the user, requiring knowledge in areas not usually familiar to architects and urban designers.

Other parameters with noticeable effects on results included time steps, context building heights and orientations and the analysis grid size. In a more exposed site, where wind speeds are greater, CFD or more detailed wind speed measurements may also be needed to provide a more accurate representation of the effect of wind.

It is recommended that, to create a more direct connection between designer, design, microclimate and user, the model, once validated, is used to calculate more communicative indices, such as the UTCI, which can be calculated using LBT components. A further step in this research would be to use the calibrated model in designing an optimised shade canopy design for thermal comfort, and in testing its effect in different microclimatic contexts thus linking microclimate to design.

5. CONCLUSION

The described methodology, using already established design software for simulation, paired with field measurements, was adopted in order to assist in an in-depth analysis of the shade parasol case study and provide an example of how design and microclimate can be linked. The software is parametric with extremely rapid processing time and this, in addition to the Arduino sensor kit allowing for easy and localised data collection, provide an accessible design tool that allows designers to study how both material and shade contribute to thermal comfort in urban settings.

The simulation can be used to optimise microclimate strategies such as shade canopies and through careful assignment of accurate material properties, to understand the effects of more advanced cool materials, photovoltaics and double skin structures that are beginning to be applied to urban surfaces as climate adaptation measures. The speed of simulation and additional scheduling and optimisation capabilities that LBT and native Grasshopper components allow also means responsive structures that adjust to environmental conditions throughout the day can be modelled allowing further design development of this fast-growing field.

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