DESIGNING OUT URBAN HEAT ISLANDS

Optimising paving material layouts through evolutionary algorithms

S. GREEN,
UNSW, Sydney, Australia
Stephengreen3s98@gmail.com

Abstract.

The Urban Heat Island (UHI) effect is pronounced in dense urban developments of Western Sydney, Australia, 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 developing 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 problem will be approached using visual scripting software such as Grasshopper to simulate daylight analysis and to generate the 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.

Keywords. Urban Heat Island; Evolutionary Algorithms; Optimisation; Pavement Materials; Radiation Analysis.

1. Introduction: Research Aims and Motivations, context, problem

Since the advent of the twenty-first century there have been a significant surge in urbanisation. The united nations (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 Sydney, Australia, (Irger 2014) as temperatures of 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 Sydney, they 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 (Santamouris 2013) the amount of pedestrian engagement and preventing social interaction. 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 Aims and Observations

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.

3. Research Questions

How can evolutionary algorithms which optimise pavement material layouts mitigate urban heat island effect? First, the idea itself will be discussed with such questions as; What is UHI effect? Why use evolutionary algorithms? Apart from scripting algorithms for the evolutionary optimisation, environmental impacts and weather needs to be researched 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. Finally, understanding which research methods would be the most efficient in gaining results, is an important question to be tested and solved.

4. Methodology

The methodology of developing an evolutionary algorithm in Grasshopper for optimising pavement material layouts uses action research in an iterative process. Action research is a popular approach to methodology due to its effective and practical uses. The best definition of action research is to “learn by doing” (O’Brien, R. 1998, p.1) where planning is initially involved and then sets of iterations carry out results to be reanalysed.

The action research process is easily observed through the diagram by Stephen Kemmis. [Fig.1] The planning phase consists of researching academic articles and performing literature reviews. This planning stage can be broken down into three steps. First, understanding what the UHI effect is, and what it is impacting. From this understanding, a specific topic such as pavement materials can be chosen as the case study for this research. Secondly, researching what kinds of parametric algorithms have currently been used to solve similar problems in the field regarding UHI. From these literature reviews, the software of Grasshopper and plugins Ladybug and Octopus can be selected for the use in this research.

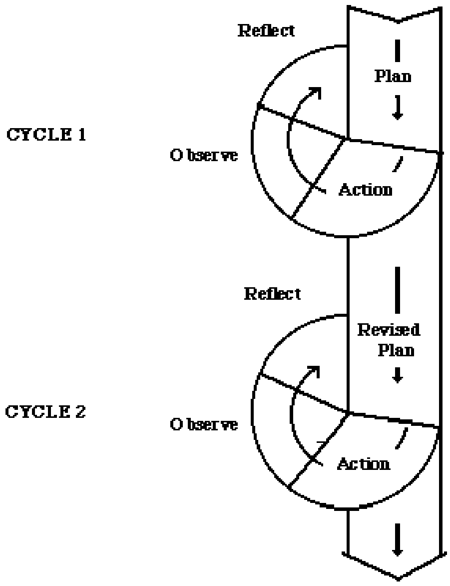

Figure 1. Diagram of Action Research Protocol

Lastly, from understanding the use of albedo in the UHI field, surface temperature data needs to be obtained personally on the five materials that are being tested to compare what properties each material have against each other. After this planning stage is complete, an action phase of iterative testing can begin where the results can be observed, reflected, and revised. Action research is unique in the fact that it combines the results and processes of theory and practice synergistically where "research informs practice and practice informs research." (Avison, D. et al., 1999, p.1)

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.

5. Background Research

To assess the impacts of the urban heat island (UHI) effect in a chosen location, the reasons why this has become a growing problem must first be understood. Matthias Irger defines the UHI effect as "the phenomena where urban areas experience higher temperatures than rural locations" (Irger, M. 2014, p.2) in his PHD on urban microclimate. Throughout his research paper, 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 allows the readers to visually understand the effects that this topic has on the world. (Irger, M. 2014, p.51) 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, Dana Cupkova and Patcharapit Promoppatum question if heat absorption radiation can be significantly delayed by changing the geometric surface pattern over the same amount of thermal, (Cupkova, D. Promoppatum, P. 2017) Their motivation is from 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 they 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 requires further research. With these successful results, a framework could be designed where designers could understand how to use materials and composition better. This kind of work shows that to study and research heat absorption it does not have to be in the traditional methods, using coatings or reflective qualities to reduce the heat absorption but to think outside the box about alternative methods. This kind of 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 Huy's 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. (Huy, N. 2008) 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, the simulation was possible to a certain level. These ideas were supported by several other projects which use GIS instead of AutoCAD (Nichol, J. 2004) (Mardaljevic and Rylatt. 2003) that show that the simplicity of the 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. This significance of Huy'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.

More comprehensive 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 Elif Ensari, Bilge Kobaş, and Can Sucuoglu, have used evolutionary algorithms to analyse given zones of a built environment from an architecture team for an airport roof. (Ensari, E; Kobas, B; Sucuolu, C. 2017) 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 Octopus, Grasshopper, and Rhino 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 as some sort of material absorption testing.

From reviewing these pieces of academic literature, they seem to pose similar concepts and methodology to that of what would be studied and researched in the field urban heat island effect. Gathering different perspectives on how work has been accomplished in the past on similar topics, allows the forthcoming research to be valued and considered more carefully.

6. Case Study

This research project was initially to develop a general algorithm for which any firm or company can use for optimisation methods, but through the beginning weeks of this research paper, collaborating with The City of Parramatta (CoP), the council of the Parramatta precinct in western Sydney, Australia, a case study was established. After some discussion, this project is to look at a case study of 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 to provide the CoP with information about an alternative solution for pavement material layouts, and to show that computational design and evolutionary algorithms are relevant in not just architecture firms but councils too.

Previous academic research has applied similar methods to similar case studies, but mainly towards roof orientations and not about optimising pavement material selection. The tools that will be used for this optimisation process are Grasshopper, Ladybug, and Octopus, all of which were used in another project but to define solar heat gain in roof structures. (Ensari, E; Kobas, B; Sucuolu, C. 2017)

6.1 Parramatta Geometry

Over the course of several design iterations through the research of this case study, basic geometry was used to first gain an understanding of the algorithm being applied, and then setting up the script to then be used for any alternate geometry which replaces the Parramatta precinct geometry.

When first learning how to use the Ladybug plugin in Grasshopper, 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. [Fig.2]

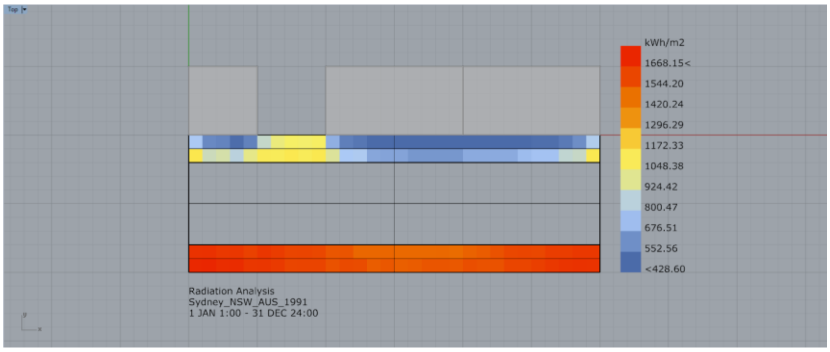

Figure 2. First iteration of pavement geometry

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 CoP was borrowed for the sake of this research project. However, the CoP uses SketchUp to develop their precinct geometry, whereas this project uses Rhinoceros as the 3D modeling program, with Grasshopper as its visual scripting plugin. [Fig.3]

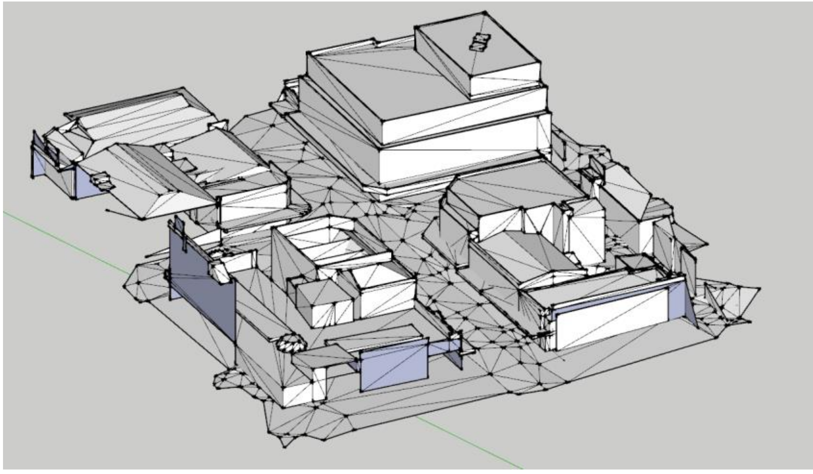

Figure 3. Cropped SketcUp file of Parramatta's Church x Philip street

So, the geometry had to be exported to fit that of Rhino, as well as being scaled down and cropped to the appropriate street intersection. The pavement footpaths were also not modeled into the SketchUp geometry as that geometry was mainly for overall building structure. So, for this case study, the pavements were modeled 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 modeled in correctly, this would be the final geometry to be used for both second and third iterations of this project. [Fig.4]

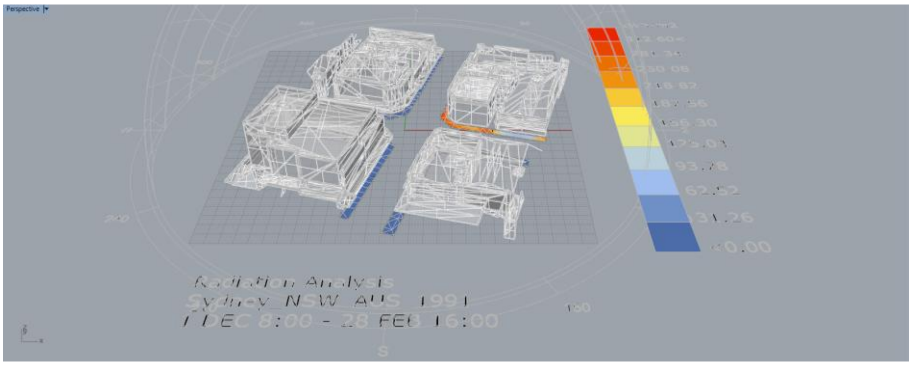

Figure 4. Church x Philip geometry in Rhino with pavement

6.2 Material Surface Temperature

To be able to gather objectives for the evolutionary algorithm to run with to optimise cool materials, the five materials that are being used for this research project will need to have their albedo levels identified for a more 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, [Fig.5] 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.

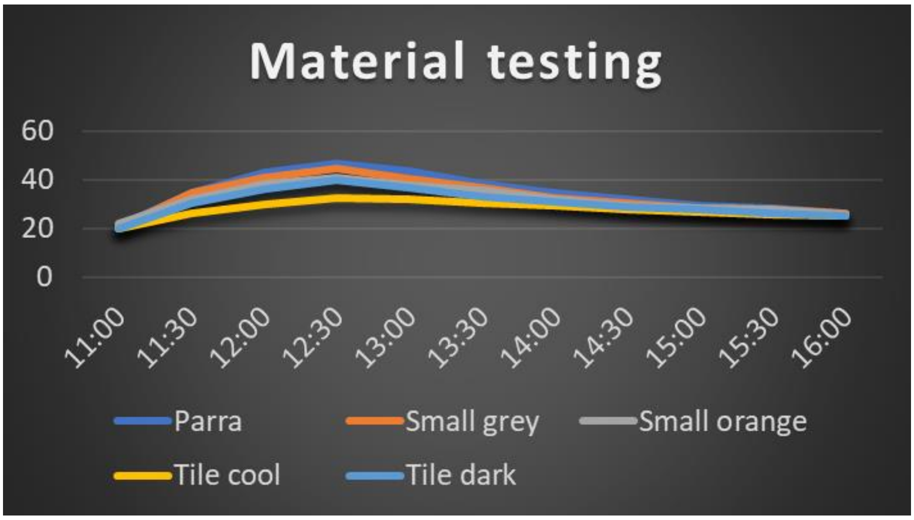

Figure 5. Surface temperature testing results, simulated albedo levels

6.3 Grasshopper

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 with more of an environmental analysis focus than 3D modeling, external plugins can be downloaded from other users online who share components, to assist this research project when dealing with radiance analysis and evolutionary algorithms.

Originally, when researching academic literature and past research projects on similar topics, many different plugins for Grasshopper were mentioned, and further research needed to be done to understand which the best for this case study was. DIVA is a plugin which runs thermal daylight, solar radiation, and glare simulations which would fit perfectly for radiation analysis of the geometry. However, when installing this plugin, several complications arose, and it would not be able to install properly. Other alternatives would now have to be searched for to simulate a radiation analysis.

6.3.1 Ladybug

Ladybug is a weather analysis plugin for Grasshopper which can produce such diagrams of sun pathing and radiation analysis. With previous experience in this plugin, the basic functions of this tool package were faster to understand and setup.

The first step to setup the algorithm is to input a weather data file which is local to the proposed case study site of Parramatta. In this case we will be using one of the Sydney city 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. [Fig.6] 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.

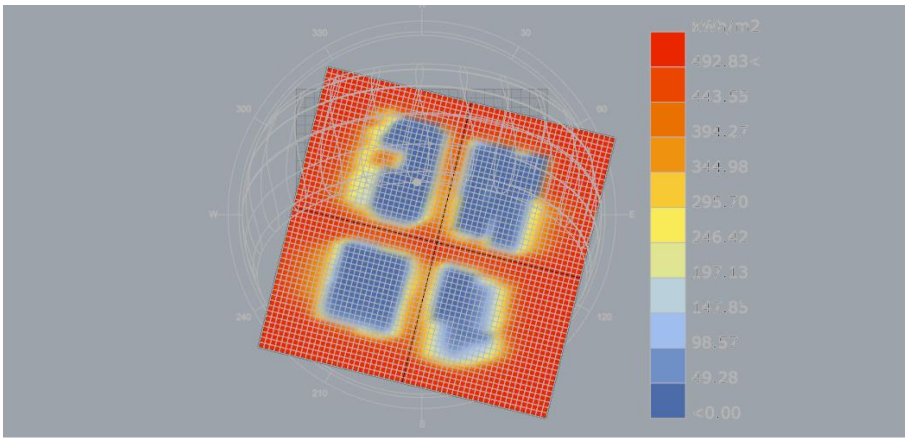

Figure 6. Visualisation of radiation analysis results

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. [Fig.7] 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.

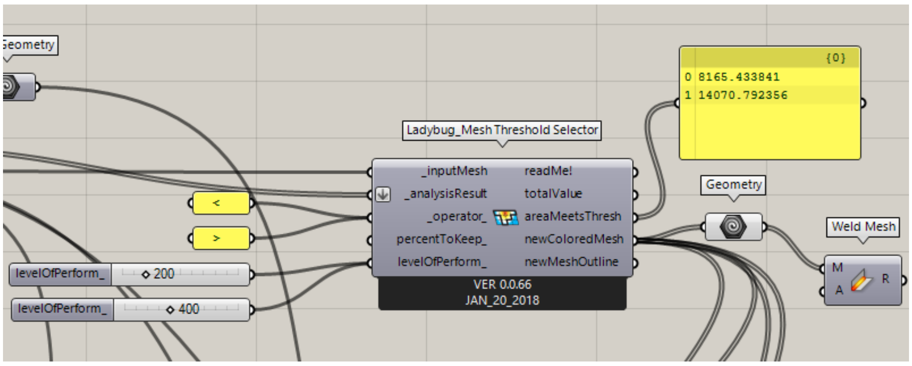

Figure 7. Mesh threshold selector tool

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, the plugin named Octopus needed to be downloaded and installed 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 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. [Fig.8]

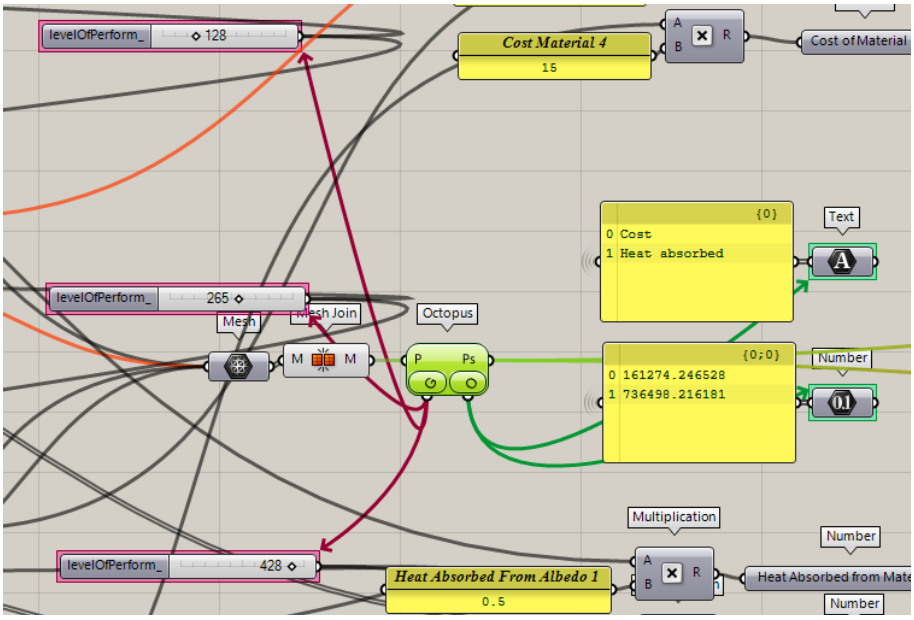

Figure 8. Octopus component (purple: variables, green: objectives)

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. [Fig.9]

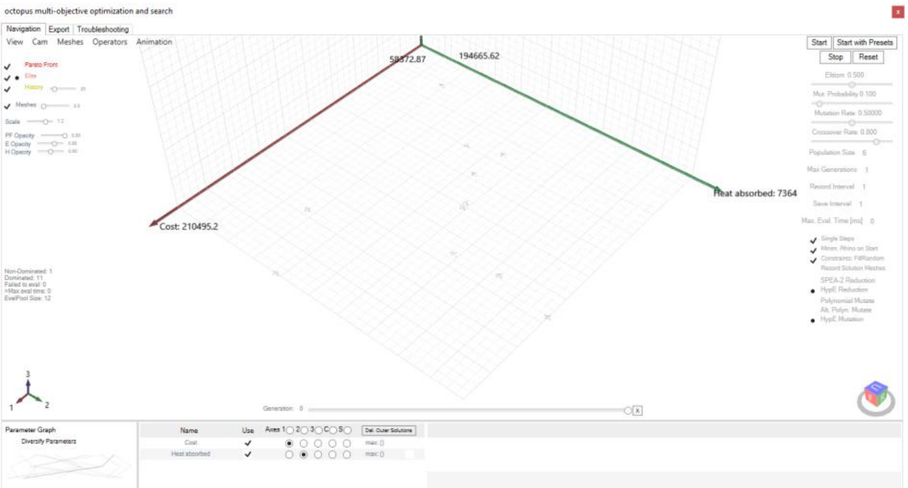

Figure 9. Octopus result output

6.4 Final Script

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. [Fig.10]

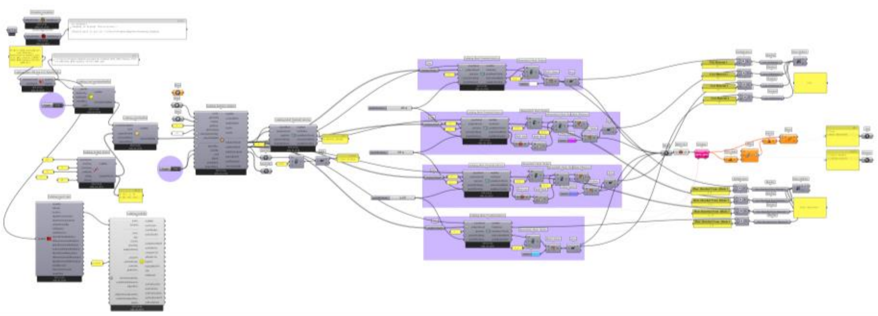

Figure 10. Complete Grasshopper script containing Ladybug and Octopus

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. Octopus recognises the history of evolutionary algorithms and is open for use in that field as well. However, with this research paper, evolutionary algorithms are used in the field of architecture where mimicking processes of nature in buildings are quite common. Past projects using evolutionary algorithms have generally been 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.

Where the utilisation of evolutionary algorithms may be beneficial in the field of architecture for optimising roof structures, this research demonstrates how the use of evolutionary algorithms can be significant in councils such as City of Parramatta when optimising pavement materials which would normally be handled by the urban design or planning department. Computational design is yet to be proven as a viable or acceptable profession in conditions outside specific architectural needs, and this research goes to out show how beneficial the use of evolutionary algorithms can be in countless other industries and fields.

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 being cost and heat gain, and the variables that of each materials area.

As successful as this research was, it is 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.

With the infrared surface temperature testing on the materials this was completely manual with only a very small pool of data, as there were not too many sunny days and the manual testing required me to be free the entire day to constantly measure temperatures. If this was conducted with a automatic surface temperature reader, a larger pool of data and a more accurate pool of data would be able to be used for this project.

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.

This evolutionary algorithm still achieves all the objectives it was set out to complete, even if they may be simple it is quite possible to build upon this algorithm to keep adding more variables and goals to be analysed.

9. Conclusion

With the increasing importance on 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 one of the most valuable discoveries in the industry. Throughout the research of this paper, by using evolutionary algorithms, Grasshopper 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.

This algorithm is also not limited to that of architecture and urban design, but to that of people interested in weather or science. It will be interesting to see in which ways evolutionary algorithms can optimise industries from all corners of the world.

Acknowledgements

Special mentions to Nicole Gardener, Hank Haeusler and the rest of the Computational Design tutors at UNSW, for providing helpful feedback and motivation during this research. Also thanks to Geoff King and City of Parramatta providing an environment for me to talk to people and understand real world industry problems relating to this research.

References

Avison, D. et al., 1999. Action research. *Communications Of The Acm*, 42(1), p.94–97

Cupkova, Dana; Promoppatum, Patcharapit (2017) Modulating Thermal Mass Behavior Through Surface Figuration. p:1-10

Ensari, Elif; Kobas, Bilge; Sucuolu, Can (2017) Computational Decision Support for an Airport Complex Roof Design: *A Case Study of Evolutionary Optimization for Daylight Provision and Overheating Prevention*. p:1-13

Huy, Nguyen Quang (2008) A Simulation Image Of Urban Heat On Solar Absorption Cofficient, *AutoCAD and GAUSS Matrix Blur Method*. p:1-7

Irger, Matthias (2014) The Effect of Urban Form on Urban Microclimate. Published by Faculty of Built Environment. UNSW

Mardaljevic, J. and Rylatt, M. :2003. Irradiation Mapping of Complex Urban Environment: *An Image-Based Approach. Energy and buildings* 35(2003): 27-35

Nichol, J. and Wong , M.S. :Modeling Urban Environmental Quality in a Tropical City. *Landscape and Urban Planning* 73 (2005) 49–58

O'Brien, R. 1998. An Overview of the Methodological Approach of Action Research

Santamouris, Mat. (2013) Energy and Climate in the Urban Built Environment

Websites

68% of the world population projected to live in urban areas by 2050, says UN. 2018. Available from: https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html (Last accessed 27 October 2018)

Evolutionary Algorithm. 2018. Available from: <https://en.wikipedia.org/wiki/Evolutionary_algorithm> (Last accessed 22 October 2018)

Weather data by region. 2018. Available from: <https://energyplus.net/weather-region/southwest_pacific_wmo_region_5/AUS%20%20> (Last accessed 25 August 2018)