DESIGNING OUT HEAT – DEVELOPING A COMPUTER-AIDED STREET LAYOUT TOOL TO ADDRESS URBAN HEAT IN STREETS AND SUBURBS.

DANIEL YU[1], MATTHIAS IRGER[2], ALEX TOHIDI[3] and M. HANK HAEUSLER[4]
[1,2,4] UNSW / Computational Design. [2]Cox Architecture.
[1]d.yu@unsw.edu.au, 0000-0002-7788-548X
[2]m.irger@cox.com, 0000-0002-8158-9704
[3]a.tohidi@unsw.edu.au, 0000-0003-1335-4943
[4]m.haeusler@unsw.edu.au, 0000-0002-8405-0819

Abstract. As cities are getting hotter, the urban heat islands effect will become an increased concern for cities. While urban heat migration strategies are well researched and understood, some strategies of implementing urban heat mitigation focus on private land - thus depend on the owner's uptake. This research shifts mitigation strategies to the public land where governments have legislative control over the corridor between privately owned cadastral – the street corridor. This paper asks the question how a computational tool could assist councils in redesigning streets to mitigate urban heat. Literature review confirmed a direct relationship between the magnitude of urban heat and street layout, vegetation and materials used, position of street to sun and wind direction - yet no tool that assists a designer exists - the focus of the research. We present first findings and the iterative development of our street design tool. Via our tool one can alter variables such as vegetation type, materials or street configuration until urban heat mitigation is optimized. This is a significant step towards cooling our cities as designers now have a process that translates expert knowledge on urban heat into a tool that lets them design as well as evaluate their design.

Keywords. Urban Heat Island; Heat Mitigation; Landscape Architecture; Urban Design; Street Design; Traffic Engineering; Computational Tools; SDG 11.

1. Introduction and research background

Temperature records around the world are being broken at an increasing rate because of accelerating climate change (IPCC, 2021; WMO, 2021; Climate Council, 2019). This upwards trend is particularly severe in cities, where temperatures are generally higher than in rural areas due to the urban heat island phenomena (Oke, 1988b; Gartland, 2008). In January 2021, the city of Penrith in Western Sydney was the hottest place on earth with a new record of 48.9°C, while six months later Lytton in Canada

POST-CARBON, Proceedings of the 27th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2022, Volume 2, 739-748.

experienced 49.6°C and Nuwaiseeb in Kuwait 53.2°C. Global warming will continue to increase the severity and length of these extreme heat events as well as their frequency (WMO, 2021; Climate Council, 2019). In Australian cities, the number of days per year above 35°C, when most people experience moderate or great heat stress, are projected to grow significantly by 2050 compared to their historical long-term average: in Western Sydney from 11 to 24 days per year, in Western Adelaide from 18 to 34, in Brisbane from 2 to 14, and in Darwin from 22 to 187, respectively (WMO 2021). Higher temperatures not only drive-up energy consumption of air conditioners, cause damage to buildings and infrastructure, diminish productivity and make people feel uncomfortable (Hart and de Dear, 2004; Kolokotroni al., 2006; Watkins et al., 2007), but increasingly reach extreme levels dangerous for human health. With more hot days people are increasingly confined indoors, while physical labour outside, active transport and outdoor recreation cease and a walk to the shops or doctor becomes a health risk, particularly for the elderly. Consequently, managing and mitigating urban heat is fast becoming an issue of great concern for cities who seek to protect their citizens from the adverse impacts on human health and wellbeing, liveability, productivity, and overall carbon emissions. The fact that urban areas are significantly warmer than their rural surroundings, a phenomenon called the Urban Heat Island effect, has been well documented and understood (Stewart and Mills, 2021; Steward, 2011; Gartland, 2008). It is caused by the replacement of natural ground cover with impervious, dark coloured surfaces, such as roads and buildings, which absorb, store and re-emit more radiation (Akbari, 2009; Gartland, 2008). The lack of trees and other vegetation reduces evapotranspiration and shade, which exposes more ground surface to the sun, thus increasing surface temperatures and enabling more thermal storage (Akbari, 2009; Kuttler, 2011). Wide, suburban streets with single storey buildings expose more road surfaces to the sun to heat up, while relatively narrow inner-city streets with tall buildings experience less solar exposure at street level over the day, but also prevent more energy from escaping to the sky (Oke, 1988a; 1988b). Unsurprisingly, precincts that experience the highest maximum temperatures are low-rise developments dominated by dark roads and roofs, and a distinct lack of shade trees and soft landscaping. Several studies have shown that urban temperatures can vary more than 10°C within a city depending on the urban form of a precinct including its building density, vegetation content and surface materials of roofs and the ground (Irger, 2014). Strategies to mitigate urban heat involve increasing tree canopy and natural ground cover, reducing impervious surfaces and rainwater runoff, and the use of lighter-coloured and reflective materials for roofs, roads, and paving (Gartland, 2012; Akbari, 2009; Muller et al., 2014). Trees not only shade the ground and prevent surfaces with high thermal mass such as roads from heating up, but they also protect pedestrians from solar radiation and further heat stress on hot days (Akbari, 2002; Kuttler, 2012). According to recent research, choosing light-coloured materials for all roofs could reduce the ambient temperature in Sydney by an average of 2.4°C (Mohammed et al., 2021), while urban reforestation could provide 1-5°C of cooling (Kurn et al., 1994; McPherson et al., 2005). A comprehensive uptake of heat mitigation strategies in architecture, urban design and planning is vital as we progressively redesign our cities to cope with rising temperatures, thus directly addressing SDG 11 - making cities and human settlements inclusive, safe, resilient, and sustainable.

Mandating white roofs, trees on site or for a portion of land to be unsealed may be achievable strategies for new developments, but they are challenging to apply to the existing built environment. Private landowners may be reluctant to invest in changing a functioning roof, dislike the aesthetics or glare. Secondly, buildings on recent suburban developments or inner-city blocks often cover the majority if not all the site, leaving no physical space for trees. As the opportunity to implement wide-spread heat mitigation policies on private land is largely tied to the rate of redevelopment or refurbishment, changing the existing building stock will be slow, incremental and a long-term effort. On public land on the other hand, which is in local or state government control such as streets, parks, plazas and other public landholdings, mitigation strategies could be implemented relatively quickly.

It is argued that a focus on streets should be a priority in mitigating urban heat for the following reasons:

Firstly, generally exposed to the sun, roads are often the hottest surface in a precinct and store a large amount of energy and are therefore a major contributor to the urban heat island effect at day and night (Gartland, 2008). This is particularly severe during a heat wave, when roads push already high temperatures to extreme levels considered dangerous to human health.

Secondly, streets are vital to public life and the economy. They exist to facilitate movement for people of all ages and abilities and are used by choice or necessity for access, work, or leisure. More frequent and severe extreme heat events as predicted impede on or outright prevent these activities, which presents a major and growing threat to the functioning of a city, its citizens and economy.

Thirdly, with about one fifth of urban areas in Australia allocated to streets and other public open spaces, they represent a large portion of land in a city that is under direct local or state government control. At this scale, rethinking streets with heat in mind would significantly improve the temperature profile of a city and make a meaningful difference to the experience of its residents.

The most important strategy to reduce temperatures in streets and improve the thermal comfort of pedestrians is the provision of shade by maximising tree canopy cover to protect people and surfaces such as roads and walkways from solar radiation. Other measures include introducing more pervious areas such as porous paving and soft landscaping, planted verges and bio swells, and choosing light coloured paving for footpaths and concrete over dark asphalt for transit lanes (Akbari, 2009; Gartland, 2012; Kuttler, 2012). Cities are also increasingly prioritizing active transport over vehicular traffic and replacing transit lanes with bike lanes, wider footpaths, and vegetation, thereby reducing anthropogenic heat and air pollution, too. While aforementioned measures could relatively easily be incorporated in the design and planning of streets, implementation is not yet widespread. Despite an increasing awareness of the mechanisms driving heat in cities as evidenced by recent publications of guidelines and policies by governments and other stakeholders, there is currently no tool available to assist urban design and planning professionals with the optimization of spatial arrangements to mitigate urban heat in a street.

Consequently, our research focused on the development of a computer-aided street design tool to address urban heat in streets and precincts presented in this paper.

2. Research hypothesis, question, objectives, and outcomes

In this research we aim to investigate the shape of the built environment by focusing on one part of the built environment **-** the street. The research proposes the hypothesis that **streets -** in their layout (road type / bicycle lane / trees / parking / etc.) and design (arrangement of the previous and the choice of materials, vegetation, etc.) **- are within the jurisdiction of a council, state or federal government and thus offer opportunities to address the shape of the built environment** and therefore urban heat. This hypothesis extends to both alterations in existing streets (grey / brown field optimisation) as well as designing new streets (green field developments) and counter urban heat aggravation as above by developing computational methods and tools to address the research problem. Our hypothesis extends further to:

- Tool would expedite street design / allow fast optioneering / testing
- Tool would allow to estimate impact of design on urban heat
- Tool would allow optimisation / testing of performance of new precinct layout
- Tool would support optimization of existing streets
- Tool would help optimize street design for heat and improve local microclimate / people's comfort / health / energy bills.

All to ask the core research question (I):

> *"What can computational design with its methods and tools offer to reduce heat at the urban scale when concentrating on street layout and design?"*

With the sub question of (II):

> *"How can these computationally enabled changes in street layout and design towards reducing heat be verified by visualising the difference in air temperature via voxel display?"*

And a follow up question of (III):

> *"How can the investigated and proposed computational tool be made accessible to design professionals in practice and government via web-based processes?"*

With these research questions the *research objectives*, as a specific result that can be achieve within a time frame and with available resources, are:

- To study and understand urban heat island occurrence specifically to reduce heat at the urban scale. In particular: Physical principles that underpin heat at the urban scale. Literature on heat at the urban scale.
- To research and apply street layout and design principles. In particular: Literature that links street layout and design principles with heat at the urban scale. Street layout and design principles in an Australian (NSW) context using Sydney and in particular Western Sydney as case study.
- To investigate computational design methods and tools appropriate to address the

research question. In particular: Literature on computational methods and tools addressing sustainable issues. Tools and computing processes that allow the interaction, presentation, and visualisation on a browser (web application).

The *research outcomes*, as a detailed description of what will be produced at the conclusion of our work are a set of computational method(s) and/or tool(s) named 'street layout planner' - addressing Research question (I) and (III).

- For grey / brown field optimisation. Understand and inspect via computational methods and tools existing street layouts and the 'material types' - geometry of a material with a specific albedo value - they are made from. Understand and compute the absorption and conversion into heat by each 'material tile' - geometry of a material with a specific albedo value. Understand and replace existing 'material tiles' with new low albedo 'material tiles.' Alter, change or improve via selection of vegetation.
- For green field development. Plan and design streets from scratch that are optimised towards: urban canyon geometry, direction of street towards prevailing wind, and optimised choice for materials.

This paper presents in the following *Chapter heading 5 'Development of Street Design (SDT) Tool' the* agile development of first steps towards this 'street layout planner' tool. As part of an ongoing yet to be published research, a further, second, computational method(s) and/or tool(s) named 'Voxel air temperature tool' - addressing research question (II) and (III) will be developed.

- For grey / brown field optimisation as a well as green field development. Calculate reflection and emission of long and shortwave radiation. Calculate and incorporate wind. Calculate and incorporate anthropogenic heat (cars, air conditioner). Representing above as air temperature via a voxel grid (volumetric pixel). Allow interaction and evaluation of urban design via voxel visualisation.

The first early steps of this development are shown in Figure 3.

3. Research Methodology

Exploring the problems and opportunities associated with emerging digital technologies in an applied and pragmatic context towards researching *"What can computational design with its methods and tools offer to reduce heat at the urban scale when concentrating on street layout and design?",* is well-suited to an immersive and participatory approach that engages users as well as researchers. As argued by Hamilton et al. (2020), Action Research (AR) is the overarching methodological framework for this research project. Consequently, the research has followed the spiral of steps typical to the AR process of *'plan', 'action', 'observe'* and *'reflect'* (Kemmis 2009). The useability of the Action Research methodology investigating the opportunities offered by computational design for urban heat has been subject of and argued for in the 2019 paper *'Designing out Urban Heat'* (Green et al), when optimising footpath materials with different albedo values through evolutionary algorithms to address the urban heat island effect. Green et al argued in the paper with O'Brian (2001) that Action Research as an iterative process was the chosen methodology due to its effective and practical uses, and further argued with Avison (1999) who points out that action research is unique in the fact that it combines the results and processes of theory and practice synergistically, and *"research informs practice and practice informs research."* As outlined in Action Research literature, the planning phase for this research consisted of researching relevant resources and performing literature reviews. Here the research was informed by research in three fields:

- First, understanding what an Urban Heat Island effect is, and what it is impacting. From this understanding the core research question was identified.
- Secondly, research has identified algorithms, equations, and tools that have been prior used to solve similar problems and translate this understanding to the field of enquiry. Here GH, Python or C-languages or web-based languages will assist.
- Lastly, from understanding of voxelization of information as a means to spatial temporal display as chromatophoric architecture to address research question (III).

The computationally assessing, reducing, and designing out heat at the urban scale while focusing on streets workflow method for understanding *'What can computational design with its methods and tools offer to reduce heat at the urban scale when concentrating on street layout and design'* will be iteratively developed, deployed and assessed through cycles of action and reflection in this research.

4. Literature review specific to Street Design Tool (SDT) development

In general, streets can be categorized into different typologies according to their function, traffic carrying capacity and transport mode mix, surrounding land use and immediate context. As streets have traditionally been designed to facilitate vehicular traffic, common classifications are based on traffic volumes and speed providing minimum requirements for transit, parking and bicycle lanes, and footpaths (Austroads, 2021). While recent guidelines indicate a shift towards people-oriented design (Gehl, 2013), none mentions heat mitigation or thermal comfort.

Roadcorridor geometry guidelines - Best practice

Road Type	MAX AADT (av.cars/day)	MAX Speed (km/h)	MIN Footpath width (m)	MAX Footpath width (m)	MIN Lighting zone (m)	MAX Lighting zone (m)	MIN Bicycle lane (m)	MAX Bicycle lane (m)	MIN Green Intrastructure (m)	MIN Travel lane width (m)	MAX Travel lane width (m)
Laneways / Local service road	1000.0	30.0	1.2	1.8	0.3	0.6	0.0	0.0	0.0	2.7	3.5
Pedestrian-only streets	0.0	15.0	3.5	7.5	0.3	0.6	0.0	0.0	1.5	0.0	0.0
Shared streets - residential	1000.0	30.0	1.8	2.4	0.3	0.6	0.0	0.0	1.5	2.7	3.5
Urban Local access road	1000.0	50.0	1.8	2.4	0.3	0.6	1.2	2.5	1.5	2.7	3.5
Shared streets - commercial	8000.0	30.0	2.4	7.5	0.3	0.9	0.0	0.0	1.5	2.7	3.5
Urban Local collector road	8000.0	60.0	2.4	3.0	0.6	0.9	1.8	2.5	1.5	3.0	3.5
Neighborhood Main street	8000.0	50.0	2.4	7.5	0.6	0.9	1.8	2.5	1.5	3.0	3.5
Urban arterial road - single carriageway	14000.0	70.0	2.4	4.5	0.6	0.9	2.0	2.7	3.0	3.0	3.5
Urban arterial road - devided carriageway	30000.0	80.0	2.4	4.5	0.6	0.9	2.4	3.6	3.0	3.5	4.2

Table 1. Range of dimensions for each street typology and component according to international best practice

For the purpose of this research, the following nine street typologies has been identified as universally applicable, capturing vehicular capacity and traffic modes as well as the prevailing land-use context and urban setting: laneways or local service roads, pedestrian-only streets, shared streets - residential, urban local access roads, shared streets - commercial, urban local collector roads, neighbourhood main streets, Urban arterial roads - single carriageway, and Urban arterial roads - divided carriageway.

These typologies entail associated spatial requirements of street components such as footpaths, bicycle lanes, lighting zones, parking and transit lanes, green infrastructure and public transport corridors. Table 1 shows a range of dimensions according to international best practice (GSDG 2016, Gehl 2013).

Following a systematic review of computerized and computational tools we can safely assume that currently no street design tool that features parametric design capability and supports spatial, urban heat specific optimization exists. While there are street design tools examples within platforms such as Test Fit.io, Giraffe.build or urban design and evaluation tools in GH such as Urbano or Decoding Spaces Toolbox, these do not allow an integration of different materials (albedo) or vegetation (shadow).

5. Development of Street Design Tool (STD)

Prior to scripting we set up the program architecture as we aimed to have the 'Street Design Tool' as a 'backbone' that allow a later addition of various yet to be determinate 'plugins', such as a simulation of tree growth over time to calculate shade and potential cooling. We have categorised these into the following groups:

- **Usability and compatibility.** Works with current street typology conventions. Easy to access and operate. Compatible with common database formats (csv.). Allows the user to choose street typology and select components. Assists the user by suggesting dimensions for street components based on best international practice but allows the user to modify these values according to specific design requirements. Works parametrically to allow real-time optioneering.
- **Road features.** Assists to Minimise Road space and maximise space allocated to green infrastructure. Uses Cadastral data to establish the road corridor width and design boundary, centre line. Allows 3d data/city model as model input.
- **Vegetation.** Optimizes tree positioning and selection to maximise shade. Simulates tree growth over time.
- **Environmental.** Calculated sun exposure for any location. Calculated wind exposure for any location.

The Street Design Tool was developed using Rhino3D, Grasshopper & Python. The SDT has four major components:

- **Centreline. Linear** infrastructure is identified by its centreline. User of the system is to provide the associated centreline of the road.
- **User Interface.** As part of the UI development, a collection of components was developed in Grasshopper using Python. These components served as a data entry point to the system. User input are captured and stored in a self-explanatory *.JSON Data Format. By utilising this data structure, the system became scalable. It also allows for future integration of the tool into a later proposed web-based applications, using languages such as JavaScript. Additionally, some descriptive metadata can be captured from the user. (See Figure 1 - below).
- **Stack Of Elements.** All collected data from users are captured and stored in a sorted list. Each element in list describes an individual component of the road (see Table

1). By combining all data, the overall geometry of the road segment can be created based on the specification. The order of the elements in the list are important as they define the location of the element around the centre line.

- **Draw Method.** Draw method is responsible for the creation of the geometry in Rhino 3D. This method is written in Python and interacts with Rhinoceros 3D API to draw the object in Rhino. The method iterates through the list of *.JSON files and for each *.JSON file extracts the element type assigned to it, to call on the appropriate draw function for each *.JSON file (See Figure 2).

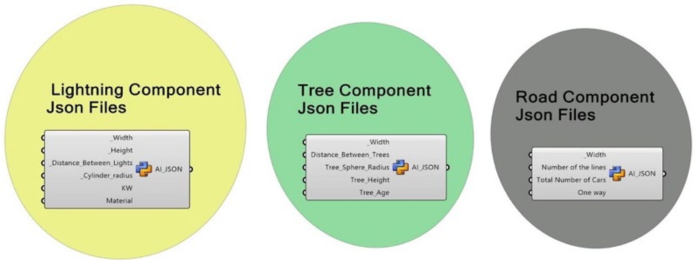

Figure 1. Street Design Tool components

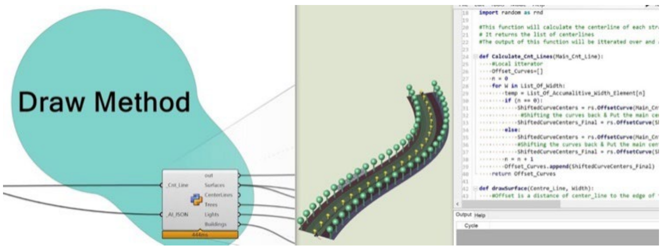

Figure 2. Draw method component with generated road and screenshot Python script.

- **Alert Display system.** The system will check the user input against the set of design guides and standards to check for discrepancy between them. Following this, the system displays appropriate alert messages to the user, helping them to design within the guidelines. By design choice, the system will not restrict the ability of the users to draw non-compliance elements.

6. Results and discussion

The tool in its current iteration at the submission of the paper can generate street layouts based on curves. Further the tool can take width of street elements as listed in Table 1, it allows the later integration of other in detailed developed components such as listed in Figure 1. What are the tools implications? Following the hypothesis that streets play an important role in combating urban heat we have provided a programming 'backbone' with four major components. Each component will be further developed in future research. We have already completed research and published its finding in computational landscape architecture publications (White et al., 2020) for the 'tree component' to visualise simulated plant growth. Other components such as materials will follow. This research is a significant step as it allows a user to design streets with a computer-aided tool that contains knowledge on the various elements of a street.

7. Conclusion

The tool in its current iteration has its limits. It is yet not able to work on intersections nor can one segment the street into smaller elements that are all designed individually, i.e. the street in front of each cadastre looks different due to driveways or above ground and below ground services that would not allow i.e. large trees - nor has it been tested.

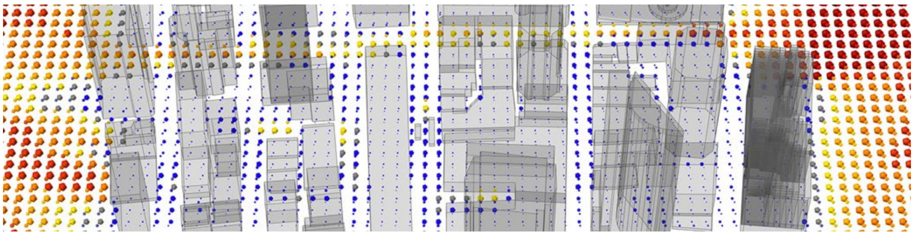

Figure 3. 'Next Steps - Development of a voxel-based air temperature calculation tool'.

These are features that we aim to develop and address in the tools next iteration as future research as well as building up each 'component' to a greater level of detail. While we argue that the research up to this stage could demonstrate first steps towards answering the first research question of *'What can computational design with its methods and tools offer to reduce heat at the urban scale when concentrating on street layout and design?'* one important question (Research Sub Question 2) has not yet been answered with the tool - *'How can these computationally enabled changes in street layout and design towards reducing heat be verified by visualising the difference in air temperature via voxel display?'* In parallel we are working on the development of a voxel-based air temperature calculation tool (see Figure 3) to address this question.

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