

URBAN HEAT ISLAND AND VEGETATION COOLING

**VALIDATING QUANTITATIVE THEORY THROUGH
BUILDING INFORMATION MODELLING**

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MSc Construction Management & Engineering



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URBAN HEAT ISLAND AND VEGETATION COOLING: VALIDATING QUANTITATIVE THEORY THROUGH BUILDING INFORMATION MODELLING

Master Thesis by

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PREFACE

This report is the culmination of my Master's graduation thesis, as part of the MSc in Construction Management and Engineering at the Technical University of Delft. It contains a detailed account of the progress in the investigation of my chosen topic: the interaction between Building Information Modelling and the Urban Heat Island effect.

Firstly, I would like to thank the members of my graduation committee, who took the time to guide my efforts through this project. Thank you to Prof. Dr. Henk Jonkers for supporting my idea from the very beginning and cautioning me on the bumps along the road. Thank you to Eva Stache, for so gracefully lending her own thesis to be the basis of my project and making herself available to help me with the many theoretical doubts along the way. Finally, thank you to Prof. Dr.ir. Sander van Nederveen, for showing his support when my graduation thesis was at its lowest point and sharing his vast knowledge on digital design.

Secondly, I feel extremely fortunate for counting on the Technical University of Delft, to propel my knowledge and growth as an engineer and person. Despite the difficulties presented by the recent coronavirus crisis, I felt supported throughout my investigative efforts by a highly competent team of professionals and a solid educational institution. It is a great honor to conclude my studies here.

Last, but not least, the effort to conclude this work was mentally and sometimes physically demanding. It would not have been possible without the continuous support of my friends and family. For that, I am grateful beyond words. No meaningful achievement is ever individual.

Lucas M. Terreri

EXECUTIVE SUMMARY

Urban Heat Island (UHI) is described as the increased temperatures in urban areas in relation to their rural surroundings, due to the presence of heat absorbing surfaces (Oke, 1976). This phenomenon has been acknowledged extensively without finding greater representation in policymaking and counteractive measures. This is partially due to the difficulties in quantifying the phenomenon for consideration in design and cost-benefit analysis, compiled with the general absence of quantitative methods based on thermodynamic theory. A straightforward solution to UHI is the presence of vegetated surfaces. Unlike manufactured materials, vegetated surfaces use the heat from the sun in evapotranspiration. In this process, vegetation uses the heat to transform water into vapor, which consequently disperses the heat energy instead of accumulating it. This solution is known as vegetation cooling, and may be used to balance out the effect of constructed surfaces.

In practice, this phenomenon must be contemplated in the context of the Architecture, Engineering and Construction industry (AEC), that together with local policy makers, decide the fate of urban environments. In its current state, UHI has been associated with many undesirable side effects, including health problems associated with excessive heat, higher energy consumption and decrease in productivity. However, the phenomenon suffers from the essential drawback of being difficult to quantify. As the AEC industry bases its decisions on numerical tools such as viability studies and cost-benefit analyses, a factor that is not easily quantifiable is usually neglected. Fortunately, efforts have been made, in academic research, to propose quantitative models to better understand and analyze the Urban Heat Island effect. One of these studies, developed by Eva Stache, applies the Thermodynamic theory of energy balance to calculate surface temperature, using surface properties and weather condition data. It also quantifies the different heating profiles of vegetated surfaces, by estimating the portion of heat that is used in evapotranspiration. This quantitative model is the basis of this study

In order to further validate the quantitative model, this study proposes the use of Building Information Modelling (BIM). BIM is described as a series of concepts and tools that collaborate to store relevant project information inside of computer models. In practice, BIM is a set of softwares evolving from Computer Aided Design (CAD), combined with collaboration and information sharing philosophies. BIM has spearheaded recent developments in the AEC industry, enabling projects to be concluded in less time and with lower expenditures. However useful, BIM is still at its infancy, and the AEC industry has strived to put in place regulations and protocols towards an effective BIM execution.

This investigation consists in the creation of a BIM tool to connect the quantitative model, proposed by Stache, and the information contained within BIM models. Not only does BIM represent new possibilities to further implementation and validation of this quantitative model, it also contains variables necessary for its calculations in industry-standard models. With that goal in mind, *Revit 2019*, a standard, widely used BIM software was chosen to carry out this study.

Moreover, *Revit* is equipped with an inbuilt coding platform that allows for the programming of additional functions. The development of this tool is described in detail in the body of this report. More importantly, the delivered result manages to successfully extract information from a sample model and use it in surface temperature calculations. These values are all associated with spatial coordinates, and through those, the tool is able to generate a heat map with the help of GIS software, ARCGIS Pro.

The generated heat map is analyzed in comparison to thermal satellite imagery. The objective of this comparison is to assess how close the quantitative model comes to representing what is captured through thermal imagery. The results obtained show a promising resemblance to the thermal imagery. Using the same color scheme, it is evident that there is a strong correlation between different surface-types and their expected temperature ranges. Different surfaces show their particular temperature profiles in the areas of the map where they have been sampled. The visualization tool not only indicates that the quantitative model correctly interprets the thermodynamic phenomenon, but also constitutes a powerful tool in the process of design. As BIM embeds itself further in the AEC industry, designers must have into account how their propositions will contribute to Urban Heat Island. This tool allows for the previsualization of surface temperature performance during early stages of design, when changes to surface, layout or the addition of vegetated patches are yet inexpensive. Additionally, the tool may be applied to pre-existing areas for identification of hot spots and testing of possible contingency measures.

Despite the success of the tool in providing further validation for the quantitative model, it does suffer from drawbacks that are characteristic of BIM. The attempt to execute a multi-disciplinary task, such as the one contemplated here, often entails the collaboration of multiple softwares. When transferring information from one software to another, a great deal of information, which is what makes BIM valuable, is lost through proprietary file formats. This also results in additional manual inputs, which prevents the tool from having a desirable level of automation and user-friendliness, resulting in higher level of specific knowledge required to operate the tool. Through this experience, it also becomes evident that despite the many possibilities offered by BIM technologies, softwares are designed to cater to specific industry needs and the lack of focus on sustainability-oriented tools translates to a deficiency in softwares that group the type of data required for specific studies in the area. This, in turn, requires the use of multiple softwares to accomplish a single task and falls prey to the problems of software interface.

The recommendations following the study focus on two particular areas: refining of the script and refining of validation methods. The first could be achieved through factoring in more sophisticated approaches to surface temperature calculations, such as the three dimensional effect of vegetation in affecting surfaces and the thermodynamic interactions between different surface-types; the latter could be accomplished by devising a scientific method to analyze the similarity between the compared images. A suggested alternative proposes the translation of reference satellite images to individual temperature values and coordinates, enabling a quantitative comparison between theoretical and empirical results.

1 TABLE OF CONTENTS

- 2 Introduction and Context..... 9
- 3 Literature Review 11
 - 3.1 BIM and the AEC Industry..... 11
 - 3.2 Sustainability and Green BIM 12
 - 3.3 UHI and BIM..... 12
- 4 Research gap and research question 14
 - 4.1 Research Gap 14
 - 4.2 Research Question 14
- 5 Source Material and Tools 16
- 6 Deliverable and methodology 18
 - 6.1 Deliverable..... 18
 - 6.2 Methodology 19
- 7 Location and Reference Selection 21
- 8 Modeling 23
- 9 Script Design..... 26
- 10 Calculations 34
- 11 Heat Map Generation 36
- 12 Results..... 37
 - 12.1 Sampling frequency..... 37
 - 12.2 Scaling..... 38
 - 12.3 Algorithm output 38
 - 12.4 Generated heat map 39
- 13 Validation and limitations 42
 - 13.1 Intermediate temperature zones..... 42
 - 13.2 Overrepresentation of roof surfaces..... 43
 - 13.3 Scaling..... 43
 - 13.4 Point Sampling 44
 - 13.5 Validation..... 44
- 14 Discussion..... 46
 - 14.1 Software interface..... 47

14.2	Discrete sun path analysis	47
14.3	Automation.....	48
14.4	Accessibility	48
15	Recommendations.....	51
15.1	Script improvement	51
15.2	Further validation.....	52
16	Conclusion	53
17	Personal reflection.....	55
	Appendix A - Reference Area.....	56
	Appendix B - Reference Thermal Image	58
	Appendix C - Location study	59
	Appendix D - Color Study	61
	Appendix E – Temperature range in the month of November, 2019.....	62
	Appendix F - Surface dependent variables and weather information	63
	Appendix G - Convection Coefficient theory and air properties.....	64
	Appendix H - Produced heat map 1:1900 scale	66
	Appendix I - Produced heat map 1:500 scale	67
	Appendix J – Input/output diagram	68
	References	69

2 INTRODUCTION AND CONTEXT

An urban environment and its climate will affect one another reciprocally. Much like the development of an urban center affects its surrounding environment, the very existence of a city will change the way in which climate behaves. The first references to climate effects in local urban environments were recorded by Luke Howard, in “The Climate of London”, 1818. Howard observed that the temperature of London was slightly higher in densely populated areas, and that London was, in general, warmer than its rural surroundings, especially at night (Mills, 2009). That characteristic constitutes the most common definition of Urban Heat Island Effect (UHI) in use today: “UHI is the part of the urban environment presenting higher air temperatures compared to its rural neighborhood” (Oke, 1976).

Manmade materials have a different relation to climate than natural vegetation. Surfaces such as asphalt, concrete and brick, absorb heat more proficiently, creating a heat storage system in urban environments. Not surprisingly, this accumulated heat contributes to higher temperatures close to these surfaces, creating a warmer environment in what are called: Street Canyons. These are sections of cities composed by walls on both sides and pavement at the bottom, with an open top, where the majority of human activity is concentrated.

In recent times, rising temperatures have caused increasingly hot summers, which are felt all the more intensely in urban environments. The European Environment Agency states that the 2000s was the warmest decade on record, with 2010s not far behind. The projections indicate that the temperatures will rise even further and heat waves are likely to become more problematic in urban areas (European Environment Agency, 2020).

The consequences of higher temperatures are often discussed in the context of global warming, however, the short-term impact is not to be undermined. In the context of UHI they include: altered outdoor and indoor comfort, lower public health accompanied by increased mortality, increased air pollution, higher energy consumption and lower productivity (Stache, 2019). With urban population projections expected to rise to a whopping 68% by 2050, according to the Revision of World Urbanization Prospects by the United Nations, the issue of Urban Heat Island requires proactive mitigation strategies.

Vegetation is an interesting solution to UHI. When added to urban landscapes, vegetation will convert the energy of incoming solar radiation to latent heat, in the process of evapotranspiration. Latent heat, by definition, does not contribute to raising temperatures. Instead, the energy is consumed in changing water states (Moran et. Al 2010). The corollary here is that the more vegetation in relation to manufactured materials, the less susceptible an area is to UHI. Naturally, the vegetation has to be strategically placed in relation to its fabricated surroundings in order to have a meaningful effect.

Urban environments are always developing in the context of the Architecture, Engineering and Construction Industry (AEC). This industry, together with governments and policy makers, prioritize and address the needs of urban environments through infrastructure decisions, new buildings and the reform of existing urban environment. For that reason, the Urban Heat Island phenomenon is intrinsically connected with this industry and any solution must be contemplated in relation to it (Song et. Al 2017). For that reason, the discussion must be brought to BIM. BIM may be defined as a group of practices, policies and technologies that aim at grouping the essential information of a building in data format (Penttilä, 2006). More than computer models and softwares, BIM embodies the idea that project information has to be compiled and accessible, for ease of analysis and communication. Through tools that enable that, the industry can learn, optimize and grow. This idea has transformed the AEC industry of late, offering many possibilities to integrate the different phases in construction projects and to optimize tasks.

It is difficult to quantify the impact of BIM in the industry. The numerous possibilities that the concept proposes, together with an overwhelming “newness” factor, has left the industry both hopeful and helpless. In one hand, many tasks can now be revolutionized, done differently and more effectively; on the other, there has been struggles with coordination of efforts and regulating and standardizing of BIM practices (Won, 2013). In addition to such challenges, the topic of sustainability has also found its way to BIM. As sustainability goals come into the foreground, BIM has been seen as a new tool to help the AEC industry make its way to more sustainable practices (Davies 2018).

In the past years, the industry has seen the growth of Green BIM, which embodies the application of BIM practices to the area of sustainability. The possibilities of BIM are then applied to AEC practices with the objective of enhancing sustainability in their activities (Wong, 2015). Nevertheless, sustainable solutions still suffer from difficulties in quantifying the contribution of Ecosystems. As AEC projects are assessed numerically, through tools such as cost-benefit analyses and viability studies, factors that are difficult to quantify are often left out of these calculations. In order for sustainable practices to gain considerable importance in the AEC industry, efforts must be made to quantify these contributions (Constanza, 1997). This brings us back to Urban Heat Island. As a problem currently affecting cities and projected to increase in relevance in the upcoming years, efforts must be made to correctly quantify it. If that is done correctly, possible solutions are put on the correct path to create positive change in the industry.

The starting point of this Master Thesis project is the quantitative model proposed by Stache, in partnership with Jonkers, previously developed at the Technical University of Delft. This model proposes a quantification method for surface temperatures and their contribution to UHI, based on thermodynamic theoretical knowledge. Part of their study also included empirical testing of the calculation with positive results. The objective of this study is to take the theory one step further by applying the possibilities of industry standard BIM software to further verify the validity of the theoretical model.

3 LITERATURE REVIEW

In order to understand the current efforts and difficulties in the area of interest, this section is dedicated to reviewing the available literature on the topics surrounding this project. This is also done to highlight the research gap, as emerging from the absence of what is hereby proposed. The focus is firstly on the innovations brought on by BIM technologies in the context of sustainability. Touching upon the relationship between BIM and the AEC industry, the difficulties in BIM implementation, the directing of BIM tools towards increasing sustainability as Green BIM and the yet unexplored case of Urban Heat Island and BIM.

3.1 BIM AND THE AEC INDUSTRY

BIM has represented a new era of design in the AEC industry. The information stored through BIM elevates computer models beyond simple visualization and opens a myriad of opportunities, such as “new means of predicting, managing and monitoring the environmental impacts of project construction and development through virtual prototyping/visualization technology.” (Wong, 2015) The focus of this study lies on the design phase of projects, as that is when environment-oriented solutions are effectively decided upon, with the most efficiency and positive cost-benefit (Azhar, 2011). As expected, the design phase contains many assumptions, given the absence of information at early stages. As technology advances, designers are able to better predict the performance of their designs. Computer models, combined with theoretical knowledge, bring to light predictive information during the design phase. The value of this information lies on the possibility of analyzing performances and implementing changes before passing the project on to following phases, where changes are more costly to impose. Moreover, traditional design environments have been criticized for providing little foreseeability in terms of performance and feasibility of solutions (Wong, 2015).

Despite all its apparent benefits, BIM has found difficulties in the AEC industry and much research has been dedicated to understanding exactly why that is. The literature outlines that BIM will enhance a project’s performance in terms of time and cost savings (Azhar, 2011), however, due to how recent this technology has been implemented, there is limited evidence to this claim (Neelamkavil, Ahmed 2012). In addition to a fundamental lack of evidence, there are debates in the industry as to whether BIM implementation is truly beneficial for projects. That has to do with a present awareness of the costs and difficulties of implementing this technology, namely: lack of trained professionals and formal education, lack of protocols and industry standards, industry’s aversion to change, to name a few. For those reasons, the rate of BIM implementation in the AEC industry has been slower than expected (Walaseka & Barszcz, 2017). Additionally, research efforts have tried to understand what kind of projects benefit from BIM implementation. It may be the case that BIM is beneficial only to certain types of projects. The study *Where to Focus for Successful Adoption of Building Information Modeling within Organization* derives critical success factors based on interviews with leading BIM experts. These

factors encompass the conditions that should be considered before making decisions concerning BIM adoption. This gives companies with limited manpower and budget a way to decide to what extent BIM is beneficial in their particular context. More importantly, it shows that BIM is not a one-size-fits-all tool and that its implementation may be more nuanced than the industry is comfortable with.

3.2 SUSTAINABILITY AND GREEN BIM

Despite the environmental focus on sustainability as a growing societal priority in the 21st century, the AEC industry is still very much a major pollutant and energy consumer (Rode & Burdett, 2011). Increased pressure from regulations and resource scarcity are likely to push the AEC industry into finding more sustainable methods in upcoming years. BIM is regarded as the bridge to adapt existing tools to sustainable purposes, giving origin to Green BIM. Nevertheless, research has indicated that there are still many obstacles to a widespread adoption of BIM as an everyday tool. Among these obstacles are: companies lack a detailed BIM execution plan, willingness of project managers, companies do not feel technologically caught up to effectively administer BIM among others. This situation has seen BIM tools usually limited to clash detections and spatial coordination by their use in the industry (Won, 2013).

The literature not only outlines the shortcomings of BIM industry applications but also the undermining of the services of ecological systems. Due to difficult valuation, the services provided by ecosystems (services such as erosion prevention, climate regulation and waste treatment) are not included in cost benefit analysis and policy decisions (Costanza, 1997). This contributes to the aforementioned delay in the adoption of more sustainable AEC industry practices. In a cost benefit analysis, any contribution that is not directly, or easily translatable, into a monetary figure, is left out of calculations. Such negligence tends to propagate in investment decisions and in the way investors think about projects (Adler, 1998). This practice, until now dimly opposed, hinders the strife to combat environmental issues in the twenty-first century (Atkinson, Mourato, 2008).

The potential behind BIM and ecosystem services has gladly found some traction in academic research. As a first step to creating more adequate solutions, investigators have dug deeper into exactly how the ecosystems may be better represented numerically and have their value accounted for. According to Kleerekoper, policy makers are hesitant to use sustainable design principles due to lack of quantification (Kleerekoper, 2012). A natural corollary is that with eventual quantification, the science itself will drive change in policy.

3.3 UHI AND BIM

The relatively recent advent of BIM technologies are yet to be applied to the context of UHI. Despite much research being done at different levels, in the academic medium, most of the knowledge gathered has not found its way to the field of digital design. Consequently, review of relevant literature focuses on understanding the UHI phenomenon theoretically and empirically. Since the late 70s, early 80s, Oke has documented higher temperatures in urban environments

and laid the foundation of theoretical explanation of the phenomenon (Oke, 1976). Subsequent studies have proposed quantitative models to numerically capture the phenomenon (Stache, 2019) while other efforts were made to unify the information on the subject and propose solutions in the realm of urban planning (Kleerekoper, 2012). Studies are also seen at regional levels, focusing on specific urban environments and the validity of quantification methods. Recently published studies by Yan et. al. measured air temperatures in Shenzhen along an 8km long street canyon for a year. Concluding that vegetation coverage, among other things, reduces fluctuations in air temperature (Yan, 2020).

An early attempt at investigating the extents of Urban Heat Island is seen in the research of John C. Price. In this study, a NASA deployed satellite was used to estimate surface temperature in urban surfaces. Higher temperature averages (10 to 15 degrees higher) have prompted the research to suggest that this phenomenon required further exploration and that the particular contributions of industry should be a focus of further research (Price 1979). A more recent study done in the urban area of Milan, correlates data obtained from ground weather station with infrared imaging from satellites, emphasizing that Urban Heat Island is not an occasional phenomenon and highlighting the usefulness of satellites to not only identify but also monitor this effect (Pichierra et. al 2012). Because investigative steps, such as the ones presented here, have been taken, I have the necessary base to explore their implications in BIM technology.

Despite these significant efforts and the confirmation of the UHI phenomenon as caused by the excess of man-made surfaces in limited geographical space, the literature is scarce, relative to other weather-related phenomena that have been highlighted in recent years. The aforementioned difficulty to quantify the phenomenon have prevented it from exerting more urgency in being efficiently dealt with. Additionally, the lack of viable quantitative models contributes to its status as a background issue. With the possibilities brought on by BIM tools it is necessary to explore how that may contribute to the effort of understanding and propelling quantitative methods of calculation for UHI.

4 RESEARCH GAP AND RESEARCH QUESTION

4.1 RESEARCH GAP

It is widely agreed that vegetation cooling presents a viable solution to UHI. Many studies have been conducted into the properties of vegetation cooling, investigating the thermodynamic properties of vegetation coverage. However, there is yet no universally accepted calculation method for problem solving and urban design purposes (Stache, 2019). Recent studies have proposed a quantitative model, through which we now have access to a theoretical calculation method, revealing insight into UHI and vegetation cooling in street canyons. This model, developed by Eva Stache and Henk Jonkers (Stache, 2019), is based on the First Law of Thermodynamics and analyzes the energy balance of surfaces struck by the sun's radiation and how these surfaces interact with surrounding air throughout the day.

The potential of this quantitative model may be propelled forward with the help of Building Information Modelling (BIM). The centralization of information, enabled by BIM, results in practical access to it for decision making, general communications and visualization purposes. The richness of information and in-depth detail are visible in models produced today, nevertheless, important aspects of building design are yet to find appropriate representation in this technology. Such is the case of UHI and vegetation cooling. Despite largely containing relevant data for UHI and urban cooling calculations, BIM models have seen limited exploration of developments in this direction and therefore represent an untapped potential.

Through this project, I proposed to bring the aforementioned quantitative model into the BIM environment. This will be done through the programming of a BIM tool, which will use information already contained in the element-based models, to provide designers with insight into how Urban Heat Island and Vegetation Cooling may play a role in their designs. Moreover, the add-on will provide means of validating the quantitative model by outputting heat maps which can be compared to existing satellite imaging. These procedures will be further explained in the methodology section.

4.2 RESEARCH QUESTION

To guide the efforts of this study, I have formed a research question which accurately summarizes what is to be answered. Through the investigation of the relevant topics and add-on development, I aim to answer the following research question:

To what extent can the information contained in standard BIM models be used in UHI and vegetation cooling calculations?

This question captures the untapped potential already existing within BIM softwares to create tools, which in turn will help us make better use of ecological services. To explore some of this potential is the aim of this research. Sub Questions that will be relevant to the investigation and addressed are also listed below:

1. *To what extent does the quantitative model represent reality according to the result of this study?*
2. *How may the script aid designers in making environment-oriented design choices.*
3. *Can BIM tools provide a viable method to validate quantitative models?*

By answering these questions, I aim to apply the theory of UHI to a digital context, where BIM can also offer insight into how to better optimize urban planning and the use of vegetation.

5 SOURCE MATERIAL AND TOOLS

This section is dedicated to explaining some of the tools which will be used in this project. These are resources and online tools that were used in the development of the project but not designed specifically for it. In many aspects, the understanding of these tools is important to the understanding of the progress of the project. From the obtaining of reference materials from online sources to the platform where the add-on is developed, this is a short explanation of all support tools used.

Quantitative model - As previously mentioned, this project is based on theoretical work carried out by Eva Stache. By analyzing sun radiation and air temperature around urban landscape, a set of equations, derived from the first law of thermodynamics, was proposed as a method to quantify the effects of UHI and counter-effects of vegetation cooling. These equations describe the energy balance on surfaces within the urban canopy layer, which is where the effects of increased temperature can be felt. This quantitative model is not the focus of this research, but nevertheless essential to understanding the logic of it. The essential equations and thermodynamic logic are presented in the *Calculations* chapter.

Revit 2019 - Building Information Model has many softwares that come with different advantages and disadvantages given their capabilities. For the purpose of this project, it is important that the chosen software is element-based, that is, information is stored in units that represent parts of buildings. These units, or elements, may be walls, columns, floors or other architectural elements, and they store information regarding the material, shape, color, dimensions and most importantly, thermal properties. Revit 2019 is produced by Autodesk, which has continuously furnished the Architecture Engineering & Construction industry with many useful design tools. It has been chosen due to its user-oriented platform: the software allows for the programming of Python-based code, which can execute tasks beyond the program's original functions. Furthermore, the software is able to simulate sun paths according to geographical location and orientation (Figure 1), which is relevant to the simulation of the quantitative model.

Excel - Spreadsheet software developed by Microsoft. Enables complex calculations with a high number of variables arranged in rows and columns. Also enables graphic representation of data and programming of Macros. Especially relevant in the context of this project given its compatibility with Dynamo for exporting and importing data from and to the model.

ArcGIS - Geographic Information System developed by Esri. Presents its users with a dynamic and far-reaching tool to develop maps that can store several types of information. The information therefore is attached to a specific geographic location of relevance, for example: a reflectivity value attached to a particular surface to indicate that that specific value pertains to that specific surface. Beyond this simple example, the tool allows for many ways to display the information and also offers a selection of basemaps that are periodically updated to account for changes in the environment. ArcGIS also offers an online platform where users may share their creations

and explore other user’s creations. Government agencies and research facilities have used this tool to organize and share the information from scientific studies.

Australian Bureau of Meteorology - An online database that provides historical weather data for the entire Australian territory. The service is free and may be filtered according to the variables desired by the user. The data is divided into different weather stations located in different territories of Australia and provides an accurate and reliable hourly variation of the variables. This is the source for all of the manual input variables cited in the deliverable section of the report.

In the image below, find a diagram detailing how each of the programs interact between themselves to generate the desired output. Their interactions and specific functions will be further explained in following sections of the report.

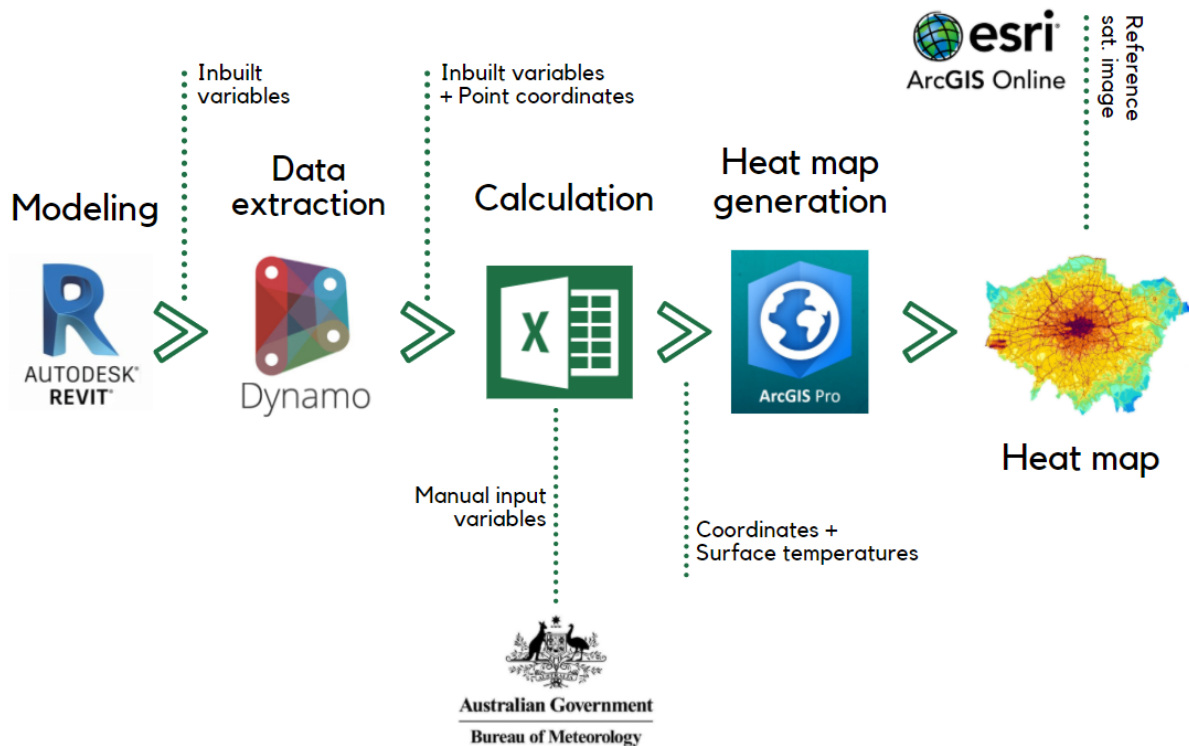


Figure 1: Flow diagram of interaction between software

6 DELIVERABLE AND METHODOLOGY

6.1 DELIVERABLE

Beyond answering the proposed research questions, and investigating the extent to which BIM technologies may aid the understanding of UHI, this project will also aim to develop a tool to enable visualization of surface temperatures in urban settings. This tool will be designed to calculate surface temperatures of a given model using a series of variables, both from within the model and as manual inputs. The list of expected variables can be found below. These are to be inputs in the formulae proposed by the quantitative model. The expected result is to represent surface temperatures in a comprehensive way, so that designers may understand the performance of buildings and urban settings in the context of Urban Heat Island. The desired outcome of this tool is a heat map, derived from a model compatible with the Software as detailed in the *Tools and Source Materials* section of the report. The 2019 version of this software is an industry standard adopted by many designers, which makes it an ideal candidate for the investigation. It is also the most recent version available that has been in the hands of the industry for a considerable period of time at the off set of this research.

Manual Input Variables	Inbuilt Variables
Solar radiation	Material
Albedo	Color
Latent Heat of Evaporation	Dimensions
Surface Emissivity	Shape
Air temperature	Shaded area
Air properties	Sun orientation
	Geographical position

Table 1: expected variables

The Air Properties variables will include gravitational acceleration, expansion coefficient and thermal conductivity, which can be further understood in the context of the quantitative model by referring to Appendix G. The tool will run an algorithm to extract relevant information from the surfaces of the model and its general layout. This information will be used in calculations to quantify the heat contribution of each surface along the exposed dimensions.

Having ascertained the temperatures of different points on the map, the next step will be to create a heat map of the model, showing temperatures and how they change along surfaces. Satellite imagery obtained through ARCGIS online will be used as a point of departure for comparing the modeled temperatures to ones measured in specific dates. This comparison will allow the study to draw conclusions as to how close the quantitative model reflects the reality captured by the satellites. *The tool will be successful in its purpose if it accurately calculates surface temperatures based on the previously developed theoretical model and displays it in heat map format that enables comparison.* This leads us to the following Validation statement:

Validation - The validation of the aforementioned quantitative model will be carried out by visual comparison between the heat map yielded by the script and the one generated through satellite capture. An appropriate area with high visibility and significant vegetation must be chosen. The same area is to be modeled in Revit 2019, with sufficient degree of precision, entailing that it should be enough to contain the information necessary for the calculations to be carried out. By running the script on the model, the desired output will be a heat map of the area, This heat map's accuracy may then be compared to the satellite capture. A conclusion may then be reached regarding the quantitative model's proximity to reality.

6.2 METHODOLOGY

Revit 2019 possesses an in-built coding platform, *Dynamo*. It allows for function programming and data extraction. The data mentioned in the table above, under Inbuilt variables, will be extracted from the model and stored for use in calculations. The add-on will then prompt for the variables that it does not possess, namely the ones listed under manual input. The algorithm will run calculations based on the formulae listed in the paper by Stache, for each unit of surface. The resulting temperatures must then be mapped back to their respective surface units, in such a way that each square meter is now coupled with a surface temperature value. Following this, each temperature range will be assigned a respective color and each unit of surface will be colored accordingly. The result is then used in a comparison to satellite thermal image, available online through the ARCGIS online platform. The similarities and differences between the images will be assessed for patterns and correlation between calculated temperature and actual temperature. To do so, both images must be in similar scales and make use of the same color scheme. These particularities are addressed further on. The methodology is better understood as a step-by-step activity sequence, as detailed below:

Dynamo study period - In order to develop the add-on, I must become familiar with Revit's programming platform: *Dynamo*. Despite having some experience with it, I believe it is prudent to experiment further. That is because my understanding of the platform's capabilities will be deeply connected with the following step.

Satellite image selection - Envisioning the final step of comparing heat maps from satellites and heat maps generated during the project, it is paramount to select the satellite images at the beginning. This will dictate which days and location will be modelled in the add-on for

comparison. It also places important restrictions on following steps. Satellite images will be obtained from the United States Geological Survey website.

Algorithm design - This will consist of planning the logic steps involved in the algorithm. A detailed analysis and planning of which coding mechanisms and functions will be used to accomplish the overarching task. A deliverable of this phase is a flow chart indicating subsequent steps, inputs and outputs.

Choice of location - Since the final objective is to compare the output of the developed add-on and satellite images, a common location must be chosen. This location will be selected based on the available images chosen in the “satellite images selection step”.

Modeling - The information from the chosen location must be transferred to the digital environment in this step. The level of detail of this model is determined by the task to be accomplished, in other words, we must furnish the model to enable the add-on to work. The focus will be on dimensions and surfaces, the limits of the tested section must also be determined during this step.

Script development and testing - This step entails the coding of the add-on. The functions detailed in “Algorithm design” must now be coded into Revit’s programming platform Dynamo. Testing and coding will be done simultaneously, that way it becomes easy to identify problems and implement feedback. It has been divided into two halves, in order to accommodate the midterm meeting in between. It is believed that this is a crucial step for the project, therefore, the presence of a formal meeting will aid monitoring of the progress.

Heat map visualization scripting - Assuming the add-on’s success in calculating surface temperatures within the control volume, the data obtained will be used to generate a two-dimensional heat map. This will entail mapping each area of the model to its calculated temperature and assigning colors to specific temperature ranges.

Heat map generation - Activity allocated to running the final version of the heat map script and generating the images for comparison.

Algorithm vs. satellite imagery comparison - Using the same color scheme for the same temperature ranges as the satellite images, it should be possible to make comparisons between the accuracy of the add-on and in turn to infer the accuracy of the quantitative model used as the basis of this research. At this stage, the comparison will be solely visual, comparing the ranges and locations of each color to derive insight into how the model represents reality.

Result processing and concluding - with the new information brought on by the experiment, I will evaluate the results of the project based on the proposed research question and sub-questions.

7 LOCATION AND REFERENCE SELECTION

In order to compare the generated heat map with satellite images, a control geographic location was chosen. The choice of location took in consideration the following aspects:

- Abundant presence of vegetated surfaces.
- Availability of surface temperature satellite image coverage. The surface temperature data for given days.
- Ease of modelling.
- Weather profile (appendix E).

Despite presenting all of the selection criteria, the chief limiting was the availability of online data. While the other three can be abundantly found, the specific, refined data needed for a relevant comparison was the bottleneck criterion. The selected location was the port town of Port Adelaide Enfield, which fit the four criteria above and provided further uniformity to aid modelling. This area is harshly affected by Urban Heat Island, due to its geographic location and the associated climate. As a consequence of such, it has been the subject of scrupulous climate studies, as part of the *Adapt West* Initiative. The following excerpt can better describe this initiative: “the plan addresses key priorities for local council operations and decision-making, and informs our community and key stakeholders about opportunities for practical action to adapt to our changing climate” (Tideman et. al. 2013). In keeping up with climate changes, the initiative commissioned a series of studies. These studies are an example of relatively early detection of the Urban Heat Island phenomenon, in addition to other temperature-related issues faced by the region. Other areas, which are also affected by the phenomenon, have failed to direct the appropriate resources to its investigation, and thus cannot hope to better understand it. The *Adapt West* initiative has also favored the scientific community and general public information, by making public and accessible their results, which have enabled studies such as this.

In an effort to better understand these effects, the studies have produced a series of maps displaying the collected climate data, including the data relevant to this project. Within the limits of Port Adelaide Enfield, satellite images have been generated and compounded with measured data for online availability. With the aid of GIS software, values such as surface temperature, thermal imagery and albedo have been taken and displayed according to the geographic location to which they belong. This exercise was carried out with a degree of precision that allows users to track a given value to its precise square meter, but no further.

Beside the data’s easy accessibility, it also has a favorable location, as the suburban setting of Port Adelaide Enfield has a balanced ratio of vegetated and non-vegetated surfaces. Furthermore, similar shape, height and materials used in construction facilitate the creation of

the model due to their repeatability, and thus enable an analysis of greater scale. The city of Port Adelaide Enfield is located in Lat: -34.848160, Lon: 138.600250. Since data was collected for the entire area of the city, a specific reference area was chosen within the city for the purposes of this analysis. This area contains ample variation of surface types and balanced presence of vegetation and built environment. A more detailed description of the reference area can be found in appendix A.

It is also relevant to point out that the data used in the construction of the maps was created based on average values, spanning the period of the study. That period was comprised by the entire month of November 2019, which entails that the image generated by the algorithm must also contemplate this period. This is further discussed in the *Sampling Frequency* section of the report, nevertheless it is clear that an average must be obtained.

8 MODELING

As a prerequisite to the successful application of the algorithm, it must operate within the environment of Revit. Among other requirements, that means that models built from Revit's standard building blocks are adequate for the algorithm's functions. Having chosen the reference area, a model was built to represent that urban setting, to a certain degree of fidelity. Using tools such as Google Maps and ArcGIS Online, the layout was reconstructed in a Revit model for use in this project.

Starting from the base map obtained from the Google Earth Software, (Appendix A) streets, walls and vegetated surfaces were placed on the model. This was a manual process of ascertaining where elements were located in the reference images and placing them in the model. As mentioned in *Location Selection*, this particular environment facilitated the modeling process due to the similarities between the present geometry: houses at same height, equidistant streets, similar building materials, among others. Given these similar characteristics, some aspects of the model were designed in a simplified manner, based on the following assumptions:

- All houses in the reference location are one-storey houses of similar height. Accounting for their attic space and using 3D impressions, the average height was simplified to 5 meters and generalized to all constructions in the model.
- All roofs are sloped roofs with a relatively low slope (less than 30%). These were therefore simplified to flat surfaces. For the present computation, this roof shape is not particularly relevant, as the increased surface area is marginal and the casting of shadows is only relevant when the sun is shining horizontally. As this model works with average temperatures, the extremes may be approximated to the mean values.
- Roof color was simplified to a single color. Despite the different shades encountered in the Location Study (See appendix C) the initial development of this add-on would be severely hampered if each roof had to be modelled with its particular color, demanding a much longer time-horizon. Usual red-brown roof tiles are predominant in the area, therefore the color R: 157, G: 096, B: 095 was chosen as a representative. The impact of this assumption is expected to be relatively small, given that roofs have a more distant effect on street canyon temperatures, nevertheless, it may impact the generation of images. This will be further discussed in the results section of the report.
- Other, less abrupt, color simplifications were also made to homogenize the colors of walls (Mostly slightly off-white), concrete, asphalt and vegetation. These, however, are not expected to affect the results, as the generalized colors are very similar.
- Vegetated areas are flattened. Despite the presence of trees and bushes, it is impractical to consider every relief when analyzing such a vast area. The vegetated areas are thus

considered as flat patches. Tree canopies are not included in the model, which also alters the presence of shade in the model. This assumption is expected to cause slight distortion of surface temperature values near vegetation. Nevertheless, given the scale of the model, these are considered an acceptable disadvantage.

- Minor surfaces were eliminated from the model. Small ground patches of different colors were present in many backyards, once again due to the scale of the area under consideration and the feasibility of the study, their influence is considered to be negligible.
- For calculation purposes, all surfaces were assumed to have a horizontal length. Despite not being modelled in this way, this assumption will simplify the convection coefficient calculations, and may be better understood through Appendix H.

To better understand how the location was surveyed and modelled, please refer to Appendix C - Location Study. Another factor supporting these model simplifications is the nature of the final comparison. Differences in surface temperature between materials will remain visible in the final product as long as the simplifications affect all surfaces equally. The possible impact of these limitations will be further discussed in this report. The final version of the model can be seen in Figure 2, rendered with Ray-tracing technology available in the Revit 2019 package.

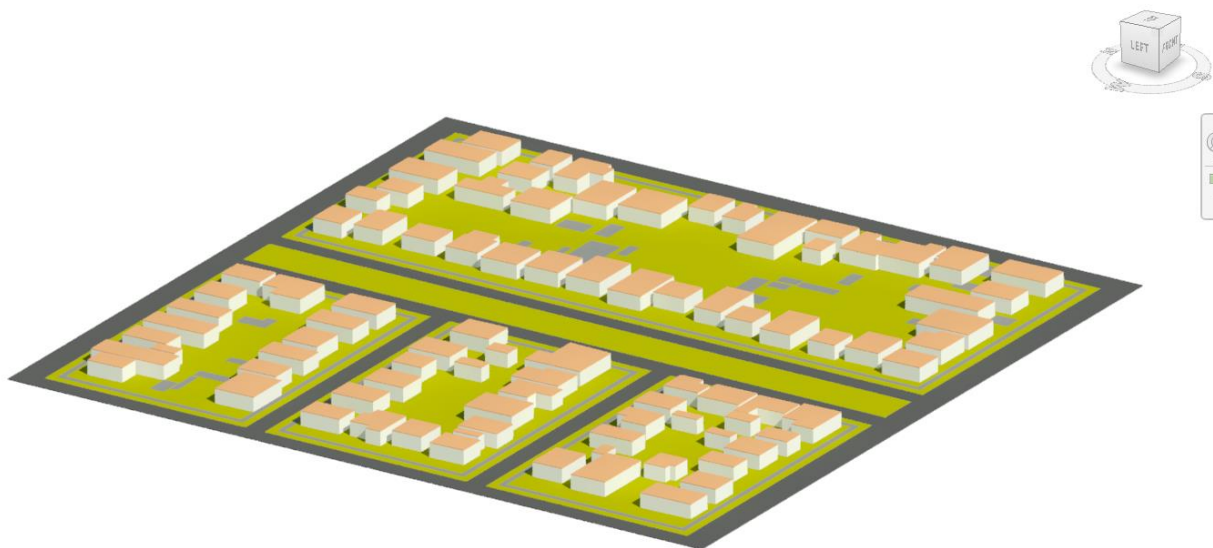


Figure 2: Finalized model rendered

At early stages, it became clear that the computational power to intricately analyze a model of this magnitude was large. As a way to circumvent this issue a further division of the model was necessary. This was accomplished by a layering strategy described as follows:

Model Layering – Given the assumptions made, the resulting models consisted of three discernible element elevations. The floors at ground level, the roofs at five meters height and the

walls in between. The layering strategy consisted in separately evaluating floors, walls and roofs and layer their effects in that order. It is important to emphasize that sectioning was only necessary in this case due to the scale of the model. In models of smaller size (areas of one squared kilometer or less), the algorithm should operate without. The effects of layering concerning user-friendliness of the algorithm are discussed in the Discussion section of the report.

Setting of Geographical Location - Revit 2019 enables the user to adjust the geographic coordinates of models. This feature is key to the success of the algorithm, given that the projection of the sun's path will be calculated based on these coordinates. More than coordinates, the model's orientation, based on the geographic north, must also be manually input. These two tasks are achieved by inputting values on a dialog box. The coordinates and orientation mentioned in Appendix A were used for the model in question. Because this is a manual input, future users of the algorithm must carry out this task independently.

9 SCRIPT DESIGN

In order to describe how the algorithm conducts its function, a basic understanding of Dynamo programming is necessary. This section explains how some of the basic dynamo programming blocks operate in relation to the Revit environment and how they will be linked together to carry out the overarching goal of the add-on.

Dynamo Environment - Dynamo is a visual programming platform associated with a Revit Model. Due to Revit's consistency in its use of families, functions can be run in multiple models in a generalized form. Revit can be used for tasks such as rotating individual objects by a fixed amount of degrees, extracting the amount and weight of steel rebar used in a building. A Dynamo script is commonly referred to as a *graph* and can contain multiple functions. Graphs are designed to perform their functions on the model contained in the Revit design environment (Figure 3).

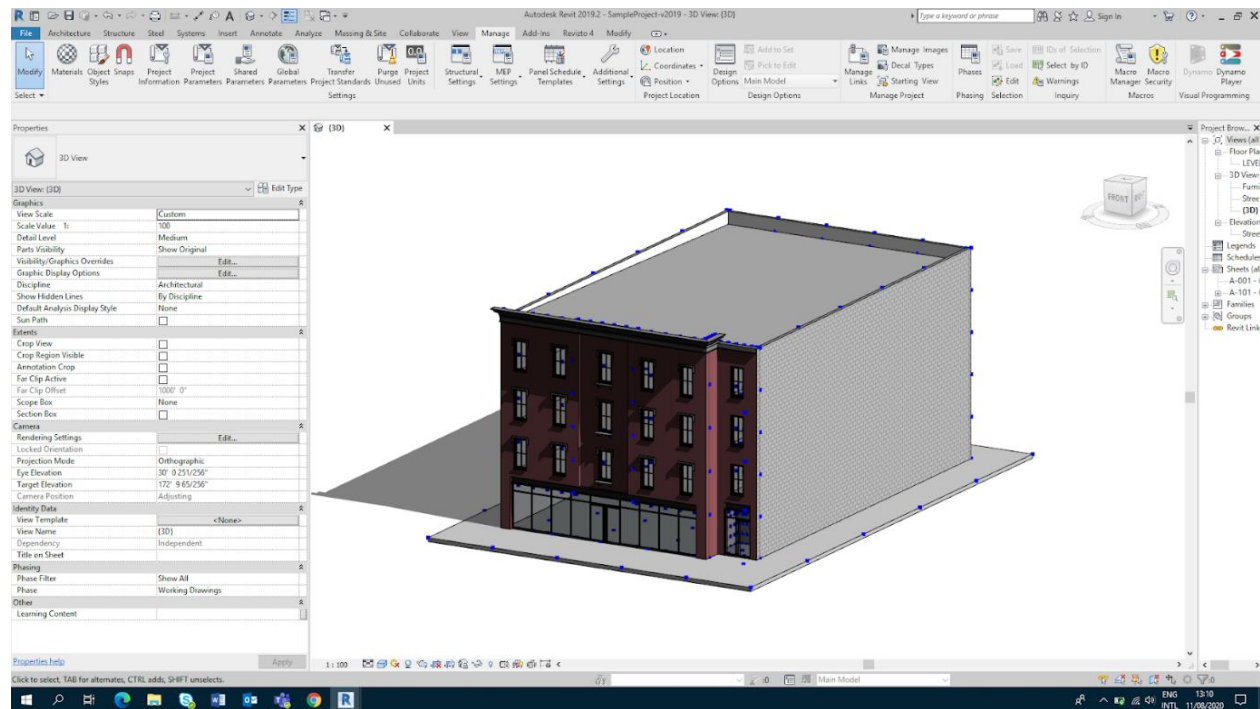


Figure 3: Revit environment

Functions are organized in nodes, each with a singular pre-programmed function, most nodes having an input and an output. These nodes are connected to each other in the Dynamo environment (Figure 4) which also contains a visual display for the geometry being generated. The visual display may be updated each time the code is changed, depending on whether Dynamo is set to *automatic* or *manual*. The latter feature controls whether the code is run whenever a change is performed or only when the user chooses to activate it. While automatic

gives users the chance to track the progress of the graph, manual is usually preferred for lengthy scripts, as these may take longer to update.

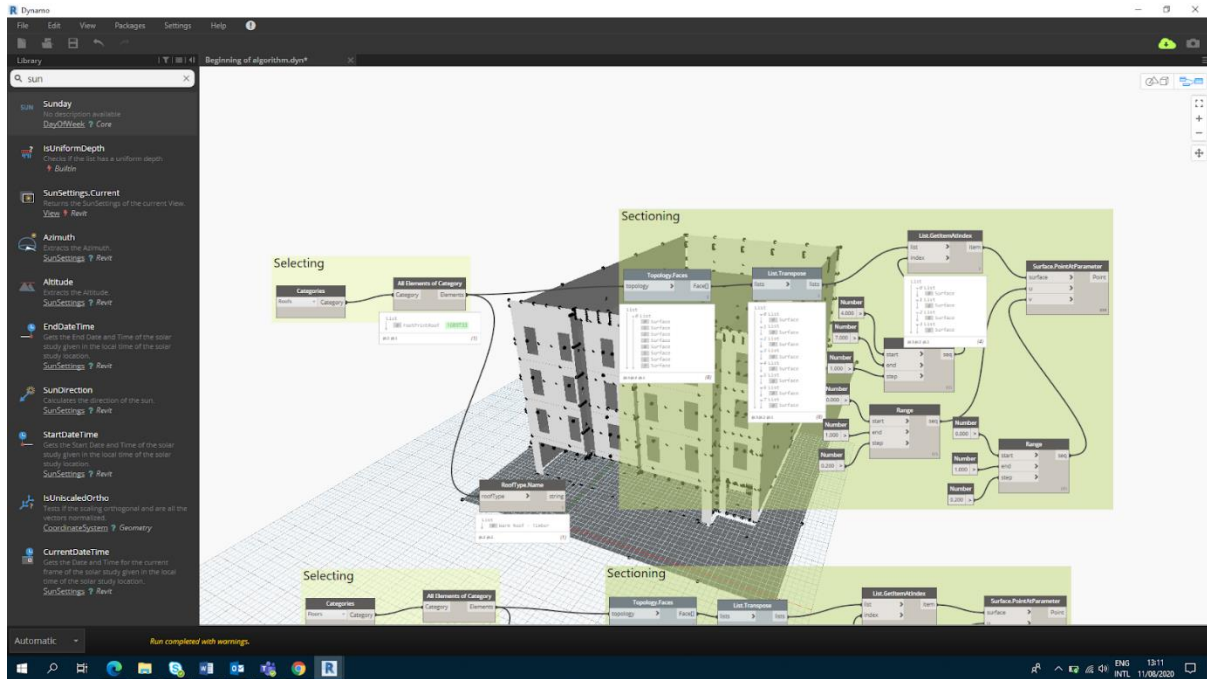


Figure 4: Associated Dynamo environment

The basic building blocks of Revit are instances. These perform differently depending on their function, for example, door and window instances must be placed on a wall instance, wall instances, in turn, may be placed independently on a plane. Instances are directly drawn on the environment by the designer. An instance is composed of its spatial geometric shape, surface textures and information, such as material, material properties, weight, surface area, among others. All instances belong to a Category, Family and Type, which represent a hierarchy of classifications as displayed in Figure 5.

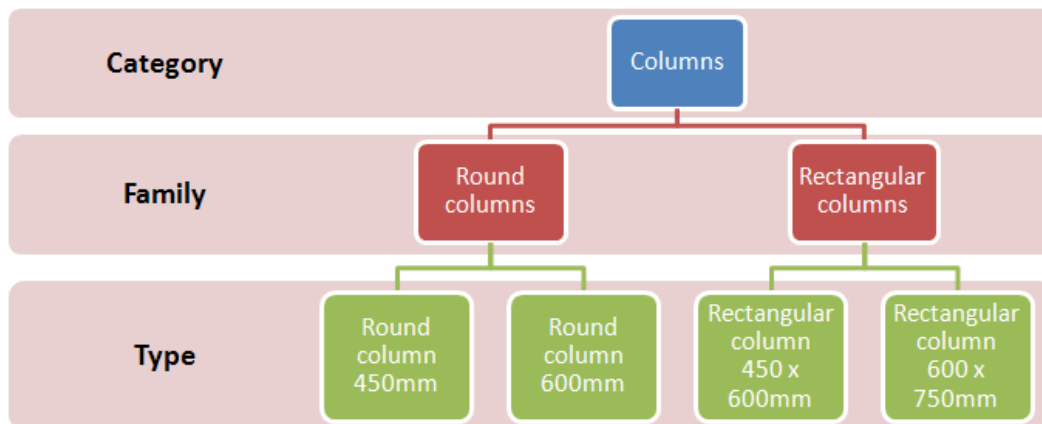


Figure 5: Categories of classification in Revit Instances.

Selecting Function - This basic overview is enough to comprehend the functions which compose the algorithm and will henceforth be reported. From this point on, the algorithm has a full-scale model to operate on, modeled according to previously mentioned assumptions. Connecting the Dynamo environment and the Revit model are *Selecting* nodes. These nodes allow users to indicate which instances of the model a given function is to be performed upon. For the purposes of the algorithm in question, all instances in the model must be selected, as they all form part of the surface which is exposed to sunlight. At this point, they are already divided into their family categories, namely: Wall, Roof and Floor. This division helps with data processing further along, as the algorithm is not burdened by having to separate instances into categories.



Figure 6: Selection node.

As seen in the figure above, a selection node (shown on the right) may be fed as an input with any type of element present in the model. Elements of that type are now selected and highlighted in the Revit environment, and any functions that stem from this node are to be performed on those specific instances.

Element-Surface transformation - Revit-elements are three-dimensional objects containing a series of information. Though this information is vital for the calculations to come, 3D objects are complex to analyze and may burden the algorithm with unnecessary processing. The next step taken was therefore to simplify these objects into 2D surfaces, which contain much less information but the same spatial presence. The node *Topology.Faces* was used in this instance. Having an element as an input, this node is responsible for discerning the different surfaces that compose the element (6-faced in the case of most prisms, such as floors, roofs slabs and walls) and creating a hollow mass. Now that the element is stripped of its information and content. The algorithm selects the specific surface of that element which will be in contact with the outside. These are out-facing surfaces of walls and top surfaces of roofs and floor slabs. With the representative surfaces of all elements accounted for, the algorithm passes these surfaces as the input to the following step.

Sectioning Function - As outlined earlier in the report, one of the basic building blocks of the add-on is dividing the entire surface into smaller sections for the calculations to be performed upon. Revit is equipped with a node that creates points along any surface. The node uses a UV system, where a u and v number dictate the amount and spacing of divisions to be created. By feeding this node a range as opposed to a single integer, the node creates an array of points in both x and y directions, forming a primitive grid. It is important for this step that all surfaces considered are flat. An irregular surface would introduce many irregularities in the absolute distance between points, driving the required logic of the algorithm to a higher level of complexity. Applying this algorithm to irregular topology would require a different path with programming, that would rely more heavily on specific functions available exclusively in the Revit program.

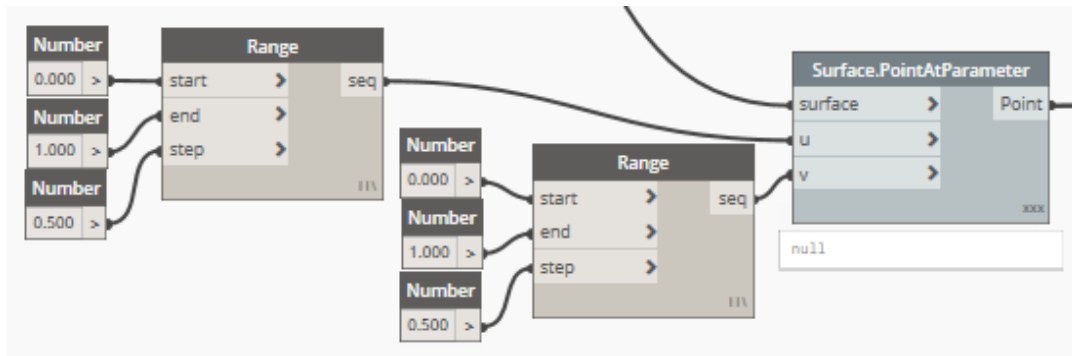


Figure 7: Sectioning function

As seen in the figure above, the *Surface Point at Parameter* node receives as input a surface, or list of surfaces, as well as the range and step at which points are to be created. The creation of these equally spaced points allows for a uniform mapping function of all the surfaces studied in the model. Moreover, the algorithm allows the user to adjust the step function, which may increase or decrease the density of points mapped. Consequently, the detail of the temperature study may be increased or decreased to fit other parameters, such as scale and LOD. A natural corollary is that the increase in points burdens the algorithm with additional processing requirements and may take longer to output results.

A specific hurdle found with this function is the following: the UV points created on a surface do not necessarily follow the shape of the surface. To illustrate this case refer to the figure below. The points created by the node are on a surface described by the irregular surface's length and width parameters, as opposed to the actual surface. In order to remedy this, a sub-function was devised to clean the points that do not lie within the surface's boundaries.

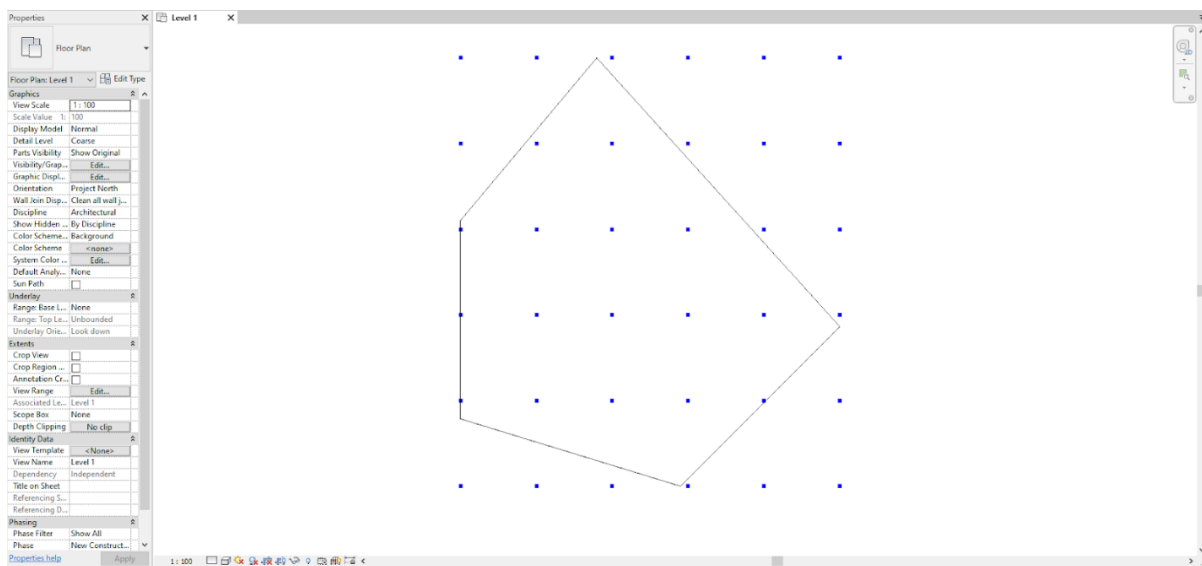


Figure 8: Surface Point at Parameter node applied to a non-rectangular surface

The sub-function receives as input the list of points created on the surface and the surface itself. Using a node called *Geometry Intersect*, it checks whether each individual point intersects with the surface. By definition, every point on a surface represents an intersection between two geometrical objects, therefore, points on the surface will output a Boolean value of “true”, while points outside boundaries returns a “false” value. The list of points is then subsequently filtered to include only true values.

As this function concludes its job, it passes on, as output, to the following function a series of points, referred to as point clouds. These points are distributed along the surfaces and limited to their corresponding boundaries, each of them containing an identity number and xyz coordinates.

Sun Positioning - as previously mentioned, Revit stores information regarding the sun’s path as a function of a model's geographic position. Following the steps described in *Setting Geographic Location* already prepares the algorithm to use that information as input. Nevertheless, as the algorithm works with geometric objects, it is essential to translate the sun’s position into a set of coordinates that are usable. By using the node *Sun Direction* the algorithm creates a vector, linking the origin point (0,0,0,) to the direction of the sun in the model. An important caveat is that the node imposes a vector magnitude that is relatively small. Therefore, using the direction, paired with the node *Line by Start Point, Direction and Length*, one is able to create a line from the origin to the position indicated by the sun vector. As described by the name, the algorithm takes as input a start point, origin and a length, which were respectively fed with the origin (0,0,0,), the output of *Sun Direction* and an arbitrarily long length. This length must be enough to ensure that the sun is located, in its appropriate direction, at a distance much larger than the proportions of the model.

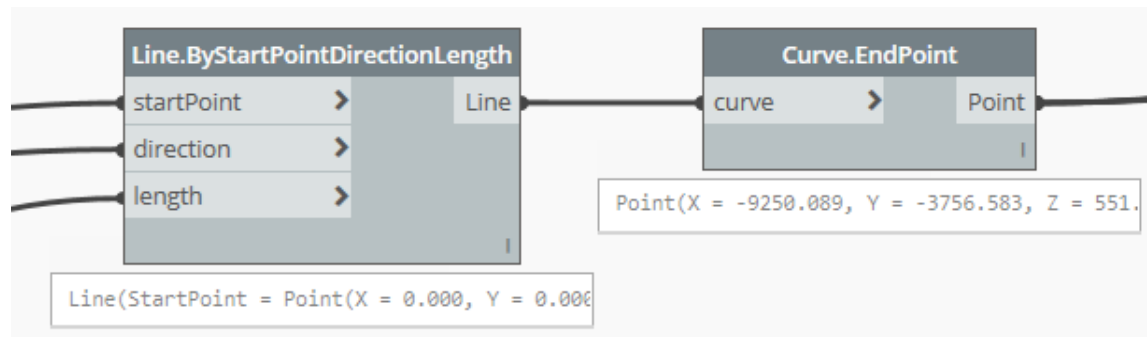


Figure 9: Line creation node for Sun positioning function

A line is, however, not entirely favourable to work with in the context of the program, so it must be made into a point. This is accomplished with the node *Curve End Point*, which retrieves the coordinates of the end of a curve, or, in this case, line. This function has thus as its output a point, which stands for the sun’s position at a given day, time and geographic location.

Shade Verification Function - with subdivided surfaces, from the sectioning function, the next step is to assess whether each point is receiving direct sunlight or not. Shaded areas throughout

the day will accumulate little heat and contribute a negligible increment to UHI. In order to verify this, in-built functions of Revit were used, but more importantly, the principle used to check whether the retrieved points were in the shade or in the sunlight is as follows: can a straight line be traced from the sun's position to an individual point without intercepting any other objects in the model? The reasoning behind this being that if it can, then the object is exposed to sunlight, as sun rays can be deduced to behave as straight lines from the sun to surfaces on the planet.

To initiate this task one must first create the object to be checked for an intersection. At this stage the reason for the simplification of the elements into surfaces becomes apparent. Through the Polysurface node, the algorithm compiles all the individual surfaces into a single object. This object is not joined together, but rather grouped, and may be moved around or used as input in functions as one. Without this step, the sun ray lines would have to be checked for intersections with most walls or roofs.

Lines are then created between each of the surface points, extracted from the Sectioning Function, to the sun's position, taken from the Sun Positioning function. As represented in the figures below, the lines are also created in the Revit environment and match the sun's position. Moreover, the time of the day may be changed dynamically in the interface and accordingly, the algorithm adjusts the lines. The configuration in the left shows the sun at 12:45 in an equatorial zone; the image in the right shows what is accomplished if the time is changed to 9:45.

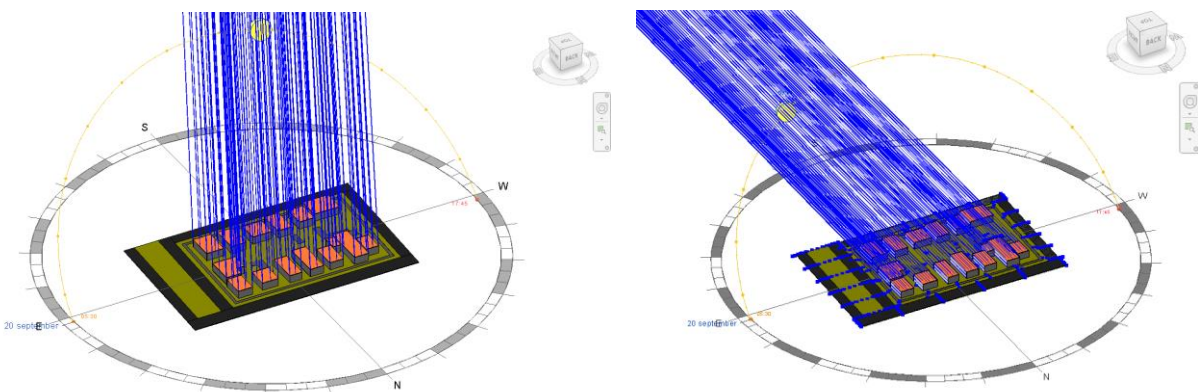


Figure 10: Sunray simulation for intersection assessment

Once again the *Does Intercept* node is used to verify geometry intersections. As input the node is fed the list of lines and the generated Polysurface. The output is a list of boolean variables matching the indexes of the lines fed as input. Since this information is related to the points through an element ID, the algorithm now possesses a list of point coordinates extracted from the surface and whether or not they lie in the shade given date, time and geographic position.

Material Properties – The relevant information contained in the Revit model are archived under each element and their respective types. That information is stored with material properties and may be edited using Revit functions. In order to obtain and export this information, Dynamo offers different ways to go about the task, each associated with a characteristic function node. For this algorithm, the *Get Material Properties* node was used. This node takes a string as input,

containing the name of the material property to be acquired, and outputs either the value (numerical property) or a string (qualitative property). In the overarching context of the algorithm, each point is associated with the material of the surface from which it was extracted. As the points are exported, so are the specific properties of the surface relevant for the calculations.

Export - Once the data is acquired, the algorithm proceeds to export it to a format that allows for data processing. In summary, every point is exported as x and y coordinates to form the 2D environment desired. Connected with each point is an instance of the variables cited in the *Deliverable and Validation* section as Input variables Due to the complex nature of the calculations to be performed, Dynamo is not the ideal software for carrying out this task. These are a few reasons why this is the case: all values are contained in list format, the values in this list remain hidden during processing, which hinders the inspection of values; Dynamo nodes perform one operation at a time, for complex calculation this means that each addition and multiplication would represent an individual node. Luckily, Dynamo is able to export data in standard format to many versions of Microsoft Excel. A spreadsheet software is ideal for the performing of these calculations. The image below shows how Dynamo takes care of this function with a *Write to File* node.

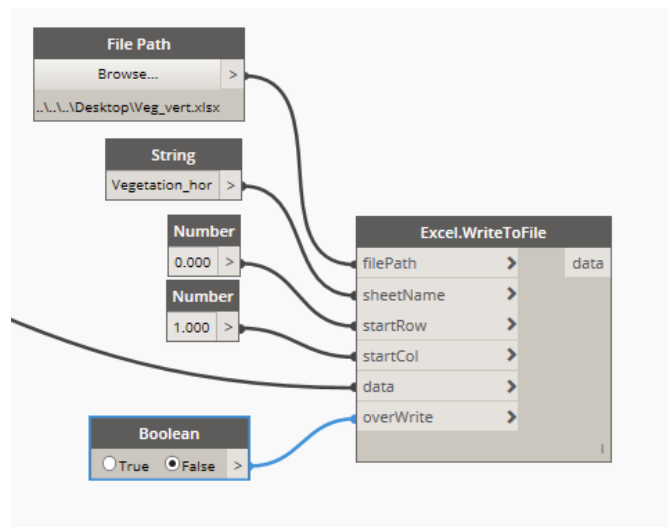


Figure 11: Export node

The desired data is fed as input to the node along with the file path to a desired excel file and the starting row and column. For every column of data, one of these nodes is required, therefore, one was created for each inbuilt variable.

Color range - To ensure that the comparison between satellite imagery and the generated heat map is simplified and accurate, an identical color scheme was constructed. Using the legend information, provided online, each shade was deconstructed and placed in a range. A Color Picker was used. This is a common tool in most image processing softwares, which allows users to deconstruct any colors in an image into their RGB numbers. These are the colors' red, green and

blue light numbers, which can also be used to reconstruct that color. The resulting color pallet can be seen in the figure below. Each of the colors in the pallet is associated to a temperature range where the surface temperature of the points will be fitted. Their section of the map will be thus colored with that same hue for the construction of the heat map. For each color's RGB description refer to Appendix D.

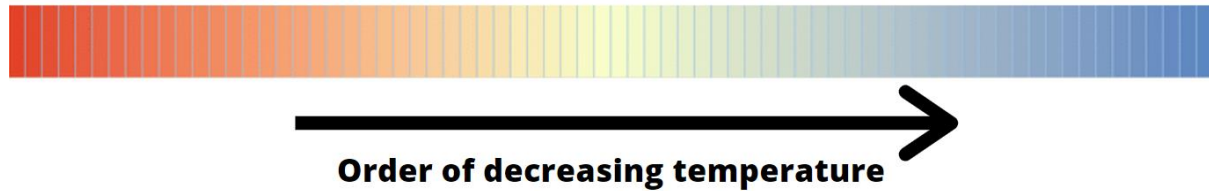


Figure 12: Color scheme used for temperature range

The temperature boundaries of the satellite surface temperature map were 80.2241 °C and 10.1094 °C, which constitute an overall temperature range of approximately 70°C. This range was subdivided.

10 CALCULATIONS

The calculations, following the data extraction from the model, are based on the Quantitative model cited in the *Source Material and Tools* section. This model proposes a series of formulas to quantify the temperature of surfaces given the meteorological data of their surroundings. It focuses specifically on vegetated surfaces and how they present different thermodynamic properties when compared to man-made surfaces. The theory can be found in detail in the report *Quantification of Urban Cooling by Vegetation - a Modelling Approach* by Eva Stache. For the purposes of this report, a brief summary is presented in the following paragraphs, however, the theory will not be discussed in detail.

The energy balance, which characterizes the Urban Canopy Layer, that is, the atmospheric layer closest to the surface, may be quantified by the following formula (1):

$$Q = Q_H + Q_E + Q_G + Q_R$$

Where:

- Q is the net incoming solar radiation, in Watts per meter squared (W/m^2).
- Q_H is the sensible heat produced by convection, in Watts per meter squared (W/m^2).
- Q_E is the latent heat produced by evapotranspiration, in Watts per meter squared (W/m^2). This variable is not contemplated for non-organic surfaces, as it is dependent upon particularities of vegetation.
- Q_G is the via conduction transfer heat and was considered negligible in the development of the quantitative model (W/m^2).
- Q_R is the longwave thermal radiation emitted from material surfaces (W/m^2).

Each type of heat, cited above, may be further characterized through the following equations [(2), (3), (4), (5)]:

$$Q = S (1 - r)$$

$$Q_R = \sigma \epsilon T_s^4 - \sigma \epsilon T_{air}^4$$

$$Q_H = h(T_s - T_{air})$$

$$Q_E = \phi \Delta h_{fg}$$

Where:

- S is the total incoming solar shortwave radiation (W/m^2).
- r is the proportion of reflected shortwave radiation, the albedo.
- σ is the Stefan-Boltzmann constant $= 5.67 \times 10^{-6} \text{ W}/\text{m}^2\text{K}$.
- ε is the surface's emissive power (W/m^2).
- T_s and T_{air} are the surface temperature and the temperature of the air, respectively, in Kelvin.
- h is the convection coefficient of a surface ($\text{W}/\text{m}^2\text{K}$).
- ϕ is a surface's rate of evapotranspiration ($\text{kg}/\text{m}^2\text{s}$).
- Δh_{fg} is the latent heat of evapotranspiration (J/kg).

Each of these variables is further expanded. The calculations also hinge on a proportionality to the area of surface exposed to the sun. As this study contemplates points as opposed to surfaces, the theory must be calculations must be adapted. Instead of using area proportions, the surface points' exposition to the sun is characterized through conditional formula. For each point sampling, every point contemplated is either exposed to daylight (non-zero surface temperature) or in the shade (surface temperature equals 0). As different point samplings will be taken from different times of the day, the Surface temperature values will be averaged; this will help form a holistic picture of a surfaces daily exposure to sun. Furthermore, the incoming solar radiation will be limited by a surface's albedo, which depends, among other factors, of the surface's color. A surface will be therefore characterized by the following equation (6):

$$(1 - r) S = \sigma\varepsilon(T_s^4 - T_{\text{air}}^4) + h(T_s - T_{\text{air}}) + \phi\Delta h_{\text{fg}}$$

The above equation was obtained from substituting equations (2), (3), (4) and (5) into equation (1). For all dry surfaces, that is, all non-vegetated surfaces, the last term of the equation is zero. The above equation is solved for T_s and ϕ using *Excel's solver* function. All other variables were values obtained from literature, or extracted from the model through the algorithm. For points in the shade, the surface temperature is considered negligible and therefore is taken as zero. All surface dependent variables and weather data used in the calculations can be found in Appendix F. Appendix G further specifies the calculations to determine the convection coefficient of a surface, along with the air properties used in calculations.

11 HEAT MAP GENERATION

The chosen software for generating the heat maps necessary for this study was ARCGIS Pro. As the result of the last section, each of the points exported from the model becomes associated with their calculated surface temperatures. The inputs to ARCGIS are therefore a set of coordinates and the associated temperature. Due to the layering strategy mentioned in the *Modeling* section, the points were imported in three different batches. Nevertheless, when this strategy is not applied, all points may be entered in a single batch.

The heat map function of ARCGIS is preprogrammed to work as a function of density, that is, to take the proximity between points as a value and indicate higher heat areas where points are closer together, and consequently colder areas where points are sparse. This must be changed to reflect the imported temperature value, which must be in the same Excel sheet as the coordinates. Moreover, since all points are deliberately at equal distances, a density-based function would show a single color. When switching the density-based function to imported values, the program computes the range of values and assigns the limits of the color range. The last step of generating the heat map consisted in adjusting the color scale, to fit that from the satellite image, along with other visualization settings, such as rendering quality and point diameter.

The color range was broken down as described in the *Color Range* section and using those colors' RGB values (Appendix D – Color Study), the color scale was reconstructed. It was also necessary to set the same limits used in the reference surface temperature study, to make sure that all calculated temperature values were assigned a color in relation to the reference image. Two points, a minimum and a maximum (Appendix B – Reference Thermal Image) were added to the data, but were excluded from the visualization by setting their transparency setting to 100%. With the color scheme adjusted, each point was given the same diameter setting, and a high resolution, to enhance the option of zooming in to certain areas while being able to retain a high level of precision. An important exception was the temperature contribution of the walls, which were assigned a higher diameter. That ensures that the contribution of the walls to surface temperature is not obscured by the high temperature values of the roof surfaces. In the following section, the resulting heat map is reproduced.

12 RESULTS

With the completed algorithm and calculations came the calculation of the results. Some inputs of the algorithm's function are discussed here, as these are of importance to ensure a viable comparison between satellite imagery and the algorithm output. The analysis relevant to this study consists a single application of this algorithm and the data it outputs. It is here used to verify the quantitative model's ability to reflect reality, however it still constitutes a tool for designers in many other applications of vegetation cooling and urban heat island mitigation.

12.1 SAMPLING FREQUENCY

In order to accurately represent each surface's contribution to surface temperature, points should be sampled within a reasonably short distance from each other. Different surfaces will also demand different point spacing as input to the algorithm. By basing the point spacing on a surface's length and width, the algorithm assures that the points are taken within a certain range of each other. For the purposes of the analysis, the points were here taken to be no less than two meters away from each other in either direction.

The algorithm outputs a static analysis, that is, it analyses a given snapshot of time, where the sun is in a particular location of the sky. Given that the chosen reference image is an average of the month of November, the algorithm must be used to construct a complete picture of the sun exposure and surface temperature throughout the month. Since the algorithm works with static analysis, the chosen strategy is to choose representative times of the day and days of the month in order to obtain an accurate estimate. For that purpose it is necessary to establish sampling intervals. Given Australia's geographic location and the consistency of the climate in the region, samples may be taken further apart, rather than continuously monitoring the data, which would require a tremendous amount of time. The chosen intervals were therefore five hours of the day during six different days of the month of November. The hours are equally spaced throughout the day in representative points, considering the sun at different locations in the sky. The selected times and days can be seen in Appendix G. These were selected taking in account the month's overall weather information, summarized in Appendix E - Temperature range in the month of November, 2019. Careful consideration was taken to choose equally spaced days that represented the variations within the month.

The sampling frequency decisions made here were relevant to this specific analysis. For future uses in different applications, it is expected that the analysis will have different requirements, including different climate, different weather data and perhaps even different objectives. It is therefore clarified that sampling frequency is a project-specific decision process. Nevertheless, during the design phase it is common to simplify weather conditions, given the estimative nature of the task. If this algorithm was to be used by designers to test different vegetation layouts and

their contributions to cooling and the Urban Heat Island effect, weather data could be greatly simplified, thus allowing the user to bypass many of the steps taken in this analysis.

12.2 SCALING

As part of the heat map generated by ARCGIS, the user is able to zoom in and out and visualize the map at different levels of precision given a scale value. For the purposes of comparison, it is important that the scale of visualization is the same as the one used for the reference image (Appendix B), which can be ensured by inputting the desired visualization scale in ARCGIS. Nevertheless, when more detailed data visualization is desired, the heat map permits users to zoom in for a closer look at individual temperature areas and values. This is key for the use of this add-on outside of the specific context of validating the quantitative model proposed by Stache.

12.3 ALGORITHM OUTPUT

This particular application of the algorithm requires the detailed analysis of a wide area, which in turn, requires great point sampling efforts. As explained in previous sections, this is due to the scope chosen to validate the quantitative model proposed for UHI calculations and the contribution of vegetation cooling. Given the high volume of points exported from the model, the resulting numerical values may not all be displayed. In total 89450 points were sampled, each with two coordinates (x and y). Instead, find below a sample of different surfaces temperature values calculated for distinct times of the day on the first day of November 2019:

Positioning		01/11/2019 - In Shade Result					Surface Properties		
x-coord.	y-coord.	600	900	1200	1500	1800	Albedo(r)	Emissivity (ε)	Latent Heat of Evap. (kJ/kg)
-79,131	0,889	TRUE	TRUE	FLASE	TRUE	TRUE	0,3	0,92	2426
Solar Irradiance		19,59	23,41	32,8	30,2	24,59			
Air Temperature		20,83	22,17	34,87	33,13	25,83			
Surface Temperature		0,0	0,0	19.6	0,0	0,0			

Table 2: Calculation of surface temperature sample

This excerpt is still far from the total scope of data and calculations used to produce the map. However, it is important to note that the splitting of the model into these sections and the recording and exporting of these values were achieved completely through the Dynamo graph, demanding limited manual input. Moreover, the same calculation was performed for all of the points contemplated in this study, with a high degree of automation, given the manual inputs required at the beginning.

This particular case also aids the understanding of how sun position and shade are taken into account by the calculations programmed into the script. Taken here is a point in a vegetated

surface, which, in the particular conditions of the first day of November 2019, is only exposed to the sun in the hours closest to noon. For this particular trial, the *In Shade* function returns a TRUE value for all other studied hours, meaning that the point is in the shade. That results in a zero-value result for surface temperature. For the noon snapshot analysis, however, the function returns a FALSE value, meaning that there is sun exposure. This results in a positive value for temperature, in the low-range blue color. The zero values are not taken into the average so as not to skew the results to an exceedingly low temperature value.

12.4 GENERATED HEAT MAP

The heat map produced by the algorithm may be observed below on the right. For a side-by-side comparison with the reference image, both maps were represented at the same scale. As aforementioned, the scale and resolution can be visualized at different degrees. Appendix H and I contain different scales of visualization for further side-by-side comparison. The higher the resolution the more distinguished the features of the map and the easier it is to analyze an area's temperature profile. However, higher resolution images had to be stitched together using image processing softwares, which may justify some continuity anomalies in the images.

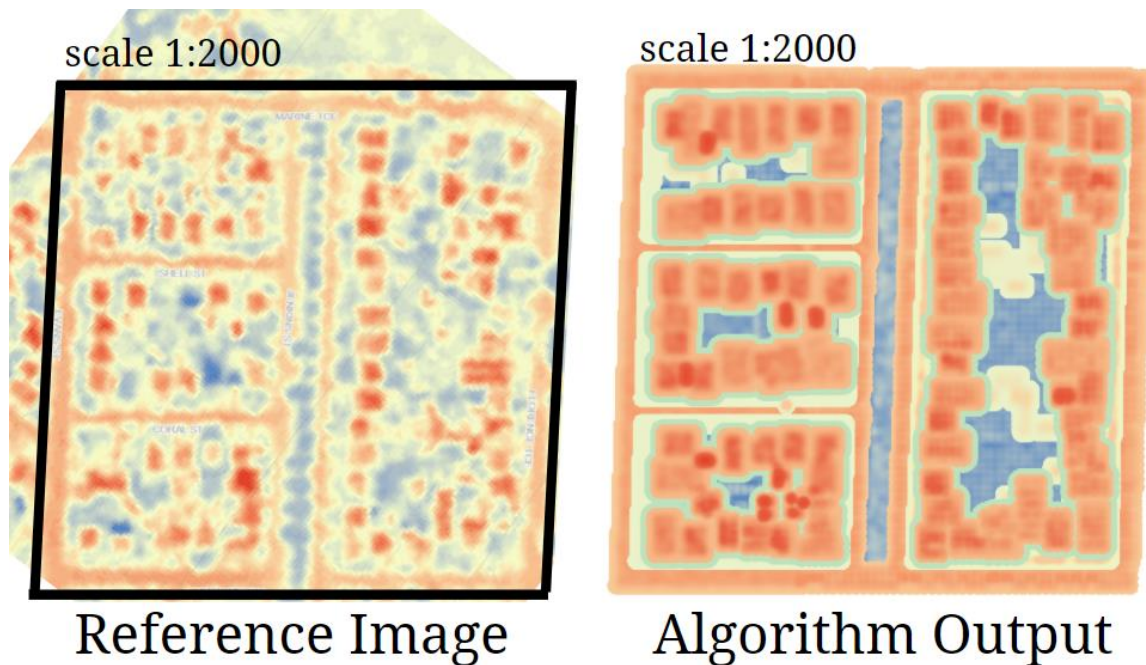


Figure 13: Side by side comparison of reference and product image at 1:2000 scale

Without diving too deep in the analysis due for the discussion section, there are obvious similarities and differences between the images. Many of the differences can be traced back to the careful assumptions and simplifications made when modeling, therefore they were expected. These were the assumptions made in order to ease the modelling process, allowing the project to tackle a larger area, relevant for a significant comparison. The comparison must thus be made with these assumptions in mind. That does not imply that other applications of this tool must

make the same modelling assumptions, therefore, these limitations do not belong to the developed script, but to the model itself. Script limitations are discussed in the *Limitations* section of the report.

At face value, there are various correlations between the satellite image and the one taken as reference. Similar temperature ranges are observed in relation to the same positions, associated to particular object-types, for example, blue shades where vegetation is present, shades of red on asphalted areas and roofs. One of the greater dissonances between the images is perhaps the more abundant presence of yellow shades in the reference image. Upon analysis, this may be due to a series of factors that the theoretical model does not take in account, the major one being the effect of wind. Nevertheless, it is also connected to one of the assumptions made in this study, namely the point analysis strategy. By analyzing isolated points, or even areas for that matter, the model fails to compute how adjacent surfaces affect each other. By isolated, it is meant that each point has a given surface temperature, which does not take in account the flow of temperature between adjacent areas. This explains the absence of yellow shades in the produced image, which is so abundant in the reference image. In reality, adjacent surfaces will exchange heat between themselves, either through a common interface or through air (Moran et. Al 2010). Having this in mind, it is logical that a heat map will contain transition areas between surfaces of different temperatures. That is what the model fails to represent. Between areas of high temperature (darker shades of red) and areas of low temperature (dark blue zones) there should always be a zone where these two extremes balance each other out, creating a middle ground between them, represented by the color yellow. Both the theoretical model and the script

Another immediate observation that may have occasioned less shades of yellow, is the presence of objects obscuring surfaces in the reference area. As seen in the *Location Study – Appendix C*, many random objects are cluttered in the backyards of houses, consequently obscuring the underlying surface. These objects, for obvious reasons, were not contemplated in the modeling process, and should have been excluded from the thermal imaging of surfaces, had it been possible. Only then would the reference image reflect surface temperatures close to reality. This is, of course, an impractical and time-consuming task for the scale of this study; nevertheless, when contemplating a specific area, these objects will alter the visualization of relevant data.

In the case of the area contemplated here, obstructing objects could be located anywhere in the area. Typically, however, they are placed in residential backyards, and the surfaces eclipsed are, usually, vegetated ones. This explains the lesser degree to which blue shades are seen in the reference image. In the generated heat map, blue surfaces are present to a higher degree in backyards, given that these objects were left out of the modeling procedure. A good deal of blue shades (vegetation) is therefore substituted by intermediate temperatures (yellow), generated by the presence of these objects. It could be argued, in this case, that the generated heat map presents a clearer representation to surface temperatures, given that it bypasses superficial obstructions to relevant underlying surfaces.

Another noticeable factor present here is the higher proportions in which roofs are represented in the generated heat map. Greater sizes of their heat signatures are seen in the generated heat map in relation to the reference image. The shades of red associated with the temperature values from the top of the roofs are much more pronounced in the generated heat map. This is a sign that the roof temperature profile has been overrepresented. This is, once again, associated with the isolated nature of point sampling. As these red concentrations are surrounded by lower temperature signatures, one would naturally see a transition zone in between them. However, at the scale used in comparison, the transition zone is obscured by the heat signature of roofs.

These limitations, as mentioned, were expected. They are important in understanding the validity of the results and should be kept in mind throughout the analysis. However, they were foreseen consequences, expected to not alter significantly the resulting heat map. The unpredicted consequences are elaborated in the *Limitations* section of the report.

13 VALIDATION AND LIMITATIONS

This section is dedicated to identifying the shortcomings of the algorithm, how they relate or undermine the validity of obtained results and to what extent the product achieved what it set out to accomplish. Remembering what was aimed at in the *Methodology and Validation* section, this would be a successful algorithm if it calculates correctly the surface temperature of each surface and displays them correctly in a heat map. As the reference image does not provide data points of surface temperature, there is no possibility for a direct quantitative validation. The temperature values are only indicated through color and how each tone fits in the color scale. Furthermore, as discussed in the previous sections, the assumptions and limitations (which will be further elaborated here) have thrown their own light in the results, which make a quantitative comparison between results impractical. This limitation of the validation is not only specific with this case. Any study carried out using satellite-generated images will suffer from the absence of numerical results and therefore, different methods of validation will be necessary.

The main method of validation relies on visual inspection, as is sometimes the case with images. Because they take in account large areas, it is counter productive to think of them in terms of single values. Instead, emerging larger patterns must be analyzed to know what the images share in common and where they diverge. Some of their diversions were already explained in depth in the results sections.

13.1 INTERMEDIATE TEMPERATURE ZONES

This limitation addresses the underrepresentation of areas of intermediate temperature, observable in the picture comparison, by the relative lack of yellow areas in the generated heat map. This was considered an expected limitation, traced back to the assumptions made in the modeling phase. This limitation can be seen here in detail as the images are zoomed in to their upper left corner.

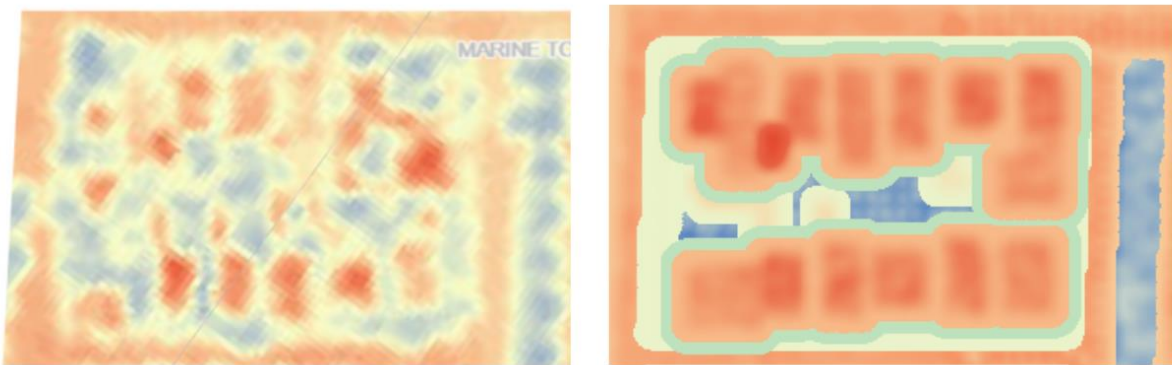


Figure 14: Comparison of upper left corner for intermediate temperature zones. On the left reference image, on the right, resulting heat map.

The above image lends itself to in-depth comparison. Not only are the yellow zones more present in the left image, the delimitations are less regular. On the right, the yellow sections are shown as clear lines, limited by the precise areas where concrete and walls are present. These two materials were characterized by a midrange temperature. It should also be mentioned that interfaces of high-low temperature surfaces would naturally show as yellow. This interface is what characterizes the abundance and irregularity of the interface zones, present on the left image to a higher degree. Since the model does not take in account heat exchange phenomena between adjacent surfaces, these interface temperature zones were underrepresented in the generated heat map.

Having said that, the results do show a correct sequence of colors in the interface zones. They may not be irregular and follow the interfaces that are captured in the satellite imagery; nevertheless, there is a correct sequence of colors moving from higher temperature surfaces (red zones) to cool surfaces (blue zones) through shades of yellow. That correct color gradient shows an accurate assignation of surface properties, which is captured by the model at a high fidelity to reality.

13.2 OVERREPRESENTATION OF ROOF SURFACES

Still following the zoomed in upper left section (Figure 14), the red temperature signature of the roof seems to cast a larger footprint in the produced heat map in relation to the satellite image. This is likely a consequence of the point sampling procedure and the nature of the *In Shade* function.

During point sampling, points are extracted from the perimeter of the roof. As aforementioned, the algorithm does not take in account the interaction between surfaces, but limits itself to calculating the temperature at a given point. These two facts combined contribute to a systematic error in the visual representation. The points taken closer to the interface section are therefore misrepresented as red, instead of showing the beginning of a transitory (red to yellow) color shading. These effect becomes more evident at different scales. In appendixes H and I, the image shows an even clearer distinction between the two temperatures, ignoring even further the interface between surfaces. This may be remedied by limiting visualization to scales closer to that of the reference image. This leads to the following limitation identified.

13.3 SCALING

As another limitation of the tool developed, we may cite the choosing of the scale factor. 89450 points were sampled in account to form the temperature profile of the region. This was done to guarantee a high level of fidelity to what is captured in the model. That every corner and patch of concrete is accounted for and represented in the final product. Nevertheless, in hindsight, it is evident that a higher resolution of results accentuates the differences between the model and reference image. This is due to the role that scale plays in this project.

From the start, it was emphasized that a high definition was required to enable a valid comparison with the satellite image. However, scale and resolution turned out to be not a variable one would want to maximize, but one that the research should strive to balance. Here is why: satellite images are taken from a great distance, they will capture the effect of temperature in a large scale, and how zones interact with each other in the realm of thermodynamics. A model will simplify those interactions, as far as necessary to make the modeling viable. As discussed in this section, the interaction between surfaces is perhaps the main shortcoming of this investigation. The quantitative model does not make this same mistake, by basing the calculations on conductive surfaces as opposed to singular points. This oversight was introduced in this study and must be accounted for moving forward. An optimal sampling frequency must be decided upon early in the study and has to take in account the level of detailed required of the study.

13.4 POINT SAMPLING

Another factor that was impacted by the high level of definition was point sampling. In the effort to not undermine any surface's contribution to the heat map construction, an exaggerated number of points was sampled. While this is not necessarily a bad factor, after all, the points do allow the user to form a complete picture of the area's temperature profile, the additional effort to sample more points does not bring the heat map closer to reality. In fact, a higher sampling frequency may instead place unnecessary calculative burden on the algorithm, causing it to take longer while yielding equally valid results.

13.5 VALIDATION

Much of this section focuses on where the algorithm fails. However, there is much that the algorithm correctly calculates and represents. After citing the observed limitations of the model, it is important to emphasize that which it does well, which brings back the sub question:

- 1. To what extent does the quantitative model represent reality, according to the result of this study?*

This question must be answered with something in mind. Both the quantitative modelling, upon which this study is based, and this study itself, present assumptions. This entails that there are two levels of assumption between the satellite imagery and the heat map representation created here. The limitations of this study have been discussed at length in this session, however, it is not the aim of this study to evaluate the assumptions made in the quantitative model. Instead, this section focuses on the differences and similarities of the generated heat map and the reality captured by the satellite reference image.

As discussed in the calculation section, the formulas of the quantitative model were applied to each point extracted from surfaces. By observing the image produced, there is a direct correlation between surface-types and their expected color ranges. By associating the color range to approximate temperature values, as seen in Appendix D, the colors in the heat map become

better contextualized in numerical values. This correct color-surface association is a powerful indication that the quantitative model yields correct temperature values. This was already indicated in the study done by Stache, nevertheless, we see that the association also holds for studies at larger scales. Moreover, this indicates that despite the assumptions made when modelling, the link between theory and capturing the reality of surface temperature still holds. We can extend this train of thought to say that in models that do not rely on so many assumptions, the quantitative model will become more accurate.

When analyzing the images in the same scale, one can also see that all surfaces find a fair representation. Despite the overrepresentation of roofs, concrete, asphalt and the other studied materials, are correctly placed in their temperature range. Variations in the tonalities are created from the averaging factor of different times of the day, combined with slight alterations to surface properties as a means to represent their heterogeneity. Interface zones have been underrepresented by neglecting thermodynamic interactions between different surfaces, nevertheless, the presence of intermediate materials, such as white brick walls

Finally, in answer to the sub question: I believe it is fair to say that macro scale patterns are well represented by the quantitative model and the algorithm. As reality must be simplified for modelling purposes (not to mention theoretical studies) the images generated will always bare differences to reality. However, it is evident that the correlation is a powerful one that correctly indicates higher and lower temperature zones. When approaching more detailed areas, that is, micro patterns on the image, the comparison diverges and may require further refining of the algorithm or quantitative model, to achieve a higher fidelity of representation.

14 DISCUSSION

This chapter of the report proposes a retrospective analysis of what was achieved in the project in relation to its initial objectives. That entails an exercise of answering the research questions that guided the research and development of the algorithm, as well as an effort to contextualize the findings in the overarching context found through literature review.

As the results have come to show, the achieved algorithm places the quantitative model proposed by Stache in a greater scale. By applying BIM techniques and software, the theoretical model can leap from local experimentation to neighborhood-scale validation. Nevertheless, that validation must be reflected upon every step of the way. At the beginning of the report, the following research question was proposed:

To what extent can the information contained in standard BIM models be used in UHI and vegetation cooling calculations?

That question has as its starting point the fact that BIM models archive an array of data that describes the information characteristic of a project. Moreover, this information is organized locally as belonging to specific physical elements of projects, describing beams, columns walls and other construction elements. The agglomeration of these elements may be placed in relation to each other, but also within its particular geographic context, for the purpose of sun studies and temperature analyses. To top that, the particular BIM software used here, namely Revit 2019, offers an inbuilt programming platform where users may expand on the possibilities offered by the software. It is this overwhelming array of possibilities that begs the question, to what extent can all of that be used to aid the quantifying of UHI.

The answer is neither a resounding yes nor a disappointing no. Throughout this project many factors came into light that have clarified the difficulties as well as the possibilities brought on by BIM technologies. To begin the discussion, let us look at *Dynamo*, the *Revit* programming platform. It constituted a powerful ally for extracting information and assessing elements of the model, which is verified by the ease of programming and operating of functions such as Shade Verification and Export. Notwithstanding, when attempting to create functions of a different nature, such as visualization or calculation functions, the platform fell short. I was driven to the conclusion that the procedures would take excessive programming and would require tremendous processing power and time to come to fruition, which made me aware of the fact that this would have to be executed outside of Revit for sheer practical reasons. That goes to show that however broad tools may be, each tool will always serve a specific purpose and touch upon others. Revit was made to design and assess structures, even though it counts with a seemingly endless programming platform, it may not always be practical to think within the bounds of one software alone.

14.1 SOFTWARE INTERFACE

The result of the realization documented above was that in order to accomplish any multi-level complex task, one would have to look at a series of software, each of them carrying out a portion of the task in delivering the final product. That brings me to another point of discussion: software compatibility. In order to pass on the product of one software to the next, much thought must go into how any two software work with each other. File compatibility is a big issue. Despite having common files in the world of BIM, as is the case with Industry Foundation Classes (IFC), the information contained in a Revit model must be oversimplified for exportation. This results in a tremendous loss of information in most interfaces between software. Needless to say the purpose of storing information, which empowers BIM tools, is severely undermined whenever two software from different manufacturers must cooperate.

Previous allusions to this type of difficulty, involving software interface, had already been detected in the literature review. Cited as one of the obstacles to widespread BIM implementation in the AEC industry, the multiple tools of BIM are often hindered in their potential by incompatibility issues. Despite many efforts towards the unification of tools, individual manufacturers will always be motivated to individualize their software through unique file formatting. Moreover, unique file formatting allows software developers to create individual tools and expand the many options offered by their software, without the constraint of working within a universal format. This poses a dilemma for BIM in general, for interfaces will likely present barriers to file communication in the future. Software of many kinds will have limited communication and are likely to create microcosms of their own.

14.2 DISCRETE SUN PATH ANALYSIS

In the particular case of surface temperature and UHI calculations, the analysis of shade casting depended heavily on the sun path function available from *Revit*. Despite being very useful and flexible, taking in account geographic positioning and sun orientation, the extraction of information from this tool is only available in snapshot format. There is the option of analyzing sun studies over a time period, however, *Dynamo* functions will only assess the model given a specific sun position. This limits the analysis of any four-dimensional tool that may be interested in the sun path over a given period. Consequently, it limited the analysis proposed here to snapshots followed by an averaging of values. For the use of this tool in other applications, it may be better to choose a day with strongly representative weather conditions or an extreme design case, allowing the simulation to be done a single time. This may entail neglecting small sun path variations, which may only be justifiable for short time spans (week, month). Another option is to pick opposing extremes, such as winter and summer conditions and make the assumption that all other days will fall somewhere in between those two. Thus allowing the algorithm to create a range of possible values.

14.3 AUTOMATION

The above sections have touched on particular challenges faced during the development of the script. These are of particular relevance to how automatic the task of the script is. At this point, it is relevant to bring into the analysis the second formulated sub question:

2. *How may the script aid designers in making environment-oriented design choices?*

From the points discussed above, it is fair to say that the script does not benefit from a high level of automation. For the successful use of the script, many instances of manual inputs are required. Starting from weather data, which must be fetched from online sources given the geographic location of the project. The weather information contained in Revit is limited to average monthly temperatures, which are very general for any complex task. Once again it brings us back to the idea that a software is constrained to the industry that it aims to comply with. Revit was designed for use in the AEC industry, and therefore it only collects weather information relevant for that industry. In interdisciplinary functions, or complex weather-based calculations, such as the one contemplated in this study, there will likely be a need for additional external information input.

Beyond requiring weather data input, the script also demands the parallel design of the study. What that means is: users are required to decide and implement their own sampling frequency (how many points and with what frequency in time) the samples will be taken, as relevant to their investigations. If the analysis does not require constant monitoring of time frames, design weather conditions may be selected as a representative, and given that condition, some level of automation may be retrieved.

The remainder of the program's operation is relatively automated, with a simple interface between Excel and ARCGIS for the generation of the heat map. Nevertheless, the flow of data from one software to the next make the task of automation a difficult one. As argued before, this was necessary given the impossibility of carrying out the entire task within a single software.

14.4 ACCESSIBILITY

Another key aspect of answering the second sub question is to reflect on how user friendly the script is. To what extent is specific knowledge required in order to be able to apply this. By taking the automation arguments as a starting point, it is easy to conclude that the many interfaces and manual input does not make the script usage a straightforward task. Nevertheless, it is worthy of notice that all the information may be extracted out of a *Revit* model without any specific knowledge. By modelling within the general rules of Revit, and positioning the model in its geographic latitude/longitude with a correct sun orientation, the *Dynamo* script will successfully output the data necessary for the calculation to an *Excel* sheet. This knowledge of *Revit* is not considered, by any means, specialized. In fact, basic users are able to construct a model with which the script may successfully work with. Notwithstanding, further tempering of the function does require a more in depth knowledge of *Dynamo* programming. Tasks such as altering point

sampling frequencies and changing export destinations will require users to learn how to use the platform and the particularities of the designed script.

Overall, the level of accessibility is not the highest. This can be traced back to the many interfaces of data that were required throughout the project. Partially to the highly specific nature of the task and partially for the niche tasks that these software are able to accomplish. Further research could easily make this algorithm into a more user-friendly experience, however. Some work would in fact be required, in order to turn this script into a tool that designers would benefit from. That being said, the results have shown that the tool does produce useful information that could be used to predict the performance of layouts and vegetation cooling strategies in urban development. Different strategies to make the tool more accessible are explored in the *Recommendations* section.

In summary, this script may aid designers by correctly predicting areas of high and low concentration of temperature. It would allow users to test conceptual layouts and identify problematic areas, where Urban Heat Island may present a problem due to surfaces' high level of heat absorption. The identification of these areas also enables their avoidance, be it by the selection of different surfaces with different properties (resulting in lower heat accumulation) or the placement of vegetation patches. In addition to that, vegetation may also be placed in vertical surfaces, in the form of vertical gardens. This fits in with the concept of vegetation cooling in street canyons, which are composed of two vertical surfaces. Not only is the tool applicable for the design of new areas, but through the modeling of existing areas, one may target existing UHI hot spots. Solution alternatives may be contemplated using the heat maps generated by the script, in order to accurately predict the performance of different surfaces or different vegetation layouts.

The idea proposed through this project was not to simply analyze the current interaction between BIM and the quantification of sustainability-focused phenomena, but to go through the steps of creating a BIM tool for that very purpose. Not only did that enable a deep look into the current difficulties facing BIM implementation, these difficulties were lived through the journey of this project. Having discussed all the topics surrounding the design and implementation of the BIM tool created in this project leaves the last sub question to be answered:

3. Can BIM tools provide a viable method to validate quantitative models?

The immediate answer to this question is that BIM tools by themselves constitute the means rather than the end. The viability of any given validation method will rely little on the tool itself and mostly on the method of validation, a lesson that became clear through reflection of this project. However, the question centers on BIM tools and whether or not they may provide viable validation methods, to which the answer is yes. A well designed validation method paired with the possibility of BIM will generate new possibilities to test, understand and eventually validate quantitative models. As an information-rich modelling tools, the software and concept surrounding BIM present a platform, with which investigations may benefit from. Researchers must, however, be aware of the difficulty any project will face when involving BIM, many of which

were discussed in the report. Regardless of those, BIM does provide, as was the case in this project, a clear logical path for theories to be tested.

Returning the focus to the main research question, BIM may, at face value, seem to be a tool with endless possibilities. The richness of information combined with its accessibility to the industry is certainly worthy of notice, which justifies all the recent efforts to implement in a meaningful way in the AEC industry. Nevertheless, there are barriers which become apparent once these tools are not used in their more traditional use. The general lack of experience and formal education surrounding the tool constitute barriers for its implementation and use in projects, such as this one. There is little doubt that BIM is the future of the AEC industry, or at least, something that evolves from the industry's contact with this technology. However, education, regulation and culture must make lengthy strides in order to catch up with the technology.

15 RECOMMENDATIONS

The recommendations for furthering this study follow two particular possible paths. The first entails refining the algorithm, ensuring that its results further align with theoretical principles, interpreting and remedying its limitations. The second focuses on finding more sophisticated methods of validating its results in comparison to reality.

15.1 SCRIPT IMPROVEMENT

As mentioned, at length in the *Validation and Limitations* section of the report, the algorithm, despite presenting valuable results that reflect the validity of the quantitative model, still has much room for improvement. One of the outstanding areas of improvement was the need for better representation of interface temperature zones. The areas of the map where high temperature zones meet colder temperature surfaces is mistakenly represented as a clear-cut line. Instead, these interfaces should show a range of temperature change, which failed to be represented here due to the sampling strategy and failure to program this feature of thermodynamics. Therefore, a logical next step would be to factor into the script the temperature gradient between points. This could be done through the extrapolation of temperature values in intermediary points, or perhaps selectively sampling points from the outskirts of conductive surfaces to be calculated differently. These alternative calculations should take into account the interfaces between different surfaces where heat transfer takes place. If this could be accomplished, then the script would benefit from a higher level of accuracy.

The previous point may also be discussed in relation to scaling and point sampling. As aforementioned, the number of points taken from the model for this study was perhaps excessive, leading only to a marginal improvement in the comparison between images. A more efficient sampling strategy could include sampling points from strategic locations or at greater intervals, depending on the needs of any particular UHI study. Moreover, the high number of points in this study placed a burden on computational capacity, nevertheless, with lower numbers this is no longer an issue, which also allows for more complex calculations to take place. This could come in the form of what is suggested in the previous paragraph: greater attention to the temperature intermediates between different surfaces, which would likely entail more calculations.

The quantitative model proposed by Stache also takes in account the effect of trees, by orthogonal projection of canopy treetops. As one of the initial modelling assumptions, all the vegetated surfaces were flattened, for simplicity. However, the quantitative model is capable of capturing that effect. A possible enhancement of the existing script is to factor in the three dimensional shape of vegetation through these projections. As seen when comparing the generated heat map to the reference image, much of the colder surfaces are located in the presence of trees, not only because it is a vegetated surface, but also because it is one that casts significant shade on the surroundings. That effect is undermined by the simplifications needed

for the script to work. Nevertheless, with ample time, it is very possible to factor in the additional theory into the script.

Other efforts to further refine the algorithm could come in a higher level of automation and user friendliness. These may be an obstacle to further implementation and use of this tool, as a high level of software understanding is necessary to properly use it. A remedy to that could come in the form of a user manual or in attempting to create a friendlier interface where the necessary steps are more apparent. In essence, this could be done in an infinity of ways and requires thinking creatively and user-oriented design. One possibility that comes to mind, to tackle both automation and user friendliness, would be a web crawler that fetches the required weather data from online sources. This would entail an input of geographic location of the project and time span of study, with an outcome of the relevant data being added to the computations without the need of manual input. By decreasing manual input, the script becomes more attractive to less experienced users and also provides a higher efficiency.

15.2 FURTHER VALIDATION

The other alternative path of recommendation is towards a more scientific validation of the results obtained by the surface temperature tool. Given the two-pronged objective of this project, little focus was placed on validating the results numerically. Therefore, it naturally follows that a possible path to strengthen the research is to attempt to quantify, exactly how close the generated heat map is to the reference image.

Images may be best analyzed at a macro level, where general patterns are easily visible, which was the alternative adopted in this project. However, that does not provide a solid numerical value for a more meaningful conclusion. Given that the reference image provides no individual temperature values, a possible method of further validation is to assign temperature ranges to the colors of each area, knowing the limit values. In that case, each pixel may be traced to a particular temperature range given its color. Of course, this is a painstakingly monotonous task and could be done through automation. If so, then there are now possibilities of comparing the temperature ranges from the reference images with those obtained from the calculations. That would consequently enable a quantification of error and further validation of the formulas within its margin of error.

Many simplifications and assumptions were also made to facilitate modeling. That was partially due to the scale in which this study was to be carried out. If this tool was to be applied to smaller areas, such as houses and perhaps street canyons, a higher level of detail would be expected. The enhanced closeness to reality would test the script in different conditions. This could include modeling roofs as slopes, adding tree lines, contemplating the different shades of similar surfaces. Any decision to make the model closer to reality would also require some level of testing, in order to ascertain that the script will operate correctly under the modified conditions. However, the results under those conditions would mean a higher degree of accuracy.

16 CONCLUSION

This study has provided valuable insights into the possibilities of integrating Urban Heat Island calculations and BIM technologies. As a weather-related phenomenon that grows in importance as cities become greater in size and population, much investigation will be likely required to improve the level of comfort in urban environments and minimize the side effects of UHI during summer seasons. As the scientific communities strive to better characterize the phenomenon, Building Information Modeling constitutes a powerful tool to accompany the process. Much of the relevant information is indeed stored in BIM models, however, BIM exists within the context of the AEC design industry, which poses obstacles to a straightforward integration with sustainable initiatives. These difficulties stem from different areas, which have been investigated and experienced, to some degree, during the development of this study.

The tool developed in this study successfully implements the quantitative model proposed by Stache, aiding in the quantification and visualization of larger areas in the context of Urban Heat Island. Certainly many assumptions were required for the study to be carried out in larger scales, however, those assumptions pertain to the scope of this project and speak to the applicability of the tool rather than to its limitations. Many simplifications were also made when modelling, which were supported by rational arguments, but that nevertheless, increase the gap between modelling and reality. Addressing these assumptions has been emphasized as a valid path of progress following this investigation. The application of theory and BIM, here used as a validation method, is one of many possibilities in which this knowledge could be used. If tools such as this become better developed, both designers and the industry at large will benefit from the knowledge of how specific urban setting, surfaces and layouts respond to UHI.

In answer to the research question, the information contained in BIM models is indeed very useful for UHI and vegetation cooling calculations. The issue becomes apparent when one attempts to carry out more intricate tasks in BIM software, which were not specifically, what the software was designed for. In the particular case of this research, material-dependent variables were readily available and easily extracted from models, nevertheless, the absence of the necessary weather information generated difficulties which were much harder to solve through programming. The user may here resort to manual input, which is only a partial solution. With every level of manual input the BIM tool drifts further away from a successful implementation.

Despite the difficulties found in script design, alternative solutions were found that allowed for the theory to be verified against the reference thermal heat image. Through side-by-side visual comparison, many large scale patterns aligned. Different surface-types were accurately characterized within their color range, which indicates that the results from the calculations were correct within a small margin of error. Additionally, the identification of hot spots is facilitated by the imaging and may be targeted in design. The script may also be applied to existing urban environments that are translated into Revit models. At the scale at which this study was done, many hotspots could be potentially identified and contingency measures designed

The collaboration of Building Information Modelling and Geographic Information Systems is also a powerful one in the context of Urban Heat Island. Due to GIS' mapping and visualization capabilities, the information contained in BIM models may be amplified for greater data analyses and improved understanding of the phenomenon. Unfortunately, a gross simplification of the valuable information contained in these models is necessary to achieve file compatibility. Exporting models to a file format that is supported by both Software entailed the loss of valuable information for the calculations.

Admittedly, the script suffers from many drawbacks which are not necessarily related to the assumptions made. These were discussed in detail under the *Limitations* section of the report. These limitations are not particular to this effort in modelling and can be traced back to some of the difficulties faced by the industry in the effort to implement BIM in wider scales. That is to say that the limitations found in the attempt to implement theory to BIM are symptomatic of larger problems that affect the overall rate of BIM implementation. As emphasized in literature, a significant barrier to the interaction of different BIM software is the nuances of BIM data integration, often in the form of proprietary file formats (Song et. al 2017). File compatibility and Software interface become aggravated when the task at hand is a multi-disciplinary one and requires the use of multiple Software to achieve a goal. This process significantly increases the barriers to expand the potential of BIM in the direction of sustainability, given that very few of these softwares are designed with sustainability-related applications in mind. Users that attempt to follow this path will find difficulties in automation, which in turn, increase the amount of manual input required for a satisfactory performance.

The recommendations following the study focus on two particular areas: refining of the script and refining validation methods. The first could be achieved through factoring in more sophisticated approaches to surface temperature calculations, such as the three dimensional effect of vegetation in affecting surfaces and the thermodynamic interactions between different surface-types; the latter could be accomplished by devising a scientific method to analyze the similarity between the compared images. A suggested alternative proposes the translation of reference satellite images to individual temperature values and coordinates, enabling a quantitative comparison between theoretical and empirical results.

17 PERSONAL REFLECTION

During my studies in Construction Management and Engineering I have learned plenty regarding management. Given TU Delft's excellence, one can assume that a master's in management will give you all the academic medium has to offer in terms of knowledge. That, I believe, is true. However, so much of the world of management lives outside of academia. This thesis, along with other professional experiences I have had, has shown me that experience has no substitute when it comes to management. This is an all-encompassing field, where knowledge is but a fragment.

The Master Thesis is an effort in managing yourself and your professional and academic skills. The conditions of isolation imposed by the international pandemic add strain to this effort. Isolation turns thoughts inwards, makes all things reflexive, which can be both a powerful learning tool and an easily overwhelming idea. Not only can it be both, but it often is. After many accounts of colleagues regarding the difficulties of the thesis I went through it myself, to come out bearing new perspectives on the effort required to complete academic studies and work independently. A truly humbling experience, which is in itself, a lesson in management.

A secondary lesson, which also stands out when looking back, is the responsibility of graduates to uphold values of scientific knowledge. Carrying out studies in the academic medium places the obligation on students to abide by good scientific practice, placing it above the many other pressures governing a student's schedule. I will carry this lesson into my practice in the future.

The overarching personal lesson was that to manage things effectively, one must first manage oneself. That entails an active effort to maintain balance in one's life, which shapes many personal decisions. Among the many faces of a balanced life, perhaps fostering positive interpersonal relations spoke the loudest to me. I was fortunate to be surrounded by individuals who helped me navigate the ups and downs of, not only the thesis months, but the entire degree. Family, friends and academic counselors to whom I owe my gratitude.

APPENDIX A - REFERENCE AREA

The area selected for modeling encompasses a number of blocks in a residential neighbourhood. With a total area of approximately 0.7 Km². The presence of gardens and a treeline along the main street ensures the presence of abundant vegetation. Consequently, this diversifies surface temperatures, ensuring that the testing of the deliverable is done in a representative location.



Figure A1: Geographic location of reference area

A: LAT -34.848031; LON 138.525616

B: LAT -34.846094; LON 138.524071

C: LAT -34.847389; LON 138.52156

D: LAT -34.849449; LON 138.523191

The following figure was obtained from *google maps* to aid in the dimensioning of the Revit Model of the area. The layout bares a significant resemblance to the real layout of buildings in the area. Though some constructions have shown slight changes over the years, the general layout of suburban houses has remained similar. Through Location Study (Appendix C) the region has also been further investigated in a 3D scenario



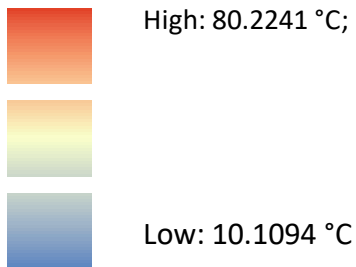
Figure A2: Reference area in street view; modelling aid

APPENDIX B - REFERENCE THERMAL IMAGE



Figure B1: Reference thermal satellite image

Scale: 1::2000



APPENDIX C - LOCATION STUDY

To test the predictive capacities of the quantitative model, it is important that the BIM model used in this study has a conservative level of fidelity to the real constructions. The higher level of fidelity the more capable the add-on is to produce an accurate result of Stache's quantitative model. In order to observe the area, free, internet-available, imaging services were used, namely Google Earth. This software enabled the three-dimensional visualization of the area for replication in the model. Among the many pieces of information that were extracted, the height of buildings was recorded; comparison with satellite imagery was possible, to ensure layout of buildings did not show alterations spanning the different capture-dates.



Figure C1: Study area bounded by red line

This neighborhood is characterized by uniform constructions, which is one of the main reasons why it was selected, allowing a wide area to be analyzed while enabling assumptions and simplifications regarding the buildings, all of which are documented under the *Modeling* section. Most constructions possess two floors, with an average of 2 meters height each. Adding the roof slant to the height contribution, it is fair to assume most buildings will reach an overall height of 5 meters. This assumption affects the model deeply, as it will be important with regards to what size shadows these buildings cast in their surroundings. The effect of this assumption is further discussed in the *Discussion* section of the report.

Another feature of the area is the different shades of roof tiles. This would of course affect the albedo and overall heat absorbance of the surfaces. An assumption was also made in this case. Given that capturing the particular shade of each roof tiling would be an expansive task for this scale, it is preferable to assume a typical color and generalize all tiles. This generalization is supported by the fact that a material's albedo is only partially affected by hue and color, among

many other factors. In this case it is preferable to use a standardized value for roof tile albedo and other material-dependent properties.

Lastly, in the figure below, it is evident that the trees in the area help cast significant shade on the surrounding surfaces. By flattening the vegetation this effect will be neglected. In order to bypass this issue, it is important to notice that trees are located in very specific areas of the map, mostly located along the central axis running across the area (Figure C1). Other trees in the map are sparsely located, and can only hope to create a local cooling effect, which should be negligible in the scale of the investigation. Nevertheless, the possible effects of this assumption are discussed in the *Limitations* section of the report.



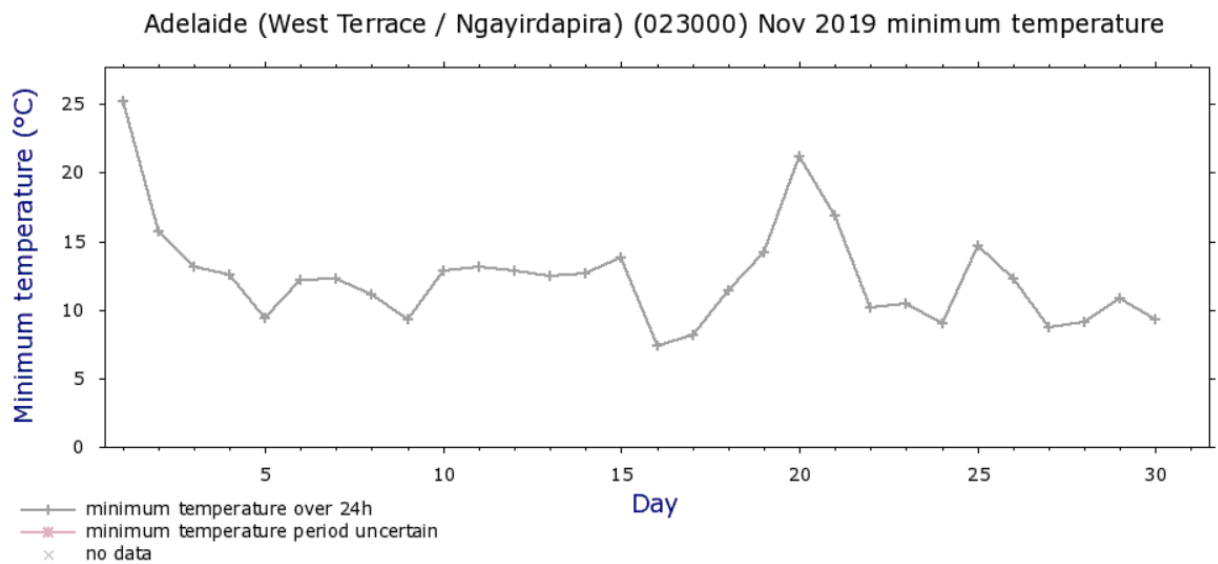
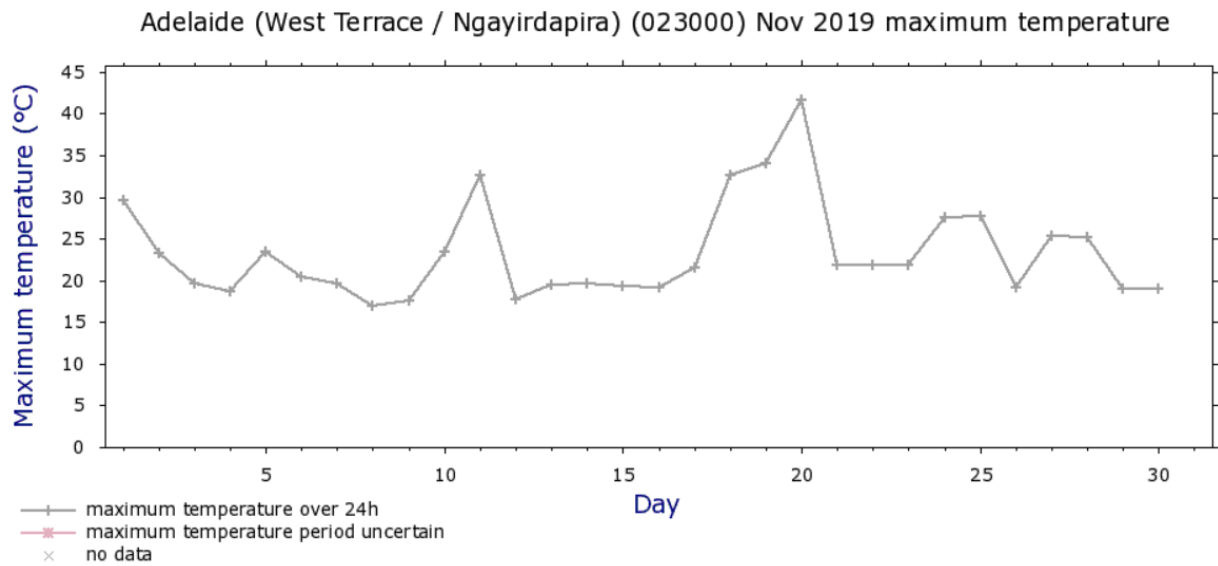
Figure C2: Typical layout of reference area

APPENDIX D - COLOR STUDY

ID	R	G	B	SAMPLE	VALUE
1	226	66	39		80
2	227	73	46		79
3	229	81	52		78
4	231	87	57		77
5	232	93	63		76
6	233	100	69		75
7	236	105	73		74
8	237	111	76		73
9	239	118	80		72
10	240	123	85		71
11	241	129	89		70
12	241	134	93		69
13	242	139	97		68
14	243	143	101		67
15	245	150	104		66
16	245	155	109		65
17	245	160	115		64
18	246	165	120		63
19	247	170	125		62
20	247	175	128		61
21	248	181	132		60
22	248	186	137		59
23	249	190	141		58
24	250	195	146		57
25	248	202	152		56
26	248	206	156		55
27	249	211	161		54
28	249	216	165		53
29	249	221	169		52
30	248	225	174		51
31	250	236	183		50
32	250	236	183		49
33	249	241	187		48
34	248	245	192		47
35	248	250	197		46
36	250	253	202		45

37	248	252	202		44
38	243	250	202		43
39	239	247	202		42
40	235	243	202		41
41	231	240	203		40
42	228	237	203		39
43	223	233	202		38
44	219	229	202		37
45	216	226	202		36
46	212	222	202		35
47	208	219	202		34
48	204	216	202		33
49	198	211	202		32
50	194	208	202		31
51	190	205	202		30
52	186	201	202		29
53	182	198	202		28
54	178	194	201		27
55	173	191	201		26
56	168	187	201		25
57	164	184	201		24
58	160	181	201		23
59	157	178	199		22
60	152	174	198		21
61	146	170	198		20
62	140	168	198		19
63	137	164	197		18
64	132	160	197		17
65	128	157	196		16
66	123	154	195		15
67	118	150	195		14
68	112	146	194		13
69	107	143	194		12
70	102	139	194		11
71	96	136	193		10
72	91	135	193		9

APPENDIX E – TEMPERATURE RANGE IN THE MONTH OF NOVEMBER, 2019



(Australian BOM)

November Climate & Weather Averages in Port Adelaide Enfield

High Temp: 27 °C

Precipitation: 20.2 mm

Wind: 11 km/h

Low Temp: 13 °C

Humidity: 47%

Pressure: 1015 mbar

Mean Temp: 20 °C

Dew Point: 7 °C

Visibility: 14 km

(Australian BOM)

APPENDIX F - SURFACE DEPENDENT VARIABLES AND WEATHER INFORMATION

Surface dependent properties

Material	Albedo(r)	Emissivity(ε)	Latent Heat of Evapotranspiration (kJ/kg)
BRICK	0,28	0,93	
CONCRETE	0,4	0,96	
ASPHALT	0,12	0,88	
VEGETATION	0,3	0,92	2426

(Incopera 2017); (Moran 2010).

Air Temperature in degrees Celsius

Hour	600	900	1200	1500	1800
01/11/2019	25,2	26,3	29,6	31,2	30,1
05/11/2019	9,4	20,9	23,4	24,5	13,0
10/11/2019	12,9	15,4	23,5	19,8	17,3
15/11/2019	13,8	16,7	19,3	19,9	17,0
20/11/2019	21,2	22,9	41,6	25,8	24,1
25/11/2019	14,7	23,6	27,7	26,3	17,4
30/11/2019	9,3	15,8	19,0	20,7	14,2

(Australian BOM)

Solar Irradiance in (kWhm⁻²)

Hour	600	900	1200	1500	1800
01/11/2019	1,7	3,2	4,3	4,1	2,1
05/11/2019	2,5	7,6	10,1	9,1	5,1
10/11/2019	1,4	7,8	10,2	9,4	5,4
15/11/2019	0,8	5,2	7,0	5,4	3,4
20/11/2019	1,4	8,3	9,8	8,8	6,8
25/11/2019	0,9	2,9	4,1	3,7	1,7
30/11/2019	1,3	7,7	9,6	7,8	5,8

(Australian BOM)

The calculation of the convection coefficient h requires a surface's Nusselt Number and Raleigh number to be calculated. The different equations are related as shown below.

$$h = \frac{k_a}{H} Nu_L$$
$$Nu_L = 0.15 Ra_L^{1/3}$$
$$Ra_L = g\beta(T_S - T_{air})L^3$$

Where:

- g is the gravitational acceleration of the air (m/s).
- β is the the expansion coefficient (K^{-1}).
- L is the length of the convection surface.
- k_a is the thermal conductivity of air (W/mK).
- Nu_L a surface's Nusselt number.
- Ra_L is the Raleigh number associated with the air flow.
- H is the length (for horizontal surfaces) or the height (for vertical surfaces) of the connective surfaces.

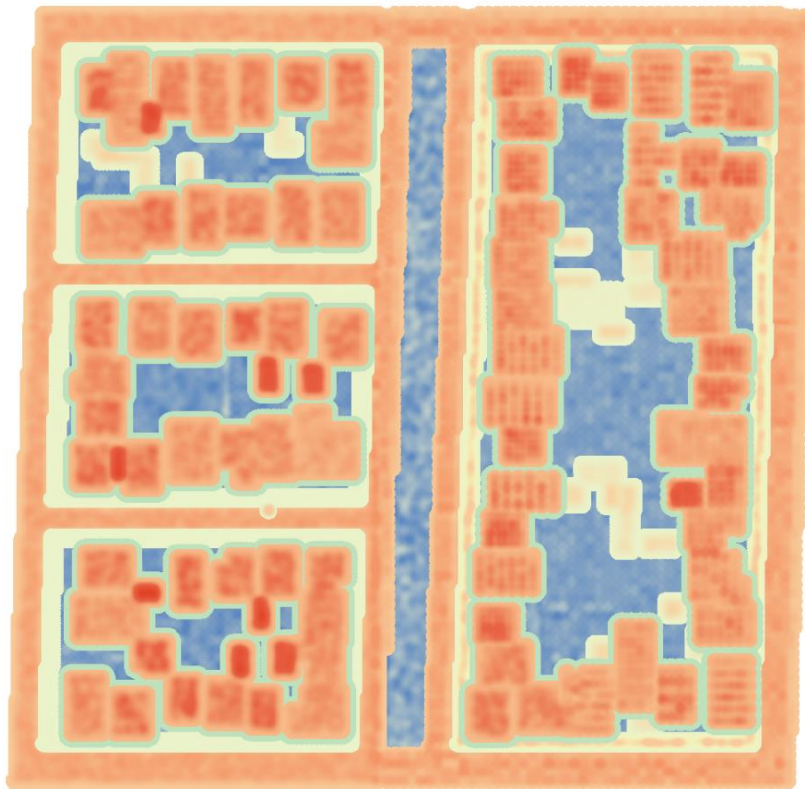
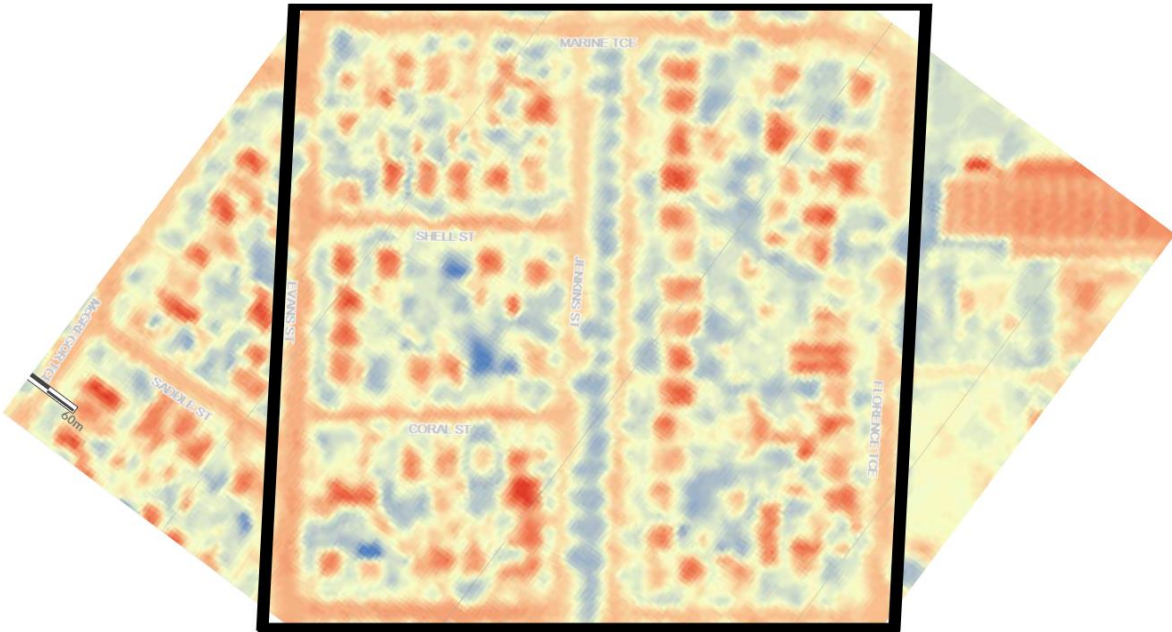
An important assumption is made here. In order to simplify calculations, every surface was considered to be horizontal. This would assume that the contribution of vertical surfaces is placed on the same plane as that of horizontal surfaces. This is considered in the layering strategy devised in the modeling section of the report, and the contribution of walls is accounted for in the final heat map generation. This assumption is to have a negligible effect on the results. Below, find the constants used in the convection coefficient calculations. For the calculations carried out here, the air properties below were used. As thermal conductivity is a function of air temperature, the values associated to given temperature values are also listed below. For temperature values falling within the intervals given below, the closest thermal conductivity correspondent was taken.

Air properties

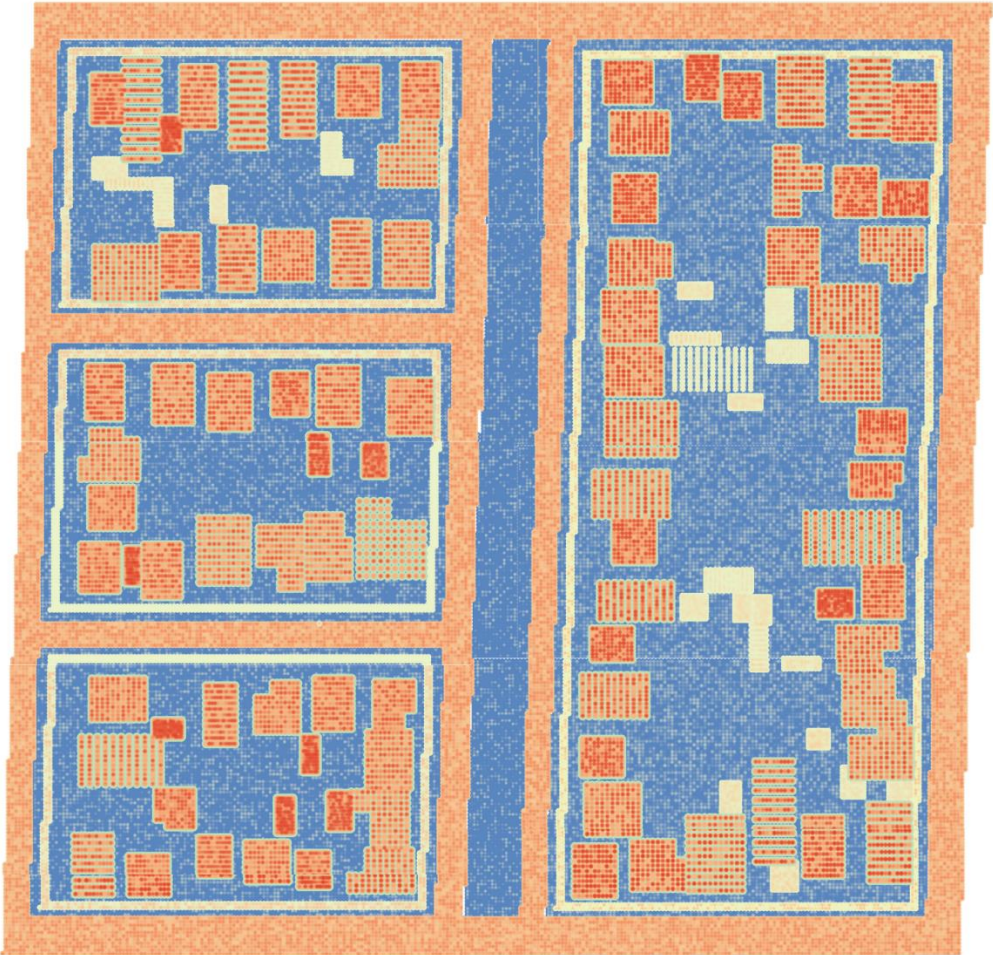
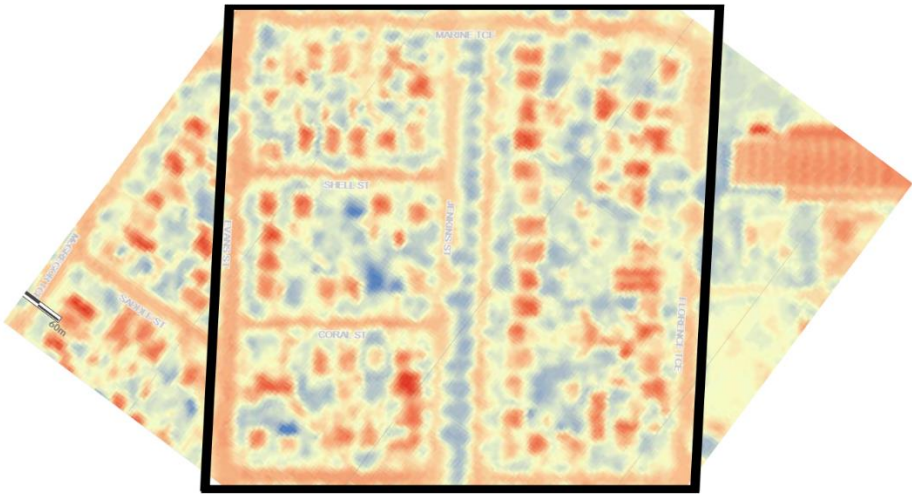
	Gravtational Acceleration (m/s ²)	Expantion Coefficient (1/K)	Thermal Conductivity (mW/mK)	Temperature (°C)
Air	9,8	0,00333	24.74	5
			25.12	10
			25.50	15
			25.87	20
			26.24	25
			26.62	30
			27.35	40
			28.08	50

(Incopera 2017); (Moran 2010).

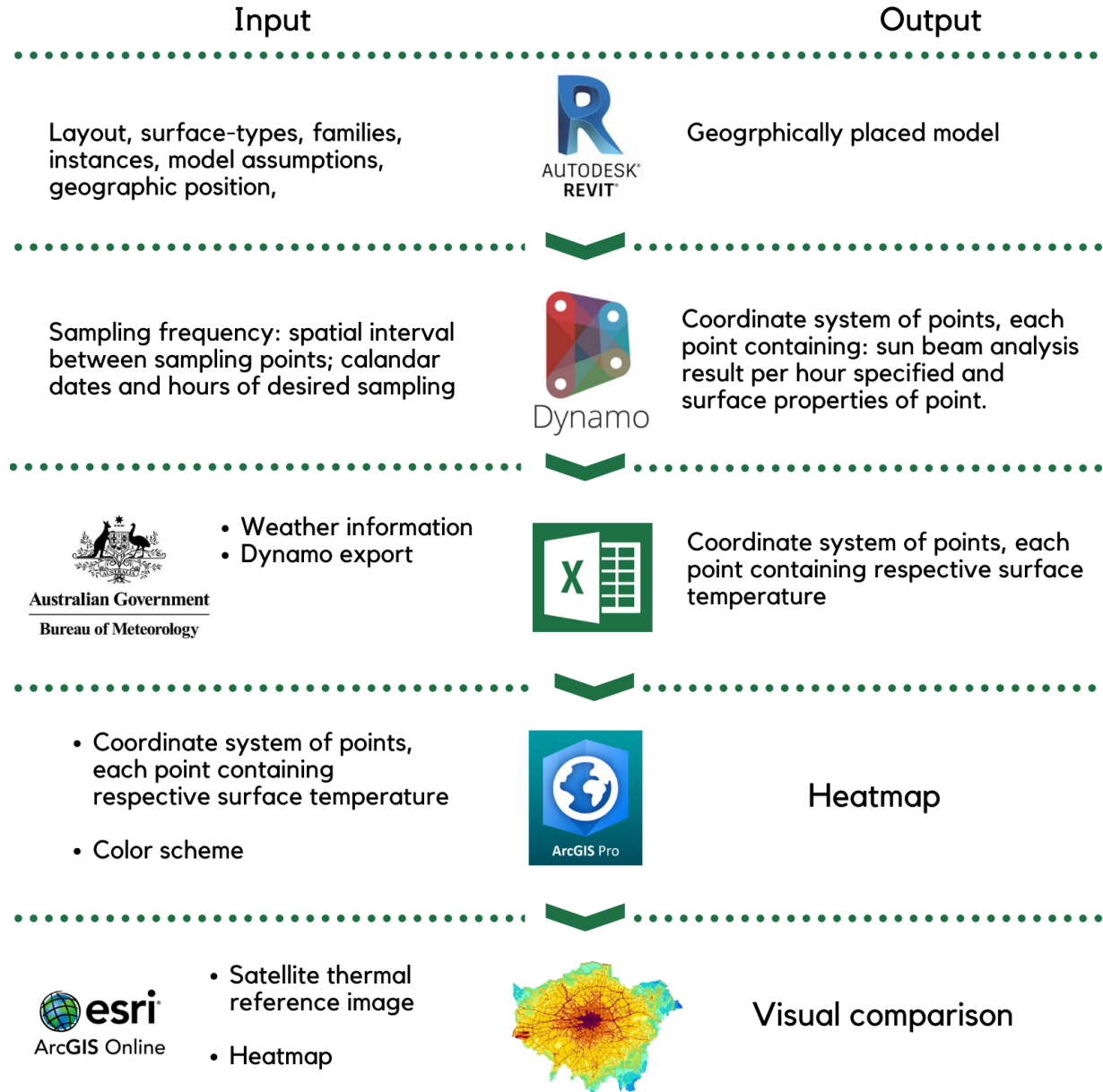
APPENDIX H - PRODUCED HEAT MAP 1:1900 SCALE



APPENDIX I - PRODUCED HEAT MAP 1:500 SCALE



APPENDIX J – INPUT/OUTPUT DIAGRAM



*Weather data corresponds to all the variables listed in Appendices F and G, excluding surface properties.

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