Ibrahim, YI, Kershaw, T & Shepherd, P 2020, 'A methodology For Modelling Microclimate: A Ladybug-tools and ENVI-met Verification Study', Paper presented at 35th PLEA CONFERENCE SUSTAINABLE ARCHITECTURE AND URBAN DESIGN, A Coruña, Spain, 1/09/20 - 3/09/20.

PLEA 2020 A CORUÑA

Planning Post Carbon Cities

A methodology For Modelling Microclimates:

A Ladybug-tools and ENVI-met verification study

YASSER IBRAHIM[1], TRISTAN KERSHAW[1], PAUL SHEPHERD[1]

[1]Department of Architecture & Civil Engineering, University of Bath, Bath, UK

ABSTRACT: Over the last decade, outdoor thermal comfort has become of considerable significance to urban designers and planners. In that concern, parametric design models were acknowledged for supporting the design process with iterative performance-based solutions and for being relatively less time and resource consuming. However, validation studies for such parametric models on the outdoor urban scale are lacking. Meanwhile, studies concerned with geometry optimisation are computationally expensive due to the time required per each simulation. This paper consequently investigates the accuracy and time efficiency of using the workflow comprising the environmental analysis Ladybug-tools, the plugins of Grasshopper3D for modelling the outdoor microclimate. The study verifies the model's results against the microclimate CFD simulation tool, ENVI-met. The two models are compared in terms of two environmental metrics, the mean radiant temperature and the universal thermal climate index. In this paper, three hypothetical layouts representing basic urban geometry patterns, namely linear, dotted, and courtyard, are simulated in both models. Results show an acceptable range of consistency between Ladybug-tools and ENVI-met, particularly during the hours 8 am to 5 pm. Timewise, Ladybug-tools show their capabilities of not only modelling the microclimate but also their suitability for optimisation studies characterised by a vast number of design solutions.

KEYWORDS: Ladybug-Tools, ENVI-met, Thermal Comfort, MRT, UTCI

1. INTRODUCTION

Over the past few years, outdoor thermal comfort has gained increased attention between urban climatologists and developers who have sought to precisely imitate the built environment. In this sense, researchers have been trying to either distinguish the most accurate models or develop an ad-hoc methodology. Some have coupled different models for a concerted performance, while others have validated the computational models to field observations or verified against already validated engines. A case in point is the study of Naboni, et al. [1] who compared five models, namely ENVI-met, RayMan, CitySim Pro, Ladybug-Tools and Autodesk CFD. Their study, however, showed a significant incongruity between the models, particularly during the summer. This incongruity could be ascribed to the materiality of building constructions and the meteorological inputs for each model.

Furthermore, Jänicke, et al. [2] compared ENVI-met, RayMan and SOLWEIG to field measurements of a green façade for the estimation of heat stress. Their results for calculating the Mean Radiant Temperature (MRT) have shown a mean deviation up to 7 K from the observations. Perini*, et al.* [3] interpolated the output wind speeds, and plants vapour flux from ENVI-met into TRNSYS in a coupled methodology for estimating the Universal Thermal Climate Index ($UTCI$). Finally, Elwy*, et al.* [4] validated the Ladybug workflow against ENVI-met and field measurements. Results have shown an acceptable range of agreement in terms of Physiological Equivalent Temperature (PET) comparisons, however without a clear elaboration for the temperatures' variations. Meanwhile, the study of the effect of urban morphology on the microclimate entails a huge computational power and extensive simulation time, particularly when using CFD simulations, and hence most of the studies concerned with geometry optimisation are limited to a few number of canyon configurations [5, 6]. Consequently, this paper aims at presenting the Ladybug-tools as accurate and time-efficient for modelling the microclimate as compared to the CFD simulation model, ENVI-met v.4.4.3.

2. METHODOLOGY

Before the version 4.4.0, ENVI-met did not allow for forcing the solar radiation inputs and instead used its embedded terrestrial coordinates to obtain solar radiation values all across the globe [7]. From version 4.4.0 onwards, ENVI-met has enabled the users to full force the meteorological parameters, allowing users to make direct comparisons with other simulation engines. It is worth noting that ENVI-met accounts for the vegetation interaction with the microclimate elaborately, as opposed to Ladybug-Tools which gives an estimation of the evapotranspiration based on the green coverage ratio along with the plant's albedo and uses the UWG for doing so. Accordingly, in order to avoid these ambiguities, the three hypothetical simple layouts representing the commonly used urban geometry arrangements in Cairo, viz. linear, dotted, and courtyard (Figure 1), are modelled solely in the form of buildings and a ground surface.

2.1 Methods

Mackey*, et al.* [8] introduced the hybrid workflow for estimating the MRT, and mapping the microclimate in a graphical representation. The workflow is based on utilising the plugins of Grasshopper, presumed to simulate each of the thermal comfort determinants individually, and further combine them collectively for comfort calculation. Geometries are firstly created on the Grasshopper canvas to serve as a feeder for different plugins. An elevation model along with average building heights, ground and green coverage ratios, façade to wall ratio as well as thermal properties of constructions are fed into the -UWG-Dragonfly components to morph the .epw file to reflect the urban conditions. MRT is estimated by the three fundamental components; direct solar radiation; atmospheric long-wave radiation; and surface long-wave radiation. The latter is estimated through the EnergyPlus simulation, which is part and parcel of the Ladybug-Tools. The output of this step is outdoor surface temperatures which are further weighted by their view factors using the ray-tracing engine in Rhino. Butterfly could potentially integrate OpenFOAM simulations within the workflow for modelling the urban wind patterns. The sky long-wave radiation and the direct short-wave radiation are accounted for by following the equations specified within the MENEX model and the SolarCal model, respectively. Eventually, by virtue of a generic component, the model provides a full range of thermal comfort indices, e.g. PMV, PET, and $UTCI$ with a graphical representation.

On the other hand, among the models developed within the field of urban climatology, the 3D numerical model ENVI-met is one of the most convenient models for assessing thermal comfort. The model accounts for all the heat exchange processes between the urban surfaces, vegetation and the airflow field in high temporal and spatial resolutions, as well as calculating all the meteorological parameters governing outdoor thermal comfort, e.g. MRT [9]. ENVI-met has been validated against field measurements [7] and has already been widely used in UHI studies [10]. Drawbacks of the model, nonetheless, include overestimation of global radiation [2], unless measured data is forced to the simulation inputs. Also, ENVI-met requires increased time for modelling geometries from raster-based images, unless linked with Grasshopper which allows for exporting geometries to ENVI-met, albeit, with slight differences due to grid cells variations. The main disadvantage of the model is its excessive simulation time required which approximates real-time; in other words, 24 hours to simulate a day of the year.

2.2 Modelling and parameterisation

Layouts were modelled so far as is reasonably practicable and time-efficient within each model. Geometries are modelled in ENVI-met on a raster basis while for Ladybug-Tools are modelled parametrically in Grasshopper. Figure 1 and Figure 2 show the geometry configurations and a 3D presentation for each layout, where these configurations were estimated from real case studies in Cairo. The coloured circles denote to the points of interest, which shall be further analysed and discussed. Since the study is concerned with the assessment of outdoor conditions, buildings were modelled with no fenestrations.

ENVI-met. Buildings were modelled on a 2m grid horizontally and $h_{max} \times 4$m grid vertically with ten nesting grids from all directions, assuming a flat terrain and the absence of anthropogenic sources. Default building construction materials were used from the ENVI-met database. Building indoor temperature is set to 20 °C, where ground temperatures are set to 25 and 22.5 °C at 2m and 4m depths respectively.

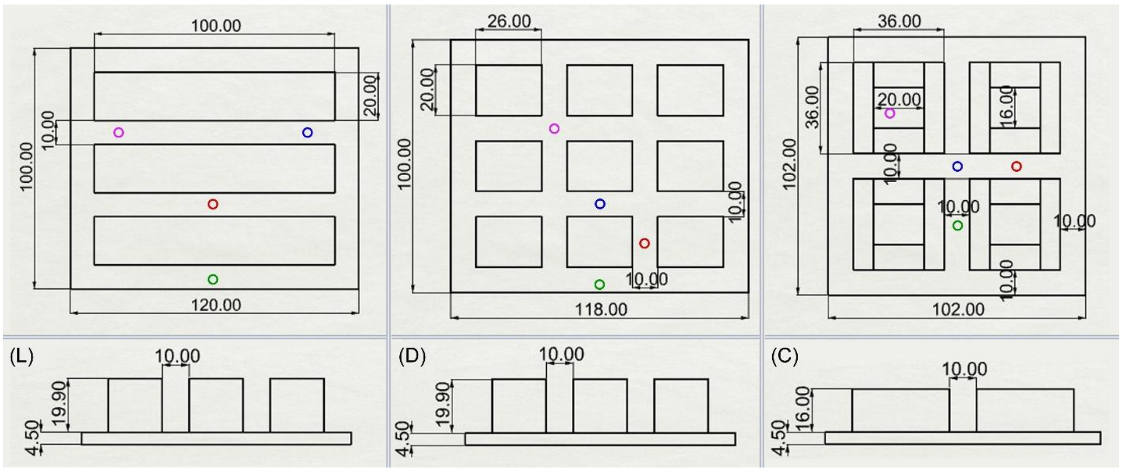

Figure 1: Geometry configurations for the three layouts; (L) Linear; (D) Dotted; and (C) Courtyard (dimensions in meters). Coloured circles denote to (Green) Receptor R1, (Red) R2, (Blue) R3, and (Purple) R4.

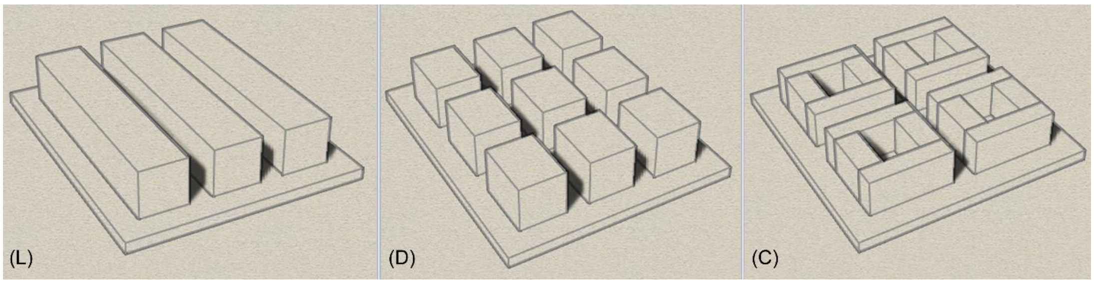

Figure 2: 3D presentation for the three layouts (Exported from Rhino viewport).

Table 1: Construction materials input for both models.

Construction		Roofs	Walls	Ground	Reference
Properties	Unit	[R1] Roofing Tiles	[B2] Brick Wall	[KK] Brick road	
Thickness	m	0.3	0.45	4.5	* obtained online from **[11]**; ** derived with reference to other properties; or # assumed
Solar Absorption	Decimal	0.50	0.60	0.7**	
Solar Reflection / albedo	Decimal	0.50**	0.40**	0.3	
Thermal Absorptance	Decimal	0.90	0.90	0.93*	
Density	$\mathbf{Kg/m^3}$	1900	1500	1900#	
Specific Heat Capacity	$\mathbf{J/Kg\cdot K}$	800	650	1053**	
Vol. Heat Capacity	$\mathbf{MJ/m^3\cdot K}$	1.52**	0.98**	2.00	
Thermal Conductivity	$\mathbf{W/m\cdot K}$	0.84	0.44	1.00	
Material Roughness	-	Medium Rough#	Medium Rough#	Medium Rough#	

Ladybug-Tools. Layouts were modelled in Grasshopper to match those grid points as in ENVI-met. Unless defined within ENVI-met database, materials' properties were either obtained online [11], derived or assumed with reference to the relevant properties (Table 1). Buildings are defined as Honeybee zones with building program set to "not conditioned" Midrise Apartments, where the ground is defined as a virtual EnergyPlus ground, assuming no wind or sun exposure and no internal loads. Following [8], EnergyPlus simulation is set to "Full Exterior with Reflections" at a time step of 15 minutes.

Boundary Conditions. As a representation of the hot arid climate in Cairo, Egypt, a EnergyPlus Weather (.epw) file for both models was available at [12]. As mentioned earlier, ENVI-met allows for the full forcing of meteorological conditions, where the lateral boundary conditions and the cloud cover are disabled and rather being inferred from the .epw file. While EnergyPlus intrinsically extracts the global horizontal, direct normal, and diffused horizontal radiation values necessary for surface temperature calculation from the .epw file, ENVI-met parses the file to get a unique direct maximum radiation which is necessary for ENVI-met to perform the simulations.

Comfort calculations. Simulations were carried out for a total of 15 hours, on June 7th from 5 am to 8 pm representing the .epw extreme hot day in the weather file. Results are demonstrated on the next section in terms of the MRT as one of the main constituents of the human energy balance, and the $UTCI$ as a representation for the outdoor thermal comfort. Results values were measured at 1.2m above ground level as to present a pedestrian thermal sensation point of view. It is worth noting here that, CFD simulations via Butterfly are not performed in this study since it has notoriously increased the time of simulation and curtailed the continuity of the workflow with no substantial effects to the $UTCI$ values. Thus, this study, instead, calculates the canyon wind speeds based on the power law using a specific Honeybee component.

3. RESULTS

In this section, the Ladybug-tools model is referred to as LB, while ENVI-met as EM, Linear, Dotted and Courtyard as L, D, and C respectively. Figure 3 shows the temporal variations of MRT at each of the points of interest, as well as the average values over each layout. The general trend of the curves at all patterns seem to be congruent except where the beam radiation abruptly changes due to being obstructed by buildings (L-R2, L-R3, D-R2, C-R1, and C-R4). Temperature differences of these cases occurred at 2-4 pm with a maximum difference of 32.5 °C in L-R2, while the other maximum differences are registered at 5 am as not exceeding 13.5 °C. Also, apart from the outliers, LB appeared to have higher MRT values during the early hours (5-8am) by almost 12 °C, then rises in tandem with EM, and holds in proximity during the peak hours, and then falls yet with the same higher values during (6-8 pm) by almost 10 °C. Moreover, a thorough analysis of the receptors has shown that those laid in similar canyon positions fluctuated in the same manner. For instance, located outside the canyon, LB-D-R1 and L-R1 keep a pace higher than those of EM by almost 8 °C, except at 4 pm drops by nearly 14 °C. Receptors in N-S canyons (LB-D-R2 and C-R1) maintain minor variations during the shaded hours, yet leap to match the EM peak values during sunlit hours, and register a variation of 17 °C at 2 pm. Additionally, E-W receptors (LB-L-R2, L-R3, C-R2 and D-R3) plummet at 3 pm recording the highest difference of 32.5 °C due to the solar obstruction. Further, canyon intersections (D-R4 and C-R3) and the west side L-R4 possess higher consistency with EM. However, the longer block length in the courtyard design curtails the solar radiation exposure of C-R3 and hence drops at 4 pm by 17.05 °C. Finally, although C-R4 maintains a high congruity during (8 am-1 pm), it plummets at 2 pm to record a 20 °C difference. More intriguing, the general trend of average MRT over the three layouts is quasi-similar. Apart from the early (5-8 am) and late (6-8 pm) hours where differences approach 12 °C, LB stays close to EM with variations not exceeding 6 °C. Influenced by the MRT values, $UTCI$ values have followed the same trend, however with no drastic variations (Figure 4). Maximum differences are manifest during the early and late hours, not exceeding 6.43 °C. That is, with 5.8 °C maximum variation for the average $UTCI$ over the three layouts, LB shows a great conformity with EM during the simulation period and hence exhibits a significant potential to speculate the impact of different urban configurations on the microclimate.

Error calculations are presented in Table 2 showing the Root Mean Squared Error (RMSE), Mean Percentage Error (MPE) and Coefficient of Determination (R^2). In terms of $UTCI$, LB results have shown a substantial level of agreement with EM ($R^2 = 0.97$).

Figure 5 depicts the comfort maps for each layout and shows the resemblance of each pertaining pattern. As aforesaid, differences are evident during the early and late hours. The maps, thus show the Ladybug-Tools model to be capable of presenting the microclimate and hence is practical for mutating multiple design solutions due to the improved time efficiency.

Table 2: Error calculations for MRT and UTCI.

	Linear		Dotted		Courtyard	
	MRT	UTCI	MRT	UTCI	MRT	UTCI
RMSE	5.65	2.42	5.41	2.43	5.44	2.45
MPE	18.97	7.43	18.76	7.30	18.70	7.53
R^2	0.94	0.97	0.96	0.97	0.95	0.96

4. Discussion and Conclusion

As shown in the results, the variations between the two models can be ascribed to different causes. The surface heat balance within both ENVI-met (EM) and EnergyPlus (EP) is calculated based on empirical equations with slight differences for estimating each component. However, the deduced amount of heat emitted and stored are not accounted for in EP. The heat conduction equation in EM is calculated by a simplified three-node method based on the exterior and interior surfaces' temperatures with reference to the previous single timestep, while in EP is calculated with reference to a series of temperatures and heat fluxes history of the previous timesteps. In terms of the outside surface temperature, EM calculation of the absorbed short-wave radiation is set to be 50% of the incoming solar radiation, while on the other hand EP uses the Clear Sky Solar Model (as the default in this study) which was reported to overestimate the solar radiation available to the building [13]. Moreover, EP intrinsically accounts for the radiative heat flux from the internal lighting (short-wave) and the zone surfaces (long-wave) in addition to the convective heat flux from the zone air. This could potentially affect the inside surface heat balance and result in a reduced conduction heat flux from the outside surface, thus keeping the outside surface's temperature higher. Although the amount of absorbed long-wave radiation in EM is almost similar to that of Ladybug-tools (LB) using the ray-tracing with almost 10° vector angles, EM takes into account the geometrical characteristics of the hemisphere, i.e. each vector is weighted by a factor of the angle of incidence to the surface (which tends to be more accurate). Furthermore, absorbed long-wave radiation from surrounding walls and the ground in EM are averaged over the model area. Consequently, irradiated surfaces' temperatures are indirectly lowered by the cooler surfaces in other shaded parts and vice versa. The effect is diminished during the peak hours where the solar radiation is fairly distributed over the model area. The aforesaid provides some explanation for the increased MRT of LB during the early hours of the day, which is evident in all cases. The scrutiny of the Python source code has revealed that, when the solar beam is blocked, LB confines the global horizontal radiation to the diffused component. The reflected radiation is defined within the SolarCal model as a function of global radiation, which is limited to the diffused radiation in case of obstructing the solar beam. This explains the sudden rise and fall in LB D-R2, L-R1 and C-R4 as well as the plummets of L-R2, L-R3, as opposed to the EM point MRT which receives an additional amount of reflected short-wave radiation from the ground and the walls, since the reflected radiation in EM is a function of the direct normal radiation times the inverse view factors. With the notion that the solar altitude reaches its maximum at midday, and the reflected short-wave and emitted long-wave radiation from the irradiated walls are minimised, point MRT receives a relatively less net all-wave radiation. This is clear in the case of EM at noon, while LB appears to show this trend earlier at 11 am and instead registers higher MRT at 12pm. The latter might be attributed to the additional ΔMRT within the LB model. As aforementioned, the MRT calculation within the LB model is based on the three components equally, i.e. the MENEX sky temperature, the solar adjusted MRT and the long-wave radiation from the surfaces. EM, on the other hand, partitions the incoming long-wave radiation into two equal portions, where the long-wave radiation from the ground represents one of them, while the sky and surfaces share the other portion, uncontestably, underestimating the latter two [7]. This is another attribution for the lower MRT EM possesses during the early and late hours. It is also worth noting that EP uses the TARP and DoE-2 algorithms for estimating the convection heat transfer coefficients for indoor and outdoor surfaces respectively in terms of the surface roughness and the difference between the surface and the immediate air temperatures as opposed to EM which depends in its calculation on merely the wind speed. This might have possibly resulted in slight differences in the outside surface temperatures and thus more MRT variations.

Furthermore, the $UTCI$ variations are shown to follow a similar trend for all the receptors as well as the average $UTCI$, however with attenuated differences.

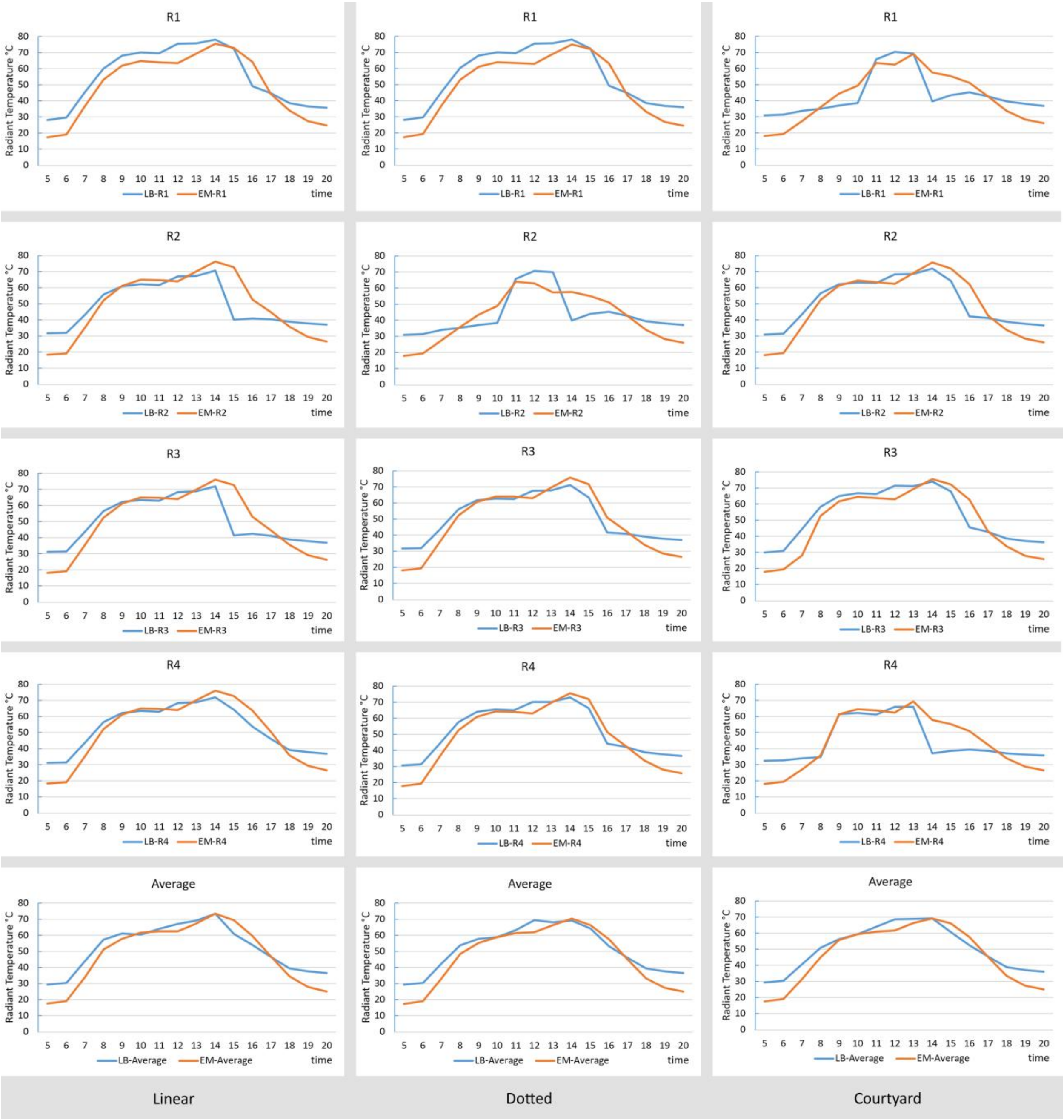

Figure 3: MRT comparison within the three layouts

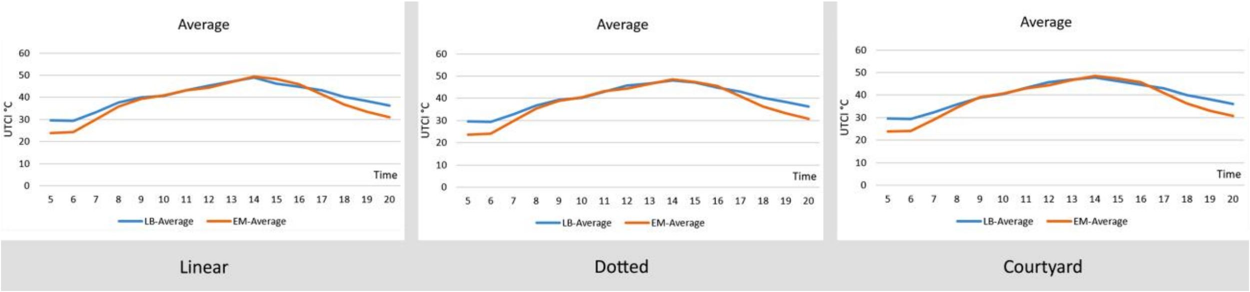

Figure 4: Average UTCI comparison within the three layouts

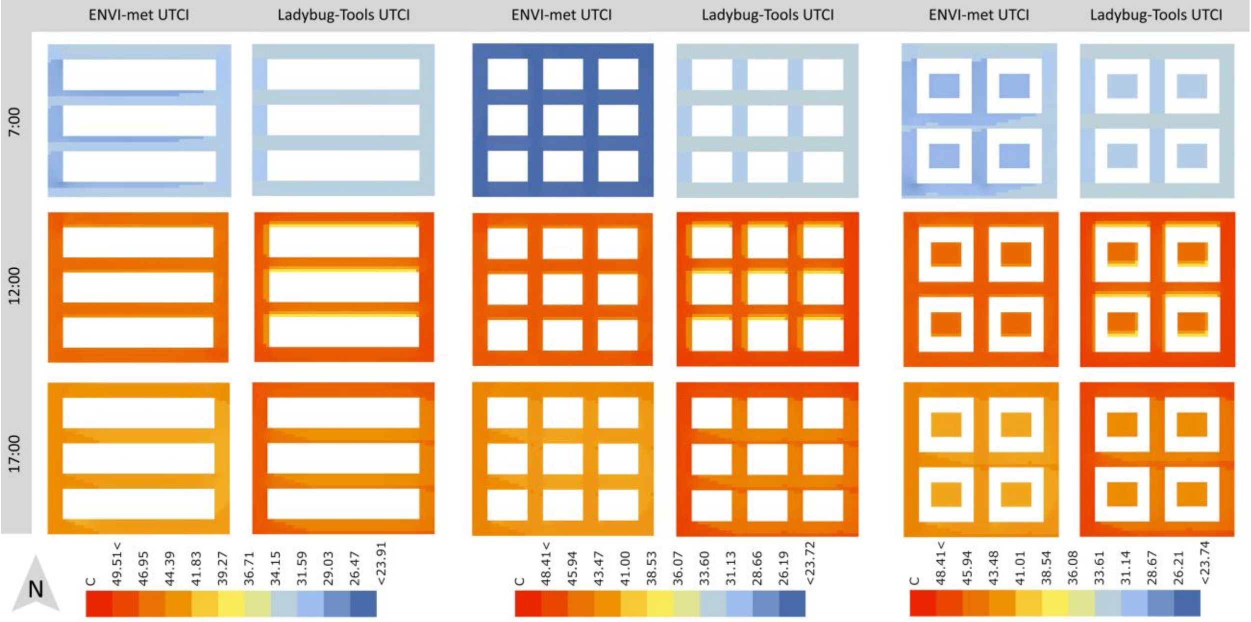

Figure 5: UTCI thermal maps for each layout at 7 am, 12 pm and 5 pm.

This is clearly due to the combination of the MRT values with the meteorological variables; wind speed; relative humidity; and air temperature. For a better representation for the $UTCI$ maps as in Figure 5, a Grasshopper plugin, Gismo, was used to allow for the extraction of ENVI-met $UTCI$ values and presenting them in the Rhino scene with the same legend. It is worth mentioning, however, that the "microclimate map" component in LB depicts the $UTCI$ values as a time interval, e.g. 6-7am, rather than at a single hour as in EM (at 7 am). Therefore, slight differences exist from those values plotted in Figure 4. Despite the $UTCI$ variations, the times required for the simulations in each model are considerably disparate. For each layout, the elapsed time differed from ~30 hours for EM to ~5 minutes for LB. It should also be noted that EM simulations run on a single-core processor as opposed to the LB simulations which were parallelised. Notwithstanding, a parallel core simulation in EM is anticipated to run in ~8 hours, which is still much longer than LB. In that sense, LB allows for assessing multiple design iterations with high spatial and temporal resolutions in a significantly shorter time. Hence it is suitable for optimisation studies yielding an immense number of design solutions, which would be infeasible using EM.

5. FUTURE WORK

As discussed, the accuracy of the Ladybug-Tools model is mostly a function of the radiation components determined through a set of Python functions describing the MENEX and SolarCal models. While the latter was initially designed for the indoor environments, future work includes intervening with the source code so as for a more accurate representation for the outdoor conditions and less MRT deviations.

6. REFERENCES

[1] Naboni, E., Meloni, M., *et al.*, (2017). An overview of simulation tools for predicting the mean radiant temperature in an outdoor space. *Energy Procedia*, 122: p. 1111-1116.

[2] Jänicke, B., Meier, F., *et al.*, (2015). Evaluating the effects of façade greening on human bioclimate in a complex urban environment. *Advances in Meteorology*, 2015.

[3] Perini, K., Chokhachian, A., *et al.*, (2017). Modeling and simulating urban outdoor comfort: Coupling ENVI-Met and TRNSYS by grasshopper. *Energy and Buildings*, 152: p. 373-384.

[4] Elwy, I., Ibrahim, Y., *et al.*, (2018). Outdoor microclimatic validation for hybrid simulation workflow in hot arid climates against ENVI-met and field measurements. *Energy Procedia*, 153: p. 29-34.

[5] Jamei, E. and Rajagopalan, P., (2019). Effect of street design on pedestrian thermal comfort. *Architectural Science Review*, 62(2): p. 92-111.

[6] Allegrini, J., Dorer, V., *et al.*, (2015). Influence of morphologies on the microclimate in urban neighbourhoods. *Journal of Wind Engineering and Industrial Aerodynamics*, 144: p. 108-117.

[7] Huttner, S., (2012). Further development and application of the 3D microclimate simulation ENVI-met, Mainz University, Germany. p. 147.

[8] Mackey, C., Galanos, T., *et al.* (2017). Wind, sun, surface temperature, and heat island: critical variables for high-resolution outdoor thermal comfort. in Proceedings of the 15th International conference of Building Performance Simulation Association. San Francisco, USA.

[9] Ali-Toudert, F., (2005). Dependence of Outdoor Thermal Comfort on Street Design in Hot and Dry Climate, in Berichte des Meteorologischen, Institutes der Universität Freiburg.

[10] O'Malley, C., Piroozfar, P., *et al.*, (2015). Urban Heat Island (UHI) mitigating strategies: A case-based comparative analysis. *Sustainable Cities and Society*, 19(2): p. 222-235.

[11] Engineering ToolBox. [Online]. Available: https://www.engineeringtoolbox.com/. Accessed: 20/09/2019.

[12] Weather Data by Region - Africa Region 1 - Egypt. [Online]. Available: https://energyplus.net/weather-region/africa_wmo_region_1/EGY%20%20. Accessed: 20/09/2019.

[13] DoE, U.D.o.E., (2019). Engineering reference, in EnergyPlus version 9.2.0. p. 58-167.