DESIGNING OUT URBAN HEAT ISLANDS

Optimisation of footpath materials with different albedo value through evolutionary algorithms to address urban heat island effect

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Abstract. The Urban Heat Island (UHI) effect is pronounced in dense urban developments, and particular an issue in the case study city of Parramatta, where temperature increases are impacting use of public space, health, and economic productivity. To mitigate against elevated temperatures in built up areas, this research explores the optimisation of paving material layouts through using an evolutionary algorithm. High albedo (reflective) materials are objectively cooler than low albedo (absorbent) materials yet tend to be more expensive. To reduce the amount of heat absorbent pavement materials whilst keeping in mind material costs, a range of materials of different albedo levels (reflectivity) can be assigned on the same path using an evolutionary algorithm to optimise the coolest materials for the cheapest price. Over the course of this paper, this research aim will be approached using visual scripting software such as Grasshopper to simulate daylight analysis and to generate an optimisation algorithm. Previous research on the topics of UHI have revealed different methods for solving specific problems, all focusing on using software analysis to determine an informed decision on construction. The paper contributes via a computational approach of material selection to battle urban heat island effects.

Keywords. Urban heat island; albedo value; material properties; evolutionary algorithm; landscape architecture.

1. Introduction: Research Aims, Motivation, Context and Defining Problem

Since the advent of the twenty-first century there have been a significant surge in urbanisation. The United Nation (UN 2018) predict that by 2050 two-thirds of the world’s population will live in cities. Owing to the built-up nature of cities they
can be significantly warmer than rural contexts. This is typically referred to as an Urban Heat Island (UHI). The Urban Heat Island effect has only been recently recognised as a major environmental issue in major global cites such as Sydney, Australia, (Irger 2014) as, as research by Irger demonstrates, temperatures of Sydney’s western suburbs have elevated dramatically and have been endangering human health and economic productivity levels. In the past, city development was focused on practicality, aesthetics and cost, with little regard for the environmental impacts of the buildings and places. Parramatta city council is on the brink of developing 50% more infrastructure on their way to become the 2nd CBD of Greater Sydney, and have established a Future City program in an effort to become more environmentally conscious. To mitigate against elevated temperatures in built up areas, this research explores the optimisation of paving material layouts through developing an evolutionary algorithm. Pavement materials with high heat absorption are not only impacting cities microclimates, but they can also be uncomfortable to walk through, reducing the amount of pedestrian engagement and preventing social interaction (Santamouris 2013). High albedo (reflective) materials are objectively cooler than low albedo (absorbent) materials yet tend to be more expensive. To reduce the amount of heat absorbent pavement materials whilst keeping in mind material costs, a range of materials of different albedo levels (reflectivity) can be assigned on the same path using an evolutionary algorithm to optimise the coolest materials for the cheapest price. This research explores this problem by using one visual scripting software Grasshopper, to simulate daylight analysis and to generate the optimisation algorithm. Previous research on UHIs has revealed different methods for solving specific problems, focusing on using software analysis decision-support as a tool.

2. Research Question

Based on this motivation and observation the paper asks the core research question: How can evolutionary algorithms which optimise pavement material layouts mitigate urban heat island effect? Still, the core research question itself needs to be discussed with asking sub questions as: What is an UHI effect? and What value have evolutionary algorithms to this enquiry? This is relevant as apart from scripting algorithms for the evolutionary optimisation, and an understanding of their operation, environmental impacts and weather needs to be researched deeper to understand what variables and objectives need to be used in the algorithm, and why these are important in the efforts to mitigate UHI effect. Post answering these question an appropriate research methodology can be identified.

3. Research Aims and Observations

With this in mind this research project aims to explore how optimising pavement material layout through parametric simulation and analysis can mitigate the UHI effect. The overall goal for this case study is to provide City of Parramatta with an alternative method to measure material properties in pavement materials and an evolutionary algorithm which demonstrates an opportunity for computational
design to optimise the pavement material layout. This research project aims to explore how a script can be applied to the case study area in Parramatta, and if it can be applied to any given geometry or space to adapt to new contexts and shading. Another objective is to determine the estimated albedo of a range of materials through personally testing the infrared surface temperature during daylight hours, which can be used as an objective for optimising pavement material layout.

4. Background Research

To assess the impacts of the urban heat island (UHI) effect in a or any chosen location, one needs to understand firstly its context. Irger (2014) defines the UHI effect as “the phenomena where urban areas experience higher temperatures than rural locations”. Throughout Irger’s research, he initially discusses topics such as climate change and UHI introducing their important history and upbringings, and what importance they still have in today’s environment. By introducing schematic diagrams of past findings and their relevance, it allowed to visually understand the effects that UHI has on cities. There are a number of variables which influence UHI ranging from daylight material absorption, material composition, and urban planning. For example, a significant contributor to the urban heat island effect is the choice of materials and their formal composition.

In their paper on Modulating thermal mass behaviour through surface figuration, Cupkova and Promoppatum (2017) question if heat absorption radiation can be significantly delayed by changing the geometric surface pattern over the same amount of thermal. Their motivation is based on the lack of information and research on how the physical composition of materials effects heat absorption, and their aims are to develop a set of rules for designers to understand thermal lag behaviours of complex geometric systems. Coming from backgrounds of Architecture and Engineering, they used thermal simulation software on complex geometry to show heat reduction on different form with the same mass. From these simulations on iterative designs Cupkova and Promoppatum have come up with an ideal surface to mass ratio to optimise reduction in heat absorption in materials. This study on thermodynamic behaviour in architecture is a significant contribution in the field however also one that arguably requires further research. Yet, with these successful results, a framework could be designed where designers could understand how to use materials and composition better. The above mentioned work shows that study and research heat absorption does not have to be undertaken via ‘traditional methods’ - using coatings or reflective qualities to reduce the heat absorption, but to think outside the box about alternative methods. This new thinking could be implemented into more heat absorption studies, allowing others to experiment with other possible simulations to optimise materials in different ways. Nguyen Quang (2008) work on urban heat simulation discusses the absence of simulated urban heat software in architecture and aims to test if the same level of data can be achieved on AutoCAD compared to professional simulation software. The motivations for developing an easy to use urban heat simulation in AutoCAD is that the program is typically used in the architectural industry and having the choice to use simulation in the
same software makes it easier for beginners wanting to experiment with urban design tools. By running a basic simulation through an absorption coefficient of material tool in AutoCAD, then importing the image into Photoshop to apply a gauss blur, a simulation was possible to a certain level. Nguyen Quang’s argument was supported by several other projects as well, all using GIS instead of AutoCAD, (Nichol, J. 2004) (Mardaljevic and Rylatt. 2003) demonstrating that the simplicity of the AutoCAD simulation is ideal for the target audience of architecture students. This level of simplicity has its weaknesses including overlooked factors in simulation, which overall are affected by urban heat. Still the significance of Nguyen Quang’s (2008) article is that it demonstrates it is possible to develop simulations inside AutoCAD as opposed to relying on GIS or external simulation software. This suggests it may be possible to use programs such as Rhino or Grasshopper to similarly create urban heat simulations.

This argument is supported by more comprehensive, current studies looking at how daylight can impact UHI have focussed on using computational decision support for a complex airport roof design. The project conducted by Ensari, Kobas, and Sucuolu (2017) have used evolutionary algorithms to analyse given zones of a built environment from an architecture team for an airport roof. Their objectives to accomplish with this evolutionary algorithm was to minimise energy consumption, provide enough natural daylight for the interior, and to take into consideration additional environmental elements such as rain wind. By undertaking solar radiation simulations of the base cases, they could use the results to grade zones based off their daylight coverage and use this information to optimise and manipulate the performance of the spaces. Utilising Grasshopper’s Octopus plugin the team were able to develop the right algorithm for their desired tasks, showing how particular software can be used for specific problems such as these in architecture. This example can be applied to the research of heat island effect especially if study using daylight coverage was used for material absorption testing. Based on the above literature review the paper hypothesis to pose similar concepts and to define a methodology to study and research urban heat island effect using computational tools. Here the paper argues that the gathering of different perspectives on how work has been accomplished in the past on similar topics, a forthcoming research to be valued and considered.

5. Methodology

In order to developing an evolutionary algorithm in Grasshopper for optimising pavement material layouts the paper proposes the use of action research (O’Brien, R. 1998) in an iterative process as a chosen methodology due to its effective and practical uses. As Avison (1999) 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, the planning phase consisting of researching academic articles and performing literature reviews, has informed the research in three fields.

- First, understanding what the UHI effect is, and what it is impacting. From this understanding, a specific topic such as pavement materials was identified
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as the case study for this research.

Secondly, research has identified algorithms and tools that have been prior used to solve similar problems and translate this understanding to field of enquiry UHI. Here Grasshopper plugins Ladybug and Octopus were selected for the use in this research.

Lastly, from understanding the use of albedo in the UHI field, surface temperature data were obtained on the five materials that were tested to compare each material albedo properties.

After completing this planning stage, an action phase of iterative testing began where the results can be observed, reflected, and revised.

By developing a simple first iteration with limited variables and objectives to understand if the algorithm works, knowledge can be drawn from the success to go back and collect more data, adding more complex conditions to the next iteration. By expanding the original range of the experiment, further understandings can be gained such as the extent of the process and what it could possibly be used for in the future if given enough research and iterations.

6. Case Study

As outlined earlier this research project aims to develop a GH workflow any firm or company can use for optimisation methods, using the site defined via the collaborating with Parramatta City Council as case study. Hence the project used a specific intersection in the heart of Parramatta (the intersection of Philip street and Church street) where the developed optimisation algorithm can be applied to geometry of that space. All with the objective to provide the Parramatta City Council with information about an alternative solution for pavement material layouts.

6.1. PARRAMATTA GEOMETRY

Over the course of several design iterations through the case study research a basic geometry was used to first gain an understanding of the algorithm being applied. This was followed by setting up the script to then be used for any alternate geometry which replaces the Parramatta precinct geometry. Hence the first iteration geometry was a very simple layout of a street which did not consider dimensions, curves, or orientation, as it was purely to see if the radiance analysis was working.

Upon reevaluating after the first iteration, the geometry was updated to fit the actual case study of Philip street and Church street, where official geometry of Parramatta City Council was used in this research project. However, the Parramatta City Council uses SketchUp to develop their precinct geometry, whereas this project uses Rhinoceros as the 3D modeling program, with Grasshopper as its visual scripting plugin.

Consequently, the geometry had to be exported into Rhino, as well as being scaled down and cropped to the appropriate street intersection. Further, the pavement footpaths were also not modelled into the SketchUp geometry as the
provided geometry was created by council for overall building structure. Thus for this research the pavements were modelled in as correctly as possible, however not using exact measurements or the same measurements that the building geometries were based on. When these footpaths were modelled in correctly, this would be the final geometry to be used for both second and third iterations of this project.

6.2. MATERIAL SURFACE TEMPERATURE

To be able to gather objectives for the evolutionary algorithm to run with to optimise cool materials, five materials were used for this research project:

- Standard pathing material used in council [Adelaide Granit Black]
- Standard decorative pathing material used in council [small orange]
- Standard decorative pathing material used in council [small grey]
- Albedo improved material [Tile cool]
- Albedo improved material [Tile dark]

For all five material albedo levels were identified for an accurate example for the algorithm. To try and evaluate the levels of reflectivity of the materials myself, each material was tested by recording their surface temperatures through a manual infrared surface temperature gun repeatedly and consistently over a sunny day. By tracking the surface temperature of each material over a full sunny day, a rise and decline of each material’s temperature can be visualised to understand out of these five materials, which order they belong in when discussing the materials with the highest albedo level, and the material with the lowest albedo level. These results were then used as data for the lowest heat gain of each material using their albedo levels for the objectives of the evolutionary algorithm. The research team is aware that this might not be an accurate scientific way to provide exact data for UHI studies but the focus of this research was in complementing existing research in UHI through a computational method and this generating a workflow that allows to alter the input data with correct data at a later stage.

6.3. GRASSHOPPER MODEL

Grasshopper is the visual scripting program that is run through the 3D modeling platform Rhinoceros and is the basis of the algorithm in which will be produced. However, as this project deals more with an environmental analysis focus than 3D modelling, external plugins were downloaded to assist this research project in dealing with radiance analysis and evolutionary algorithms. Through researching academic literature and past research projects on similar topics, DIVA as a plugin which runs thermal daylight, solar radiation, and glare simulations appeared originally as a perfect fit for radiation analysis of the geometry. However, when installing this plugin, several complications arose, and consequently the research had to identify alternatives to simulate a radiation analysis.

6.3.1. Solar radiation using Ladybug

Ladybug is a weather analysis plugin for Grasshopper which can produce such diagrams of sun pathing and radiation analysis. The first step to setup the algorithm was to input a weather data file which is local to the proposed case study site.
of Parramatta City Council. In this case we will be using one of the Parramatta weather files which will be used to simulate the geometries sun orientation and path over the year. Once the weather file is set up, a sun path tool can be run using Ladybug for use as an input for the radiation analysis. The radiation analysis will use the sun path results along with the hours, days, and months of study to produce an estimated simulation of the amount of kw/h in a tile like visualisation mesh. The areas of the pavement which are exposed to the most amount of sunlight over the daylight hours in the season of summer are indicated in red, where areas which have lower sunlight intake are indicated in blue. The radiation analysis results can then be multiplied with the amount of heat each material will absorb to produce results on what the heat gain of each area of the pavement would look like over the summer period when the five different materials are introduced.

To be able to select specific areas of the output mesh from the radiation analysis, the mesh threshold selector tool was used frequently to obtain areas based off their values and not their items. This tool however proved difficult when trying to select areas between specific values as they would overlap instead of stopping at the boundaries. The opposite values had to be selected to then be subtracted from the overall mesh to get the values in between, however this mesh difference also only worked once making a 3D mesh. In the end, the correct areas were able to be selected but only after a messy process.

Originally, manual parametric methods were used to produce three different layouts to then be exported into a spreadsheet to understand what the differences were in price and heat gain when assigning different amounts of each material to different layouts. This did produce results to show out of the selected arrangements which would be the most optimal solution, however this algorithm could be taken a step further to automatically produce the most optimal layout to begin with where manual analysis and parametric adjustments are not needed. To produce an evolutionary algorithm to compute these kinds of results, Octopus worked in conjunction with Ladybug. Honeybee was also attempted to be used in this project to gather more variables for the final algorithm to incorporate. However, when trying to understand how to use reflective material properties it was too difficult to get working and follow along and so was discontinued from the research project.

6.3.2. Evolutionary optimisation using Octopus

Octopus is a plugin for Grasshopper which applies evolutionary principles to parametric design and can be used to optimise multiple goals at once when also given multiple variables. Using this plugin in combination with Ladybug, Octopus can produce an evolutionary algorithm to optimise minimal cost and minimal heat gain, using the albedo data generated from infrared surface temperature testing, and the heat results from the radiation analysis and sun path.

With the goals of the algorithm to optimise cost and material heat gain, and the variables being the areas in which each material are assigned, the algorithm will run through several different area combinations for each material aiming to find the material layout with the lowest cost and lowest heat gain. The results from this analysis are the produced alternatives to what the pavement material layouts could
be, providing information on how much each alternative will cost in total and how much heat gain is in total as well.

With the full evolutionary script completed using the combination of Ladybug and Octopus, the results which become outputs in Grasshopper can then be exported into Rhinoceros for visual images of the optimum pavement material layout, or into a spreadsheet such as Excel to produce graphs and tables of the numerical data.

7. Significance of Research
Evolutionary algorithms are incredibly effective optimisation algorithms used mainly in fields of evolution strategy and genetic programming as the algorithm itself derives itself from the process of biological evolution such as reproduction and mutation. In this research paper, evolutionary algorithms are used in the field of architecture in order to developed an intelligent and informed strategy to minimise the impact of Urban Heat Island in our cities. We argue that past projects as the ones discussed (Ensari, E; Kobas, B; Sucuolu, C. 2017) use evolutionary algorithms for optimising roof orientations changing the angle or size of the roof and keeping the amount of materials in the roof the same. Whereas, in this research, multiple variables are put in place to demonstrate how effective evolutionary algorithms can be at producing to multiple goals whilst altering multiple variables. This research demonstrates how the use of evolutionary algorithms can be significant in councils such as Parramatta when optimising pavement materials which would normally be handled by the urban design or planning department. While the algorithm as such does not provide any new knowledge or is as such significant its application is. Cities are becoming under increased pressure and as argued in the beginning of the chapter Urban Heat Island is not only a matter of discomfort but have been endangering human health and economic productivity levels (Irger 2012). Here we further argue that this research engages with the conference theme as it engages explicitly with the innovative, intelligent and informed exploitation of computational design and apply them on two of the grand challenges of the 21st century - rapid urbanisation and climate change.

8. Evaluation of research project
The aim of this research project was to develop an evolutionary algorithm using Grasshopper to optimise pavement materials layouts to mitigate urban heat island effect. From experimenting and analysing the results given from Ladybug and Octopus an optimisation algorithm was achieved with the goals of the optimisations being cost and heat gain. As successful as this research was, it is yet unclear if this algorithm alone would be the most optimal solution in pavement materials to mitigate urban heat island effect, as there were some limitations holding back the full potential of the evolutionary algorithm. Firstly, with the infrared surface temperature testing on the materials completed only manual and only on a very small pool of data, a point of criticism exists. Further most of
the thermal testing were conducted in Spring and during days with less optimum sun exposure. Thirdly, the manual testing required the entire day to constantly measure temperatures and needs to be automated. Consequently the temperature measurement should be conducted with a automatic surface temperature reader as this would provide a larger pool of data and a more accurate pool of data. Plugins of DIVA and Honeybee were discontinued from the course of this research as there were many issues with installation and tool management, Honeybee would have been able to provide more weather variables such as reflectivity from buildings which could have added another level of depth to the algorithm. Still, the GH workflow still achieves all the objectives it was set out to complete, even if it is a simple workflow it is possible to build upon this GH workflow to keep adding more variables and goals to be analysed.

9. Conclusion
What did this paper achieve? With the increasing importance on addressing climate change and the effects of UHI in our urban communities, research on ways to optimise the most beneficial solutions to mitigate this UHI effect become an important research focus. Yet at the point non of the UHI literature reviewed has considered the use of computational tools for optimising the material selection using an evolutionary solver. Throughout the research of this paper, by using evolutionary algorithms, our developed GH workflow was able to produce optimised results for configuring pavement material layouts, which can demonstrate in lower material heat gain in the lowest costs possible. If this research and algorithm are to be expanded upon, more variables and objectives can be applied for a more complex and accurate set of results, with the ability to substitute any amount of geometry possible for this algorithm to be assigned on pavements in other cities all over the world. As often the adoption of more sustainable materials come with cost consideration this tailor made approach uses expensive and albedo improved materials only at areas where they need to be used and leave the second grade materials for areas that are overshadowed anyway. We hope that this paper will open up an interest for computational designer to engage with the topic of UHI and make use of the vast amount data collected in the field for a computational urban heat island design.

References

