Urban Morphology and Streetscaping as an Approach to Mitigate Urban Heat Island in Glasgow City Centre

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Abstract

The urban heat island or UHI is perhaps one of the most apparent consequences of climate change in cities. UHI is characterised as an urban area that is considerably warmer than its surrounding [Oke, 2017]. This phenomenon occurs mainly due to population increase, which associates with many factors, such as the construction of new structures, emission build-up from motor vehicles, and demand for urban environments. Although densification affects the city's environmental condition, many studies have recognised it as a key to sustainability since it prevents the further expansion of built-up urban areas. Thus, there is a need for UHI mitigation strategies in order to stop the anticipated effects of urbanisation.

One of the cities that have been experiencing climate change over the last century is Glasgow. Being the most urbanised city in Scotland, Glasgow is not far from facing intense UHI in the near future, especially since the local authority plans to double its population by the year 2050. Currently, Glasgow is implementing action plans to adapt to climate change and integrate sustainable spatial strategies, such as placemaking initiatives, streetscape improvement projects, and preservation of heritage buildings. This dissertation analyses the impacts of UHI in Glasgow through an urban form modification approach, taking into account the urban morphology and streetscaping of the city centre. Urban morphology is the study of urban form [Lilley, 2009]. For this purpose, the thesis critically assessed two key streets to use as objects of study in implementing the urban form modification and the streetscape improvement plan using simulation software. Because of the emergence of UHI, many related studies have recognised the benefits of simulation software in understanding better the UHI impacts on a local scale. Likewise, aspect ratio and sky view factor (SVF) were essential in answering the main objectives of this dissertation since these are two commonly used indicators of urban morphology.

With the help of fieldwork and experimental research, this thesis has observed several key findings: (1) An open geometry, or high SVF, does not always favour urban areas, especially if the environment incorporates impermeable surfaces and lacks green infrastructure. (2) Although street orientation has a significant influence on air temperature, the aspect ratio has a stronger correlation to it. Regarding the latter observation, this thesis proves that (3) increasing the aspect ratio could lead to a decrease in the incoming solar radiation, thus cooling the temperature during the day. (4) Of all the streetscaping elements, urban trees demonstrate the optimum benefit in cooling the microclimate. Next is shading, and the least benefit is observed in surface materials. Therefore, these findings conclude that incorporating urban morphology and streetscaping is sufficient in managing UHI in Glasgow. Moreover, this thesis demonstrates the importance of an integrated approach in UHI mitigation schemes on a local scale.

Keywords

Urban Morphology, Streetscaping, Urban Heat Island, Glasgow

Originality statement. I hereby declare that this Master's dissertation is my own original work, does not contain other people's work without this being stated, cited, and referenced, has not been submitted elsewhere in fulfilment of the requirements of this or any other award.

Signature

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ABBREVIATIONS

AGL	Above Ground Level
AQS	Air Quality Strategy
BCR	Building Coverage Ratio
BNG	British National Grid
BRE	Building Research Establishment
CDP	City Development Plan
CFD	Computational Fluid Dynamics
CHR	Context Height Ratio
DEM	Digital Elevation Model
DSM	Digital Surface Model
DTM	Digital Terrain Model
EIIPR	Enabling Infrastructure - Integrated Public Realm
FAR	Floor Area Ratio
GCC	Glasgow City Council
GIS	Geographic Information System
H/W Ratio	Height to width ratio or aspect ratio
IFSD	International Financial Services District
LCZ	Local Climate Zone
LST	Land Surface Temperature
MRT	Mean Radiant Temperature
NDVI	Normalized Difference Vegetation Index
OS	Ordnance Survey
P1 / P2	Proposal 1 / Proposal 2
PAT	Potential Air Temperature
PGT	Pasquill–Gifford–Turner
SDF	Strategic Development Framework
SVF	Sky View Factor
SWOT	Strengths, Weaknesses, Opportunities, and Threats
UBDC	Urban Big Data Centre
UCL	Urban Canopy Layer
UHI	Urban Heat Island

CHAPTER 1: **INTRODUCTION**

1.1 Rationale

"Around 70% of the world's population is projected to live in cities by year 2050" [UN, 2018]. Because of the population increase, many cities are continuously growing despite already being highly urbanised. This growth corresponds to the construction of new infrastructures, which could generate local warming effects in addition to climate change [Zhao, 2018].

Glasgow, for instance, is the largest and most densely populated city in Scotland. And like any other metropolis, it has been experiencing climate change over the last century. Probably the most affected area is its city core because of its anthropogenic environmental conditions. The presence of various commercial and industrial buildings and emissions from motor vehicles corresponds to air pollution, which adds to the emergence of urban heat island (UHI). Consequently, Glasgow is implementing action plans to alleviate urban climate change and make the city future-proof. The local government is currently renovating its streets through the Avenues programme – an initiative to transform *"the city centre's streetscape and public realm"* to make the streets more pedestrian and cycle-friendly, attractive, sustainable, and economically competitive [GCC, n.d.-a].

Indeed, a well-designed street is essential in improving airflow and shading. Similarly, a holistic approach to urban morphology could be applied to achieve a more satisfactory thermal comfort. Urban morphology is the arrangement of buildings, the space between structures, street patterns, and the presence of other street infrastructures and vegetation [Lilley, 2009]. Hence, modifying the urban form can also add to enhancing thermal comfort and mitigating the UHI. The urban form modification referred to here is the alteration of the built-up areas' physical characteristics, including the shape, size, and density of the structures [Williams, 2014].

Moreover, it is important to consider the city's character. At present, Glasgow comprises mid-rise structures with multiple listed buildings. According to the City Centre Strategic Development Framework [GCC, 2019a], protecting heritage buildings is vital in order to display Glasgow's uniqueness. Besides preserving the city's identity and social cohesion, the conservation of old buildings will also bring in adaptive building reuse that will offer environmental advantages, establishing a more sustainable city [Orbasli, 2009].

In the next decade, the city will experience an upturn of new construction and retrofitting buildings due to the continuing economic development and demand for more commercial property. The purpose of this study is to examine the consequences of urban form modification and streetscaping and their possibilities of becoming elements of UHI mitigation measures in Glasgow city centre. In doing so, it will then be possible to demonstrate innovation while at the same time preserving the city's cultural heritage and making it fit for the future.

1.2 Aim and Objectives

The aim of this study is to critically assess the impacts of urban morphology as a means of managing UHI through an urban form modification approach, with the view to evaluating the effectiveness of the Avenues streetscape project.

Objectives:

1. To appraise the impacts of urban morphology on the city centre.
2. To examine two key streets from Glasgow's streetscape improvement project and use them as objects of study in implementing the urban form modification.
3. To analyse the local urban climate consequences of the Avenues programme.
4. To propose alternate approaches in mitigating UHI by modifying the building form in addition to the streetscape improvement plan.
5. To determine whether streetscaping is sufficient to alleviate UHI in urban areas or should urban morphology be regarded.

1.3 Outline of the Methodology

The study intends to examine the impacts of urban morphology and streetscaping in managing UHI in Glasgow city centre through an in-depth analysis. In achieving this, four phases of the methodological approach were established.

The methodology begins with reviewing documents and archival research obtained from the local government to serve as a foundation for the research topic, followed by spatial analysis to assess patterns and relationships between adjacent urban areas. Here, the criteria for selecting suitable streets for the implementation of the urban form modification were also formulated. Next, the selected streets, which are labelled the "focus areas", were comprehensively assessed through qualitative and quantitative fieldwork. The collected data and theories from related studies were applied through experimental research by altering the geometry of the urban canopy layer (UCL)[1]. This is to examine how different factors of urban morphology affect the microclimate on the local scale. Then finally, implementing the urban form manipulation strategies and proposal of new street designs through integrating 3D modelling and simulation software. Assessment criteria were significantly employed in the construction of final proposals. The analyses of the results come afterwards, answering the main objectives of this dissertation.

[1] Oke [1976] defined UCL as the layer of air contained between the ground in urban areas and the mean building height. While according to Hang et al. [2009], it is *"the space under the street roofs and between buildings"*.

1.4 Disposition of the Thesis

The dissertation is structured into five chapters as follows:

Chapter 1 is the foundation of the research topic. It determines the problem, defines the aim and objectives, and describes the scope of the study.

Chapter 2 discusses the previous works related to UHI, urban morphology, and streetscaping and a general understanding of Glasgow city centre and its strategic development plan in adapting to climate change. This chapter gives an insight into earlier findings related to the research topic and also identifies knowledge gaps.

Chapter 3 deals with the methodological approach in achieving the aim and objectives of this thesis. It summarises the research structure, various datasets used, and how data collection was carried out.

Chapter 4 establishes the results and analyses of the collected data. Here, a thorough discussion of the proposals and key findings are presented.

Chapter 5 concludes the research topic based on the results and discussion and answers the aim and objectives, followed by limitations that were perceived throughout the dissertation. Last are recommendations for future studies and for Glasgow's local authority, urban planners, and designers in the likelihood of improving the urban morphology and streetscaping of the city centre.

CHAPTER 2: LITERATURE REVIEW

The impacts of climate change in cities will depend on the type of environment they have as it affects different places in different ways [DELWP, 2020], which explains why place-specific strategies are essential. Glasgow's local authority has established a broader place-based approach to developing a more effective strategic framework that is unique and specifically designed for the location. Similarly, many cities have also recognised the need to create a site-specific policy that would respond to the location rather than follow standard guidelines without considering its context. As cities grow denser, urban form manipulation strategies for UHI mitigation is becoming more vital. It is therefore essential to assess the unique characteristics of a city to understand its urban morphology and its effects on the surrounding.

2.1 UHI Mitigation Strategies

An urban area that is considerably warmer than its surrounding is known as the urban heat island (UHI), which usually occurs due to human activities [Oke, 2017]. Aside from anthropogenic heat, other significant factors of thermal comfort and UHI on a street scale are the materials and objects incorporated within the surrounding. Giguere [2009] categorised four UHI mitigation measures on a street scale (Table 2.1).

Table 2.1 *Four UHI mitigation measures on a street scale. Source: Giguere, 2019.*

Strategies	Description
Greening	Green spaces, green walls, and other vegetation provide cooling, shading, evapotranspiration, enhanced air quality, and health benefits. In choosing the right vegetation type, it is vital to consider species that can tolerate temperate climate and urban pollution, block solar heat, and allow airflow.
Urban Infrastructure	The higher the reflectivity of a material, the less it stores heat. Thus, it is advisable to apply light-coloured facades, roofs, and pavements to minimise the effects of UHI in a local area.
Stormwater Management and Soil Absorptivity	Through evaporation, moist soils are capable of cooling like vegetation. Examples of these surfaces used in urban areas are permeable interlocking pavements and porous paving stones.
Anthropogenic Heat Reduction Measures	Energy consumption for heating and cooling buildings will emit carbon, contributing to the intensification of UHI. Incorporating passive design strategies can lessen these consequences. Furthermore, reducing vehicular traffic in urban areas and providing good transportation planning will significantly minimise anthropogenic heat.

As seen in Figure 2.1, Glasgow has the largest traffic volume in Scotland for two consecutive decades, making heat from transport one of the city's key challenges [GCC, 2017]. Although heat is not an immediate concern in the city centre at present, this would likely be the main problem in the next decades if the upward trend continues. Therefore, strategies such as the above mentioned are essential in tackling the rising temperature on a street scale.

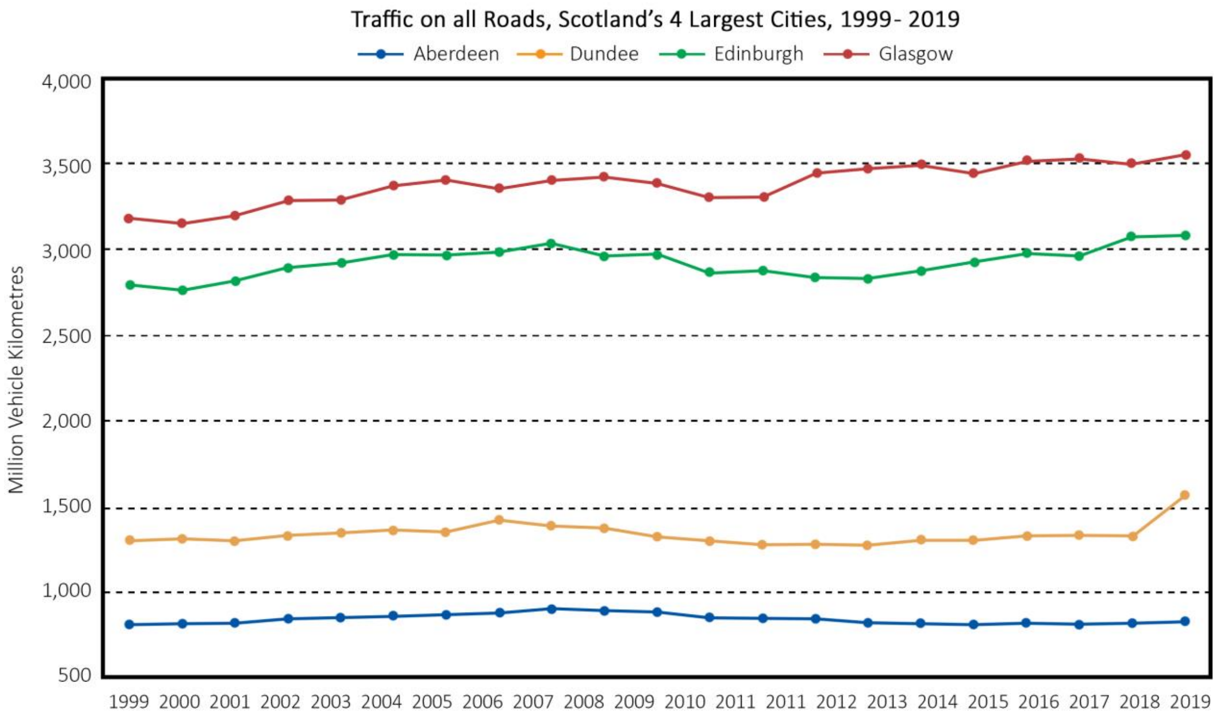


Figure 2.1 *Traffic volume on all roads, Scottish cities. Source: Scottish Transport Statistics, 2019.*

2.2 Understanding Urban Morphology

2.2.1 Effects of Urban Morphology on UHI in High-Density Area

Urban morphology is the *"study of urban form"*. It is the transformation and arrangement of neighbourhood and buildings, the space between structures, street patterns, and the presence of other street infrastructures and vegetation [Lilley, 2009]. Hu et al. [2016] studied the effects of varying built densities and building forms on the urban microclimate and how adjusting the sky view factor (SVF) value can implement urban form manipulation strategies to mitigate UHI. SVF is "*the ratio of the visible sky area and the total sky dome of an observation point on the ground"* [Oke, 1981]. Its numerical value ranges between 0 to 1, wherein bigger values signify better sky visibility.

Recent studies show that UHI is closely associated with the urban form. Hu et al. [2016] wanted to understand the extent to which the UHI is mitigated through urban form optimisation and what kind of forms are conducive to the scheme. The study subject used 30 hypothetical high-density urban areas with various buildings of varying sizes based in an existing Chinese city. Fig. 2.2 only shows two of the 30 urban areas because both showcase distinctive distribution forms. The floor area ratios (FAR) of these plots are 6 and 12, respectively. After examining different urban form distribution models using simulation software (Rhinoceros 3D and GIS), the result indicated that the best distribution form is establishing a low SVF area in the centre and gradually increasing the SVF value as it goes outward. And with regards to building form, a compact allocation is better than dispersed.

For the UHI effect, "*the compactness of urban form is a key feature*" [Hu et al., 2016, p.172]. This experiment demonstrates that the layout of the density distribution of an area is as significant as the layout of specific building forms, and both are vital in the development of UHI. Likewise, manipulating urban form based on SVF is effective in UHI mitigation. This process will help indicate urban form modification capability to reduce the UHI effect in Glasgow's streets.

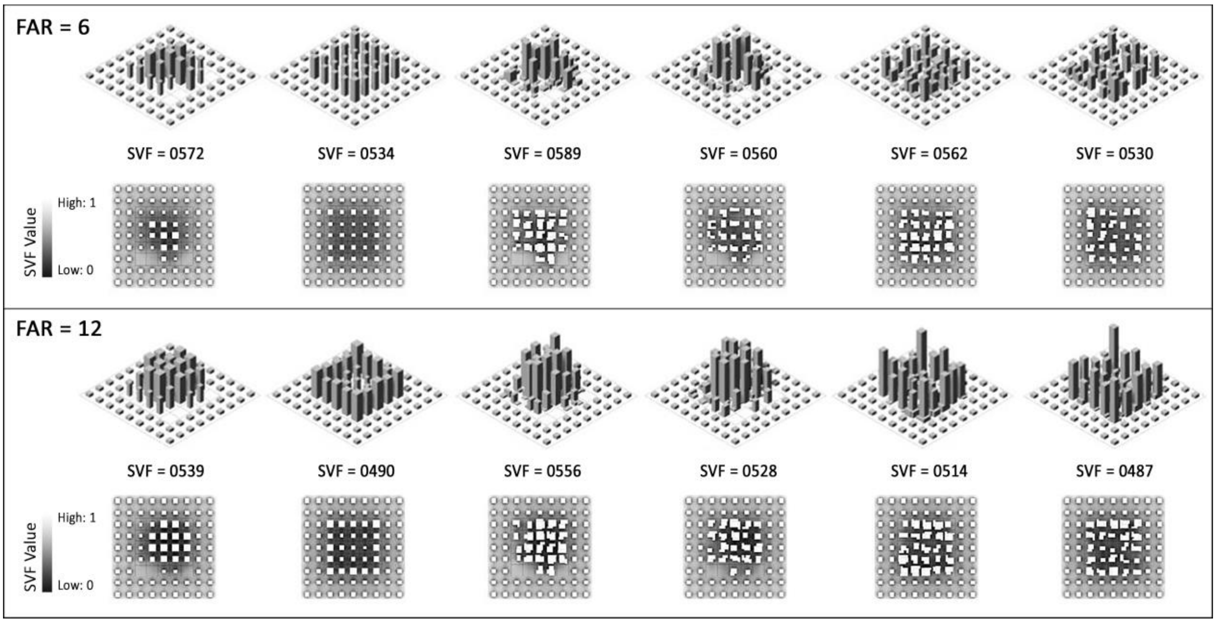


Figure 2.2 *Two of the 30 hypothetical urban areas with SVF map, FAR=6 (above) and FAR=12 (below). Source: Hu et al., 2016.*

2.2.2 Improving Air Quality through Urban Form Modification

Another study that shows the importance of urban form is conducted in Mong Kok, a high-density area in Hong Kong. The city is characterised as a crowded environment with insufficient green space and heavy traffic [Gov HK, 2011]. Although the study focused on improving air quality rather than UHI, both have similarities with their methodologies.

Yuan et al. [2015] did model configurations using Mong Kok's urban conditions to investigate how air quality varies in different urban forms. Here, the group created eight simulation scenarios with different building forms (Fig. 2.3).

The results in Cases 1 and 2 reveals that the future urban development could further aggravate the air quality if planners keep the current design strategies. On the other hand, Cases 3 to 8 prove that appropriate strategies can disperse the air pollutant in high-density cities.

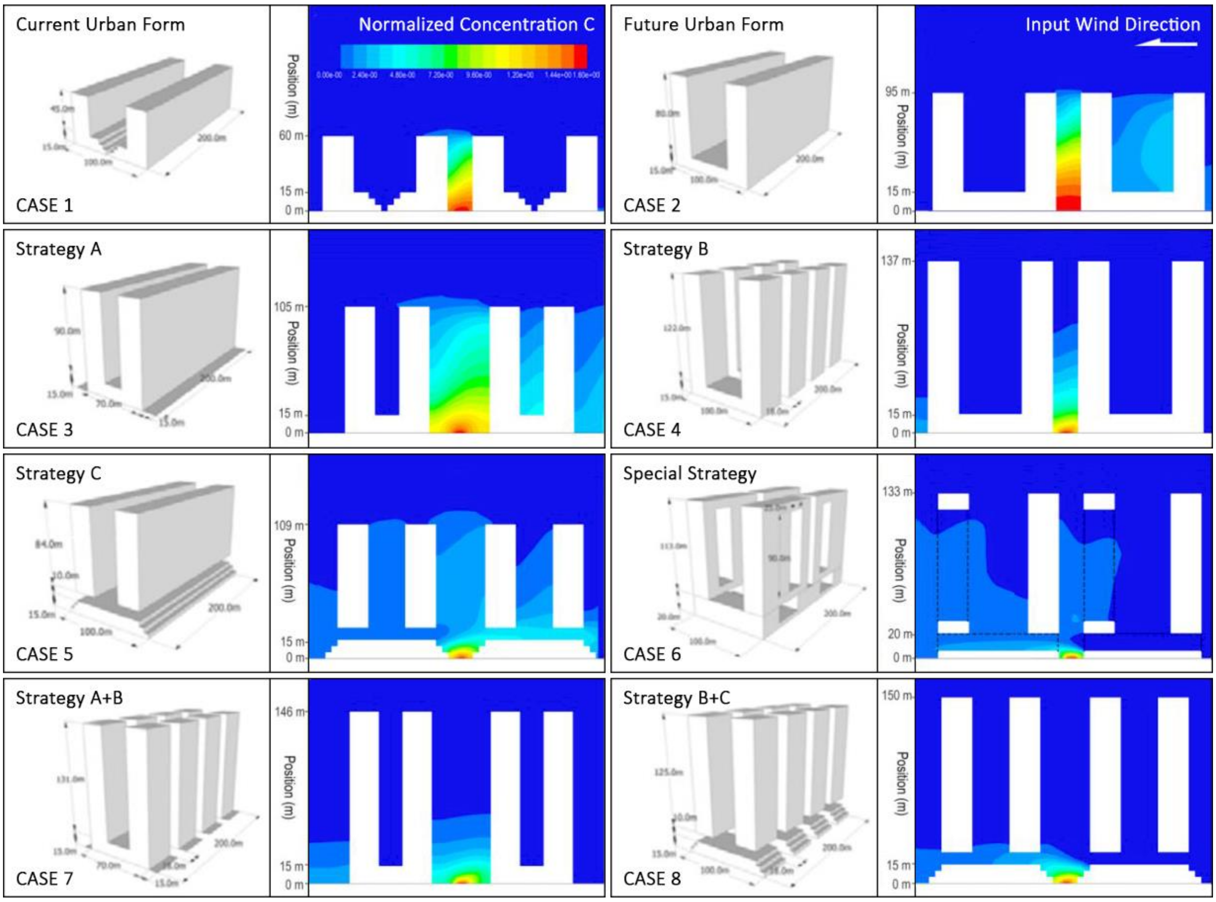


Figure 2.3 *Eight simulation scenarios with different building forms. Source: Yuan, Ng, and Norford, 2015.*

With the use of SketchUp and Ansys Fluent software [Yuan, 2021], the building geometries in Cases 5 to 8 were applied in the actual urban morphology of Mong Kok to illustrate the feasibility of the suggested design strategies in real urban design practices (Fig. 2.4). Using Counihan's roughness model (Eq. 1), formulated by Grimmond and Oke [1999], the group calculated the urban permeability of D1 and D2 to analyse the surface roughness of the adjacent structures, which can consequently alter wind flow and air quality. Urban permeability is defined as *"the extent to which urban forms permit movement of people or vehicles"* [Handy et al., 2005]. Thus, higher FAR and site coverage ratio indicate low urban permeability.

$$\lambda i = (C_1 \cdot \lambda p - C_2) \cdot P \qquad (1)$$

where:

λi = urban permeability

λp = site coverage ratio

C_1 and C_2 = 1.4352 and 0.0463

The simulation results indicate that the mitigation strategies in D2 can substantially enhance the wind permeability and reduce the traffic air pollutant concentration. Likewise, this experiment could change architecture design and urban planning from *“experience-based to more scientific and evidence-based decision making”* [Yuan et al., 2015, p.1].

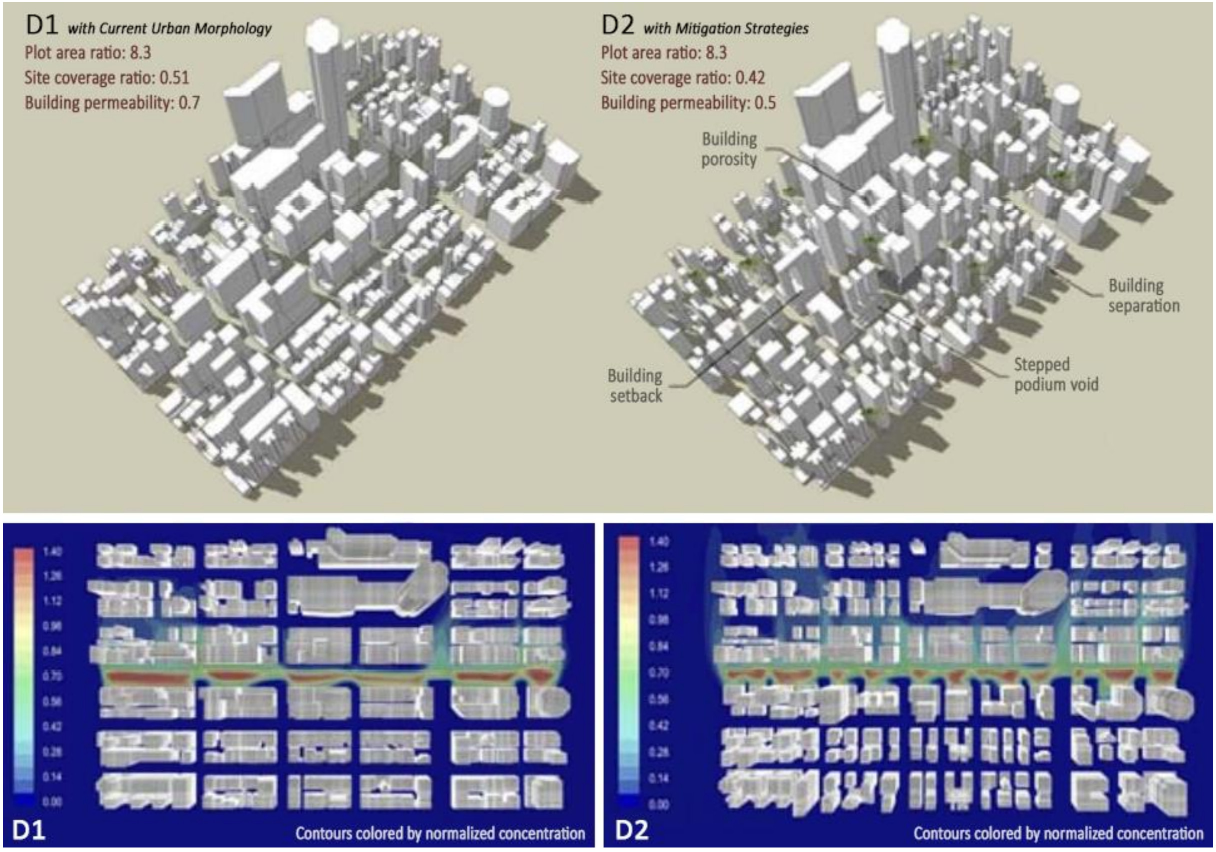


Figure 2.4 *Mong Kok ‘s current urban area (left) and urban redevelopment with mitigation strategies (right). Source: Yuan, Ng, and Norford, 2015.*

A similar study was conducted using Singapore city’s physical features. Yuan et al. [2020] concluded that diluting anthropogenic heat is a challenge in high-density city centres because of stagnant airflow due to closely packed tall buildings. They provided scientific understanding to support decision-making in urban planning practice.

These research papers prove that urban form modification experiments are mainly performed using the Asian city context due to their distinctive climate and high-density characteristics. There is a lack of study where similar experiments used European cities, possibly because of their mid-rise and low-density features. Additionally, the protection and preservation of the built environment are vital in Europe as it displays its significant culture through its historic buildings. That is why many European cities limit the construction of high-rise buildings in an attempt to conserve the landscape. But due to the changing climate and continuing urban growth, it is essential to investigate how heat can affect the future of city cores and develop strategies that would alleviate UHI, while safeguarding the cultural heritage of an area.

2.2.3 Calculating UHI Intensity based on Urban Geometry

One of the many uses of the geographic information system (GIS) is calculating the UHI of an urban area. According to Nakata-Osaki et al. [2015], the emergence of UHI is one of the most discussed climatic concerns related to urbanisation because it results from various fundamental issues like air pollution, heat from human activities, thermal properties, and urban geometry. Their study incorporated GIS in determining UHI based on Oke's model [1988] (Eq. 2).

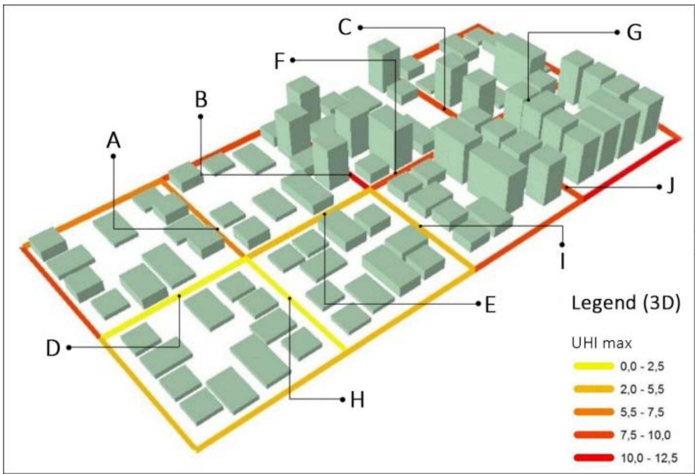
$$\Delta T_{u-r(max)} = 7.54 + 3.97 \ln \ (H/W) \qquad (2)$$

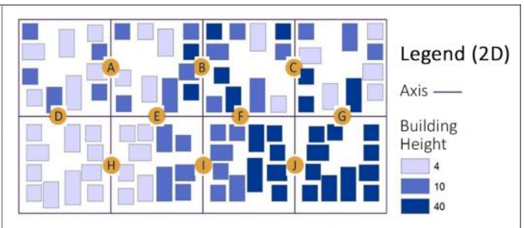
where:

$\Delta T_{u-r(max)}$ = maximum UHI

H/W = relationship between height and width

Urban geometry variation affects the temperature difference, wind speed and direction, and the amount of obtained shortwave and emitted longwave. The H/W ratio [Oke et al., 2017], which is commonly used to represent the urban geometry, simulates the 'urban canyon' – a term for streets bounded by buildings on both sides. A higher H/W ratio means greater UHI. Thus, it implies a lesser visible sky, reducing the areas' airflow and trapping the longwave radiation. The researchers used ArcGIS for the simulation, where a hypothetical setting with streets and buildings of various shapes and heights was applied (Fig. 2.5).





Axis	Ave. H	Ave. W	H/W Ratio	UHI max
A	7.50	12.27	0.61	5.50
B	25.00	12.39	2.02	10.24
C	20.75	12.25	1.70	9.54
D	5.50	21.72	0.25	2.00
E	11.50	25.72	0.45	4.25
F	20.50	15.34	1.33	8.60
G	31.00	20.32	1.52	9.12
H	4.00	25.05	0.16	0.17
I	10.00	24.56	0.40	3.88
J	40.00	26.74	1.50	9.05

where:

UHI max = the maximum intensity of UHI using Oke's model
Ave. H = the mean height of all buildings on the left and right sides
Ave. W = the mean width from the axis to the buildings on both sides

Figure 2.5 *Hypothetical setting using ArcGIS. Source: Nakata-Osaki, Souza, and Rodrigues, 2015.*

After the simulation, they conclude that different settings can acquire similar values of UHI max. For instance, axis F and J have roughly the same UHI max values, but both have a well-defined arrangement - axis F consists of buildings with differing heights, whereas the other axis involves structures with varying distances from the axis line.

This experiment describes why a micro-scale analysis of urban form is essential in establishing more effective UHI mitigation measures. The width of streets, distance of buildings to the street axis, and building heights are vital elements in determining the appropriate urban geometry of Glasgow city centre.

2.3 Compatibility of LCZ Parameters for Climate Sensitive Street Design

In an article written by Maharoof et al. [2020], they examined the microclimate of three street types within Glasgow and how they can use the local climate zone (LCZ) classification system for climate-sensitive urban planning. The LCZ classification system can be a tool in improving the local microclimate; it measures the UHI of certain regions, standardises urban fabric [Stewart and Oke, 2009], and incorporate place-specific climate guidelines.

The paper used the SVF, aspect ratio (height/width ratio or H/W ratio), and surface features (surface albedo) of the three streets. The method was conducted through a traverse and simulation-based (ENVI-met) approach. ENVI-met is a computational fluid dynamics (CFD) modelling software that simulates microclimate in an urban area [Langer et al., 2012]. After the simulation, the result shows that a fixed design strategy for all street types is not applicable due to various considerations like orientation, building fabric, façade geometry, shading, wind speed, and humidity. This research accords to an earlier published material about Glasgow's urban morphology [Drach et al., 2018, p.790] where *"differences in air temperature are noticeable in urban canyons, with a direct correlation to the site's SVF and with an inverse trend under open-air conditions"*.

These studies may have similarities with the dissertation topic because it talks about the urban canyons in Glasgow city centre and how a place-specific approach is important to achieve effective urban planning. But the application of urban form modification in the thesis made it distinct from the above literature reviews. The study conducted by Maharoof et al. [2020] prove that a generic street design strategy is not feasible for all urban areas. And this thesis will validate this finding by establishing alternative proposals for Glasgow's streetscape improvement project.

2.4 Streetscaping as a Tool in Sustainable Urban Design

The literature review on urban form modification experiments evidently shows that there is a lack of interdisciplinary study about urban morphology and streetscaping. Just like urban form modification, streetscaping plays an essential role in mitigating UHI at the pedestrian level. *"Streetscape is a term used to describe the natural and built fabric* of *the street"* and defined as the overall appearance of all elements along a street, including all buildings, street surface, landscaping, and street furniture and fixtures [Charlwood, 2004]. In identifying the streetscape elements and principles, it is important to apply sustainable solutions to provide a sustainable urban environment. The main features of a sustainable streetscape are listed below.

Table 2.2 *Main features of a sustainable streetscape. Source: Rehan, 2012; Li et al., 2013.*

Features	Description
Sidewalks	The materials should be reflective and permeable to absorb less solar radiation and let water seep into the soil to filter out pollutants.
Trees and Planters	These are efficient in creating buffers from vehicles and street noise and help pedestrians feel more comfortable walking along the street. Both should withstand pollution, heat, and other urban issues.
Street Furnishing	Should be locally produced or recycled.
Bus Shelters	Provide a barrier-free ramp and standard signages for accessibility.
Bicycle Facilities	Bicycle lanes and secure parking racks should be safe and secured.

It is understood that these features are generic to any street enhancement projects, yet these will serve as supplementary guidance in proposing alternative streetscape designs. Consequently, the Designing Streets – a policy statement for Scotland by The Scottish Government [2010] – provided more comprehensive guidelines for the street design and material consideration. The Avenues programme thereby follows this document, in addition to the place-making policy, to ensure that it meets Glasgow streets' necessities. It should be mentioned that the streetscaping proposal presented in Chapter 4 did not explore the latter features, i.e., street furnishing, bus shelters, and bicycle facilities, in order to validate the existing plans for the Avenues project.

There is a great number of academic papers where researchers explored the probability of urban forms and building arrangements as UHI mitigation measures. However, there are limited studies on the effectiveness of street designs using simulation-based approaches. This thesis can further scrutinise this research gap as a way of grasping the knowledge between what is produced in research studies and what is applied in actual city development plans.

2.5 Glasgow City Profile

2.5.1 An Overview of the City Centre

Glasgow city centre (Fig. 2.6), situated in the north of the River Clyde, consists of medium to high-density developments. Its LCZ classification is identified as a compact mid-rise [Emmanuel and Loconsole, 2015]. It comprises industrial and commercial buildings that are a mix of Victorian and modern mid-rise buildings with streets based on a grid system [People Make Glasgow, n.d.]. In general, the city has a damp climate due to its proximity to the west coast [Met Office, 2016].

Glasgow's historic environment has established a rich foundation of listed buildings and conservation areas. However, the demands of modernising the city may affect its preservation. On that account, the city council has taken action to protect and enhance the historic environment in order to maintain the city's cultural identity [GCC, n.d.-c]. Furthermore, the council encourages new residential development in the city centre to double its population by 2050 [GCC, 2019a]. Although this would sustain the centre's economic success, it would affect its environmental condition because population increase stimulates climate change.

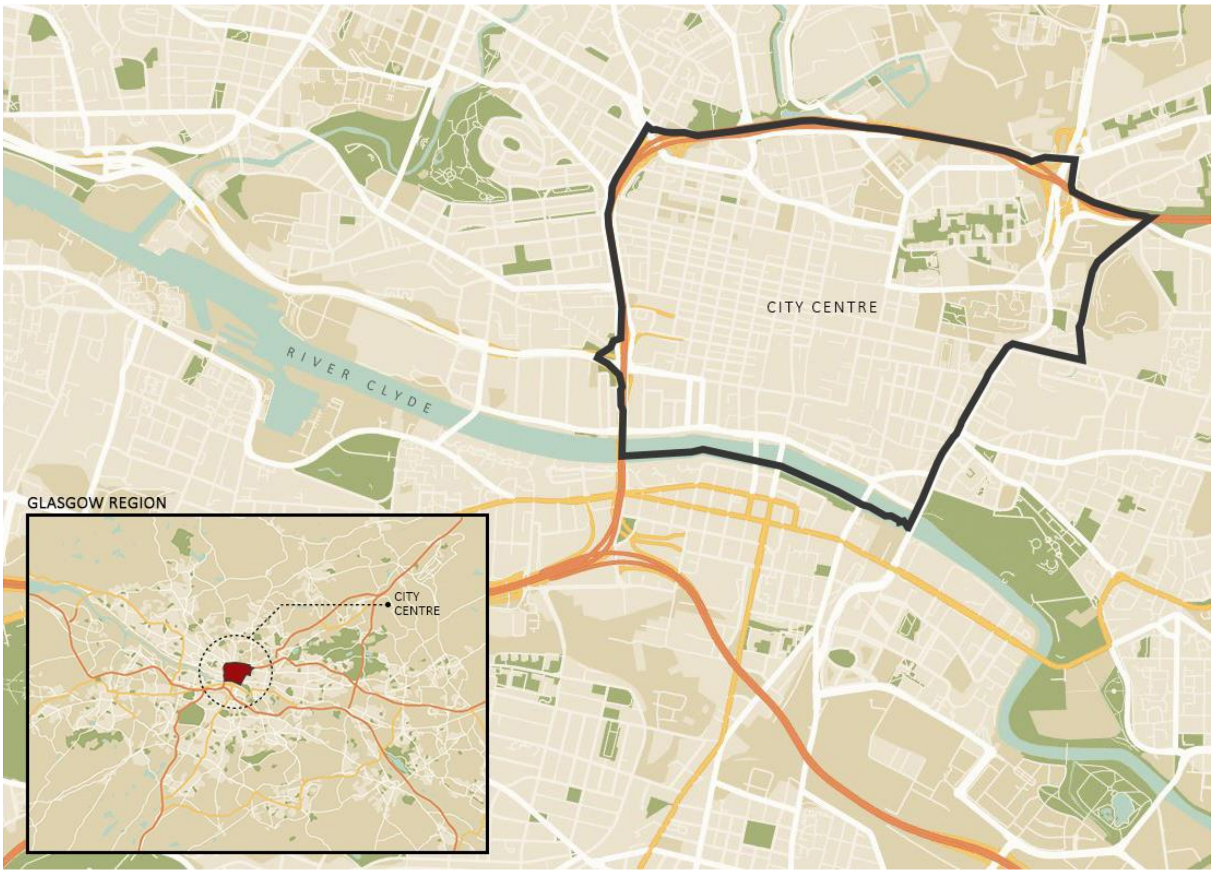


Figure 2.6 *Map of Glasgow. Source: Google Maps, 2021.*

According to various reports, Glasgow is among the cities that will drastically experience the effects of climate change in the next 30 years. Table 2.3 summarises the key climate change risks in the city.

Table 2.3 *Key climate change risks in Glasgow. Source: Adaptation Sub-Committee, 2016; Carrell, 2018; Brown, 2019.*

Warmer land temperature	Warmer, wetter winter
Increased annual rainfall	Extreme summer temperature
River flooding	Surface water flooding
Regular heatwave	Socio-economic impacts

Nevertheless, the city is improving its social, economic, and environmental aspects while becoming more climate-resilient for the coming decades. Their long-term action programme aims to shape the physical environment and create a sustainable, liveable, and people-oriented place while adapting to climate change [GCC, 2019a].

2.5.2 Climate Change Adaptation Plan of the Local Government

Being the most urbanised city in Scotland, Glasgow is a key contributor to climate change [UN Environment Programme, 2020]. The city centre particularly plays an integral part in this phenomenon because much of the pollution from transportation, buildings, human activities, and commercial hubs are found in this area.

The City Development Plan (CDP) of Glasgow [GCC, 2017] consists of two key policies – The Placemaking Principle and Sustainable Spatial Strategy – which must be considered in order to adapt to climate change.

The Placemaking principle states that each local community should be planned and managed by its municipality to satisfy the people's needs [The Scottish Government, 2020]. It encourages incorporating the right type of development in the right place, which aims to provide a sustainable and strong community, making use of the place's distinctive characteristics. New developments should respond to Glasgow's strategic aims, policies, and objectives while meeting the Placemaking requirements. Therefore, fully understanding Glasgow city centre's context is vital in achieving a sense of place [GCC, 2018a].

According to the Designing Streets [The Scottish Government, 2010], a well-designed street is a critical element of the country's attempt towards sustainable development and reduction of climate change impacts. The document follows the principle of Placemaking, wherein mitigation measures are understood to be place-specific to respond to the local environment. Therefore, in adopting this principle on a street-scale, an assessment of building height and form should be taken across a district, block, and street to consider its contribution to the city centre's urban morphology [GCC, 2019a].

On the other hand, the Sustainable Spatial Strategy features Strategic Development Framework (SDF) to respond and implement strategies to the city's particular area's context and issues. This policy will help the city meet the challenges of a changing climate and build a resilient environment.

Because of Glasgow's distinct geographic contexts with other Scottish cities, Glasgow will have different approaches in adapting to climate change. The use of various simulation programs and gathering of essential data, such as the government publications mentioned above, can offer a more precise analysis of a rather complex environment.

2.5.3 The Avenues Programme

The Glasgow City Council (GCC) is currently transforming its streets to make it "*more pedestrian and cycle-friendly"*, which they call the Avenues programme. It aims to improve connectivity and make car-dominated streets people-friendly and public transport-oriented while making them more attractive [GCC, 2019a].

The programme plans to transform 17 crucial streets (Fig. 2.7) that will finish in 2025 [GCC, n.d.-a]. Moreover, the local government has obtained funding from Sustrans Scotland (Places for Everyone) to improve four more additional streets, making it 21 Avenues streets in total [Get Ready Glasgow, 2021]. All these, while protecting and respecting its historic environment through careful consideration of building heights, scale, performance, and façade design, and enhancing the cityscape by associating old with new buildings [GCC, 2019a].

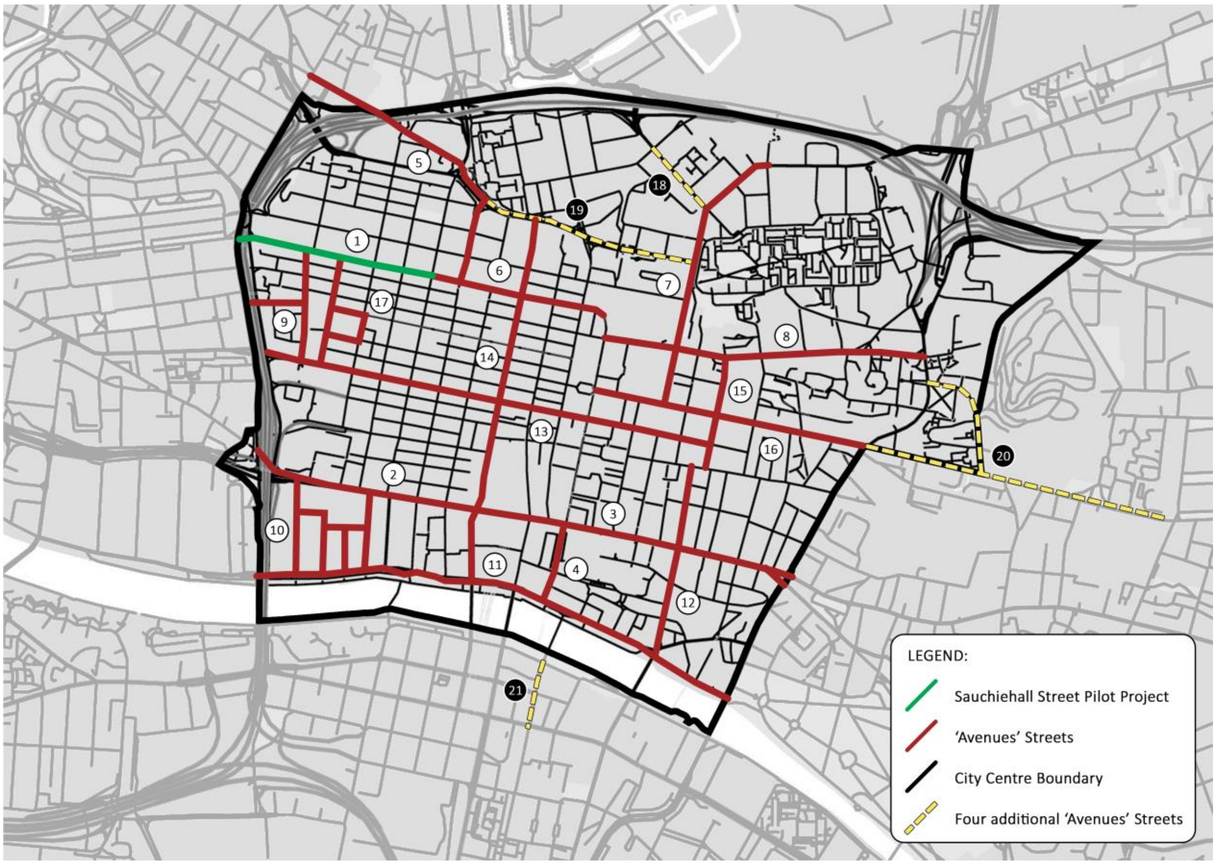


Figure 2.7 *Avenues Programme Map. Source: Adapted from Get Ready Glasgow, 2021.*

The redevelopment of Sauchiehall Street is the pilot project and was constructed from 2018 to 2019 (Fig. 2.8). The improvements that were implemented are summarised below.

Table 2.4 *Improvements implemented in Sauchiehall Street. Source: GCC, n.d.-a*

Extension of paved walkways	Addition of cycle lanes	Provision of leisure space
Removal of parallel parking	Street greening	Provision of bus stop

Figure 2.8 *Sauchiehall Street before (upper left) and after (upper right) redevelopment and visualisation for Sauchiehall Street (lower left and right). Source: Urban Movement, 2021; Google Maps, 2019; GCC, n.d.-a.*

Combining the Avenues programme and urban form modification strategies will significantly enhance Glasgow's streets not just at present but also for the future of the city centre. The implications of this research study can provide the local government, developers, planners, and architects in the decision-making for the development of new infrastructures.

CHAPTER 3: METHODOLOGICAL APPROACH

This chapter presents the research methodology used to achieve the objectives of the thesis. This study follows a multi-faceted approach in order to deliver a comprehensive analysis of the subject, including urban morphology and streetscaping as UHI mitigation strategies, Glasgow city centre context and its strategic action plans, and the Avenues programme.

3.1 Research Philosophy

In reference to the research onion developed by Saunders et al. [2007], the nature of this dissertation describes a combination of positivism and interpretivism research philosophy. However, it will concentrate mainly on positivism since urban form modification is the focal point of this research. In positivism, knowledge can only be obtained through empirical research, such as measurement and observation. However, it does not depend on human reasoning. On the other hand, interpretivism highlights social and cultural influences [Crossley and Jansen, 2021]. In assessing the effectiveness of the Avenues programme, it is vital to study the people's thoughts and ideas regarding the Avenues project because the community should be engaged in city development plans as described in the Placemaking principle [GCC, 2018a]. But due to Covid-19 restrictions, a secondary source, i.e., community engagement report, was used to substitute community involvement. Thus, the interpretivist approach of this thesis is not as distinguished as that of the positivist approach.

3.2 Research Approach

This research follows a deductive approach as it begins with theories and experiments obtained from the literature review, which this thesis aims to develop further. Regarding the research philosophy, the author conducted a mixed-method approach to combine qualitative and quantitative data, starting with documents and data review to serve as a foundation to Glasgow's urban morphology and streetscaping and understanding the community's needs to a certain degree through archival research. Next is formulating criteria in selecting suitable streets for the implementation of the urban form modification. Then, getting meteorological data and an in-depth study of the subjects through fieldwork. Finally, applying the collected data and the theories from the literature review through experimental research.

3.3 Structure of the Research

An outline of the methodological approach is shown in Fig. 3.1, while its connection to the research objectives is presented afterwards (Fig. 3.2).

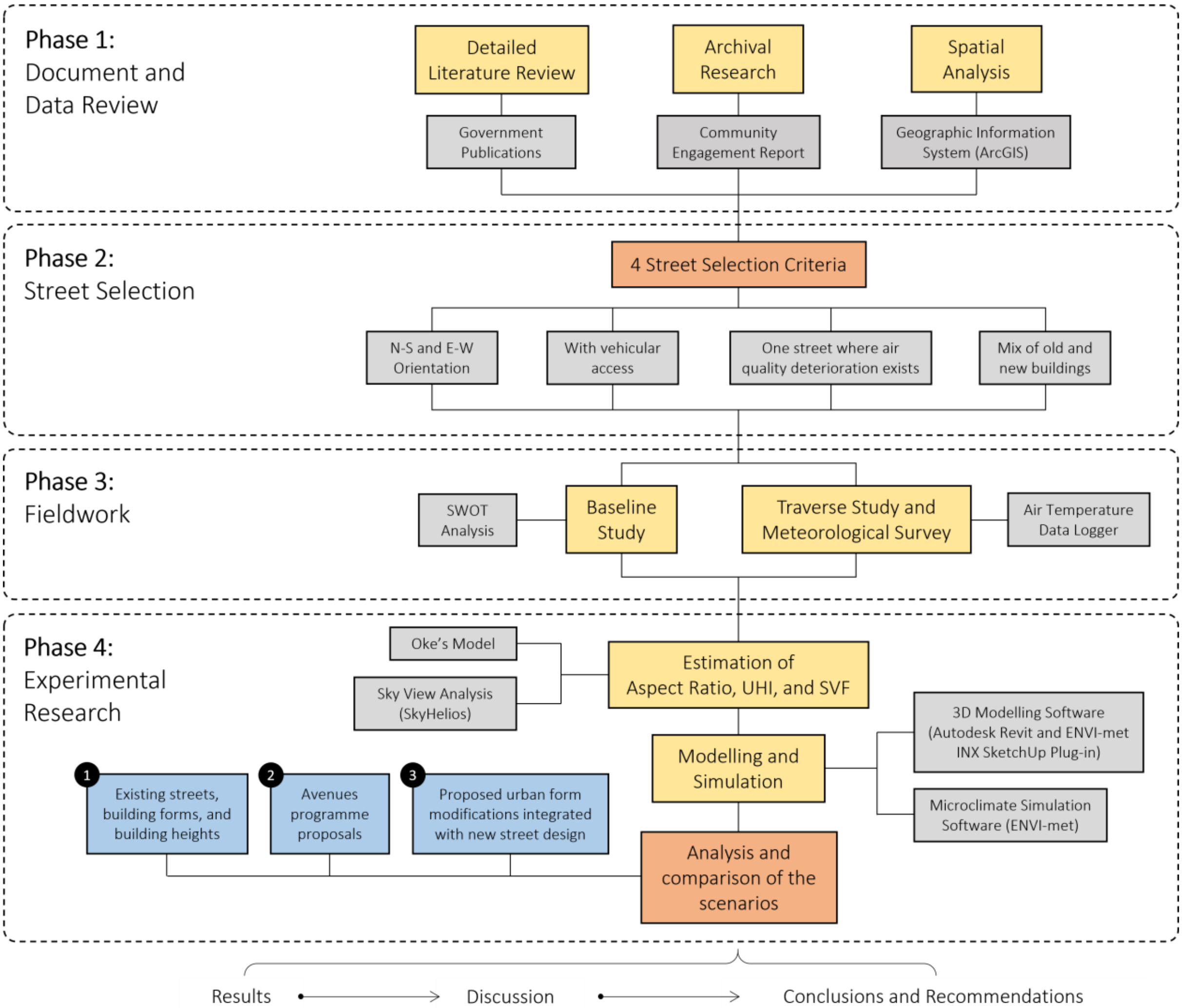


Figure 3.1 *Research Structure.*

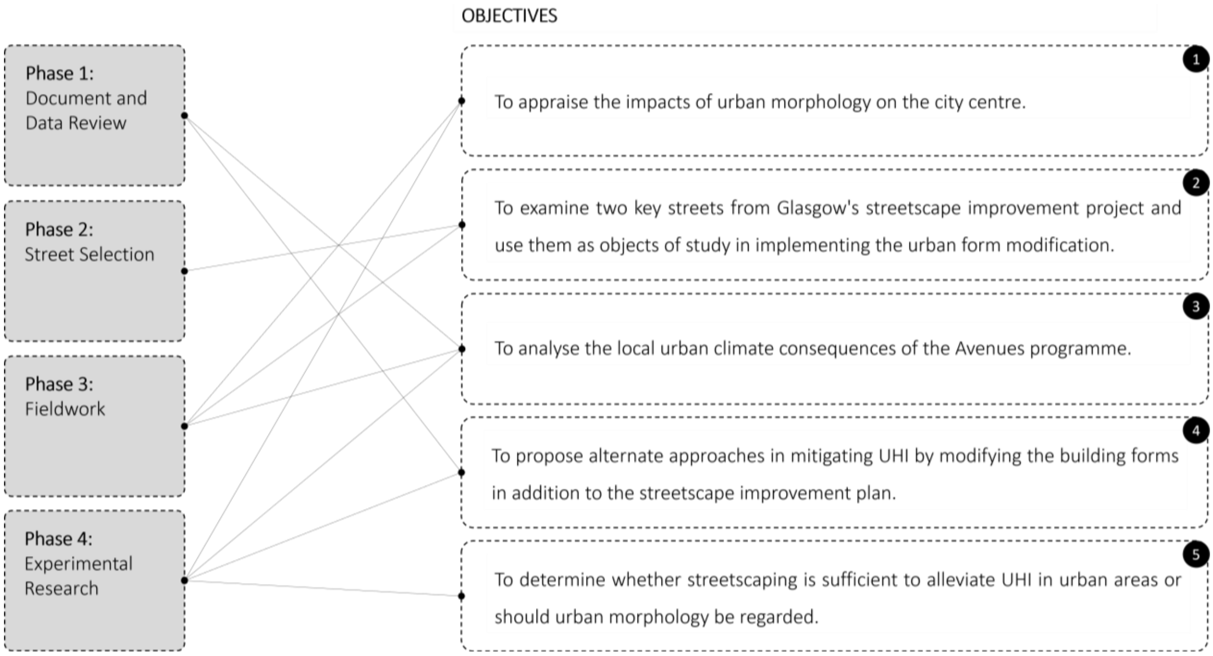


Figure 3.2 *Connection between methodology and research objectives.*

3.4 Research Strategy

3.4.1 Detailed Literature Review

Although this dissertation intends to demonstrate a degree of originality, it is vital to tackle relevant publications by the national and local governments to have a general view of the city's action plans and adaptation strategies. The government publications highlighted in the previous chapter discussed valuable points in the implementation of place-specific design criteria and guidelines in planning climate-proof urban areas. Table 3.1 summarises these documents.

Table 3.1 *Summary of the detailed literature review.*

Document	Provider	Date	Description
The Placemaking Principle	GCC	2017	It aims to deliver a place-based approach in developing the built environment, which enhances people's wellbeing, encourages responsive, sustainable, and innovative design, and harnesses the unique characteristics of a place.
Strategic Development Framework (SDF)	GCC	2017	It is a supplementary guidance of the Sustainable Spatial Strategy of the City Development Plan, which discusses the planning, spatial priorities, action plans, implementation strategies, and some design parameters exclusively for the city centre over the next three decades.
Designing Streets	The Scottish Government	2010	The Scottish Government believes that different streets have site-specific requirements and material consideration. This document adheres to the essence of the Placemaking principle, where street designs should develop from a sensible response to location and where people should be the centre of the planning process before motor vehicles' movement.

3.4.2 Archival Research

As mentioned in the Placemaking principle [GCC, 2018a], the community should be involved in the planning process to promote a sense of ownership. But due to the limitation caused by the global pandemic, this could not be examined in this thesis. Alternatively, a community engagement report was acquired from the GCC City Centre Regeneration Team. Although the information here is not as substantial as what can be obtained from primary sources, such as interviews and surveys, this report helped the author further understand the Avenues programme and determine the important information, requirements, and issues underlying Glasgow's crucial streets. An outline of the archival documents is summarised in Table 3.2.

Table 3.2 *Summary of the archival documents.*

Document	Provider	Date	Description
Enabling Infrastructure - Integrated Public Realm (EIIPR) Communication Plan: Design and Consultation	GCC City Centre Regeneration Team and Ironside Farrar	2019	A summary of key local stakeholder's previous consultations, GCC engagement results, lessons learned through the Sauchiehall Street implementation, design guide consultation results, technical design standards, and so on.
Visualisations	GCC City Centre Regeneration Team	2020	GCC open data resources of initial design proposals for the Avenues streets.
Master Consultation Record	GCC City Centre Regeneration Team	2020	An excel file of all technical consultations, stakeholder meetings, surveys, public engagement, design meetings, and supplier consultations (Appendix II).
EIIPR Project Phasing	GCC Development and Regeneration Services	2020	A phasing map showing technical information of all Avenues streets.
Master Plans and Specifications	GCC City Centre Regeneration Team	2021	A detailed plan and specifications of Argyle Street West redevelopment.

3.4.3 Spatial Analysis

The geographic data analysis assessed patterns and relationships between adjacent urban areas. In addition, GIS helped identify two ideal streets from the Avenues programme that require quality Placemaking schemes. The selected streets served as focus areas in implementing the urban form modification. Suitable streets should have the following criteria:

Table 3.3 *Criteria for selecting focus areas.*

Criteria	Descriptions
One north-south and one east-west orientation	Because the city centre consists of a grid-iron street layout in N-S and E-W orientation, focusing on two perpendicular streets prevented redundancy and were sufficient in analysing the entire Avenues programme.
Where automotive vehicles have access	To assess anthropogenic heat both from buildings and vehicular traffic.
At least one street should exhibit air quality deterioration	As the UHI intensity has not been established at this stage, it is sensible to use existing statistics of air quality in the city centre. Since UHI can significantly affect air quality [Wu et al., 2017], the latter can serve as a heat indicator in urban areas. On the other hand, the other street does not require this, so a comparison between the two scenarios can be analysed.

Where a mix of old and new buildings exists	The lack of literature review about urban form modification using the European city context demonstrates an underexplored area that this dissertation can further study. This criterion would verify that urban form modification as a UHI mitigation strategy can be applied while protecting Glasgow's conservation area.

For the purpose of this study, the two selected streets are Argyle Street West (E-W) and Hope and Oswald Streets (N-S). Their detailed assessment, as well as their location on the city centre, are presented in Section 4.2.

3.4.4 Baseline Study

It is necessary to analyse the current situation to establish the starting points for the project [Eurostat, 2014]. This qualitative method is more logical than conducting a survey since it specifies how people unconsciously behave to their surroundings, rather than providing questionnaires that manifest obvious answers. Likewise, Gehl and Svarre [2013] emphasised that city dwellers are *"not actively involved in the concept of being questioned, rather they are observed"*. The idea is to analyse the selected streets in a systematic approach. In addition, the Sauchiehall Street pilot project was part of the study to evaluate the effectiveness of the Avenues programme in terms of useability and balance of space for people and vehicles [City Centre Team, 2020]. The baseline study, although not entirely centred in the thesis topic in terms of UHI mitigation, helped recognise the effects of urban morphology and streetscaping in the physical and social environment.

The fieldwork is outlined in Section 4.3.1 in a strengths, weaknesses, opportunities, and threats (SWOT) analysis structure. A total of ten extensive baseline analyses were carried out during Covid-19 alert levels 4 and 3 lockdowns. In alert level 4, locals are advised to stay at home. Non-essential retail, indoor leisure and entertainment, and personal care sectors are all close. However, essential travels within the city are exempted. In alert level 3, restrictions and social distancing measures are gradually relaxed, and restaurants can open until 18:00 [Gov UK, 2021]. The purpose of performing the study during these times is to examine the normal city life to a feasible extent regardless of the global pandemic. The baseline studies were conducted as follows:

Table 3.4 *Baseline study during Covid-19 alert levels 4 and 3 lockdowns.*

Covid-19 Alert Level	Date	Time	
4	09 March 2021	12:00 - 14:00	19:00 - 21:00
	06 April 2021	13:00 - 15:00	19:00 - 21:00
3	29 April 2021	13:00 - 15:00	19:00 - 21:00
	07 May 2021	13:00 - 15:00	19:00 - 21:00
	14 May 2021	14:00 – 16:00	19:00 - 21:00

3.4.5 Traverse Study and Meteorological Survey

A traverse study was performed on the two intervention areas to measure air temperature and examine its correlation with the estimated SVF and aspect ratio. Both the SVF and aspect ratio are two commonly used indicators of urban morphology [Theeuwes et al., 2014]. This study was conducted using two air temperature data loggers (Tinytag Plus 2 TGP-4500); one installed on a fixed station, and another used for the mobile measurement. This device has various advantages, including high reading resolution [Tinytag, 2021] and rationality in use by preceding studies [Drach et al., 2018; Maharoof et al., 2020], making it advisable for collecting meteorological data.

Due to Glasgow's significant rainfall throughout the year, determining the date and time for the traverse study was a challenge, especially that measurements should be taken under clear sky, calm weather, no precipitation, and low cloud amount [Yan et al., 2019]. The initial plan was to conduct the surveys during April, where there is least precipitation [Weather and Climate, 2021]. But because of the availability of the devices, the study was organised during the month of May. The traverse studies were completed in nine non-consecutive days – both afternoons and evenings – throughout the second to fourth weeks of May 2021. The afternoon surveys took place between 14:00 and 16:00, when the air temperatures were most stable [Maharoof et al., 2020]. The evening surveys, on the other hand, were conducted between 19:00 and 21:00, because the greatest temperature differences can be observed a few hours before sunset [Oke, 1981; Grimmond and Oke, 1999].

The fixed station was located in a tranquil area close to the city core and was mounted 2 metres above ground level (AGL). The device itself is placed inside a naturally ventilated solar radiation shield to protect it from rain and direct sun exposure. Since the length of the traverse is only 1.65 kilometres long, walking was the preferred method in doing the mobile measurements. Walking is more economical than using a vehicle, and it avoids traffic which can influence the measurement time span [Soltani and Sharifi, 2016]. The device was mounted on the backpack which was located 1.5 metres AGL [Maharoof et al., 2020]. To protect it from direct sunlight, an inverted funnel-shaped aluminium foil was used to cover the sensor.

The measurement intervals for both devices were set to two seconds. The first 10 minutes were discarded to allow the logger to stabilise. There were 20 locations within the focus areas (15 urban canyons and five intersections). The study designated two minutes per each location for the data logger to stabilise, which took an hour and a half to finish one whole traverse study. The fixed station and the routes and locations for the mobile measurement are presented in Fig. 3.3.

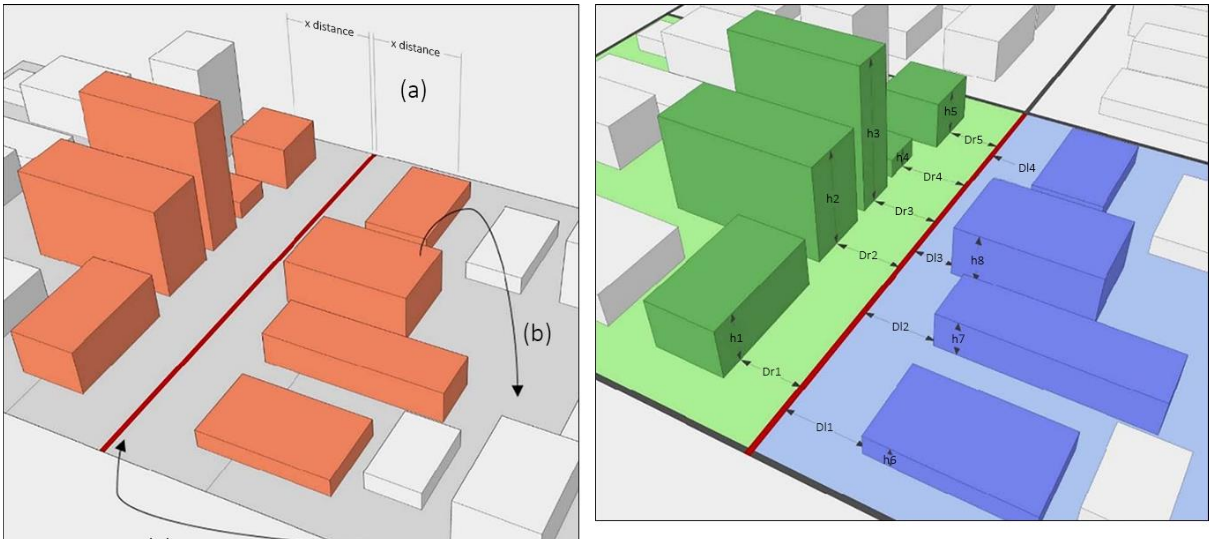
The measurements collected from the data loggers were managed using MS Excel. The temperatures taken from the traverse were corrected using the fixed station to get the temperature difference due to urban morphology and eliminate the natural temperature changes occurring during the day. These were corrected using the regression equation in MS Excel to calculate and display the regression statistics.

Figure 3.3 *Fixed station mounted 2mts AGL (left) and routes and locations for the mobile measurement (right).*

3.4.6 Estimation of Aspect Ratio, UHI, and SVF

The literature in Section 2.2.3 provided a simple tool in obtaining the UHI intensity based on different urban scenarios. As this dissertation explores the effectiveness of UHI mitigation through adjusting the building forms, the use of Oke's model (Eq. 2) primarily helped establish appropriate building masses and heights within the two study areas. Oke's model was used to calculate the UHI intensity of both existing and proposed urban forms. However, this initial analysis should not be treated as accurate values of UHI intensity. According to Montavez et al. [2007], the formula in Eq. 2 only works well for North American and European cities, while for other cities, the model does not apply accurately. The H/W ratio in Eq. 2 is based on an infinite homogeneous urban canyon, in reality, most cities do not match this setting. Also, this method disregards other parameters which influence the formation of UHI, like vegetation, surface materials, ventilation, and anthropogenic heat [Nakata-Osaki et al., 2017]. Hence, there were minor gaps, and the sole aim of this method was to give grounds as to why the buildings were modified in such a way and prevented speculating random alteration without any basis. Fig. 3.4 indicates the necessary operations in obtaining the aspect ratio required for the calculation of Oke's model.

In order to achieve this strategy, the 3D modelling software discussed in the next section was integrated. In reference to the right image of Fig. 3.3, only the estimated UHI intensity of the urban canyons were calculated since the aspect ratio of the intersections cannot be specified.



$$H = \frac{h1 + h2 + \cdots + hx}{x} \qquad W = \frac{Dr1 + Dr2 + \cdots + Dry}{y} + \frac{Dl1 + Dl2 + \cdots + Dlz}{z}$$

Figure 3.4 *Operation in obtaining the aspect ratio. Source: Nakata-Osaki et al., 2017.*

The SVF of each 20 points illustrated in Fig. 3.3 and 4.10 were developed using SkyHelios in order to analyse its relation to the measured air temperature. SkyHelios, which is a further development of the RayMan model, was used for estimating the SVF. It calculates the SVF based on different spatial formats like digital elevation models (DEM), polygon shapefiles, and Collada files. The software has several benefits, including *"short computing time, short development time, and low costs due to the use of open-source frameworks"* [Matzarakis and Matuschek 2011; Frohlich and Matzarakis, 2018a; 2018b].

3.4.7 Modelling and Simulation

For the integration of urban form modification and proposal of new street designs, 3D modelling software were used to better understand the potential impacts. This study integrated the application of Autodesk AutoCAD, Autodesk Revit, and SketchUp for modelling and visualisation. These modelling software were selected due to their straightforward technique in creating objects. Both Autodesk AutoCAD and SketchUp can be integrated with other programs, like ArcGIS. Autodesk Revit offers a more precise 3D model compared to other software. Due to its accuracy, Revit's sun-path diagram function was used to determine how the building shadows influences the adjoining streets. And lastly, SketchUp can support third-party extension programs like ENVI-met INX [Antonello, 2019] – a plug-in that creates ENVI-met models. With regards to modelling the existing structures in the study area, their building heights were corrected using LiDAR data acquired from the University of Glasgow - Urban Big Data Centre [UBDC, 2021a] for accuracy since the 3D model obtained from the Digimap's Ordnance Survey [2019] displayed some minor errors in the elevations.

Many literature reviews about urban morphology conducted experiments using CFD simulation software to measure UHI and implement urban form manipulation strategies. Correspondingly, this thesis used the ENVI-met software. This software has been used in many studies like, Salata et al. [2016] and Langer et al. [2012], to evaluate urban planning influences on environmental factors. Aside from simulating microclimates in urban environments, it can assess the effects of vegetation, architecture, and surface materials, which this project emphasises [ENVI-met, 2021]. Four simulation scenarios were generated to compare the air temperature differences and evaluate their thermal comfort. Using ENVI-met, the author performed microclimate simulations of the following scenarios:

1. Existing streets, building forms, and building heights
2. Avenues programme proposals
3. Two proposed urban form modifications integrated with new street design

Since the thesis aims to assess the impacts of urban morphology as a means of managing UHI through an urban form modification approach, it is sensible to gauge the effects of the urban geometry in the most extreme condition. So, with regards to the ENVI-met parameters, 28 June 2018 was chosen for the simulation start date as it is Glasgow's hottest day on record (31.9°C) [The Guardian, 2018]. It should be mentioned that the traverse measurements were not warm enough to use for the simulation. The meteorological data required for the simulation settings were acquired from the Met Office Hourly Observations Data 2018-2020. Appendix III summarises the detailed simulation parameters.

This study used the potential air temperature (PAT) to analyse the average air temperature in the environment [Li, 2015] and mean radiant temperature (MRT) to evaluate the impacts of the microclimate on human thermal comfort [Huttner et al., 2008]. MRT is the *"uniform temperature of an imaginary environment in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual environment"* [Li, 2015]. Hence, it is considered the most crucial factor regulating human energy balance, particularly on warm days [Thorsson et al., 2006].

The simulation results from the first and second scenarios influenced the urban form modification of the third or last scenarios. Whereas the materials identified and reviewed from The Placemaking Principle II [GCC, 2018b] and the Avenues draft proposals [Civic Engineers, 2021] were simultaneously assessed for the streetscaping proposal. These streetscaping materials were modelled in ENVI-met within a domain size of 60 × 60 × 20 and a resolution of 3m × 3m × 3m using Glasgow's meteorological conditions to assess how these elements perform in the site. The base case was set to H/W=0.8 to represent the typical aspect ratio estimated in the focus areas (Fig. 4.9). While the albedo values of the materials were reviewed from published studies and inputted under ENVI-met Database Manager.

In parallel with the SDF's densification plan and the evaluation of the Avenues streetscaping materials, assessment criteria (Table 3.5) were developed to justify the modification for the proposed scenarios.

Table 3.5 *Urban form modification assessment criteria.*

Reference	Benchmark	Measure	Description
CFD Simulation	UHI Hotspot	Fig. 4.27 and 4.28	Building forms and streetscaping in areas with substantially high temperature were taken into higher consideration compared to zones with lesser heat concentration.
Urban Geometry	Aspect Ratio and SVF	Fig. 4.9 and 4.10	Urban blocks with relatively low aspect ratios and high SVF values were regarded to conform with the city centre intensification strategy.
Albedo Value	Albedo Values of the Proposed Materials in the Avenues Project	Table 4.11	The more reflective a surface is, the higher the albedo value. In contrast, dark-coloured surfaces have a low albedo and tend to contribute to the UHI. The use of light-coloured materials is recommended to aid local-scale heating [Hulley, 2012]. The materials in Table 4.11 were sourced from the master plan of Argyle Street West redevelopment [Civic Engineers, 2021].
Building Research Establishment (BRE) Report Site Layout for Daylight and Sunlight [Littlefair, 2011][2]	Solar Geometry and Overshadowing	Table 4.10 and Appendix V[3]	The BRE guide suggests that where structures are proposed, which may affect the neighbourhood, it is relevant to plot the shadow locations at different times of the day on 21 March (spring equinox). The shadow range calculation has been carried out at hourly intervals throughout the day from 7:00 to 17:00. This is because the longest shadow occurs during the early morning and late afternoon. Solar geometry was analysed to determine the proper orientation of buildings to maximise passive solar gain.

[2] The BRE guide sets out relevant criteria for measuring the impacts on existing buildings and neighbouring properties to achieve high-quality new development. However, the thesis focuses on a micro-scale urban area rather than individual buildings. Likewise, at high-density developments, obstruction to other structures or having poor orientations are unavoidable. Therefore, the following are criteria that were given less consideration due to the scale of the proposed development being larger than the established development in the document: (1) Average daylight factor, (2) vertical sky component method, (3) 45-degree rule of thumb, and (4) 25-degree rule of thumb. These measures could only be assessed through detailed site surveys.

[3] Although the spring equinox is a suitable date for assessment, an overshadowing valuation has also been carried out for the summer solstice (21 June) and winter solstice (21 December) to illustrate the effects of the development throughout the year. The assessments have been carried out at hourly intervals between 07:00 and 17:00 for March, between 07:00 and 18:00 for June, and between 10:00 and 14:00 for December [London Legacy, 2012].

SDF and Placemaking Principles [GCC, 2018a; GCC, 2019a]	Heritage Assets	Fig. 4.1	Listed buildings and conservation areas are part of the statutory designations covering aspects of Glasgow's built fabric. Therefore, the prevailing context height of urban blocks dominated by heritage buildings should be safeguarded. Buildings of 1.5 times the context height may be appropriate.[4]
Glasgow Development Policies and Design Guidance [GCC, n.d.-e]	Height and Scale of Surrounding Buildings	Fig. 4.18[5]	New development should ensure that the height, form, scale, orientation, and proportions do not detract the surrounding buildings and wider area to conform with the local context.
Forecasts Data [Weather Online, 2021; UBDC, 2021b]	Wind Direction	Appendix IV	The prevailing wind direction, which is from the south-west, was taken into consideration for the orientation and shape of buildings.
	Weather Type	Appendix IV	The Met Office forecasts data observed in 2018-2020 indicates that the prevailing weather types in Glasgow are cloudy and overcast. These two dominant typologies suggested that new developments should benefit from the visible sky to the greatest extent.
EIIPR Communication Plan: Design and Consultation [Ironside Farrar, 2019; Civic Engineers, 2021]	Feedbacks and Comments from Stakeholders	Section 4.2.3 and Appendix II	To reinforce community input, promote a greater sense of ownership, and allow the locals to have greater influence over their environment [GCC; 2018a]. However, the factors that offer minimal improvement to the micro-climate, such as street furniture specifications, were given less attention in producing the alternative proposal for the streetscaping scheme.

The proposed scenarios, while conforming to the criteria, also acknowledge the SDF's densification initiatives. This strategy could be analysed through FAR and building coverage ratio (BCR). The FAR is a measure of the total building floor area in relation to the total lot area (Eq. 3), while BCR is the percentage of the building area divided by the land area (Eq. 4) [Designing Buildings, 2021]. A graphical representation of these measures is shown in Fig. 3.5 to better understand the relation between FAR and BCR.

$$FAR = \frac{\text{total floor area}}{\text{site area}} \qquad (3)$$

$$BCR\ (\%) = \frac{\text{building area}}{\text{site area}}\, x\ 100 \qquad (4)$$

[4] Context height ratio (CHR) is the proportion of the height of a tall building to the prevailing contextual height [Urban Initiatives Studio, 2019].

[5] The height maps in Fig. 4.18 provide a strategic understanding of the typical heights in the city centre and do not represent the actual building heights in storeys.

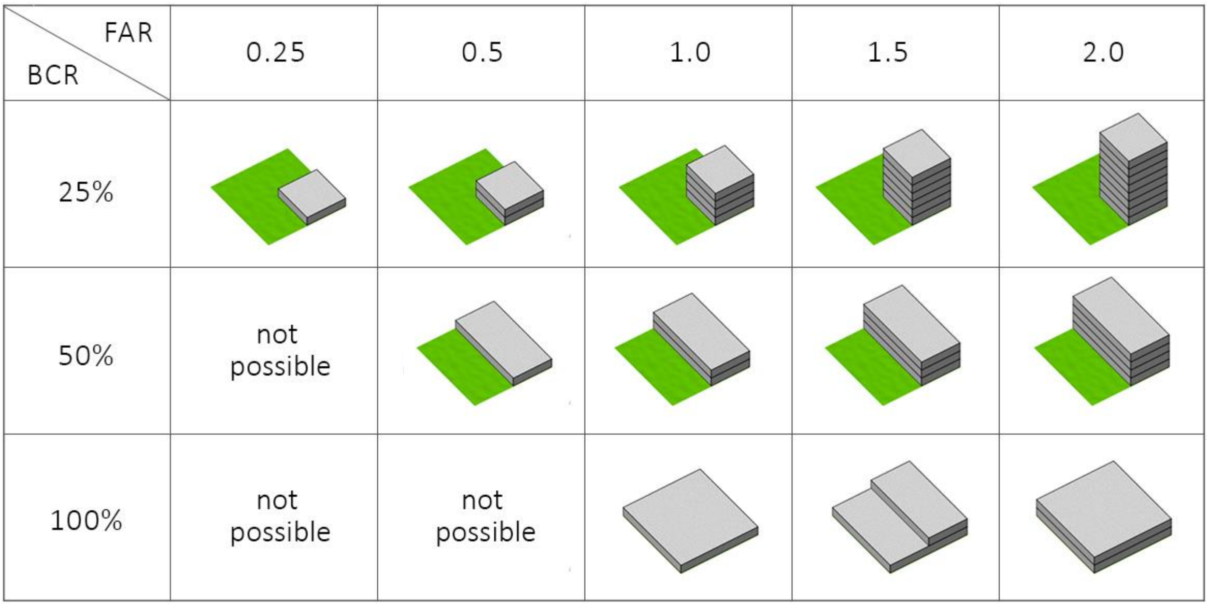


Figure 3.5 *Comparison of FAR and BCR. Source: Lee, 2019.*

3.5 Data Collection

Listed in Table 3.6 are the data that were collected and used for the above sections. All the vector and raster data used the British National Grid (BNG) as their coordinate system. The files with unknown coordinates were manually projected to BNG using Projections and Transformations under Data Management tools.

Table 3.6 *Data Collection.*

Data	Format	Provider	Date	Description / Processing Details
1m Spatial Resolution LiDAR Digital Surface Model (DSM)	Raster (.asc)	UBDC and Airbus Defence and Space Ltd.	2012	Using ArcGIS, the files were converted from ASCII text files to raster datasets and were merged using the Mosaic tool. The building heights were calculated by subtracting the DTM from DSM using the Raster Calculator.
1m Spatial Resolution LiDAR Digital Terrain Model (DTM)	Raster (.asc)	UBDC and Airbus Defence and Space Ltd.	2003	The conversion and merging were done the same with the DSM. The raster layer's base height was set to define the terrain elevation in 3D. The resolution was adjusted to 3000 rows by 4000 columns to improve its performance.

30m Spatial Resolution Landsat 8	Raster (.tif)	USGS Earth Explorer	2020	The land surface temperature (LST) is the "*skin temperature of the land surface*" [Jeevalakshmi et al., 2017]. The LST was estimated using the Raster Calculator in ArcGIS. Band 10 was used in estimating the brightness temperature, while bands 4 and 5 were used in calculating normalized difference vegetation index or NDVI (Fig. 3.6). The satellite images were acquired on 29-05-2020 at 11:15 and has a cloud cover lower than 10%.
Listed Buildings and Conservation Areas	Vector (.shp)	Glasgow GIS ArcGIS Online	2020	The polygon shapefile of the listed buildings was converted into points and was interpolated using the Kernel Density tool to create a heatmap.
Met Office Hourly Observations Data 2018-2020 (Meteorological Data)	Excel (.csv)	UBDC and Airbus Defence and Space Ltd.	2021	The raw figures were delimited in one cell per each observation. In order to split the data into separate fields, the texts were converted to columns using Text to Columns Wizard. This document was essential in getting the mean temperature, wind direction, wind speed, relative humidity, and weather type in Glasgow from 2018 to 2020.
Glasgow Air Quality PM_{10}	Excel (.csv)	GCC Open Glasgow Data Portal	2012	The monitoring station, Glasgow Kerbside, is positioned on the pavement of Hope Street adjacent to Glasgow Central Station.
Master Map	CAD (.dwg) Vector (.shp)	EDINA Digimap Ordnance Survey Service	2020	The ordnance survey (OS) master map provides accurate street and road dimensions, building outlines, street furniture location, and other infrastructure, necessary for this research. Scale 1:1250, Tiles: GB.
Master Map Building Height Attribute	CAD (.dwg) Excel (.csv)	EDINA Digimap Ordnance Survey Service	2019	Building heights were corrected using LiDAR DSM since the master map contained some minor errors with building elevations. The updated file was utilised in SkyHelios, SketchUp, Autodesk Revit, and ENVI-met for analysis, modelling, and simulation. Scale 1:2500, Tiles: ns56se, ns56ne, ns66sw, and ns66nw.
Contour lines	CAD (.dwg)	Schwarz Plan	2020	The 2D file was extruded using Autodesk Revit in order to view the contour in 3D.

Geometry of Model Environment	Area Input (.inx)	N/A	2021	The author used the ENVI-met INX SketchUp plug-in in creating model areas. This was done by inputting the necessary information to run the simulation (these are Glasgow's coordinates, horizontal and vertical grid layout, cell size, and the number of cells) and designating the materials for soils, 2D and 3D plants, and buildings. The model areas were then exported to .inx files for it to be able to run in the ENVI-met software.
SVF of Existing and Proposed Urban Form	Collada (.dae)	N/A	2021	The building models from Autodesk Revit were exported as a Collada file since it is compatible with the SkyHelios software.

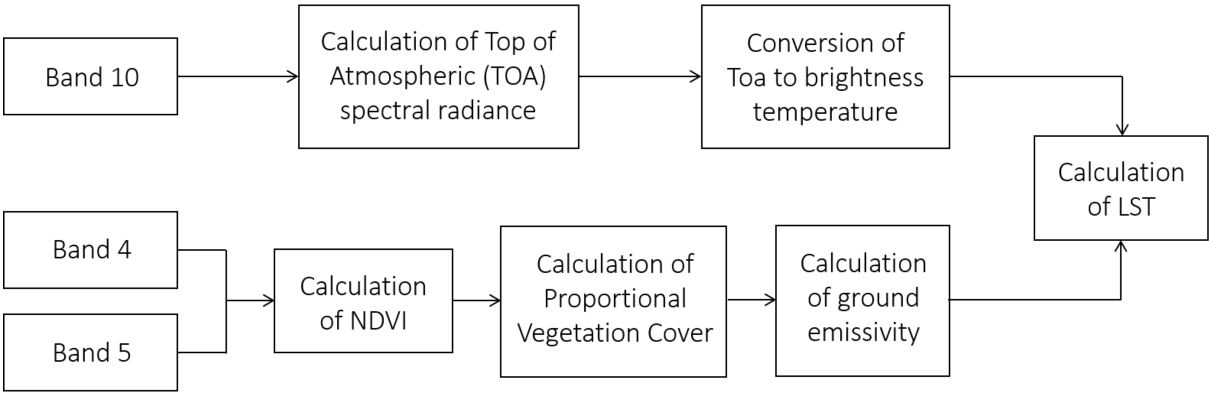


Figure 3.6 *Flow diagram of LST calculation in ArcGIS. Source: Jeevalakshmi et al., 2017.*

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Document and Data Review

The literature reviewed from The Scottish Government and GCC policies offered a more comprehensive understanding of Glasgow's strategic action plans in developing its public realm. The guidelines about appropriate street designs set out in these documents, however, are included in Appendix I so as not to disrupt the structure of the dissertation. The information contained here are essential points to consider in the proposal of new street designs, but these do not concern the general theme of this research.

4.1.1 City Centre's Spatial Development Strategy

Part of the SDF is to densify and re-populate the centre, reduce car dependency, improve public transport, enhance the urban fabric, and strengthen the city's unique heritage and character. With regards to bringing more people into the city centre, improving its place quality will be a challenge as it will require greater infrastructure, which might lead to environmental degradation. Thus, a high-quality public realm is fundamental in developing the social, environmental, and economic value throughout the city core. Moreover, the city council plans to reduce car journeys in the centre by 50% by 2050 to assist in improving the quality of the surrounding and create more space for the pedestrians and cyclists, making the Avenues project's goal more viable [GCC, 2017; GCC, 2018a; GCC, 2019a].

On the other hand, all building projects should employ mitigation and adaptation strategies to limit their impacts on the surrounding. The following should be considered for new developments [GCC, 2019a]:

- **Individual Buildings** – scale, performance, envelope, and natural place-based solutions
- **Building on the Immediate Area** – sunlight and daylight analysis
- **Buildings on the Wider Environment** – urban microclimate, wind patterns, south-westerly winds, sun path, and UHI

The city centre showcases many heritage buildings creating an attractive cityscape. Although the council encourages planners to demonstrate innovation in new developments, it is still vital that traditional buildings are protected and revived to display Glasgow's distinctiveness. Therefore, a successful integration of old and new buildings should be considered to enrich the city centre's character [GCC, 2019a; GCC, n.d.-c].

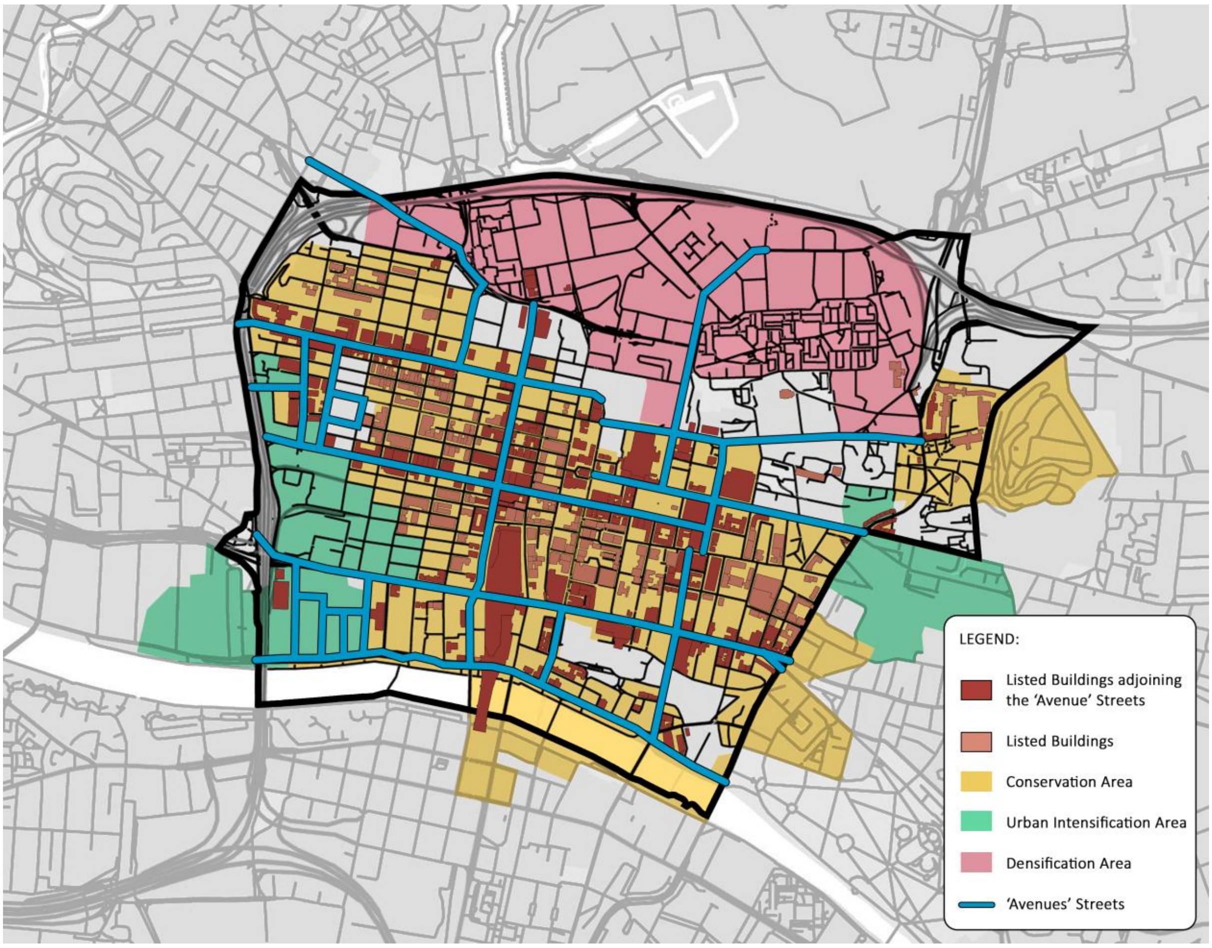


Figure 4.1 *Conservation, intensification, and densification areas. Source: Adapted from GCC, 2019a.*

Building height and scale vary across the city centre – buildings on the hilltop areas have established heights of 3 to 5 storeys, whereas those in the commercial core has chiefly mid-rise heights of 6 to 9 storeys [GCC, 2019a]. Hence, a building that exceeds these will visually impact the city centre's skyline and will create a detrimental effect on urban morphology. The SDF does not have any specific policies on tall buildings; however, it sets out general planning principles relevant to the development of high-rise buildings. The council has identified suitable sites for taller buildings to comply with the policy. The map in Fig. 4.1 presents the allocation of development areas as proposed by the SDF. The distribution of each zone is described below [GCC, 2019a]:

- **Urban Intensification Area** – suitable for buildings of scale due to its larger blocks and wider streets and its opportunity for innovative urban infill.

- **Conservation Area** – presents the opportunity to use additional height, but existing context should be respected.

- **Densification Area** – should seek to rebuild and define the built environment of the fragmented area through tenemental human-scale buildings.

If this allotment does apply, then the urban intensification and densification areas should require a more comprehensive policy as these will be the major sites for the GCC's proposal to double its population by 2050. This research could, however, provide a more accurate distribution of building scale, mass, and height within these boundaries, as well as determine the necessary development within the conservation area. Linking this with the existing building heights seen in Fig. 4.2, it could be observed that there are many opportunity areas within the urban intensification zones. Zone A consists of medium- to high-rise buildings with a few low-rises. It is feasible to build higher than the existing structures as it will not disrupt the city's skyline since it is located in the peripheral area of the city centre. Correspondingly, the SDF plans to expand the International Financial Services District (IFSD), encompassing the whole Zone A. The IFSD will deliver a combination of mixed-use development and public social spaces. Zone B has more opportunity because it has lesser structures at present. Also, the local government aims to increase the residential population in both zones. On the other hand, Zone C will need to retain its low-rise feature not to affect the city skyline since being located on a higher elevation [GCC, 2019a].

Figure 4.2 *Existing building heights in Glasgow city centre. Source: Airbus Defence and Space Ltd; University of Glasgow – UBDC, 2003; DSM created using high resolution satellite data from 2012.*

4.1.2 Streetscape Transformation

The local government aims for the public realm to make it liveable, vibrant, and sustainable. Accordingly, the Avenues programme introduces an integrated infrastructure to encourage sustainable modes of transport and improve the streets' perception in order to draw people into the centre. Apart from the city's historic environment bearing in mind, it is fundamental to comprehensively assess the surroundings and site boundary of any newly proposed street designs and buildings to fully understand how the development will respond to its environment, address wider concerns, and meet the areas' needs. Moreover, it should reinforce community input to promote a sense of ownership and allow people to have greater influence over their environment. Although as mentioned in Chapter 3, community engagement could not be performed due to Covid-19 restrictions. The EIIPR Communication Plan [Ironside Farrar, 2019] otherwise provided an insight into the stakeholder's needs. Appendix II summarises the key local stakeholders and approaches that were carried out. The consultation meticulously targeted key users and facilitated concerns specific to their needs and requirements. Therefore, the Avenues streets vary in accordance with their composition, context, nature, and users' necessities [GCC, n.d.-a; GCC, n.d.-d]. It should be mentioned that the acquired communication plan is not explicitly directed to the two focus areas, rather to other Avenues' streets. However, the information was sufficient in understanding the whole idea of the programme, as well as the stakeholders' remarks. These are outlined in Section 4.2.3.

Although the thesis focuses on the physical aspect of the streets, the community engagement report mainly emphasised the stakeholders' transportation demands, like modes of transport, numbers of vehicles, cycle parking spaces, and on-street and off-street delivery access. While these do not relate to the thesis topic, they can be derived into more concrete features such as the need for cycling spaces, roadway space reduction, wider footpaths, and provision of greeneries.

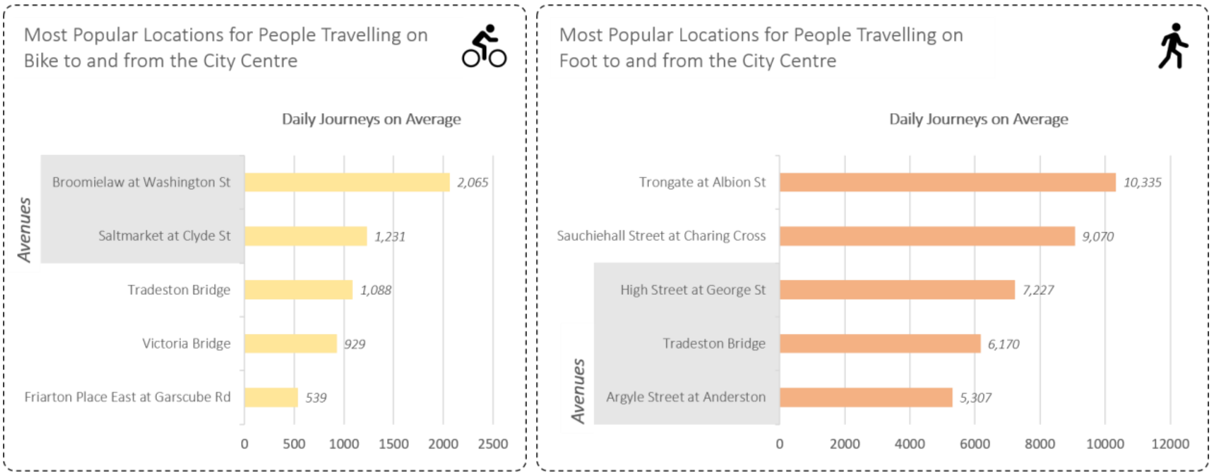


Figure 4.3 *Most popular streets for cycling and walking to and from the city centre. Source: GCC, 2018c.*

Moreover, one of the Avenues programme goals is to *"introduce an integrated network of continuous pedestrian and cycle priority routes"* [Ironside Farrar, 2019]. According to the data collected by the GCC [2018c], cycle journeys to and from the city centre has increased by 111% from 2009 to 2018. Based on the statistics, *"there were 5,712 journeys by bike into the city centre on average each day with a total number of 11,000 journeys in and out of the city centre on a daily basis".* Also, nearly 53,000 people enter the city centre on foot on average each day, totalling 102,972 journeys in and out of the city centre daily. Fig. 4.3 shows the most common streets for people going on bike and foot to and from the city centre. Among the nine locations, five of which are involved in the Avenues programme. These counts clearly highlight the need to enhance the city's cycling infrastructure and walkways, thereby reducing motor vehicular access.

4.2 Street Selection

In order to provide extensive research about the topic, the focus of study was narrowed down to two streets. It should be understood that the proposal may or may not apply to the remaining Avenues streets because planning schemes are place-specific and that there will be variances in design strategies for all streets regardless of having a similar environment. The four criteria in choosing the two streets, as mentioned in Table 3.3, are:

- Orientation
- Vehicular access
- Occurrence of air quality deterioration
- Presence of old and new buildings

The first two criteria were determined by simply using a web mapping service (Google Maps). Regarding the third criterion, Friends of the Earth Scotland [2020] ranked Hope Street as the most polluted street in Scotland. As seen in Fig. 4.4, the area surpasses the legal limits of 40 µg/ m³ NO_2 and Air Quality Strategy (AQS) objective of 18 µg/ m³ PM_{10} concentration for multiple consecutive years. Aside from Hope street's huge traffic volumes, the narrowness of the street and tall buildings created an urban canyon effect, contributing to the emergence of UHI. Fig. 4.5 shows a heatmap of air pollution zones, i.e., air quality deterioration, wherein St Vincent, Hope, Sauchiehall Precinct, and the central part of Argyle Street demonstrate high toxic air levels.

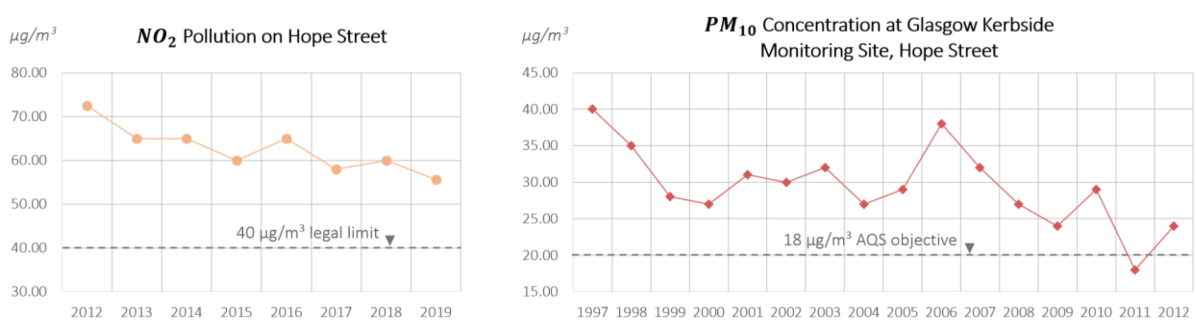


Figure 4.4 *Yearly average nitrogen dioxide pollution (left) and PM_{10} concentration at Hope Street (right). Source: Glasgow Live, 2020; GCC Open Glasgow Data Portal, 2012.*

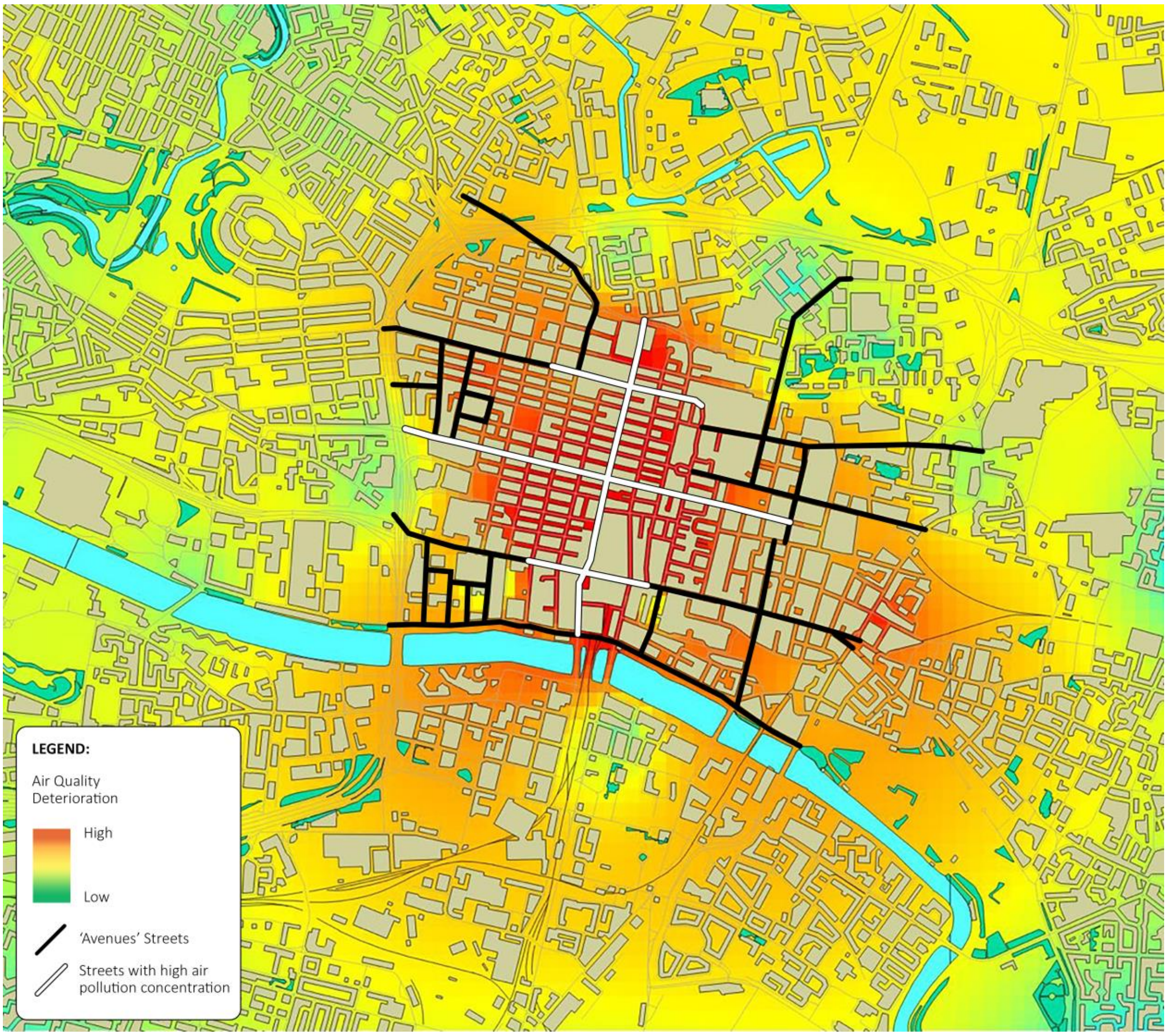


Figure 4.5 *Air pollution concentration within Glasgow city centre. Source: OK Scotland, 2015.*

The last criterion is the presence of old and new buildings. ArcGIS was used to map the listed buildings within the city centre, which was acquired from GCC GIS Data [Glasgow GIS, 2020]. The author created shapefiles for each listed building adjoining the Avenues streets. Using the kernel density under the spatial analyst tool, a heatmap, i.e., building density, was produced to analyse the magnitude of listed buildings along the 17 streets (Fig. 4.6). The following are the areas where a vast number of listed buildings are present:

- Elmbank Street (a)
- Sauchiehall Street between M8 motorway and Douglas Street (b)
- St Vincent Street between Pitt Street and Queen Street (c)
- Hope Street between Waterloo Street and West Regent Street (d)
- John Street between Ingram and George Street (e)
- Argyle Street between Glassford street and High Street (f)

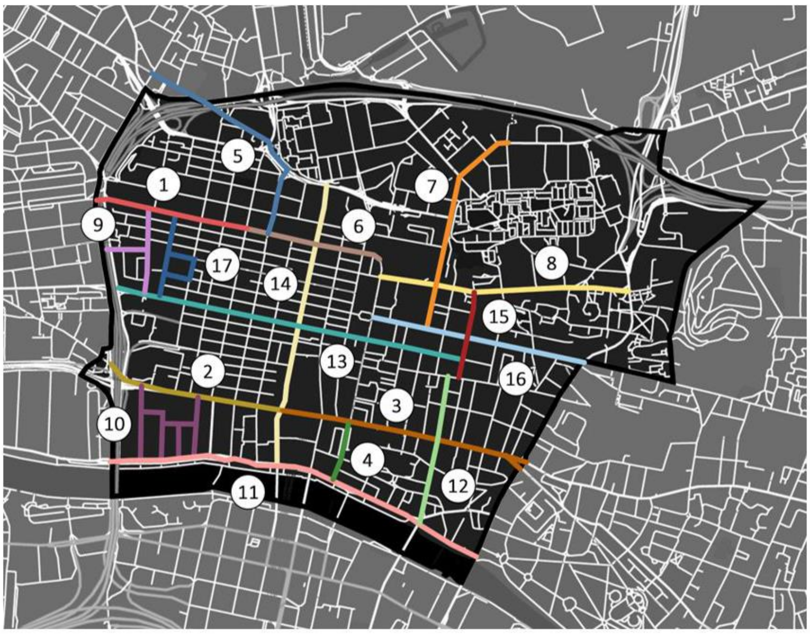
Evidently, St Vincent Street has the highest number of old buildings. But this basis made the area unfit for the street selection since there is not enough room for urban form modification. On the other hand, Hope Street does have accumulated old buildings in the centre, but the north and south parts only have a few.

Figure 4.6 *Heatmap of listed buildings along the 17 Avenues streets.*

Table 4.1 summarises all the bases in choosing the two streets. The two selected streets are Argyle Street West (between M8 and Hope Street) and Hope and Oswald Streets. The fact that a considerable portion of the streets lies next to the River Clyde gave prominence to these focus areas. This dissertation, although centred on the effects of urban morphology and streetscaping, further comprehended the influence of the river in the microclimate and its cooling effect on the south side of the centre, in comparison with the more closely packed buildings as it moves north. This finding can be apprehended as the thesis progresses. The following sections give a more detailed justification to the two chosen streets, while Section 4.2.3 presents an outline of the proposed street improvements.

Table 4.1 *Summary of the 17 Avenues Streets.*

Street Number	Street Name	Legend	Listed Buildings	CA	I / D	VA	O
1	Sauchiehall Street Pilot Project		28	●		Y	E-W
2	Argyle Street West: between M8 motorway and Hope Street		7	○	I	Y	E-W
3	Argyle Street East: between Hope Street and High Street		38	●		Y / N	E-W
4	Dixon Street and St Enoch's Square		7	●		N	N-S
5	The Underline: including New City Road and Cambridge Street		4	○	D	Y	N-S / E-W
6	Sauchiehall Street Precinct: between Rose Street and Buchanan Street		12	●		N	E-W
7	North Hanover Street and Kyle Street		2		D	Y	N-S
8	Cathedral Street		4	○	D	Y	E-W
9	Elmbank Street and Elmbank Crescent		17	○	I	Y	N-S / E-W
10	International Financial Services District (IFSD)		5		I	Y	N-S / E-W
11	Broomielaw and Clyde Street		8	○	I	Y	E-W
12	Stockwell Street and Glassford Street		9	●		Y	N-S
13	St Vincent Street, St Vincent Place, and Cochrane Street		66	○	I	Y	E-W
14	Hope Street and Oswald Street		28	●		Y	N-S
15	John Street		10	●		N	N-S
16	George Street		14	●		Y	E-W
17	Holland Street and Pitt Street		6	○	I	Y	N-S / E-W



Legend:

CA Conservation Area
I Intensification Area
D Densification Area
VA Vehicular Access
O Orientation

Y/N Yes / No
N-S North-South Orientation
E-W East-West Orientation

● Whole street is part of the CA
○ Whole street is NOT part of the CA

4.2.1 Argyle Street West

The street comprises modern buildings with a few listed ones. This area is suitable to conduct an experiment because a major part of it lies in the urban intensification zone (Fig. 4.1), which implies that this part of the city centre can be developed with greater density and scale, define the IFSD, and give opportunity for urban infill. The west part, near the M8, characterises a less historically sensitive urban area. However, the eastern portion of the street is contained in the conservation area, giving more restriction in modifying the urban form, but offering a wider understanding about varying street and building configurations.

4.2.2 Hope Street and Oswald Street

There are many rationales why Hope Street was selected. Aside from being identified as the most polluted street in Scotland in terms of air quality, its urban fabric is mainly composed of historic buildings, narrow thoroughfare, and on-street parking. And since the majority of Hope and Oswald Street is part of the conservation area, conducting research in these two particular streets was a challenge due to its limited opportunity and capacity. However, achieving this established new learning in implementing urban form modification and streetscaping to cities with similar composition.

4.2.3 Draft Proposals

The consultation and community engagement report acquired from the GCC City Centre Regeneration Team addressed the need for significant improvement in the streetscape's quality of place and functionality. The draft plan in Fig. 4.7 presents an adaptation of the street layouts and design elements. The Argyle Street West's actual detailed plan and specifications are not shown because not all drawings are finalised and presented in the public domain yet [Buchanan, 2021]. Thus, Fig. 4.7 was modified so as not to reveal this information. On the other hand, some of the 17 Avenues street plans have not been completed yet, and two of these are Hope and Oswald Streets. But in order to fulfil the objective of this dissertation, the available Avenues street proposals[6] [GCC, 2019b; GCC, n.d.-f] were reviewed, integrated, and methodically assessed to help the author establish a plan for Hope and Oswald Streets. For instance, the layout for Stockwell Street was chosen as an alternative for Oswald Street since both have similarities in terms of proximity to the river, orientation, and dominance of bus services. Whereas the layouts for Sauchiehall and Argyle Streets were taken into consideration to be fully integrated with Hope Street. This will allow the latter to tie more closely to Sauchiehall and Argyle Streets' characters. Due to the place-specific initiatives of the Avenues programme, the plan for Hope and Oswald Streets presented here should not be deemed official.

[6] The available Avenues streets that were beneficial to the establishment of Hope and Oswald Streets are Stockwell and Glassford Streets, Sauchiehall Street Precinct, and Argyle Street West (see Table 4.1 for street locations). Some of their visualisations can be viewed here: https://www.glasgow.gov.uk/avenues.

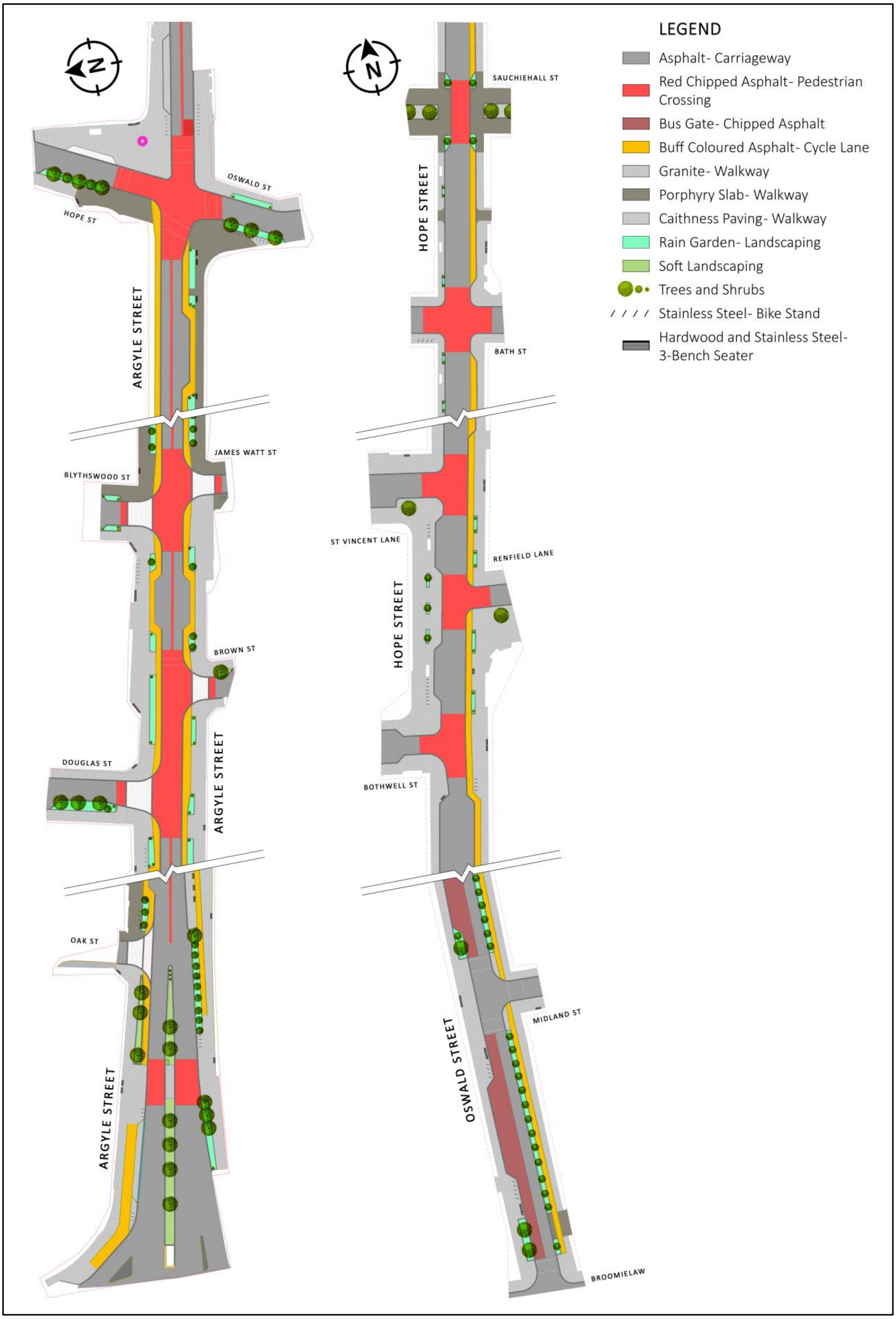


Figure 4.7 *Argyle Street West draft plan (left) and unofficial plan for Hope and Oswald Streets established by the author (right). Source: Civic Engineers, 2021; GCC City Centre Regeneration Team, 2021.*

With regards to the draft plans, people were supportive of the street appearance, cycle and walking facilities, traffic movement, and the overall proposal. However, there were some concerns regarding its useability. For instance, the demand for segregated cycle lanes and the lack of road space leading to traffic congestion, further matters are highlighted in Table 4.2. Although segregated cycle lanes effectively secure the welfare of cyclists, these cannot be achieved in all streets due to lack of spaces. In contrast, reducing the roadway dimension could protect cyclists from possible accidents because it rationalises the area as a place for people rather than cars, influencing drivers to reduce vehicle speed [The Scottish Government, 2010]. On the other hand, this strategy disregarded the people's demand for wider road space. This situation manifests conflicting factors between what society needs and what the government implies. Eventually, the need for road space reduction surpasses this matter because, after all, the SDF aims to lessen car dependency, which can benefit people in the long run.

The consultation outcomes recognised the modes of transport within the centre. In order of participants' preferences, these are bicycle, public transportation, private cars, and walking. Ranking walking as the least favoured mode of transport indicated the need for *"significant improvement in the quality of place and functionality of the streetscape"* [Ironside Farrar, 2019]. Hence, a better walking experience that can be apparent through efficient sidewalk materials could enhance this.

Table 4.2 *Relevant comments and suggestions by the stakeholders. Source: Ironside Farrar, 2019.*

	Comments	Suggestions
Proposed Street Appearance	It will create a more welcoming environment, especially that the current condition desperately lacks green spaces and activities.	Consider relocation of bus stops and the use of lighter coloured stone paving.
Proposed Cycle and Walking Facilities	It will create a positive environment and experience for pedestrians and cyclists, encouraging them to use the proposed infrastructures.	It should have segregated cycle lanes to provide better protection for cyclists. The lack of a two-way cycling connection limits its benefit significantly.
Traffic Movement	The reduction of traffic lanes might lead to a huge increase in congestion due to a lack of road space. Also, the change of materials at the intersections could be confusing and dangerous.	The continuous footway needs to be clearly signed so that drivers understand that it is a pedestrian-priority space.
Proposal as a Whole	The use of street trees, rain gardens, and the possibilities for covered bike parking are highly favoured. But although the overall proposal looks nice, it will hardly discourage private vehicle use in the city centre, which means bold steps are required to significantly reduce the use of motorised vehicles.	NA

Argyle Street is a key arrival zone to the city from the west. Thus, motorised vehicles dominate the area, especially during peak hours. The draft proposal, as shown in Fig. 4.7, could be further improved by increasing the vegetation cover, especially near the M8, to reduce air pollution caused by passenger vehicles.

Regarding the segregated cycle lanes as suggested by local stakeholders, this could be done in a sustainable approach by placing planting strips or urban swales[7] between the road and cycle lanes. But of course, it will depend on the availability of space as Glasgow city centre have a few narrow thoroughfares, especially in the conservation zone.

For Hope Street, there appears to be an allocation of on-street parking during the day. Considering that the area is already too narrow, this should be prevented. Because Hope and Oswald Streets accommodate a large number of bus services, the proposal should focus on pedestrian/bus user comfort to improve accessibility. Likewise, an additional traffic lane intended for bus bays is essential. Lastly, Oswald Street should introduce soft planting and sustainable urban drainage because, according to the City Deal City Centre EIIPR [GCC, n.d.-d], surface water flood accumulates in this area.

4.3 Fieldwork

4.3.1 Baseline Study

The national lockdown restricted the baseline study's extent to the streets' physical environment and only a little account of its social context. Regarding the presence of individuals, Hope Street has the most passers-by; this could also explain its location being near the commercial and retail areas. Next is Argyle Street West, then the least used is Oswald Street. This analysis, however, is still subjective to the current situation and should not entirely be the basis of the study areas' social environment. A summary of the observations is presented below in the form of a SWOT analysis.

Table 4.3 *SWOT Analysis.*

Argyle Street West	
Strengths	**Weaknesses**
The street houses multiple mixed-use developments, providing more flexibility in terms of building scale and mass. Some city blocks have broad pedestrian walkways which are wide enough to make way for street design elements. The presence of various new developments along the street manifests the idea of creating a more desirable neighbourhood.	The area presents a fragmented cycling network, which impedes the promotion of sustainable travel modes. The street is car-dominated as it serves as a gateway for vehicles coming from the M8. There are a few greeneries in the west (near the M8 motorway) and some street furniture in the east (near Hope Street). This layout created disconnection throughout the area as it displays a disintegrated street design.

[7] Urban Swale is a shallow channel designed to collect stormwater from hard surfaces [Local Action, n.d.].

Opportunities	Threats
It presents more flexibility in modifying the urban form since being located in the intensification zone. The wide street canyon will give adequate space for streetscaping, creating a balanced approach to vehicles, pedestrians, and cycle networks. The redevelopment within this area could expand existing residential communities and create new ones. Increasing the residential population will improve safety and security through increased levels of activity. The street consists of several old buildings which are not included in the list of protected infrastructures, giving more available sites for development.	The River Clyde is the city's most underutilised yet essential asset. According to the SDF, it currently suffers a degree of disconnection from the centre. The redevelopment of Argyle Street may aggravate this condition if caution and sustainable planning are not observed. For instance, the construction of high-rise buildings could block the view of the river from the centre. Because of its proximity to the M8, air quality within this area could deteriorate once all building constructions are completed. The area bordering the M8 could cause the pedestrians' feeling of unsafeness, affecting their use of the street features, even after redevelopment materialises.
Hope Street	
Strengths	**Weaknesses**
The whole stretch of Hope Street showcases a rich architectural heritage. High priority should be given to this area because successfully redeveloping it would repair, restore, and enhance the urban fabric, which is part of the six strategic place ambitions of the SDF. The height and scale of buildings and the careful use of materials respected the city centre's neighbouring structure, urban fabric, and urban morphology. The northern part of Hope Street, between Sauchiehall Street and Cowcaddens Road, showcases modern buildings and a wider street, giving adequate space for redeveloping the area.	A high number of public transport passes Hope Street throughout the day, which is why busses and other motorised vehicles gained such dominance in the area. Displays excessive on-street parking and taxi queue congestion, making the street look crowded. The narrow thoroughfare gave less importance to pedestrian and more value to vehicles. This also corresponded to the absence of greeneries and street furniture since the area does not have enough space to allocate street elements. Road and pavement surfaces are not well maintained and are in poor condition.
Opportunities	**Threats**
Although Hope Street has a fragmented cycle lane, few cyclists could be seen using the area. It would be reasonable to improve the cycle network despite having a narrow street as it already demonstrates the likelihood of being utilised. Because most structures are listed buildings, this leads to a more constrained urban form modification strategy. However, it will give a broader opportunity to streetscaping. And if successful in eliminating the UHI in Hope Street, then it can accentuate the potentiality of streetscaping as an effective UHI mitigation strategy.	Because it lies in the conservation zone, caution should be made regarding the urban form modification to avoid impacting its historical aspect. Strategies should be highly regarded to prevent listed buildings from deteriorating and encourage redevelopment while maintaining their character. The lack of social activity within the area could lead to the street being unused even after redevelopment takes place. The narrow street could restrict its capability in showcasing good street design.

Oswald Street	
Strengths	**Weaknesses**
The fact that it comprises many unlisted buildings will not restrain the implementation of urban form modification in the area. Its proximity to the riverbank can imply strategic pedestrian routes to and from the River Clyde. Offers better air circulation caused by the wind blowing from the river. The existing character of the street is adaptable, and there is still much room for improvement.	The street currently suffers from a lack of hospitality industry, high-quality open spaces, greeneries, and street features, leading to a sterile environment. Only a few cyclists utilise the walkways as there is a lack of cycle network despite having a wide road. Oswald Street is characterised as a one-way with a four-traffic lane, yet two of which are ineffectively utilised by busses.
Opportunities	**Threats**
The wide street will give more opportunity for redevelopment as it offers ample space for streetscaping. The redevelopment of Oswald Street would reinforce the riverbank and bring its vibrance back. It would contribute positively towards sustainable urban regeneration. The whole stretch of Oswald Street is part of the IFSD. According to the SDF, this area should showcase a mix of uses and public social spaces. Complying with this strategy will further improve the surrounding.	Caution should be taken when modifying the building heights to avoid blocking the view of the River Clyde. Overdevelopment could negatively affect the river. Street signs govern the area, which is considered visually intrusive according to the Designing Streets. These traffic management measures give clear indications of priority to motorists rather than pedestrians. Instead, streets should be arranged in an intuitive approach to reduce the dominance of signs and street markings.
Sauchiehall Street Pilot Project	
Strengths	**Weaknesses**
The wide range of leisure and public social spaces encouraged social activities which reinvigorated the area. Presents active travel, connected cycle network, improved connectivity, adequate landscaping, reduced motorised vehicle use, and high-quality materials. The wide walkways indicated the area's priority to pedestrians rather than motorists. Bicycle lanes and other street furniture have adequate users despite the 'stay-at-home' order across the city.	Fragmented greeneries in the western part of the street, near the M8. Perhaps the liveliness of the street is only observable in the area near the Central – where the commercial and civic heart of the city lies. The vibrance subsides as it goes further west.
Opportunities	**Threats**
With an integrated approach to urban climate mitigation, the streetscaping could further respond to other environmental issues on a street scale.	Further enhancement should still balance out the characteristics of the area to prevent it from overpowering its local context.

Although some analyses are too specific and were not applied in the proposals, these are still beneficial for the planners and policymakers in Glasgow city centre in enhancing the urban fabric. The findings from the baseline analyses established a starting point for the streetscaping proposal. Fig. 4.8 shows the existing and proposed plans for the respective streets. Although these proposals were formed in coordination with the succeeding sections of this chapter, the author deliberately placed these visualisations before the final results as it corresponds with Section 4.3.1. However, the rationale for these visualisations can be further understood as the thesis progresses.

Figure 4.8 *Existing and proposed plans for Argyle Street West (above), Hope Street (middle), and Oswald Street (below). Source: Google Maps (left images); Visualisations by the author (right images).*

4.3.2 Traverse Study

A total of 16 measurements were taken throughout the traverse study. These were categorised according to the modified Pasquill–Gifford–Turner (PGT) classification system (Table 4.4), such as in studies like Drach et al. [2018]. The PGT classification system was based on *"qualitative estimates of solar insolation during the day and observations of cloud cover at night, in combination with wind speed measured at a height of 10 meters"* [Pasquill, 1961]. Because this system involves only standard national weather service observations, it has proven to be a practical and widely used approach [Hunter, 2012].

Table 4.4 *PGT atmospheric stability classes. Source: Pasquill, 1961; Gifford, 1961; Turner, 1970; Venkatram, 1996; Hunter, 2012; Kruger and Emmanuel, 2013.*

Wind Speed (m/s)	Day-time SR (W/m²)				Night-time CC (Oktas)		
	High[a]	*Mod[b]*	*Low[c]*	*Cloudy*	*Low[d]*	*Mod[e]*	*High[f]*
≤ 2	A	A - B	B	C	G - F	F	D
2 - 3	A - B	B	C	C	F	E	D
3 - 5	B	B - C	C	C	E	D	D
5 - 6	C	C - D	D	D	D	D	D
> 6	C	D	D	D	D	D	D

SR – Solar Radiation, CC – Cloud Cover, [a] (>600), [b] (300-600), [c] (<300), [d] (0-3), [e] (4-7), [f] (8).

- A – highly unstable or convective
- B – moderately unstable
- C – slightly unstable
- D – neutral
- E – moderately stable
- F – extremely stable
- G – extremely stable, low wind

The purpose of classifying the 16 meteorological data is to estimate the atmospheric effects on intra-urban temperature differences so that the effect of urban morphology on local climate can be assessed [Kruger and Emmanuel, 2013]. Table 4.5 shows the summary of these measurements. The wind speed and cloud cover data were obtained from the Weather Underground station [Wunderground, 2021]. In identifying the unit of measure for cloud cover (Okta), information acquired from the World Meteorological Organization [2021] was applied.

Of all the 16 traverse studies, only the most significant data were comprehensively assessed; these are 27th May (evening), 30th May (afternoon), and 31st May (evening). These dates demonstrated high temperature and R^2 value. R^2 is a statistical measure that describes how well the regression predictions approximate the actual data points. Therefore, a high R^2 (greater than or equal to R^2=0.8) indicates that the regression predictions most likely fit the data [Frost, 2021].

Table 4.5 *Summary of the 16 Traverse Studies.*

Date	Afternoon / Evening	Fixed Station Meteorological Data				R^2 Value	Wind Speed (m/s)	Cloud Cover[a]	PGT
		MIN	*MEAN*	*MAX*	*STDEV*				
07-May-21	Afternoon	11.86 °C	12.85 °C	14.24 °C	0.66 °C	0.34	5.28	Partly Cloudy	D
	Evening	9.35 °C	10.80 °C	13.21 °C	1.11 °C	0.94	4.72	Fair	E
11-May-21	Afternoon	13.83 °C	14.46 °C	15.25 °C	0.53 °C	0.79	5.28	Cloudy	D
	Evening	15.52 °C	15.94 °C	16.80 °C	0.34 °C	0.96	1.11	Fair	F
13-May-21	Afternoon	13.84 °C	14.44 °C	14.80 °C	0.26 °C	0.56	6.67	Mostly Cloudy	D
15-May-21	Evening	13.69 °C	14.88 °C	16.05 °C	0.79 °C	0.95	4.72	Fair	E
16-May-21	Afternoon	18.14 °C	18.92 °C	19.32 °C	0.34 °C	0.77	4.72	Partly Cloudy	C
	Evening	13.88 °C	15.21 °C	17.43 °C	1.15 °C	0.92	4.72	Fair	E
22-May-21	Afternoon	13.98 °C	14.79 °C	17.14 °C	0.72 °C	0.19	4.72	Partly Cloudy	C
	Evening	10.84 °C	12.01 °C	13.84 °C	0.80 °C	0.96	5.28	Fair	D
27-May-21	Afternoon	18.72 °C	19.78 °C	20.72 °C	0.67 °C	0.80	3.61	Partly Cloudy	C
	Evening	15.68 °C	16.50 °C	17.35 °C	0.51 °C	0.99	4.72	Cloudy	C
30-May-21	Afternoon	22.01 °C	22.67 °C	24.40 °C	0.59 °C	0.85	1.94	Cloudy	C
	Evening	19.26 °C	19.97 °C	20.52 °C	0.41 °C	0.98	3.06	Fair	E
31-May-21	Afternoon	23.89 °C	24.09 °C	24.60 °C	0.16 °C	0.30	6.11	Fair	D
	Evening	19.70 °C	20.44 °C	21.71 °C	0.59 °C	0.96	5.28	Fair	D

[a] *Definition: Fair=0-2 okta, Partly Cloudy=3-5 okta, Cloudy=6-7 okta, and Mostly Cloudy=8 okta. Source: World Meteorological Organization, 2021.*

Table 4.6 *Meteorological data of PGT Classes C, D, and E dated May 27, 31, and 30, respectively.*

	May 27, 2021 | 3:00 PM | R^2 = 0.80 C - Slightly Unstable			May 31, 2021 | 8:00 PM | R^2 = 0.96 D - Neutral			May 30, 2021 | 8:00 PM | R^2 = 0.98 E - Moderately Stable		
Points	T_{Fixed}	$T_{Traverse}$	ΔT	T_{Fixed}	$T_{Traverse}$	ΔT	T_{Fixed}	$T_{Traverse}$	ΔT
A	20.40 °C	24.04 °C	3.34 °C	21.63 °C	21.77 °C	1.16 °C	20.51 °C	20.95 °C	0.45 °C
A1	20.43 °C	24.53 °C	3.84 °C	21.46 °C	22.44 °C	1.83 °C	20.50 °C	21.12 °C	0.63 °C
B	20.39 °C	23.93 °C	3.24 °C	21.30 °C	23.06 °C	2.45 °C	20.46 °C	21.57 °C	1.07 °C
B1	20.47 °C	24.68 °C	3.98 °C	21.12 °C	23.90 °C	3.29 °C	20.41 °C	21.74 °C	1.24 °C
C	20.70 °C	25.06 °C	4.36 °C	20.93 °C	23.65 °C	3.04 °C	20.38 °C	21.72 °C	1.23 °C
D	20.59 °C	24.77 °C	4.07 °C	20.79 °C	23.26 °C	2.65 °C	20.35 °C	21.65 °C	1.16 °C
E	20.46 °C	23.85 °C	3.16 °C	20.67 °C	23.01 °C	2.40 °C	20.29 °C	21.63 °C	1.13 °C
F	20.42 °C	22.79 °C	2.09 °C	20.61 °C	22.81 °C	2.20 °C	20.22 °C	21.60 °C	1.10 °C
G	20.03 °C	22.88 °C	2.19 °C	20.53 °C	22.41 °C	1.80 °C	20.15 °C	21.50 °C	1.00 °C
G1	20.27 °C	22.79 °C	2.10 °C	20.45 °C	21.95 °C	1.34 °C	20.09 °C	21.26 °C	0.76 °C
H	19.69 °C	22.94 °C	2.25 °C	20.25 °C	21.66 °C	1.05 °C	19.95 °C	21.03 °C	0.53 °C
I	19.33 °C	23.24 °C	2.54 °C	20.15 °C	21.52 °C	0.91 °C	19.83 °C	21.00 °C	0.50 °C
J	18.95 °C	23.16 °C	2.46 °C	20.12 °C	21.50 °C	0.89 °C	19.75 °C	20.89 °C	0.39 °C
K	18.92 °C	23.17 °C	2.48 °C	20.00 °C	21.49 °C	0.88 °C	19.70 °C	20.89 °C	0.39 °C
L	18.83 °C	22.79 °C	2.10 °C	19.94 °C	21.46 °C	0.85 °C	19.65 °C	20.91 °C	0.41 °C
M	18.80 °C	22.56 °C	1.86 °C	19.89 °C	21.39 °C	0.78 °C	19.59 °C	20.84 °C	0.34 °C
M1	19.17 °C	22.54 °C	1.84 °C	19.85 °C	21.46 °C	0.85 °C	19.49 °C	20.86 °C	0.37 °C
N	19.29 °C	22.81 °C	2.11 °C	19.79 °C	21.52 °C	0.91 °C	19.40 °C	20.91 °C	0.42 °C
N1	19.25 °C	22.85 °C	2.15 °C	19.74 °C	21.52 °C	0.91 °C	19.33 °C	20.96 °C	0.47 °C
O	19.15 °C	22.15 °C	1.45 °C	19.71 °C	21.58 °C	0.97 °C	19.28 °C	20.99 °C	0.50 °C

Table 4.6 presents the obtained measurements, both from the fixed station and traverse, at each 20 locations, as shown in Fig. 3.3 and 4.9. The $T_{Traverse}$ defined here is the corrected air temperature, as explained in Section 3.4.5. A completed table showing additional meteorological data can be reviewed in Appendix VI. The equation for acquiring the air temperature difference (ΔT) is shown in Eq. 5.

$$\Delta T = T_{Traverse} - T_{Fixed\ Station} \qquad (5)$$

where:
ΔT = air temperature (T_{Air}) difference
$T_{Traverse}$ = traverse T_{Air}
$T_{Fixed\ Station}$ = fixed station T_{Air}

Eq. 5 functions as a proxy of the UHI intensity formula (Eq. 6) since meteorological data from the rural area is not obtainable. For the purpose of this study, the difference of $T_{Fixed\ Station}$ and $T_{Traverse}$ is termed either intra-urban air temperature differences or local UHI.

$$\Delta T_{u-r} = T_u - T_r \qquad (6)$$

where:
ΔT_{u-r} = UHI intensity
T_u = urban T_{Air}
T_u = rural T_{Air}

4.4 Experimentation

Before recognising the effectiveness of UHI mitigation through building form modification, it is important to critically assess the urban morphology of the focus area. Thus, the aspect ratio, UHI max, and SVF of each 20 monitoring points were estimated and are shown in Fig. 4.9 and 4.11. With regards to Fig. 4.9, only the H/W ratio and UHI max of the urban canyons were calculated because the monitoring points at junction areas (A1, B1, G1, M1, and N1) cannot be specified using Oke's model (Eq. 2). However, the SVFs of these five junction points were deliberately estimated to understand how the UHI responds to higher SVF values. As seen in Fig. 4.10, all the five junction points exhibit high SVF values.

The relation between H/W Ratio and UHI max, H/w Ratio and SVF, and SVF and UHI max are demonstrated in Fig. 4.11. As observed in Fig. 4.11.c, the higher the UHI max, the lower the SVF value. However, this is not entirely the case in the measured air temperature because some exhibit an upward trend contrary to what the theory exemplifies.

	Axis	Ave H	Ave W	H/W Ratio	UHI max by Oke's model	SVF
Argyle Street West	A	21.25	72.80	0.29	2.56	0.89
	B	31.10	42.12	0.74	6.25	0.75
	C	19.67	23.57	0.83	6.73	0.65
	D	29.00	31.69	0.92	7.10	0.39
	E	25.50	62.33	0.41	3.90	0.66
	F	28.00	22.12	1.27	8.39	0.36
Hope and Oswald Street	G	20.08	19.84	1.01	7.50	0.46
	H	30.31	22.80	1.33	8.58	0.28
	I	24.50	18.10	1.35	8.65	0.37
	J	26.75	18.48	1.45	8.92	0.35
	K	16.50	18.36	0.90	7.03	0.54
	L	18.80	18.37	1.02	7.54	0.48
	M	15.75	18.48	0.85	6.82	0.51
	N	17.00	17.96	0.95	7.23	0.63
	O	18.88	19.84	0.95	7.25	0.57

***Figure 4.9** Estimation of aspect ratio and UHI max by Oke's model of the 20 point locations. Source: Detailed Map derived from EDINA Digimap Ordnance Survey Service, 2020.*

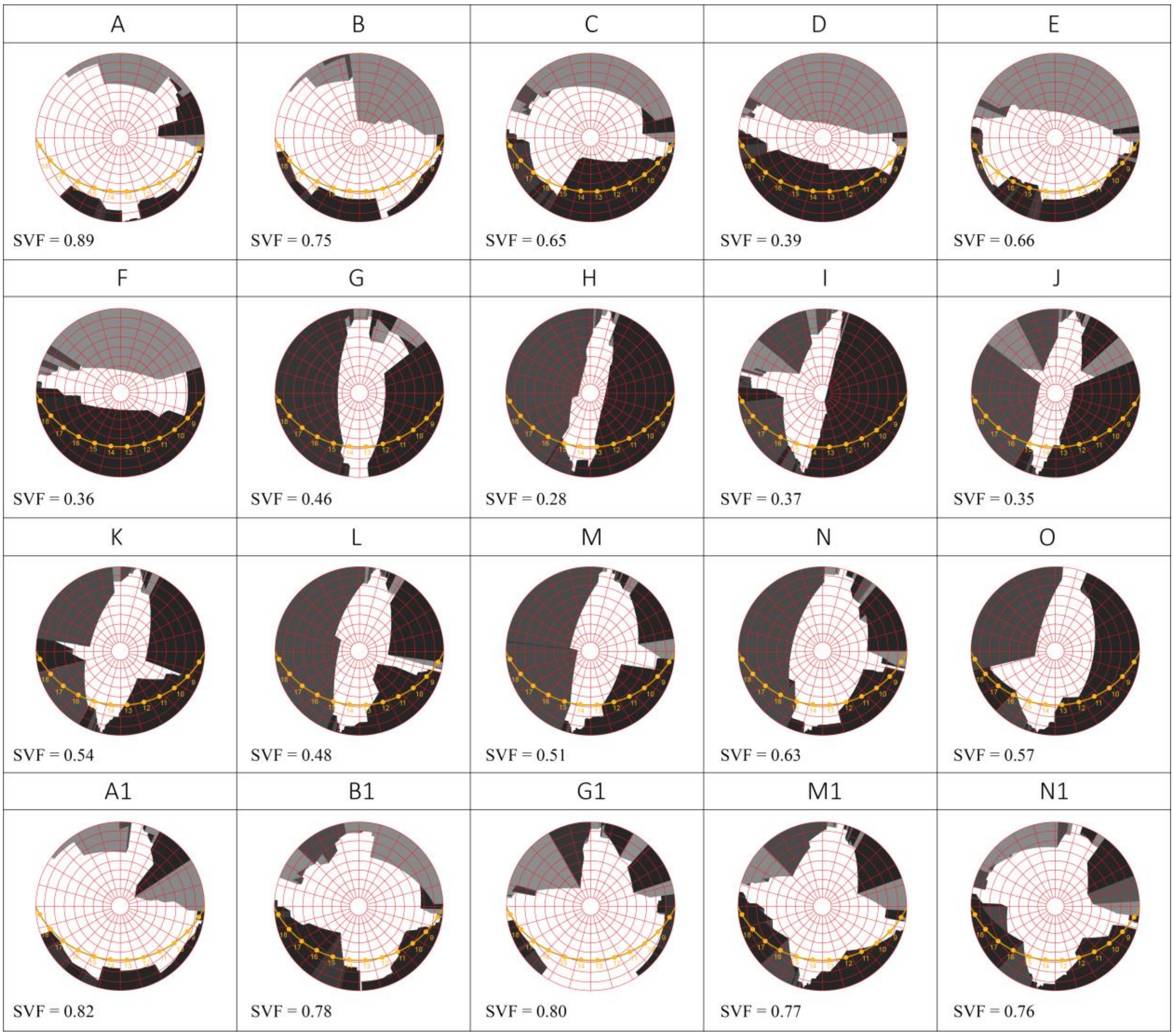


Figure 4.10 *SVF estimation of the 20 point locations. Source: Images derived from SkyHelios Version 1.5 Build 7150 Copyright © 2009 - 2018.*

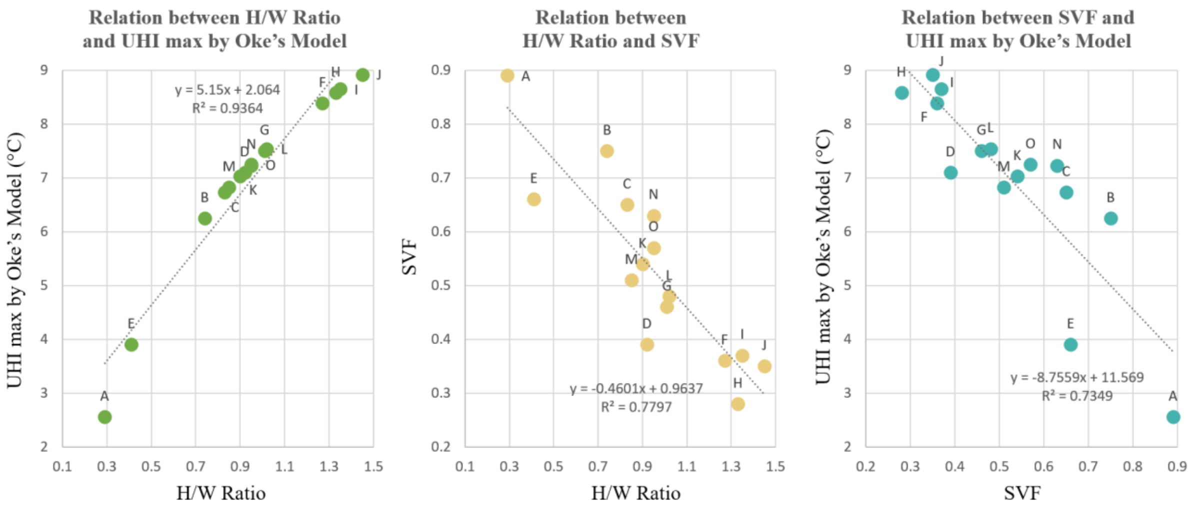


Figure 4.11 *Relation between H/W Ratio and UHI max (a); H/W Ratio and SVF (b); and SVF and UHI max (c).*

4.4.1 Analysis of the SVF, Aspect Ratio, and Measured Air Temperature

Graphical representations of Table 4.6 are illustrated in Fig. 4.12 and 4.13 to visually display the relation of air temperature differences with SVF and aspect ratio of each point in various atmospheric stability classes. According to the graph, PGT class E (moderately stable condition) shows less difference between temperatures at each point. In contrast, the more unstable condition (PGT class C) is more pronounced in terms of observed air temperature. Evidently, the temperature difference in PGT class C has higher intra-urban air temperature differences than the other two, signifying a more noticeable UHI effect. This implies that the relationship between air temperature and SVF strongly depends on atmospheric conditions. This agrees with the studies of Drach et al. [2018], in which they concluded that variations were much more noticeable for PGT classes with more unstable conditions. Their study explored the impacts of solar radiation and wind speed, whereas this thesis mainly looked into the influences of cloud cover and wind speed. The site's morphology, in conjunction with the unstable condition, produced more varied intra-urban temperature differences due to the buildings' shading effects.

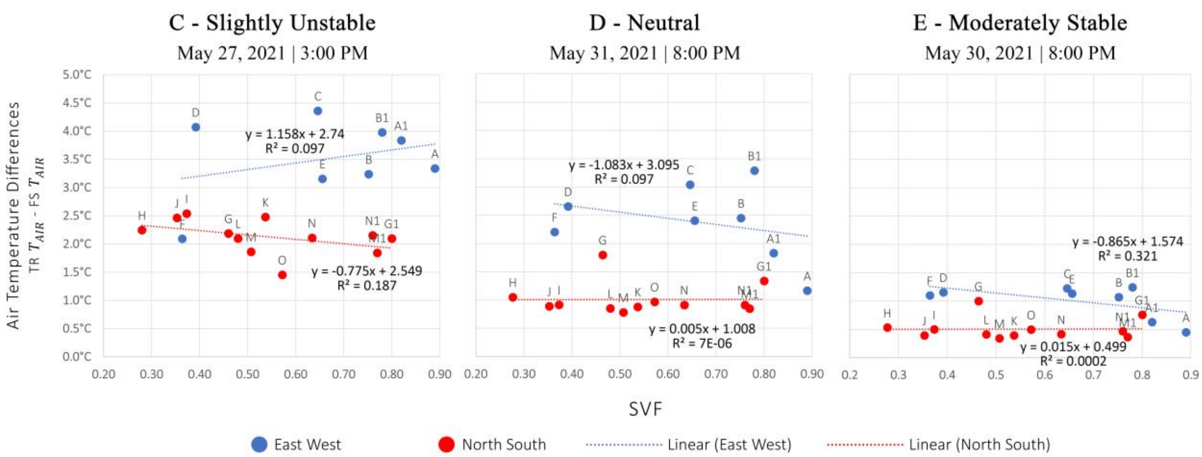


Figure 4.12 *Relationship between air temperature difference and SVF.*

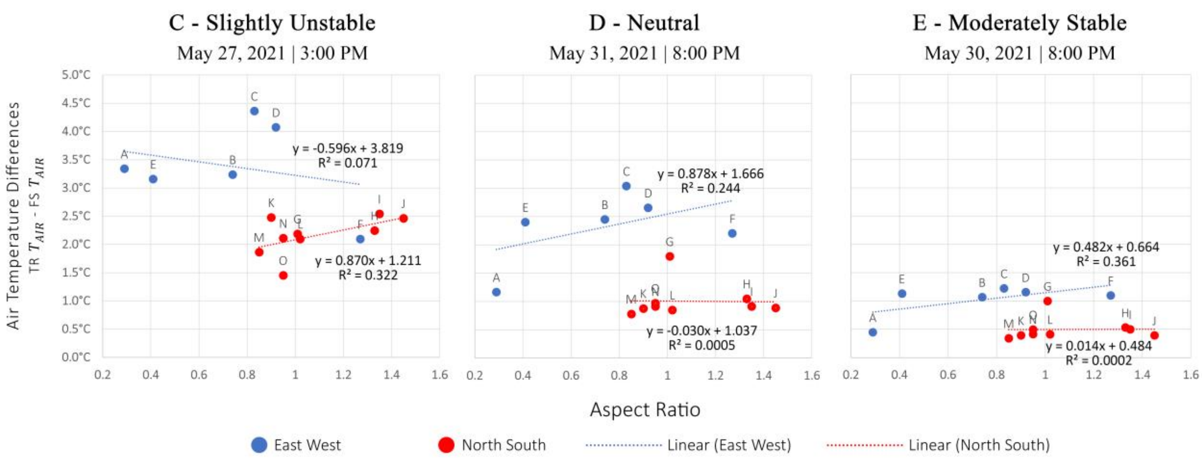


Figure 4.13 *Relationship between air temperature difference and aspect ratio.*

Comparing the SVF and aspect ratio of the measured local UHI and estimated UHI max, it could be observed that the more stable conditions exhibited a similar pattern to the estimated UHI max despite not having matched predicted regression line. In contrast, the temperature variations in N-S street does not show significant differences in stable conditions. However, Maharoof et al.'s [2020] findings show that the N-S streets have a stronger correlation between temperature and SVF. Perhaps the characteristic of Hope Street, having homogeneous building height and street width, influenced the insignificant temperature difference.

Fig. 4.14 combines both Fig. 4.10 and 4.12 to clearly exhibit the relation between the measured air temperature difference and SVF. This assessment shows that, although higher air temperature associates with lower SVF and higher aspect ratio, as in studies of Oke et al. [2017], Montavez et al. [2007], and Nakata-Osaki et al. [2017], other circumstances are affecting this behaviour, one of which is the LST [Janak and Bhatt, 2012; Kaplan et al., 2018]. As seen in Fig. 4.15, points A, A1, B, B1, M1, and N1, despite having high SVF values, also demonstrate high LST. Another factor is that many mid- to high-rise structures flank the River Clyde, blocking the incoming onshore breeze and south-westerly winds from passing through the centre. These structures are characterised as buildings of considerable scale. As a result, the air temperature is highest in E-W street (Argyle Street) despite being near the river. Above all, solar radiation has the strongest correlation between temperature and SVF. Looking at monitoring points G (SVF=0.46) and G1 (SVF=0.80), both have low LST and have access to the incoming sea breeze. Yet, their temperatures are the highest among all the N-S monitoring points due to the amount of solar radiation received. Still, the river was found to be significant in influencing the thermal environment of the built-up area, because points G and G1 prove to have the lowest temperature in comparison with the other points near the River Clyde (points B to F).

In mitigating the UHI phenomenon caused by the above findings, several related studies examined the influence of vegetation and surface cover [Santamouris et al., 2011; Soltani and Sharifi, 2017, Rehan, 2012], shading effects [Theeuwes et al., 2014; Emmanuel and Johansson, 2006], façade geometry [Maharoof et al., 2020], and urban form [Hu et al., 2016; Yuan et al., 2015]. These studies recognised the cooling effect of these parameters on urban areas, which significantly reduce the impacts of UHI. Hence, this discussion introduced greater grounds in the implementation of the proposed scenario and the urban modification criteria in Table 3.5. These are summarised below:

- The use of shaded pathways to reduce the solar radiation intensity
- The use of vegetation and surface materials with high albedo values to improve LST
- The grouping of buildings to manage airflow pattern
- The staggering of building facades to establish openness (defined by SVF and aspect ratio), especially to narrow streets

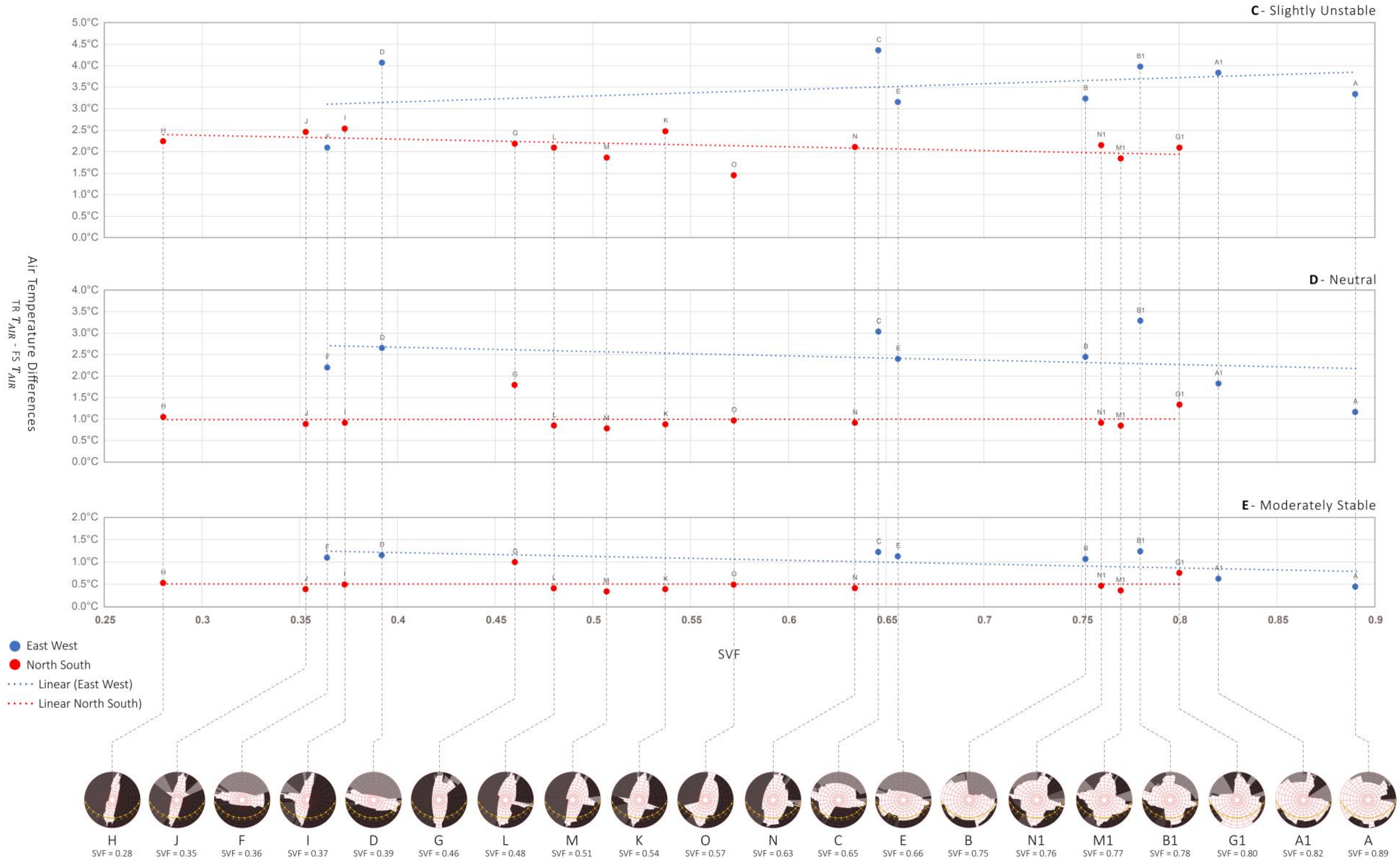


Figure 4.14 *Relation between measur ed air temperature difference and SVF of the 20 point locations.*

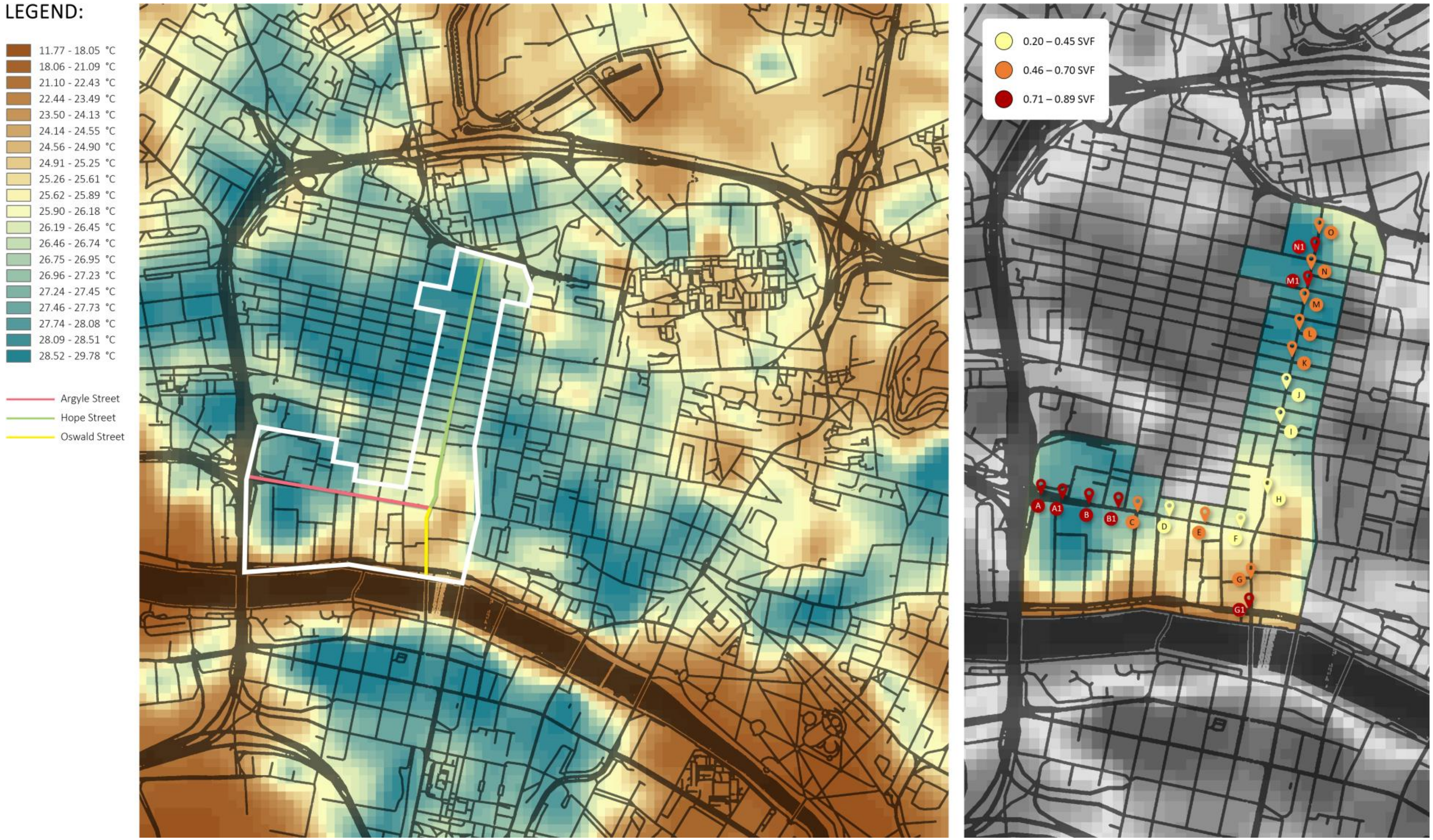


Figure 4.15 *LST of Glasgow city centre. Source: Adapted from USGS Earth Explorer, 2020.*

4.4.2 Proposed Scenarios

Going back to the SDF's underlying motive of densifying and re-populating Glasgow city centre, it is important to consider the discussion made in the previous section concerning the influences of aspect ratio and SVF. On the one hand, the densification through urban consolidation[8] and infill development[9] will prevent the expansion of built-up urban areas, ultimately impeding urban sprawl development. But on the other hand, pursuing this could cause higher UHI intensity within the city core due to increased built areas. In addition, higher densities may establish *"fragilities that reduce urban resilience"* [Jacques, 2021]. Nevertheless, this section seeks to provide solutions to the potential impacts of urban densification.

The previous chapter provided urban form modification assessment criteria (Table 3.5) in validating the proposed scenarios. While some measures are already highlighted in the appendices and preceding sections, the remaining bases are discussed here. Using the parameters in Table 3.5, the author produced two proposals; one comprises buildings with basic rectangular forms oriented towards dominant wind and sun position (P1), and the other contains buildings with internal courtyards (P2) (Fig. 4.16). For the blocks that cannot be modified, such as those comprising only listed buildings, the proposal relied on the surface material, street greening, and covered walkway, but only to some extent due to a narrow street.

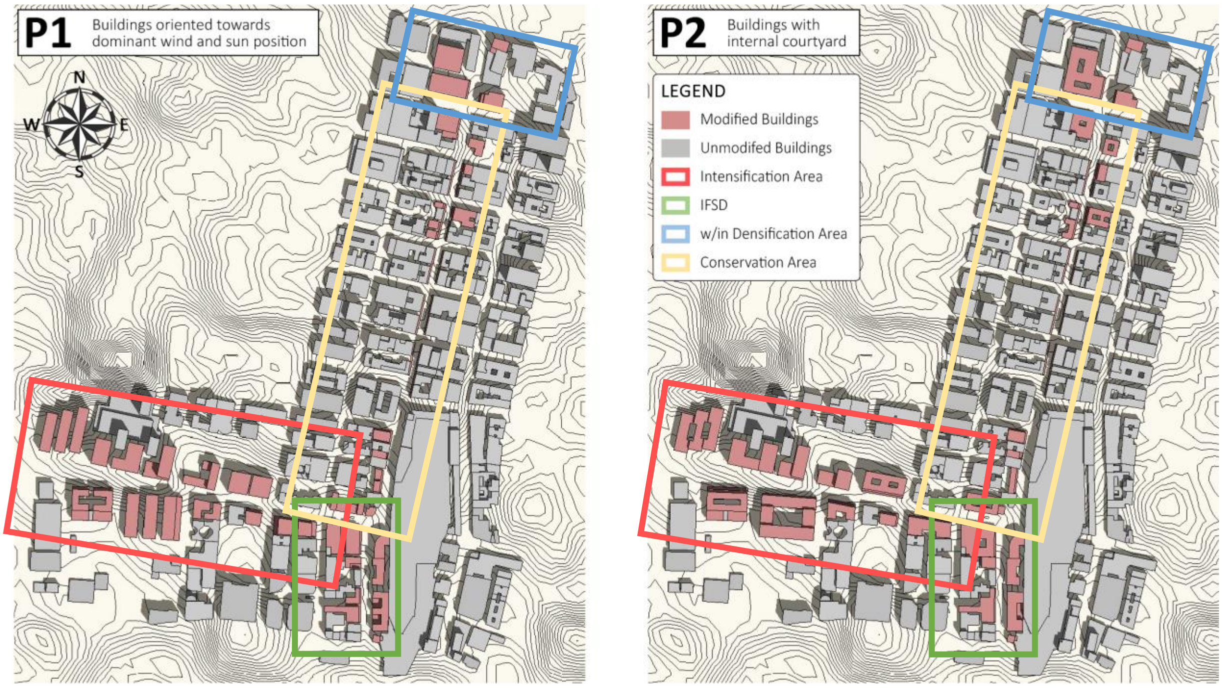


Figure 4.16 *P1 and P2 highlighting the different zones. Source: Base plan derived from Autodesk Revit.*

[8] Urban Consolidation is defined as the strategy of restricting further development and population growth to within the existing urban areas rather than expanding outward into suburban areas [Spacey, 2016].

[9] Infill Development is the development of vacant or under-used sites within existing urban areas [Future of London, 2015].

Both proposals considered basic architectural principles on using natural ventilation and lighting as passive design strategies, such as the provision of shade to public spaces and moderating the effects of wind through building orientation. Likewise, the Placemaking principles [GCC, 2018a] and Designing Streets [The Scottish Government, 2010], as summarised in Appendix I, were applied in generating the proposals.

In calculating the FAR and BCR, the author only considered the buildings facing the focus areas that are modifiable, as well as the buildings currently under construction (Fig. 4.9). Information about the latter were taken from BAM Properties & Taylor Clark [2021] and Scottish Construction Now [2020]. While the FAR and BCR of the existing buildings were estimated using the master map of Glasgow [EDINA Digimap Ordnance Survey Service, 2020] and Google Earth Pro.

Table 4.7 summarises the FAR and BCR of the existing and proposed scenarios. Looking at the figures, it is surprising to know that the intensification area/IFSD have low minimum and maximum FAR. The explanation lies in the fact that Argyle Street West is less compact than other streets within this zone. Furthermore, the street is bounded by buildings with large blocks, which offered more open spaces. On the other hand, the highest maximum FAR lies within the conservation area. This undermines the CDP’s aim in protecting the distinctive character of Glasgow city centre [GCC, 2017] and could negatively affect the adjacent historic buildings. Moreover, it could increase the UHI in the narrow thoroughfare of Hope Street. Fig. 4.17 illustrates the location of the minimum and maximum FAR of each zone in satellite 3D and LiDAR. The latter demonstrates that high FAR does not always indicate tall buildings and vice versa.

***Table 4.7** FAR, BCR, and open space allocation of the existing and proposed scenarios.*

Zones	Existing Condition			Proposal 1 and 2		
	FAR	*BCR*	*Open Space*	*FAR*	*BCR*	*Open Space*
Intensification Area / IFSD	Min = 1.4 Max = 8.8	Min = 27% Max = 100%	Min = 0% Max = 73%	x 1 to 3.0	- 5 to 10% / + 30%	+ 5 to 10% / - 30%
IFSD / Conservation Area	Min = 5.3 Max = 9.4	Min = 51% Max = 100%	Min = 0% Max = 49%	x 0.7 to 1.5	- 10 to 15%	+ 10 to 15%
Within Densification Area	Min = 3.4 Max = 7.0	Min = 73% Max = 100%	Min = 0% Max = 27%	x 1.5	- 4 to 10%	+ 4 to 10%
Conservation Area	Min = 2.6 Max = 13.0	Min = 43% Max = 100%	Min = 57% Max = 100%	x 0.7 to 1.0	- 5 to 20% / retain	+ 5 to 20% / retain

Figure 4.17 *Location of the minimum and maximum FAR of each zone in satellite 3D (above) and LiDAR (below). Source: Base Plan derived from Google Earth Pro (2021); Airbus Defence and Space Ltd; University of Glasgow – UBDC, 2003; DSM created using high resolution satellite data from 2012.*

The justification for the proposed FAR depended on how the SDF defined the urban intensification and densification zones [GCC, 2019a]. According to the document, the former is suitable for development with greater density and scale. Whereas the latter will need to maintain tenemental human-scale buildings. In examining the building forms during the methodology stage, the author assessed the building heights and scale of the surrounding structures (Fig. 4.18) and observed that the given FAR parameters conform with the typical heights and scale of buildings within the urban intensification zone and that increasing this would detriment the urban morphology of the area. While the densification zone would need to retain the tenemental human-scale buildings. Hence, the increase in FAR is only half of what the urban intensification can achieve. For the buildings positioned both on the IFSD and conservation area, the parameter was set to either 30% reduction or 50% addition to balance both the area's requirements. Lastly, most building FARs within the conservation area were retained to respect the historic environment of the centre, while others with pronounced heights were reduced to maintain the typical density. Initially, the author tried to reduce the FAR to up to 50% (x0.5), but the results were incompatible with the surrounding structures. Thus, the least reduction was set to x0.7. The BCR, on the other hand, was reduced to the extent feasible to enhance urban permeability. Likewise, decreasing BCR could lessen urban climate anomalies during winter [Salvati et al., 2019]. Table 4.8 summarises the proposed FAR and BCR of each building on each monitoring point, while Fig. 4.19 and 4.20 illustrate graphical representations to better comprehend the allocations. Building numbers can be derived from Fig. 4.9.

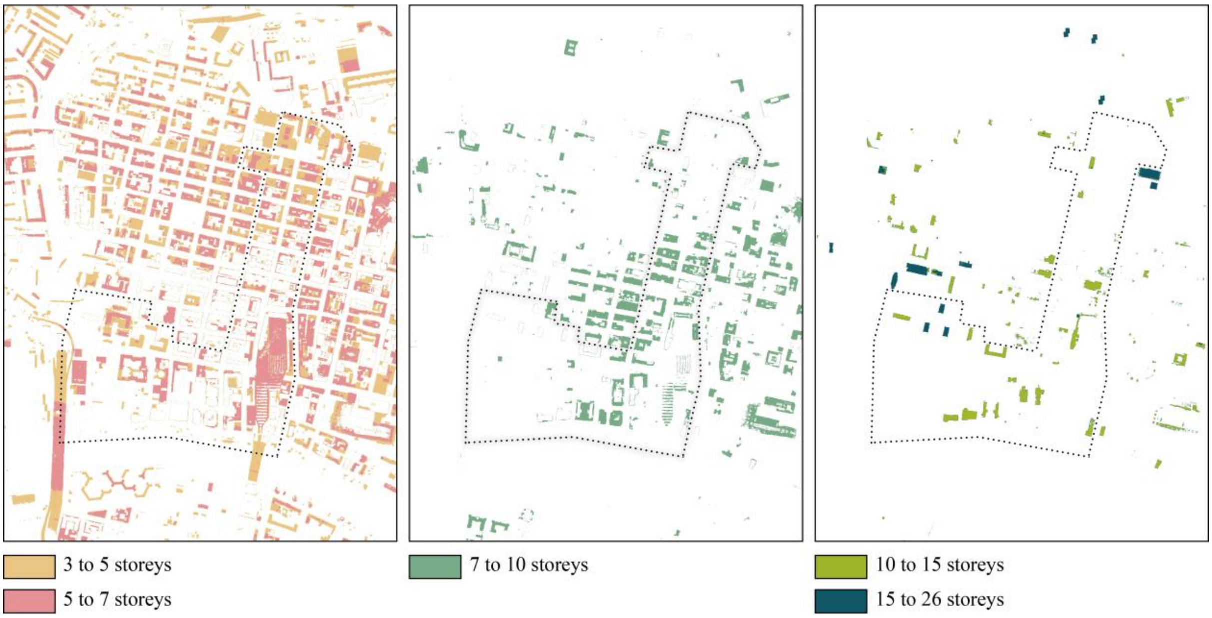


Figure 4.18 *Heights and scales of surrounding buildings. Source: Airbus Defence and Space Ltd; University of Glasgow – UBDC, 2003; DSM created using high resolution satellite data from 2012.*

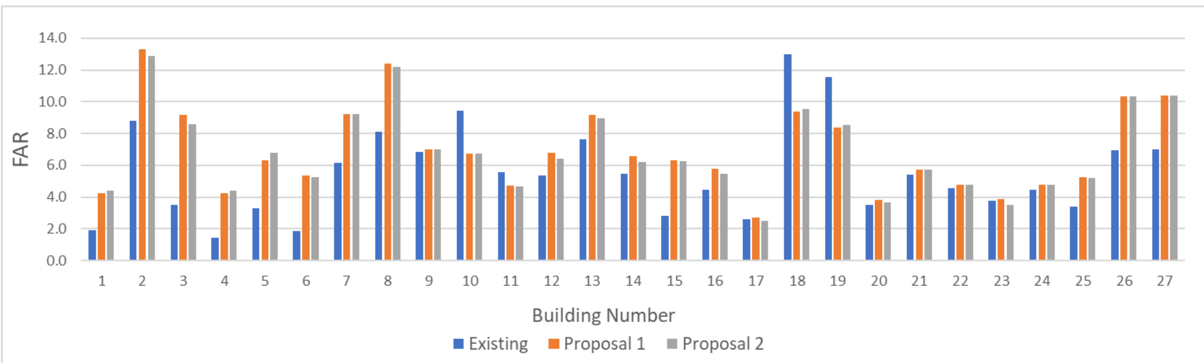


Figure 4.19 *Allocation of FAR (see Fig. 4.9 for building numbers).*

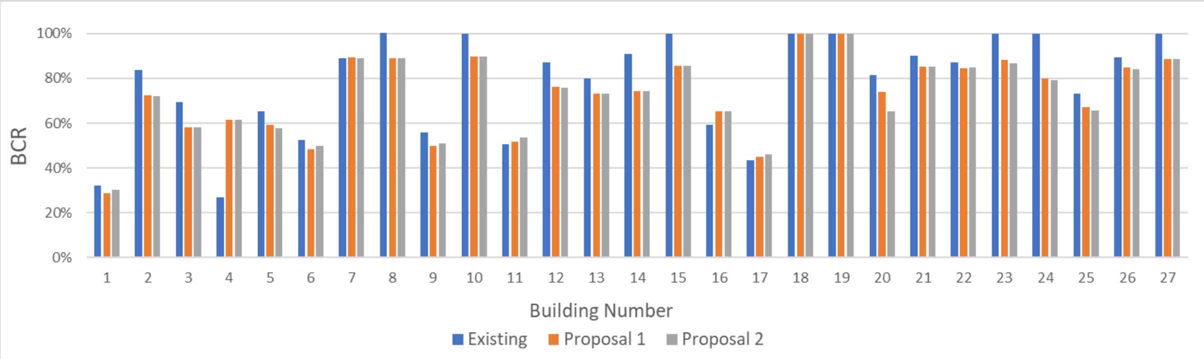


Figure 4.20 *Allocation of BCR (see Fig. 4.9 for building numbers).*

Table 4.8 *Estimated FAR and BCR of proposed scenarios (see Fig. 4.9 for building numbers).*

	Point	Modifiable Building	Existing			Proposal 1			Proposal 2		
			FAR	*BCR*	*Open Space*	*FAR*	*BCR*	*Open Space*	*FAR*	*BCR*	*Open Space*
Urban Intesity Area / IFSD	A	B1	1.9	32%	68%	4.3	29%	71%	4.4	30%	70%
	B	B2	8.8	84%	16%	13.3	72%	28%	12.9	72%	28%
		B3	3.5	70%	30%	9.1	58%	42%	8.6	58%	42%
		B4	1.4	27%	73%	4.2	61%	39%	4.4	61%	39%
		B5	3.3	65%	35%	6.3	59%	41%	6.8	58%	42%
	C	B6	1.8	52%	48%	5.4	48%	52%	5.2	50%	50%
		B7	6.2	89%	11%	9.2	89%	11%	9.2	89%	11%
	D	B8	8.1	100%	0%	12.4	89%	11%	12.2	89%	11%
		B9	6.8	56%	44%	7.0	50%	50%	7.0	51%	49%
IFSD / Conservation Area	E	B10	9.4	100%	0%	6.7	90%	10%	6.7	90%	10%
	F	B11	5.6	51%	49%	4.7	52%	48%	4.7	53%	47%
		B12	5.3	87%	13%	6.8	76%	24%	6.4	76%	24%
Urban Intesity Area / IFSD	G	B13	7.6	80%	20%	9.2	73%	27%	8.9	73%	27%
		B14	5.4	91%	9%	6.6	74%	26%	6.2	74%	26%
		B15	2.8	100%	0%	6.3	85%	15%	6.3	85%	15%
		B16	4.4	59%	41%	5.8	65%	35%	5.5	65%	35%
Conservation Area	H	B17	2.6	43%	57%	2.7	45%	55%	2.5	46%	54%
		B18	13.0	100%	0%	9.4	100%	0%	9.5	100%	0%
		B19	11.6	100%	0%	8.4	100%	0%	8.5	100%	0%
	L	B20	3.5	81%	19%	3.8	74%	26%	3.7	65%	35%
		B21	5.4	90%	10%	5.7	85%	15%	5.7	85%	15%
	M	B22	4.5	87%	13%	4.8	85%	15%	4.7	85%	15%
	N	B23	3.8	100%	0%	3.9	88%	12%	3.5	87%	13%
		B24	4.5	100%	0%	4.8	80%	20%	4.8	79%	21%
Within Densification Area	O	B25	3.4	73%	27%	5.3	67%	33%	5.2	66%	34%
		B26	7.0	89%	11%	10.3	85%	15%	10.3	84%	16%
		B27	7.0	100%	0%	10.4	89%	11%	10.4	89%	11%

Fig. 4.21 shows the two proposals exhibiting a decrease in aspect ratio and an increase of SVF, except for points A to E, because these blocks require urban infill, and point I to K, since these were not altered.

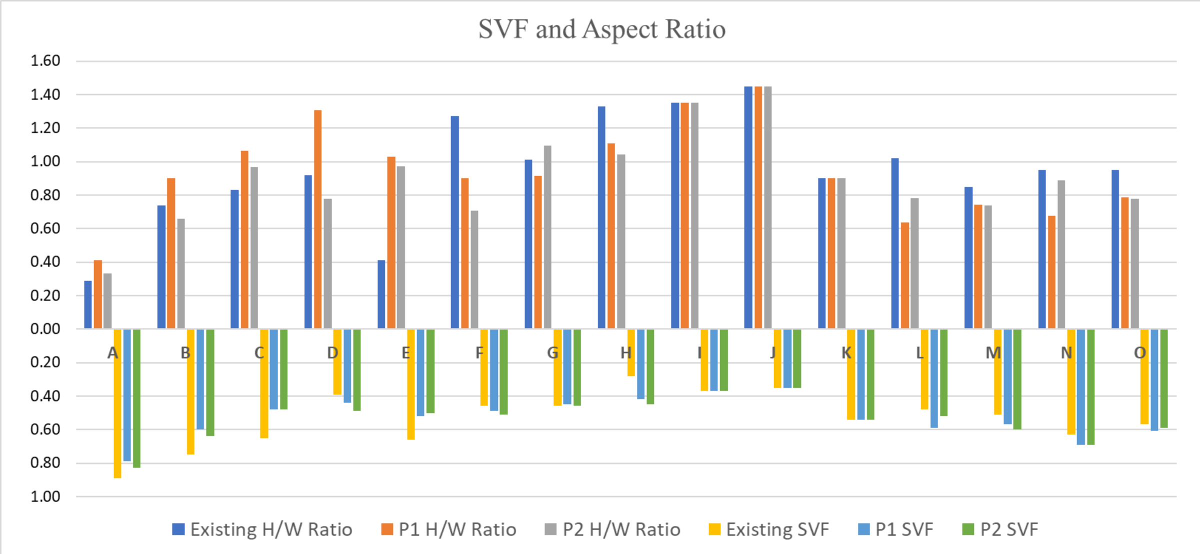


Figure 4.21 *Allocation of SVF and aspect ratio of the existing, P1, and P2 scenarios.*

The distribution of proposed street greening is summarised in Table 4.9. Although largely subjective, the given values accord to the open spaces available in each street. Also, the allocation agrees to the qualities of places as stated in the Placemaking principles, i.e., ease of movement and vibrance and density (Appendix I).

Table 4.9 *Percentage distribution of proposed street greening.*

	Argyle Street	Hope and Oswald Streets
Trees and Shrubs	+15%	+10%
Grass	NA	+5%

With regards to the effects of solar geometry, Table 4.10 shows the episodes of overshadowing of the proposed scenarios, while Appendix V illustrate the shadow ranges. As observed, there is an occurrence of overshadowing for the whole duration of the winter solstice. But this is inevitable due to the sun's position, bringing longest night and shadow length. Although shading of urban canyons leads to a lower temperature during the day [Theeuwes et al., 2014], it must not be so great so as not to cast a general gloom within the streets [Oke, 1988].

Table 4.10 *Episodes of Overshadowing.*

	Without Overshadowing	Overshadowing Hours	
Spring Equinox	9:00 to 15:00	7:00 to 9:00 15:00 to 17:00	Total = 4 hours
Summer Solstice	7:00 to 18:00	Total = 0 hour	
Winter Solstice	10:00 to 2:00	Total = 4 hours	

4.5 ENVI-met Simulation Results

As mentioned in Section 3.4.7, the streetscaping materials were simultaneously assessed using an ENVI-met model different from the focus areas in order to evaluate the impacts of various materials in Glasgow city centre. Similar studies [Chatzidimitriou et al., 2006] tested the effect of different ground surface cover using the same simulation software. To better understand the course of the simulation results section, the material assessment will be discussed prior to the existing, Avenues, and proposed scenarios.

4.5.1 Streetscaping Elements

Table 4.11 shows the surface materials employed in the Avenues proposal [GCC, 2018b; Civic Engineers, 2021] and their corresponding albedo values. Albedo (α) varies between 0 (black) and 1 (white). A value of 0 means the surface is characterised by high thermal admittance or is a great absorber of all incoming energy [Dobos, 2005]. Although the materials in Table 4.11 correspond to the local context of Glasgow city centre and contribute to its overall character, it is evident that they depict low albedo values, especially the distinctive paving, like whinstone and Caithness stone. Their dark-coloured appearances would result in a higher temperature. For the purpose of this study, the author assessed four additional materials not included in the Avenues proposal to explore other potential substitutes with higher albedo. These are light concrete (α=0.80), light-coloured granite (α=0.50), red brick (α=0.40), and yellow brick (α=0.50). Respective albedo values were derived from ENVI-met [2021], Dessi [2011], and Taha et al. [1992].

Table 4.11 *Typical streetscape element and ground surface material in Glasgow city centre.*

Material	Albedo	Material	Albedo
Asphalt	0.05 – 0.08	Granite Paving	0.30 – 0.35
Red-coloured Asphalt	0.09 – 0.11	Porphyry Slab (red-coloured rock)	0.30
Buff-coloured Asphalt	0.12 – 0.20	Whinstone (dark-coloured rock)	0.08 – 0.12
Concrete	0.30 – 0.40	Caithness Stone (dark black-grey shade)	0.08 – 0.12
Tree	0.15 – 0.18	Grass and Shrub	0.20 – 0.30

Source: Taha et al., 1992; Hulley, 2012; Yildiz, 2018; Jacobs and Delaney, 2015; Santamouris et al., 2011.

Fig. 4.22 illustrates the distribution of surface temperature of these materials. According to studies, an increase in solar reflectance will decrease thermal absorption. Whereas an increase heat in energy absorption will also increase surface temperatures [Levinson and Akbari, 2002; Hall et al., 2005]. The results indeed show that the materials with lower albedo generate warmer temperatures and vice versa. Clearly, dark materials absorb heat faster than light ones as their temperature promptly ascended at hour 11:00 to 14:00, when the sun was at the highest. The temperature eventually subsided after solar noon.

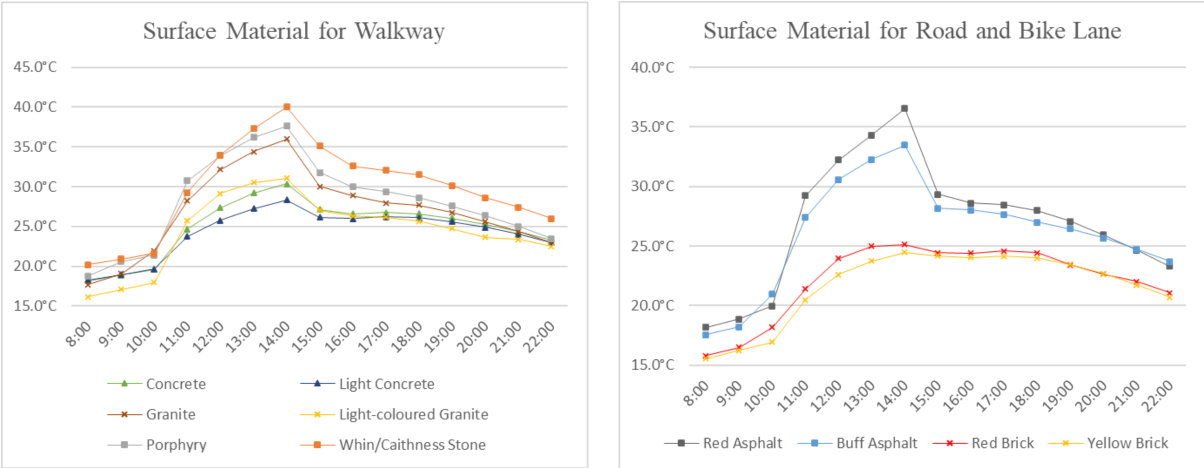


Figure 4.22 *Surface temperature of various material for walkway (left) and road and bike lane (right). Source: ENVI-met Version 4.4.5, 2021.*

Although, it should be understood that the simulation only considered the albedo values and that other properties, such as emissivity and thermal conductivity, were set to default. This resulted in an almost consistent temperature pattern, unlike in the findings of Hall et al. [2005], where he stated that high albedo components could sometimes have higher temperatures compared to materials with low albedo due to the weathering differences between the two. Also, Chatzidimitriou et al. [2006] observed an increase in air temperature above light-coloured surfaces due to the effect of reflected radiation on the sensors they used. Because the physical properties of the surface materials in Table 4.11 were not entirely specified, the results in this section did not encounter such observation. Hence, there is a need for actual field data to authenticate this evidence.

Going back to Fig. 4.22, both light concrete and yellow brick demonstrate the lowest surface temperature, having a maximum temperature of 28.33°C and 24.45°C, respectively. This reveals that low temperature could also be observed on porous surfaces. But because these two materials are not part of the Avenues proposal, it is essential to realise the role of the streetscaping elements to the character and identity of the city centre, as well as the thermal comfort it could provide to the people. Perhaps, it is important to compromise both qualities in order to acknowledge the fundamental Placemaking principles (Appendix I). For this purpose, light-coloured granite was used as a walkway material for the proposed scenarios so that there is a balance between character and comfort. While buff-coloured asphalt was employed for the replacement of the red-coloured asphalt (road intersections), as seen in Fig. 4.7. And lastly, red brick was used for bike lanes. Since brick is still considered an appropriate building material in Glasgow (Appendix I), it will not disrupt the city's character, as well as its colour.

According to Dessi [2011], *"urban space materials have a big impact on the occurrence of UHI"*. Thus, many designers and planners use high albedo surfaces to help mitigate UHI in urban areas. Although suitability plays a significant role in choosing surface materials, maintenance, safety, and long-term durability are crucial in high-traffic areas. For instance, in countries with good practices of safe cycling, as in Denmark and the Netherlands, asphalt is the standard surface on cycle track due to its even surface and low friction [Cycle Embassy of

Denmark, 2018; Bicycle Dutch, 2020]. Likewise, in terms of maintenance, cost, and weatherability, pavers and brick are not good options for cycle routes. It could be applied only to a limited extent or in areas with a low use rate. But because this thesis critically assesses the ability of these surface materials in mitigating UHI and not their durability, brick was still utilised for this purpose. This factor raises the question of how character, thermal comfort, safety, and durability could all be combined in order to achieve the fundamentals of the Placemaking principles.

Other streetscaping elements that were assessed are covered pathways and green façade at street level. Although these features are not usual in the streets of Glasgow city centre, it is essential to explore the effectiveness of enhanced shading in cooling the microclimate. Fig. 4.23 illustrates the air temperature distribution of the following conditions:

a. Base case
b. Green façade
c. Below typical/green covered pathway at 1.5-metre AGL
d. Beside typical/green covered pathway at 3-metre AGL

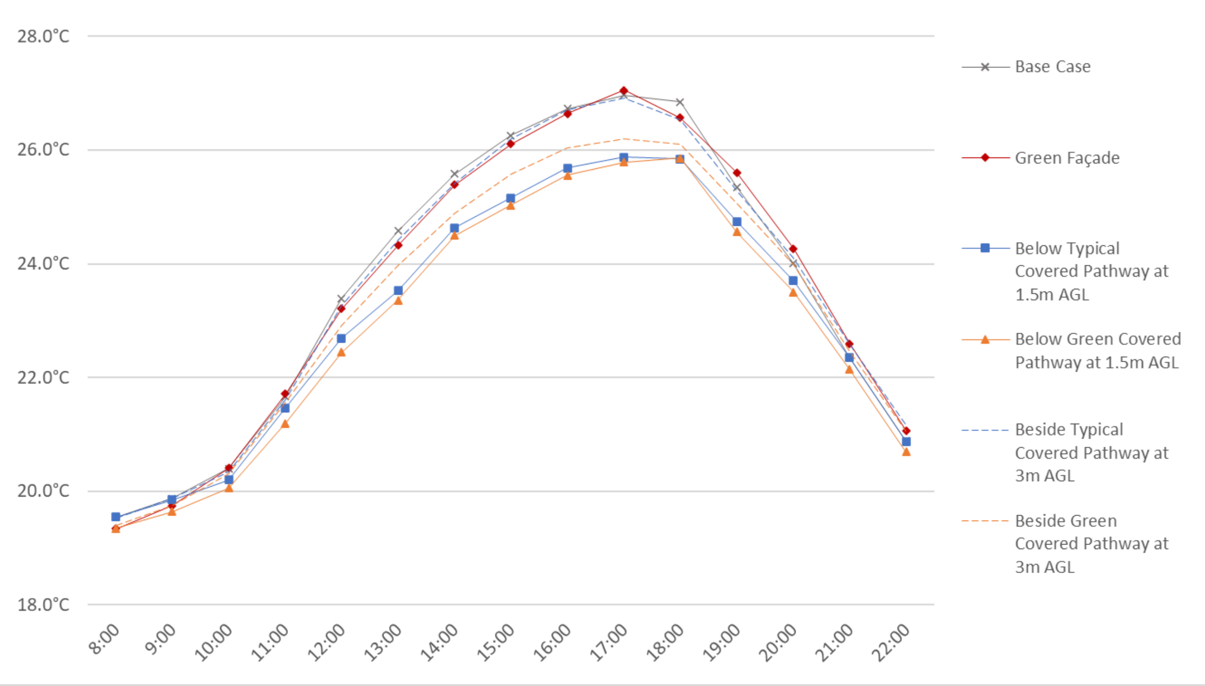


Figure 4.23 *Air temperature of covered pathway and green façade. Source: ENVI-met Version 4.4.5, 2021.*

The graph indicates that the green facade shows an insignificant temperature reduction compared to the base case. In fact, there are certain hours wherein the green façade has a higher temperature. For this reason, the green façade was not utilised in the final proposed scenarios. On the other hand, both covered pathways at 1.5-metre AGL demonstrate lower temperature, with the green case showing slightly less temperature reduction compared to that of the typical canopy. However, the difference between the two is negligible (between 0.01°C and 0.27°C).

This could explain the observation of Yuan et al. [2017] and Emmanuel [2021] that vegetative roofs have higher benefits in moderate and cold climates.

Lastly, there is a considerable temperature reduction if compared with the air temperature beside the green canopy. Whereas there is a minor difference between the base case and beside typical covered pathway case. The temperature drop in the latter could have been affected by the increase in elevation since temperature decreases slowly with height. The pronounced temperature difference between the two cases (1.5 and 3-metre levels) demonstrates the influence of evapotranspiration from the plants present in the green canopy.

To understand how the two cases enhance the street canyon of the focus areas, both typical and green covered pathways were applied in P1 and P2, respectively. These were implemented on the blocks comprising of only listed buildings (points I to K). Since the building forms in these points cannot be modified, the proposals were accomplished through surface material, street greening, and covered walkways. Because the thoroughfare of Hope Street is too narrow, only a few street greening were employed.

4.5.2 Focus Areas

Due to the extent of the focus areas, the site was divided into two models for faster simulation (Fig. 4.24). A key plan is presented afterwards to serve as a guide (Fig. 4.25). The results were evaluated for 28 June 2018 at 18:00 in order to assess the model performance displaying the highest PAT as estimated by ENVI-met (Fig. 4.26). Both PAT and MRT were evaluated at a pedestrian level (1.5 metre AGL) to investigate the outdoor thermal comfort during the warmest hour of the day.

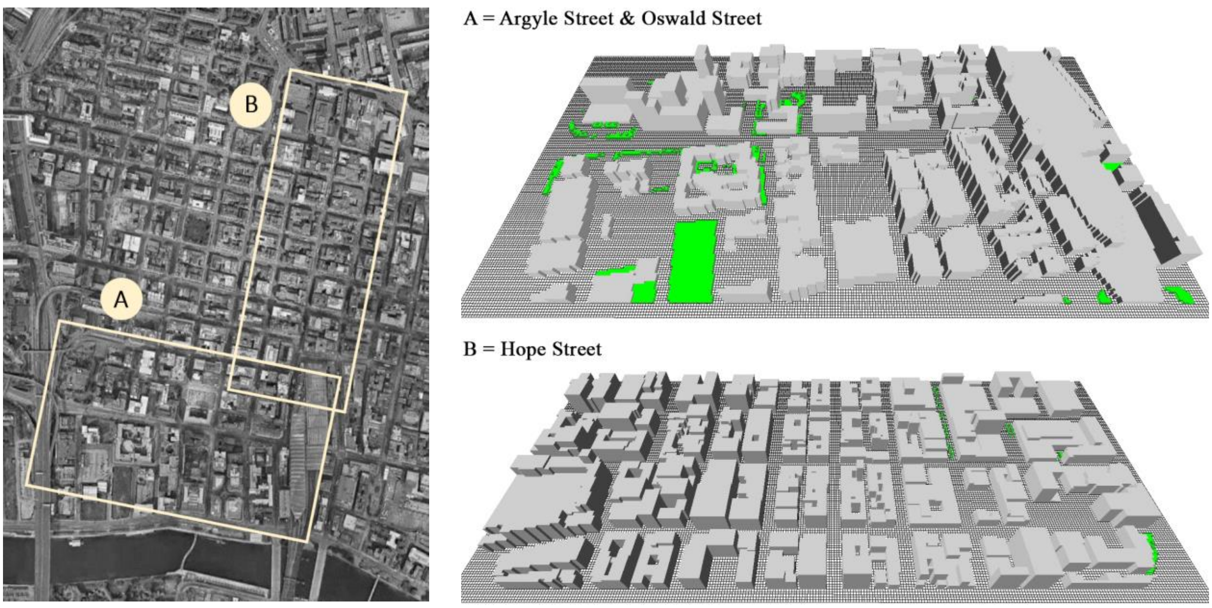


Figure 4.24 *Map and models of sites A and B. Source: Google Maps, 2021; ENVI-met Version 4.4.5, 2021.*

Figure 4.25 *Key plan of sites A and B.*

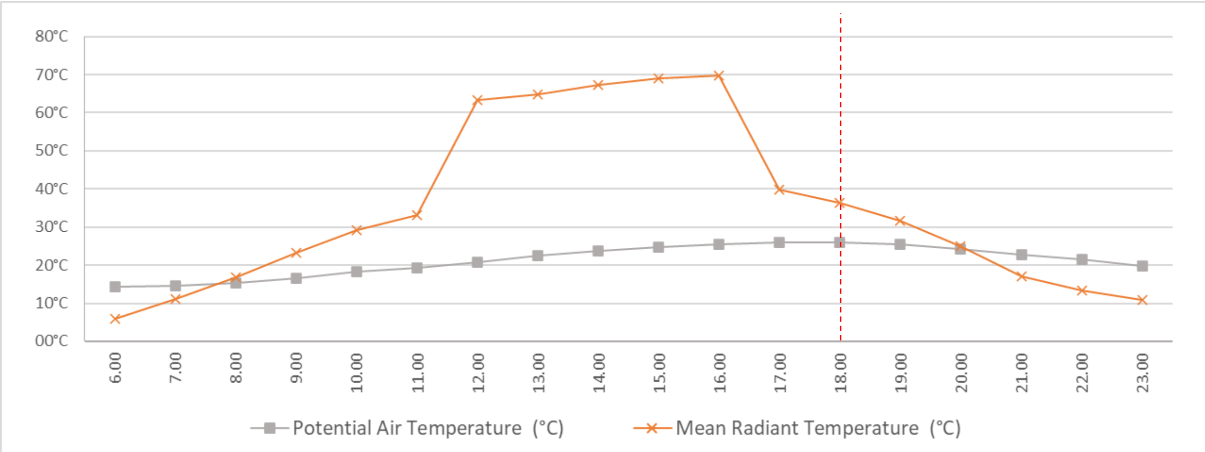


Figure 4.26 *PAT and MRT of 28 June 2018.*

Fig. 4.27 to 4.30 present the spatial distribution of MRT for sites A and B in all scenarios. However, the temperature distribution in the said figures is unnoticeable due to the domain size of the two sites. For this reason, Fig. 4.31 and 4.32 are provided to illustrate graphical representations of MRT and PAT differences of the Avenues, P1, and P2, in relation to the existing scenario. The temperatures of each point were analysed in the centre of the street canyon.

The first two cases indicate that there is a slight net radiant heat loss in the Avenues scenario, except for point A where it shows an MRT reduction of 8.31°C due to the proposed vegetation between the road, near M8, as shown in Fig. 4.28 aAS, which significantly enhanced the microclimate of the area. The most apparent changes are visible in points A, G, M, and O. Again, this is mainly due to the vegetation applied in the specified zones. Thus, proves the positive impact of space greening in urban areas. There are some instances where the Avenues scenario demonstrates higher temperature, such as in points B, E, F, and J. Possibly because of the surface material used. The existing scenario used concrete as walkway, while the Avenues scenario employed granite, as stated in Fig. 4.7. The lower albedo value of the latter could have affected the temperature increase. However, the net radiant heat gains in the said points are negligible, with a temperature increase of 0.02°C, 0.05°C, 0.04°C, and 0.09°C, respectively.

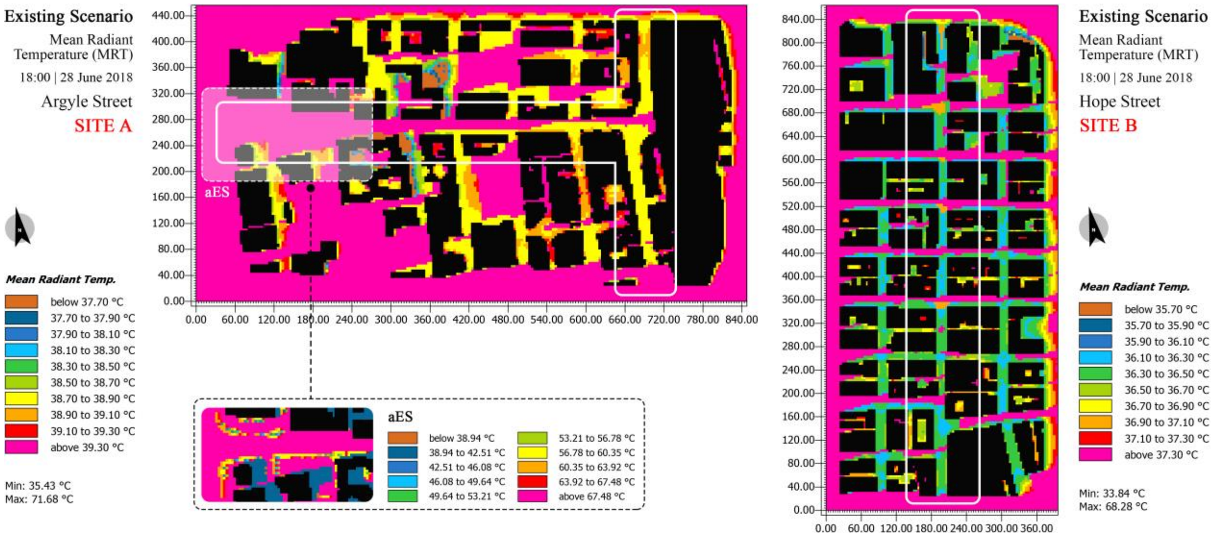


Figure 4.27 *Spatial distribution of MRT – Existing scenario.*

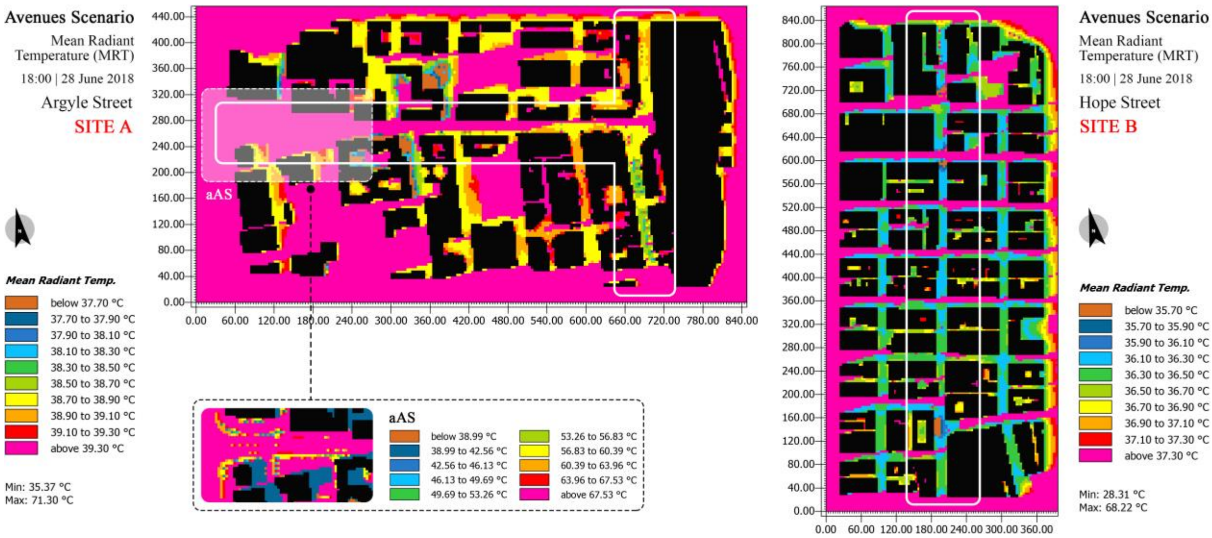


Figure 4.28 *Spatial distribution of MRT – Avenues scenario.*

Both P1 and P2 used light-coloured granite as ground surface material. For the covered pathway, the typical canopy was applied to P1, while P2 used the green canopy, both in points I to K, as stated in the previous section. The results show that both proposals demonstrate a considerable net radiant heat loss compared to current and Avenues scenarios. However, it could be observed that points I and J displayed higher temperatures than the existing scenario. Because these areas already characterise high aspect ratios (narrow streets bounded by buildings with significant heights), the structures already cast shadows in the street level, making the use of a canopy insignificant. The only time solar radiation reaches the ground is two to three hours between 14:00 and 16:00, as illustrated in Fig. 4.10. Instead, it would be beneficial if the covered pathway were implemented in areas that need shading, such as in E-W oriented streets or areas with wider thoroughfares. According to Taleghani et al. [2021], E-W street receives more direct sun, and therefore solar radiation falling in here has the most impact on the microclimate.

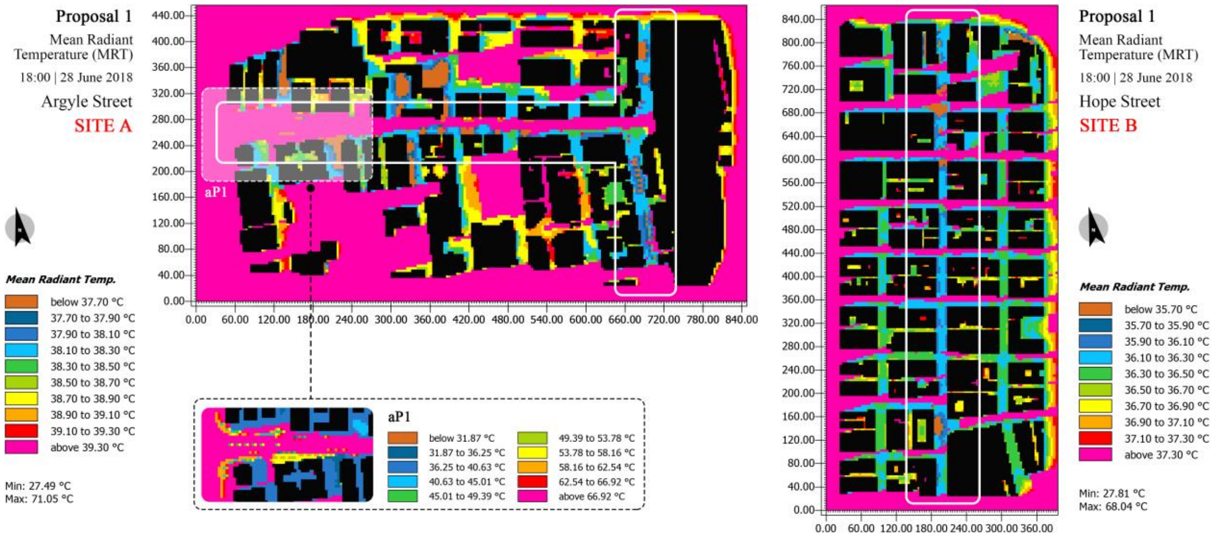


Figure 4.29 *Spatial distribution of MRT – P1 scenario.*

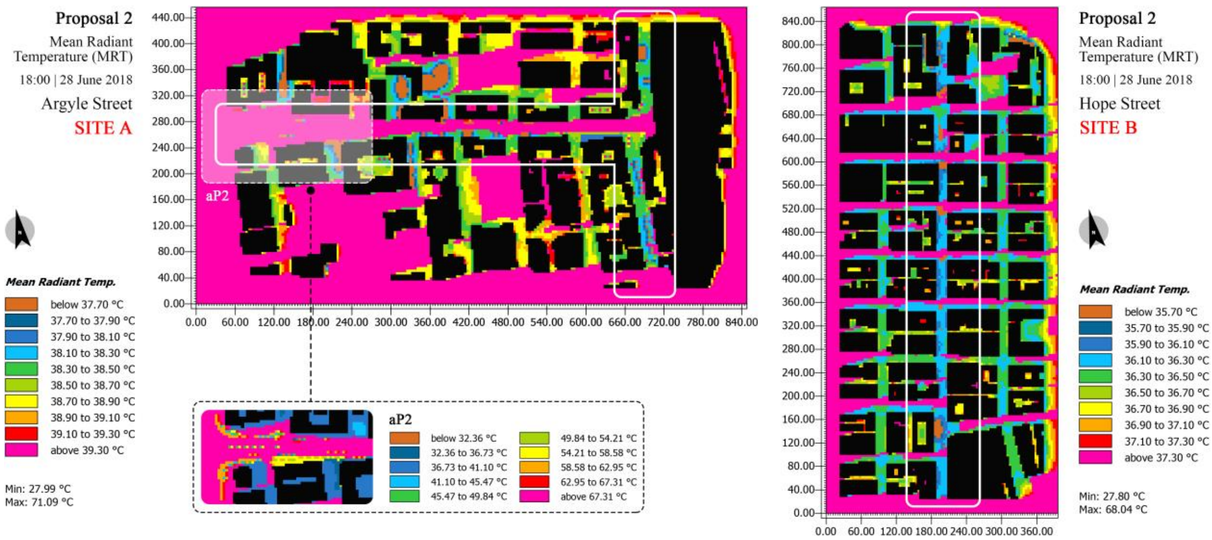


Figure 4.30 *Spatial distribution of MRT – P2 scenario.*

Note that in Fig. 4.31, the E-W street favours the P1 more than P2. Perhaps the additional building height presented in the former affected the result since it blocked the solar radiation from reaching the ground, thus providing a shading effect. Also, the fact that buildings are oriented towards the prevailing wind improved the street ventilation. On the other hand, the majority of the N-S points benefitted from P2 mainly because of improved SVF. In reality, internal courtyards introduce cross ventilation and passive design strategy. However, this was not assessed during the simulation. P1 and P2 proved that higher FAR could demonstrate lower temperature, which could also be observed in a macro scale, as shown in Fig. 2.2, where Hu et al. [2016] used high FARs (6 and 12) yet managed to lessen UHI.

Although P1 and 2 have similar FAR and BCR, P1 exhibited a more pronounced temperature drop, in which the maximum MRT drops of P1 and P2 are 30.64°C (point C) and 20.47°C (point D), respectively. While the maximum PAT decreases of both proposals are 0.33°C (P1 at point A) and 0.14°C (P2 at point O). The reduction in MRT could be mainly due to the shading effect and only little effect from the surface material it used, which is light-coloured granite. According to Dessi [2011], there are cases when light-coloured surfaces increase the amount of reflection or indirect solar radiation, thus affecting other urban areas. In another related study, Yuan et al. [2017] stated that a combination of moderate level of albedo (α=0.30) and green has the greatest capability in improving the urban microclimate. In this thesis, an albedo value of 0.50 was used in the walkway. Because it is a high albedo value, it is assumed that it improved the microclimate. But since the observations of Dessi [2011], Hall et al. [2005], and Chatzidimitriou et al. [2006] undermines this otherwise, it could also be the case in this experimentation, and that the shading of structures gave more factor to the UHI mitigation. Nonetheless, if high albedo material must be used, it should be combined with other cooling strategies to significantly enhance the thermal comfort of an urban area.

Site A (Argyle Street) exhibits a higher temperature variation and more pronounced temperature drop compared to that of site B (Hope Street) because the former has more space for improvement, thus the provision of further street greening. Site B, on the other hand, is more restricted. Moreover, the intensification zone is situated in site A. Therefore, there are more taller buildings present here that can block the sun, which eventually cool the temperature. The fact that site B lies in the conservation area, the densification of buildings, both horizontal and vertical, are only modified to some extent due to more stringent regulation.

Although an improved MRT is observed in all points in both P1 and P2 (except points I and J), it can be seen that PAT increased in some points, wherein the most prominent are in points E to H (Fig. 4.32). The confined airflow near the intersection of N-S and E-W street could have affected this, especially that there is an additional building height established in this area, thus blocking the free airflow. Also, the reductions in PAT in points I to K are not as significant due to the blocking of wind movement by the canopy. This observation concludes that an improvement in MRT is not always synonymous with a better PAT.

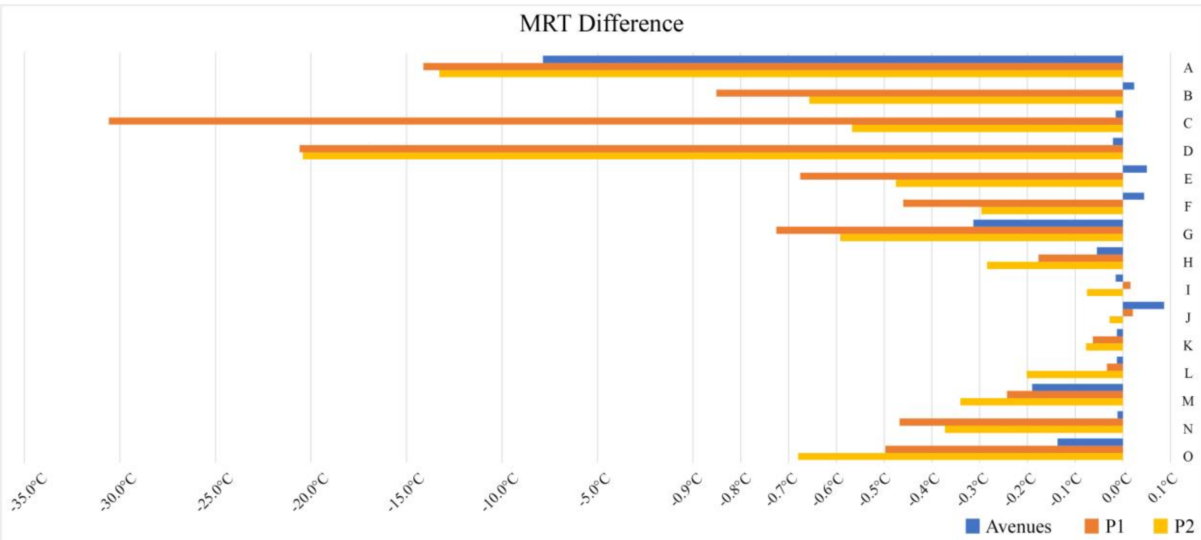


Figure 4.31 *MRT differences of Avenues, P1, and P2 scenarios.*

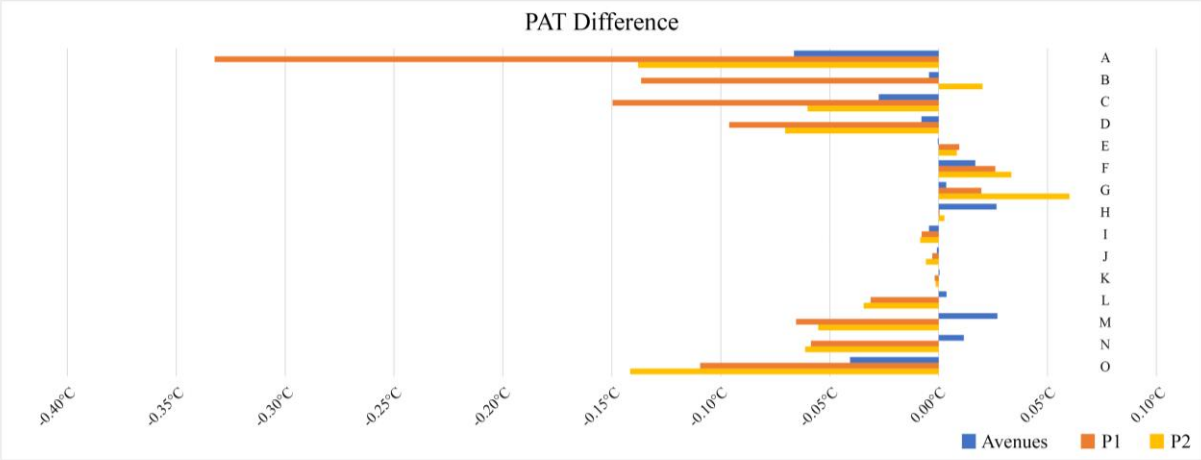


Figure 4.32 *PAT differences of Avenues, P1, and P2 scenarios.*

Fig. 4.33.a and 4.33.b illustrate elevation views of the existing (left) and better performing proposed scenarios (right) in order to clearly visualise each point's temperature allocation. It could be observed that there is a more evident net radiant heat loss in wider streets compared to those with narrower ones. Another observation is the apparent cooler temperature as streets become more compact. However, this only occurred to some extent because in points H to M, where the road is narrow, the net radiant heat loss is negligible compared to those points in the broader streets of Argyle. According to Theeuwes et al. [2014], the shading effects can lessen the UHI an aspect ratio between 0.5 and 1. However, as seen in Fig. 4.21, a few points in P1 and P2 demonstrate aspect ratios higher than 1, yet it still mitigated the UHI effect. Nonetheless, most of their aspect ratios fall between 0.6 and 1, which is still relative to the observation of Theeuwes et al. [2014].

The advantage of staggering building facades is also evident in the elevation view. This is conducive when an increase in FAR is essential, at the same time allowing solar access and air pollution dispersion at the street level. The cooling effect can be seen near walls of north-facing façades due to the shadowing effect. In contrast, there is no impact observed in the south-facing buildings. It should be noted that point B is flanked by a south-facing tall building (approximately 70 metres in height) characterised by a high albedo material (Appendix VII). Going back to the traverse study, this specific area constantly demonstrated high temperatures. Out of the 16 traverse measurements performed, 11 verifies this observation, thus validating this argument. So, although building material was not assessed in this dissertation, it would be advisable to avoid using reflective materials or those with very high albedo values on south-facing facades to prevent indirect solar radiation.

In the centre of the street, where neither shading nor street greening is present, there is no incidence of cooling, thus indicating the negligible effect of surface materials in improving the pedestrian level microclimate despite the enhanced surface temperature.

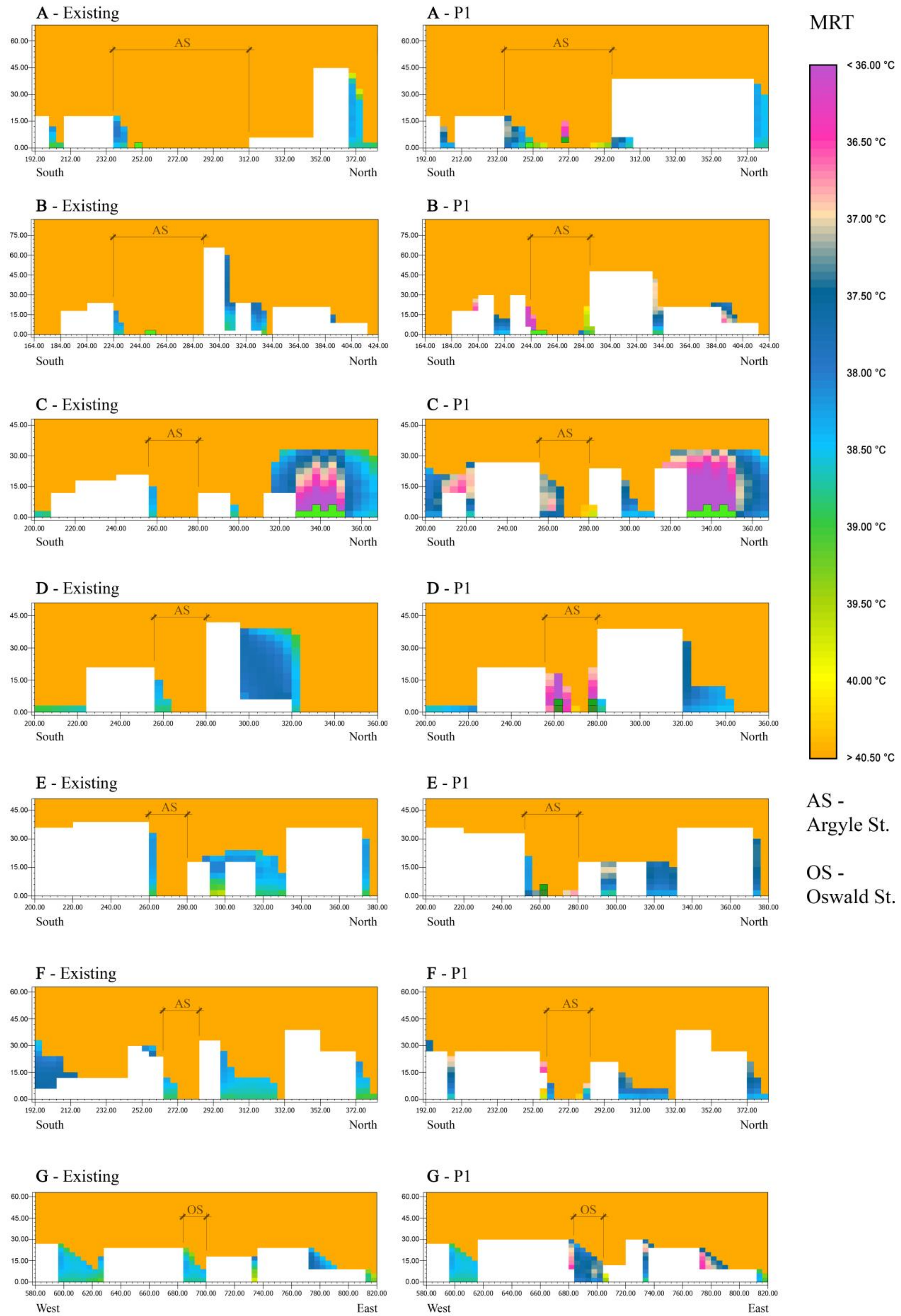


Figure 4.33.a *MRT of existing (left) and better performing proposed scenarios (right) of points A to G in elevation view.*

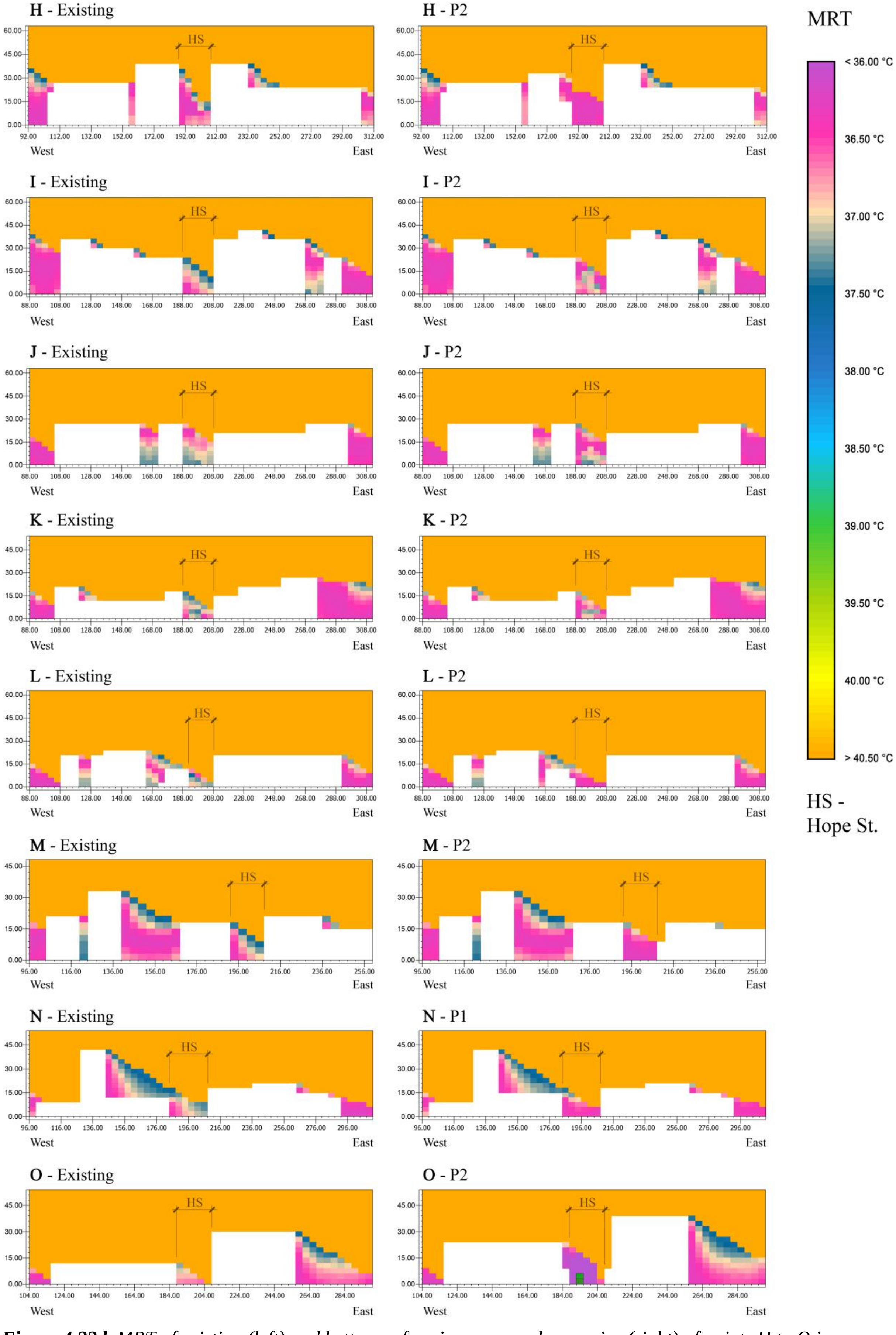


Figure 4.33.b *MRT of existing (left) and better performing proposed scenarios (right) of points H to O in elevation view.*

In order to assess the diurnal PAT and MRT variation, the points with the most pronounced difference in each street were chosen. For the purpose of this study, points A and O were chosen. Fig. 4.34 and 4.35 shows a profile of PAT over time of points A and O. There is a considerable net radiant heat loss in point A on hours were shading effect occur, whereas only a slight difference when the sun was visible, specifically at hours 12:00 to 17:00. On the other hand, the MRT overtime of point O in all four scenarios only show minor differences, except at hour 16:00, perhaps due to the absence of vegetation in the current scenario, which is present in the last three scenarios. These observations define the significant impact that shading and vegetation can provide. Both PAT of points A and O have little difference, in which point O shows lesser variation.

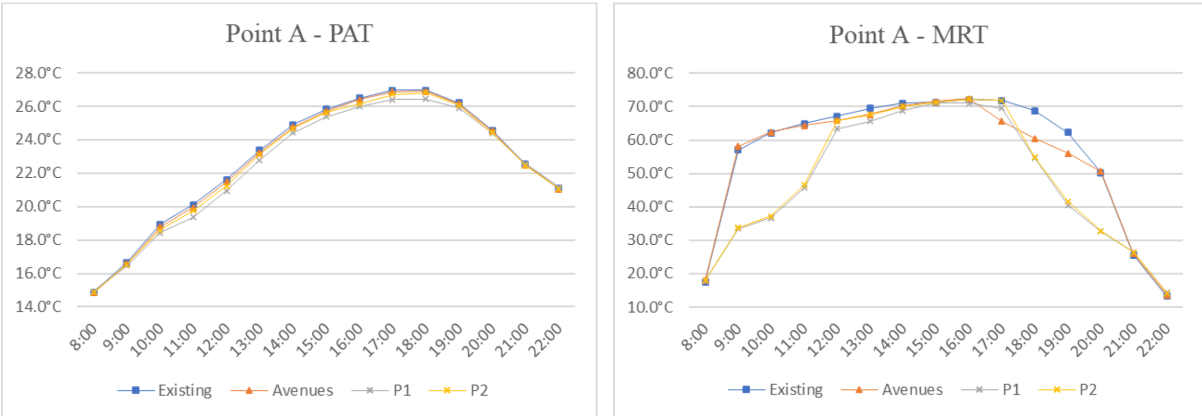


***Figure 4.34** PAT and MRT of point A.*

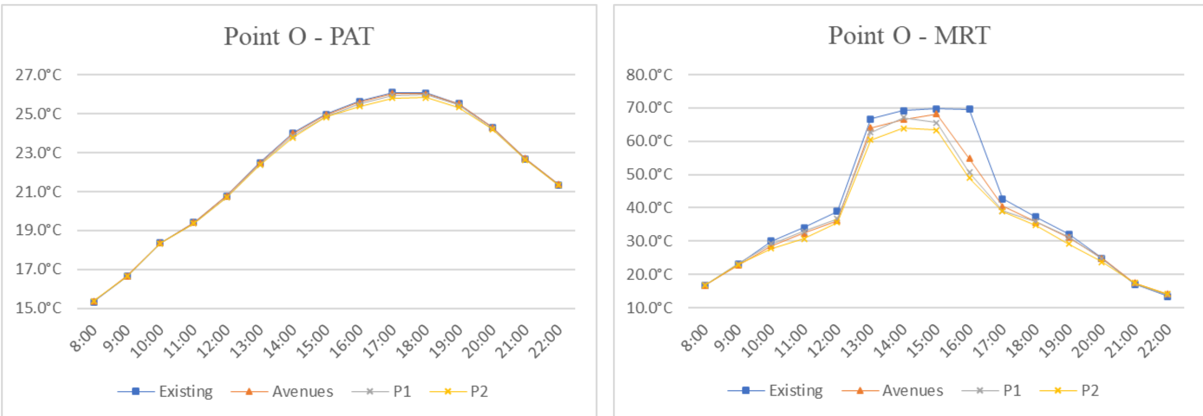


***Figure 4.35** PAT and MRT of point O.*

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The preceding chapter revealed how buildings and streetscapes could significantly mitigate UHI through an urban form modification approach. The following are the conclusions that were uncovered in the result analysis, thus answering the main objectives of this dissertation:

1. In recognising the impacts of urban morphology and streetscaping in Glasgow city centre, it has been observed that open geometry does not always favour urban areas, especially if the environment incorporates hard and impermeable surfaces and lacks green infrastructure. Therefore, a high SVF value does not constantly pertain to good thermal comfort. Nonetheless, all elements contained in the UCL are essential in managing the negative consequences of UHI, signifying the importance of an integrated approach in urban climate mitigation.

2. In analysing the two key streets from Glasgow's streetscape project, it has been observed that E-W oriented street constantly exhibits higher air temperature. This supplements the arguments of Maharoof et al. [2020], which also explored the influences of street orientation on the local climate of Glasgow. That is, although street orientation has a significant influence on air temperature, the configuration of building forms and street width have stronger correlation to it.

3. The local urban climate consequences of the Avenues programme exhibited slight improvement in cooling the environment, with only a maximum MRT and PAT decrease of 8.31°C and 0.07°C, respectively. Of all the Avenues elements, the urban trees demonstrated the optimum benefit in cooling the microclimate, which is evident on the broader street (Argyle Street). On the other hand, the narrow thoroughfare (Hope Street) hindered the addition of urban trees, therefore constraining its potential in decreasing the air temperature.

4. This thesis proves that increasing the aspect ratio could lead to a decrease in the incoming solar radiation, thus cooling the temperature during the day. However, it is crucial to take note of the loss of daylight both to the interior of buildings and streets. This contradicts the principles of Designing streets in allowing light to reach the public realm. Similarly, various contrasting factors in relation to the SDF and Placemaking principles were observed during the course of this dissertation. Therefore, there should be an established degree of agreement in all aspects of placemaking to take forward Glasgow city centre street transformation.

5. Therefore, prior to the key findings, this thesis concludes that incorporating urban morphology and streetscaping is sufficient in managing UHI in urban areas and further enhancing thermal comfort at the street level.

5.2 Limitations

The dissertation is an intensive analysis of two Avenues streets. The other 15 streets from the Avenues programme may have the same mitigation strategy, but these were not studied. Although the experiment solely focused on two streets, it gave a wider understanding of Glasgow due to their complex characteristics, which are mostly present on the other streets.

The streetscaping proposal did not present an entirely different design from the Avenues programme. Instead, just the addition of vegetation, covered pathways, change of materials for footways and road surfaces, and change of planting location whenever is necessary. This purpose is to justify the existing plans for the Avenues project. Also, since this research did not comply with the specific design guidelines set in the development policies of Glasgow, some modifications may not adhere to the restrictions imposed in the current government guidelines.

The first half of this thesis was established during the global pandemic, affecting the initial methodological approach. Therefore, although the Placemaking principle emphasised the importance of social aspects in place-specific strategies, this was not fully integrated with the study but only to a certain extent.

During the ENVI-met simulation, the anthropogenic heat was assumed to be zero since this was not assessed in the software. However, it is expected that a higher aspect ratio leads to higher anthropogenic heat due to the increased human activity that could occur in denser urban areas. Also, as stated in Section 4.5.1, only the albedo values of the surface materials were assessed, overlooking the other physical characteristics. This resulted in an anticipated surface temperature outcome that is not in accordance with reality.

With regards to the traverse study, measurements are better performed during the warmest months (June to August) to critically assess the influences of the urban geometry during the most extreme condition. But due to time restrictions, this was unlikely to follow.

Lastly, due to the combined strategies enforced in the proposals (shading effect, street greening, and surface albedo), there are uncertainties in verifying which specific factor enhanced the microclimate or whether certain approaches restricted the maximum cooling potential of the others. Nevertheless, a combined cooling strategy was evident in improving the thermal comfort of an urban area.

5.3 Recommendations

5.3.1 Recommendation for Local Authority, Designers, and Planners

Decision-making in the design and planning is a crucial part of establishing climate-sensitive strategies. There is indeed no single and straightforward solution in addressing UHI. But as argued in this dissertation and several related studies, managing UHI could be achieved comparatively by modifying the horizontal and vertical density of an urban area. This measure is especially beneficial in enhancing local thermal comfort at the street level, which could be achieved through multi-sectoral collaboration between GCC, urban planners, and designers. Below are qualitative guidelines to offer regarding urban geometry and streetscaping that can be of direct benefit to planners and policymakers in Glasgow city centre:

1. In areas where there is ample space, it is recommended to invest more on street greening in preference to other street elements. Although other approaches have shown a positive impact in enhancing the streets, it is apparent that the former offered further improvement, demonstrating a maximum net radiant heat loss of 14.13°C. And this does not consider yet the fact that trees can be effective air filters and have capabilities of storing carbon which alleviates the impacts of climate change [UN, 2019].

2. In relation to the preceding guideline, trees and other greening mechanisms stationed in traffic islands have been proven to cool the area and better circulate the airflow. In addition, Traverso [2020] found that deciduous urban trees with big canopies and dense, broad leaves reduce air pollution by filtering particulate from motor vehicles.

3. With regards to building configuration, staggering of facades at upper levels demonstrated an enhanced temperature, both in PAT and MRT, with a maximum decrease of 0.14°C and 0.73°C, respectively. This is especially beneficial in areas with stringent and narrow thoroughfares in establishing openness to allow solar access at the pedestrian level.

4. The use of high albedo ground surface materials is favoured if accompanied by shading methods. This could also apply in narrow streets flanked by buildings with considerable heights. Since the structures already cast shadows, it will prevent light-coloured surfaces from indirect solar radiation, thus avoiding the increase in temperature. Likewise, high albedo materials will aid the release of outgoing longwave radiation faster during the night since more radiation is reflected back to space. Therefore, maximising shelter, thermal comfort, and pollution dispersion.

5. On the other hand, areas with narrow streets flanked by low-rise buildings could benefit from using covered pathways, canopies, or other shading devices, to enhance thermal comfort, especially if there is no room for street greening. It could either be a green or typical roof since there is a negligible difference in cooling the environment, as observed in the results analysis. But for maintenance purposes, the author recommends the latter.

6. Although brick showed an improved air temperature at the street level, this is not a suitable material in high-traffic areas. This thesis did acknowledge the use of brick for the purpose of demonstrating the impacts of various materials in urban areas, but for

long-term durability and safety reasons, light-coloured asphalt is preferred. Agreeably, this is present in the current Avenues proposal.

7. In areas with wider streets, pushing forward of walls in higher floor exhibited good shading technique, especially in south-facing facades. This method is also beneficial in increasing the building density.

8. Lastly, in terms of aspect ratio, this thesis established some degree of agreement. An aspect ratio of 0.4 (point A of P1) showed a substantial decrease in MRT and PAT, with the provision of street greening. A dense form (H/W=0.6 to 1.0) can evidently maintain both pollution dispersion and solar access within the streets. Correspondingly, Oke [1988] concluded that an aspect ratio of approximately 0.6 is indeed suitable for retaining solar access in mid-latitude cities like Glasgow. And although an aspect ratio of 1.0 to 1.40 could decrease the temperature within urban canyons, it does not justify a significant improvement in the microclimate. In fact, it could contribute to an increase in either MRT or PAT, as observed in both proposals of points H to J. Hence, it should be avoided.

5.3.2 Recommendation for Further Studies

The previous section presented a qualitative guideline in establishing climate-sensitive strategies on a local scale. This thesis was incapable of giving specific dimensions because aspect ratio varies since it associates both street width and building height. However, there is a need for quantitative standards. Although Oke [1988] argued that setting rigid criteria for the urban canyon geometry is not sensible, the rise of new technology and innovative simulation software can be a solution to achieve quantifiable measures which are potentially helpful to the establishment of government guidelines.

As stated in the limitation section, this thesis did not fully integrate the social aspect. Hence, strengthening the community engagement facet would be a key part of future works.

Lastly, since this dissertation only considered building geometry, further research regarding building materials is essential for albedo enhancement. Likewise, there is a need for actual field data to validate surface albedo since other factors in surface materials are not assessed simply by simulation software.

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APPENDICES

Appendix I: The Placemaking Principle and Designing Streets

There are six design processes under the Placemaking principle, but only the first two stages are crucial in connection with the project. These are:

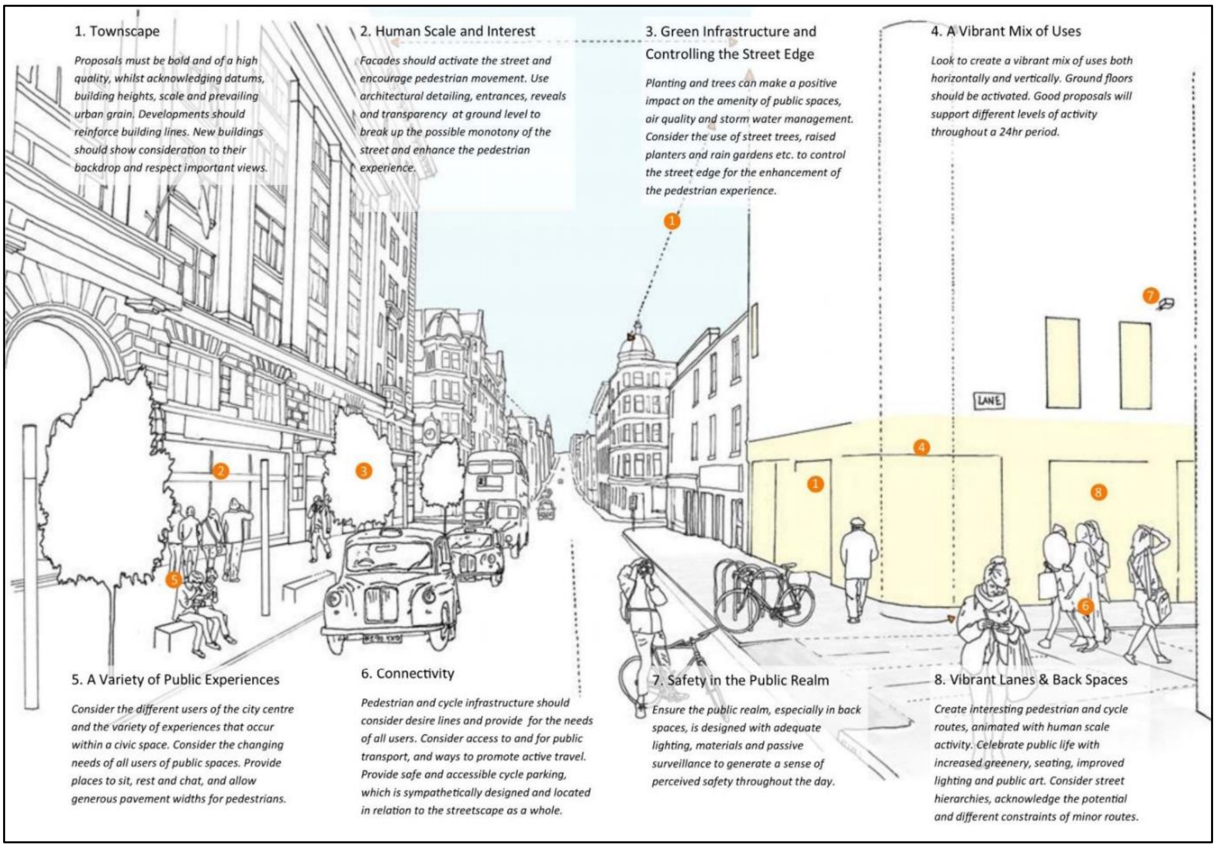
- **Site and Context Appraisal** – there should be an evaluation of the existing characteristics of a site and its surrounding, such as SWOT analysis, to address wider concerns and meet the areas' needs.

- **Urban Design Strategy** – 'Placemaking' should reinforce engagement and community input to promote a sense of ownership and allow communities to have greater influence over their environment. Moreover, design solutions should accord with city's policies and strategies, protect the historic environment of the city centre, and preserve its existing physical, social, and cultural heritage.

Table A *Six Qualities of Places.*

Character and Identity	**Successful Open Space**
Use of local materials and resources which also enhance the surrounding Ensure important views and landmarks are visible Enhance and harmonise the distinctive character and sense of place Materials should acknowledge the area's architectural context	Multi-functional spaces can adapt to future changes Offer a comfortable environment for different people at different times of day Engages individual and create opportunity for socialising Well-designed landscaping which enhances biodiversity
Legibility and Safety	**Ease of Movement**
Accessible, well-maintained, and well-lit Improved connectivity	Reduce car use, overcrowding, and air pollution Have good surfaces and obstacle-free
Vibrance and Density	**Adaptability and Sustainability**
Attract people and encourage activity Provide active travel, physical activity, health, and engagement with nature Establish a clear understanding of site context and the unique aspects Showcase variety of building forms	Sustainable in terms of materials, design, and climate change resilience Meet the existing and future needs of local communities and can respond to changing circumstances Use high quality and durable materials Incorporate planting suitable to Glasgow's climate Consider recycling traditional buildings for sustainable development

The diagram below shows the appropriate placemaking priorities specifically for the city centre. In addition, climate responsive design and nature-based design solutions should be key features for all new developments.



Characteristics of a Sustainable City Centre. Source: GCC, 2018a.

Streets can be a crucial factor in the city's aim towards sustainable development and responding to climate change. Hence, good street designs should develop from a sensible response to location rather than the prescribed standards, regardless of the area's context. In some cases, certain design guidelines are not applicable due to the nature of specific areas. Therefore, rules are modified and can be flexible, which would also encourage design innovation. Below are the Placemaking principles and Designing Streets guidelines to consider:

Table B *The Placemaking Principles and Designing Streets Guidelines.*

Street Elements	• Should encourage social interaction and maximise environmental benefits • The public realm should be distinctive with landmarks and vistas • Due to the significant rainfall in Glasgow, cycle parking should have shelter provision • Limit public off-street parking • Reduce traffic signs, road markings, and other traffic management elements, as it indicates priority to pedestrians rather than motorists

Walkways and Carriageways	• Should reduce and control vehicle speed naturally by meticulous design, such as cobbled surface and width reduction in carriageways • Cycle lanes should only be for streets with high traffic volumes and speeds • Contrasting colours and tactile paving for footway surfacing should be used for pedestrian priority, especially to visually impaired pedestrians • Street walkways may use setts, paving, whinstone, or granite kerbs • Should not be channelled between high or dense plants to avoid the creation of blind corners
Vegetations	• Proper driver sightlines should be considered when placing vegetation • Tree selection – slow-growing types with narrow trunks and canopies • Increase the canopy cover to a minimum of 5% per city block • Deciduous trees provide shade in the summer and allow heat and light during winter • Planting should not reduce wind exposure
Buildings	• Maximise solar gain through south facing façade • Consider the prevailing wind direction • Overshadowing should be avoided • Massing has the capability to maximise natural energy • Shading devices control solar access during summer while allowing sun on winter season • Provision of balconies, green walls, and roof gardens • Respect the urban morphology in terms of height, urban grain, skyline, scale, and massing • Appropriate building materials include natural sandstone, brick, cast stone, concrete, raw or treated metal, glass, slate roof, and living roof • Increased building heights should not make the street oppressive or restricted • Building heights should allow light to reach the public realm • When buildings maximise solar gain, it will lower heat and light requirements

Appendix II: The Avenues Programme Communication Plan

Key Local Stakeholders:

- Residents / businesses / passers-by
- People who work / visit the area
- Vulnerable user groups
- GCC members
- Stakeholder organisations
- Local interest groups
- Community groups
- Statutory consultees

Methodology:

- Focused stakeholder meetings
- Focused community engagement
- Wider stakeholder and community engagement
- On-street questionnaires and information distribution
- Free-standing display posters and banners
- On-line survey invitation and consultation
- Website link to wider Glasgow Avenues site
- On-line commentary through community portal
- Site walkover
- Door-knock survey distribution
- Door-to-door consultation
- Leaflets, emails, and letters
- Social media
- Workshops
- Drop-in consultation event
- Meeting and telephone consultation with business owners
- Commentary of graphic animations and visualisations of draft proposals

Source: EIIPR Communication Plan (Ironside Farrar, 2019).

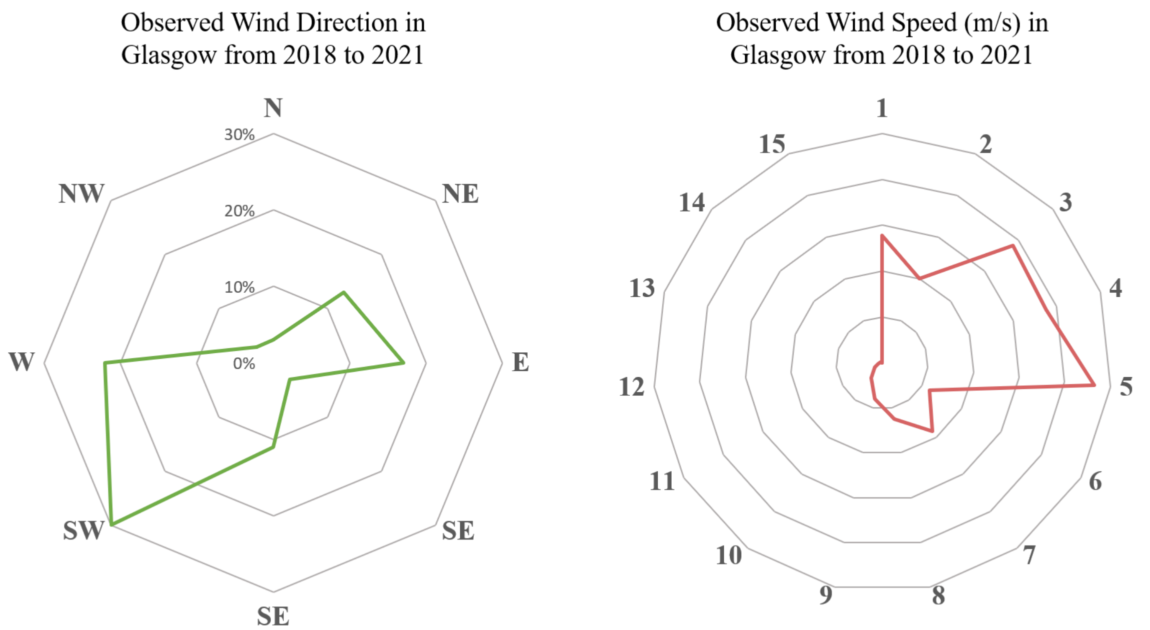
Appendix III: ENVI-met Simulation Setting

ENVI-met Model Parameter		**Setting**	
		SITE A	**SITE B**
Parameter	Definition	Argyle Street West	Hope Street
Main Data	Site Size	800 x 408 x 135 m	348 x 816 x 120 m
	Domain Size	200 x 102 x 45	127 x 287 x 40
	Cell Size	4 x 4 x 3 m	4 x 4 x 3 m
	Geo Reference North Angle	10.30°	12.50°
	Nesting Grid	3	
	Vertical Grid	Telescoping	
Simulation Time	Start Date	27 June 2018	
	Start Time	18:00	
	Simulation Time	30 hours	
Meteorological Conditions	Wind Speed	2.24 m/s	
	Wind Direction	315°	
	Roughness Length	0.10	
	Temperature (°C)	Min = 10.70 at 2:00 | Max = 29.20 at 17:00	
	Relative Humidity (%)	Min = 33.90 at 15:00 | Max = 98.00 at 3:00	
	Simple Forcing	Force temperature and Humidity	
Time Steps	Time steps (a) t0, (b) t1, and (c) t2	a: 10 | b: 2 | c: 1 sec	
	Solar angle for switching to (a) to t1 and (b) t1 to t2	a: 40° | b: 50°	

Case Parameter			
Scenarios	**Properties**		
	Urban Geometry	*Streetscape*	
Existing Condition	Existing urban geometry	Existing street layout	
Avenues Programme	Existing urban geometry	Avenues proposed streetscaping	
Proposal 1	Buildings with basic rectangular forms oriented towards dominant wind and sun position	Trees and Shrubs	+15% = Argyle Street +10% = Hope and Oswald Streets
		Grass	NA = Argyle Street +5% = Hope and Oswald Streets
Proposal 2	Buildings with internal courtyards	Trees and Shrubs	+15% = Argyle Street +10% = Hope and Oswald Streets
		Grass	NA = Argyle Street +5% = Hope and Oswald Streets

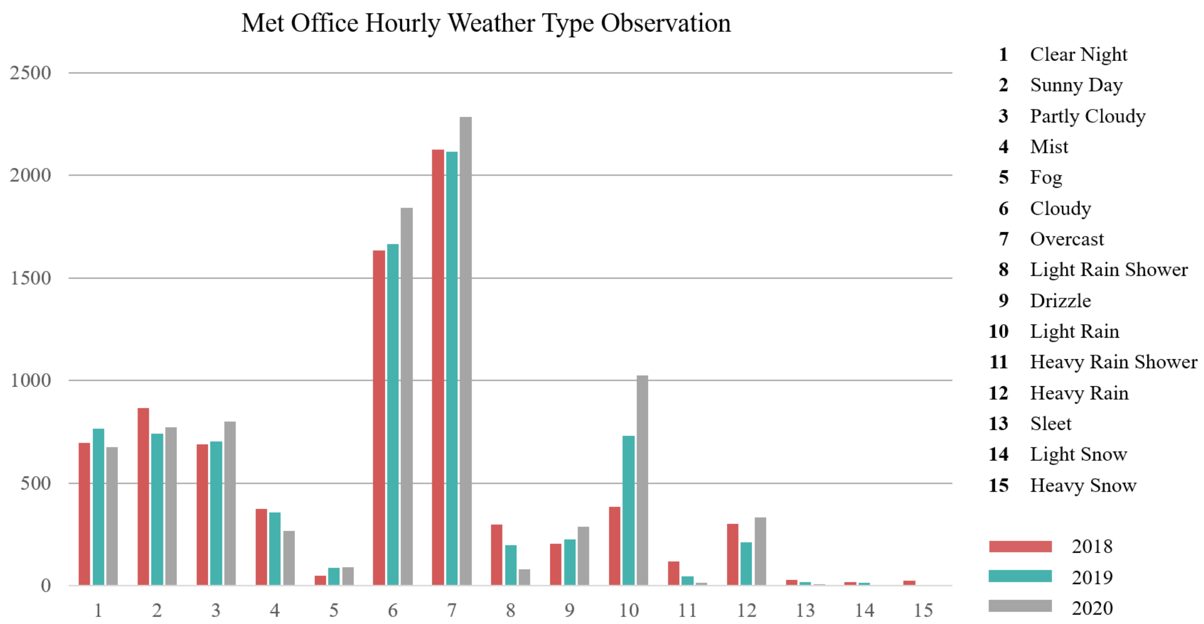
All other parameters were kept at the default setting.

Appendix IV: Prevailing Wind Direction, Wind Speed, and Weather Type



Typical Wind Direction and Speed in Glasgow. Source: Adapted from Weather Online, 2021; UBDC, 2021b.

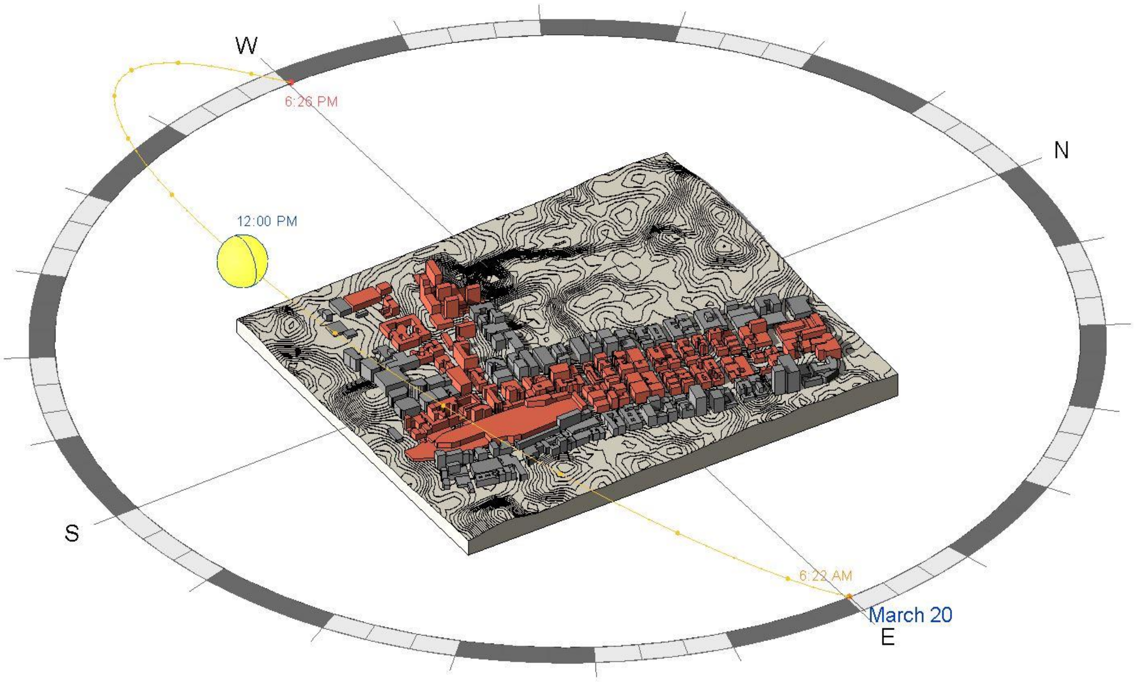
Based on historical meteorological data of Glasgow, the typical wind speed ranges from 3 to 5 m/s, signifying low to moderate wind velocity.

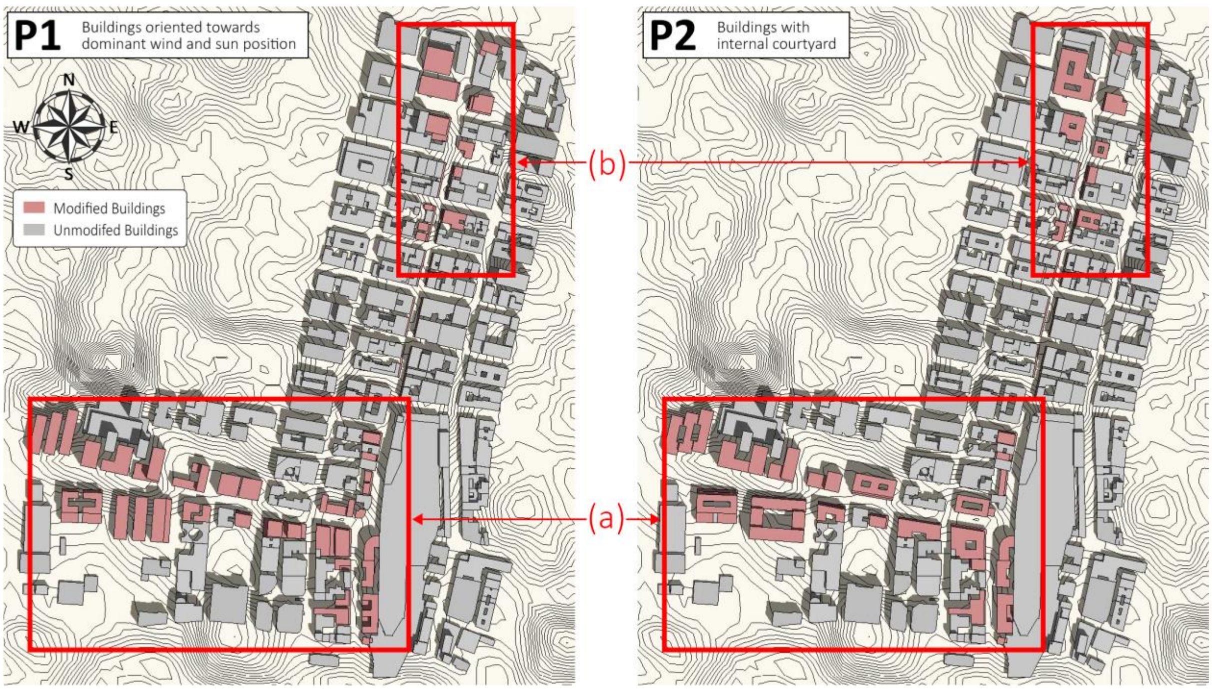


Typical Weather Type in Glasgow. Source: Adapted from Weather Online, 2021; UBDC, 2021b.

Appendix V: Shadow Range

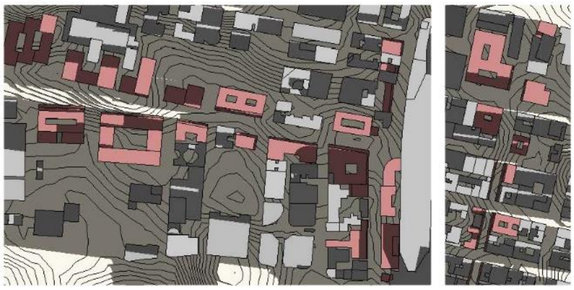
Overshadowing assessments of the proposed scenarios were carried out using the sun path diagram function of Autodesk Revit. The diagrams on the following pages show the shadow ranges at two-hour intervals.





P1 | March 21 | 7 am (a) (b)

P2 | March 21 | 7 am (a) (b)

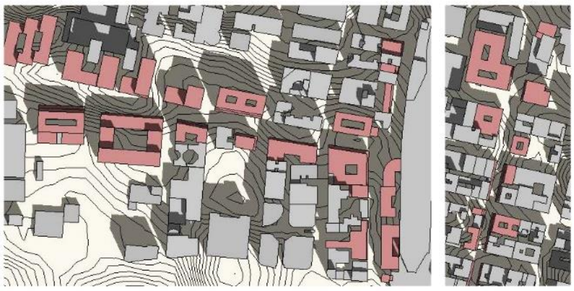


P1 | March 21 | 9 am (a) (b)

P2 | March 21 | 9 am (a) (b)

P1 | March 21 | 11 am (a) (b)

P2 | March 21 | 11 am (a) (b)



P1 | March 21 | 1 pm (a) (b)

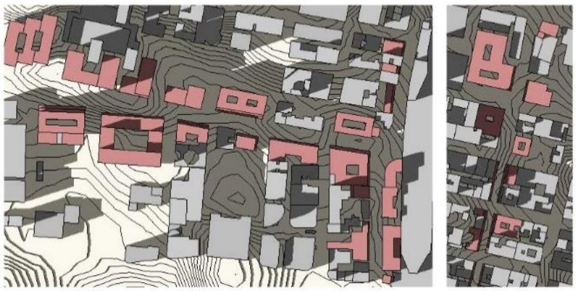
P2 | March 21 | 1 pm (a) (b)

P1 | March 21 | 3 pm (a) (b)

P2 | March 21 | 3 pm (a) (b)

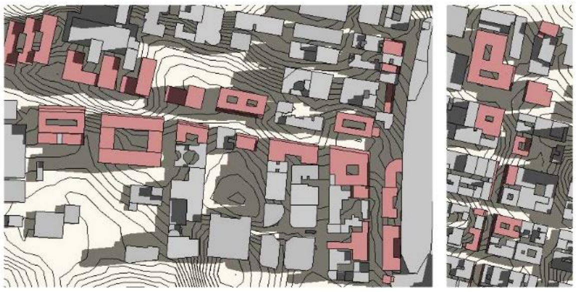
P1 | March 21 | 5 pm (a) (b)

P2 | March 21 | 5 pm (a) (b)



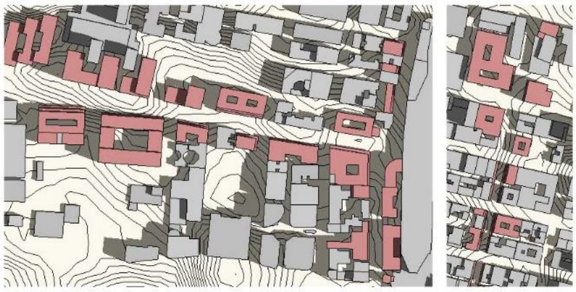
P1 | June 21 | 7 am (a) (b)

P2 | June 21 | 7 am (a) (b)



P1 | June 21 | 9 am (a) (b)

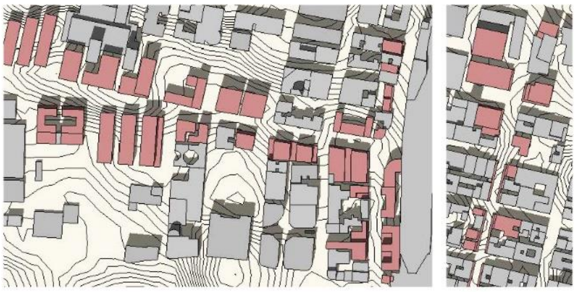
P2 | June 21 | 9 am (a) (b)



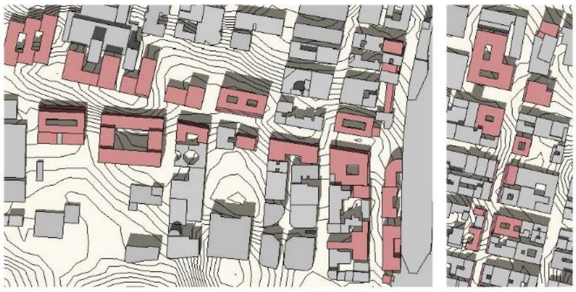
P1 | June 21 | 11 am (a) (b)

P2 | June 21 | 11 am (a) (b)

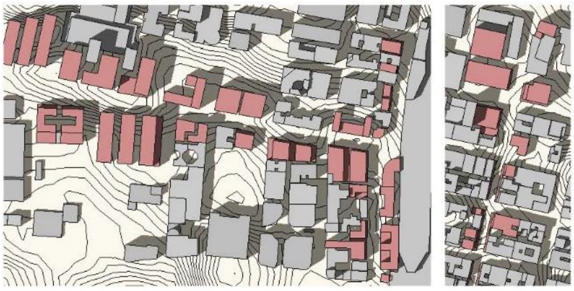
P1 | June 21 | 1 pm (a) (b)



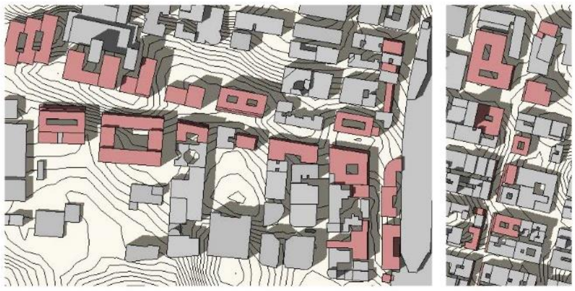
P2 | June 21 | 1 pm (a) (b)



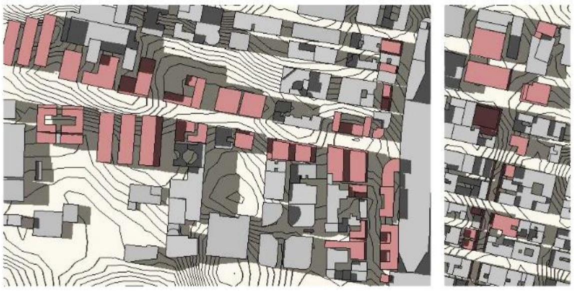
P1 | June 21 | 3 pm (a) (b)



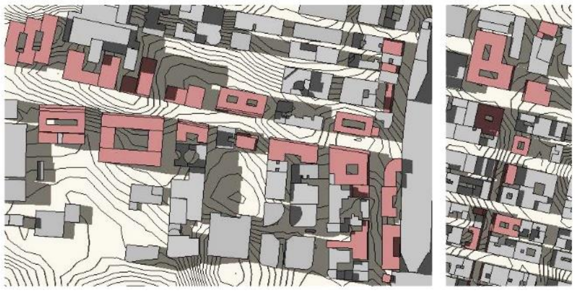
P2 | June 21 | 3 pm (a) (b)



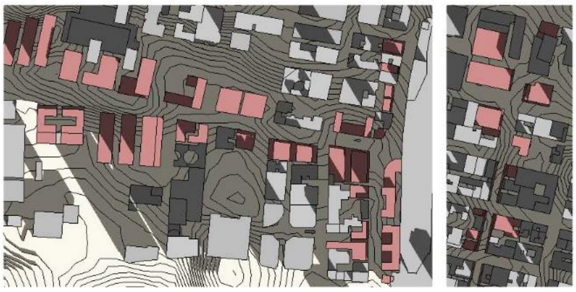
P1 | June 21 | 6 pm (a) (b)



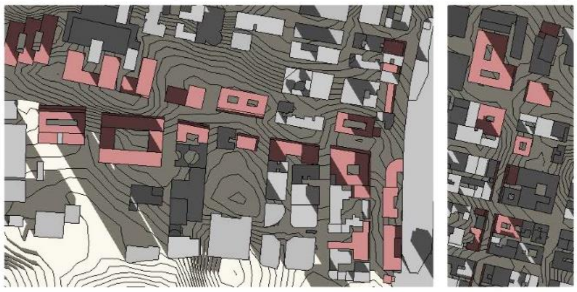
P2 | June 21 | 6 pm (a) (b)



P1 | December 21 | 10 am (a) (b)



P2 | December 21 | 10 am (a) (b)



P1 | December 21 | 12 nn (a) (b)

P2 | December 21 | 12 nn (a) (b)

P1 | December 21 | 2 pm (a) (b)

P2 | December 21 | 2 pm (a) (b)

Appendix VI: Complete Traverse Measurement

	Points	Fixed Station (FS) Measurement				Traverse (TR) Measurement				Corrected T_{AIR} at each Point	TR - FS
		MIN	*MEAN*	*MAX*	*STDEV*	*MIN*	*MEAN*	*MAX*	*STDEV*		
May 27, 2021 | 3:00 PM | R^2 = 0.80 C - Slightly Unstable	A	20.34 °C	20.40 °C	20.47 °C	0.05 °C	24.27 °C	24.40 °C	24.61 °C	0.11 °C	24.04 °C	3.34 °C
	A1	20.39 °C	20.43 °C	20.46 °C	0.02 °C	24.68 °C	24.82 °C	24.92 °C	0.08 °C	24.53 °C	3.84 °C
	B	20.38 °C	20.39 °C	20.41 °C	0.01 °C	24.03 °C	24.14 °C	24.33 °C	0.06 °C	23.93 °C	3.24 °C
	B1	20.43 °C	20.47 °C	20.57 °C	0.04 °C	24.43 °C	24.78 °C	25.00 °C	0.17 °C	24.68 °C	3.98 °C
	C	20.67 °C	20.70 °C	20.72 °C	0.01 °C	25.02 °C	25.06 °C	25.10 °C	0.03 °C	25.06 °C	4.36 °C
	D	20.55 °C	20.59 °C	20.63 °C	0.02 °C	24.41 °C	24.66 °C	25.02 °C	0.19 °C	24.77 °C	4.07 °C
	E	20.45 °C	20.46 °C	20.47 °C	0.00 °C	23.16 °C	23.64 °C	24.02 °C	0.26 °C	23.85 °C	3.16 °C
	F	20.41 °C	20.42 °C	20.44 °C	0.01 °C	22.18 °C	22.48 °C	22.72 °C	0.18 °C	22.79 °C	2.09 °C
	G	19.99 °C	20.03 °C	20.09 °C	0.03 °C	22.26 °C	22.29 °C	22.32 °C	0.02 °C	22.88 °C	2.19 °C
	G1	20.22 °C	20.27 °C	20.29 °C	0.02 °C	22.09 °C	22.33 °C	22.56 °C	0.15 °C	22.79 °C	2.10 °C
	H	19.62 °C	19.69 °C	19.76 °C	0.04 °C	21.88 °C	22.21 °C	22.53 °C	0.20 °C	22.94 °C	2.25 °C
	I	19.27 °C	19.33 °C	19.38 °C	0.03 °C	22.29 °C	22.38 °C	22.42 °C	0.03 °C	23.24 °C	2.54 °C
	J	18.80 °C	18.95 °C	19.11 °C	0.08 °C	21.61 °C	22.20 °C	22.70 °C	0.33 °C	23.16 °C	2.46 °C
	K	18.91 °C	18.92 °C	18.93 °C	0.00 °C	21.96 °C	22.13 °C	22.40 °C	0.12 °C	23.17 °C	2.48 °C
	L	18.77 °C	18.83 °C	18.93 °C	0.05 °C	21.49 °C	21.67 °C	21.95 °C	0.14 °C	22.79 °C	2.10 °C
	M	18.72 °C	18.80 °C	18.91 °C	0.06 °C	21.20 °C	21.36 °C	21.47 °C	0.09 °C	22.56 °C	1.86 °C
	M1	19.05 °C	19.17 °C	19.24 °C	0.06 °C	21.24 °C	21.27 °C	21.33 °C	0.03 °C	22.54 °C	1.84 °C
	N	19.23 °C	19.29 °C	19.35 °C	0.04 °C	21.31 °C	21.45 °C	21.55 °C	0.09 °C	22.81 °C	2.11 °C
	N1	19.19 °C	19.25 °C	19.30 °C	0.03 °C	21.20 °C	21.42 °C	21.53 °C	0.11 °C	22.85 °C	2.15 °C
	O	19.11 °C	19.15 °C	19.25 °C	0.04 °C	20.37 °C	20.64 °C	20.92 °C	0.18 °C	22.15 °C	1.45 °C
May 31, 2021 | 8:00 PM | R^2 = 0.96 D - Neutral	A	21.57 °C	21.63 °C	21.71 °C	0.04 °C	22.22 °C	22.39 °C	22.64 °C	0.14 °C	21.77 °C	1.16 °C
	A1	21.40 °C	21.46 °C	21.53 °C	0.04 °C	22.84 °C	22.98 °C	23.11 °C	0.08 °C	22.44 °C	1.83 °C
	B	21.25 °C	21.30 °C	21.35 °C	0.03 °C	23.23 °C	23.52 °C	23.82 °C	0.18 °C	23.06 °C	2.45 °C
	B1	21.05 °C	21.12 °C	21.16 °C	0.03 °C	24.23 °C	24.25 °C	24.26 °C	0.01 °C	23.90 °C	3.29 °C
	C	20.88 °C	20.93 °C	20.99 °C	0.03 °C	23.70 °C	23.92 °C	24.16 °C	0.14 °C	23.65 °C	3.04 °C
	D	20.75 °C	20.79 °C	20.83 °C	0.02 °C	23.35 °C	23.45 °C	23.57 °C	0.07 °C	23.26 °C	2.65 °C
	E	20.64 °C	20.67 °C	20.69 °C	0.02 °C	23.05 °C	23.12 °C	23.17 °C	0.03 °C	23.01 °C	2.40 °C
	F	20.60 °C	20.61 °C	20.62 °C	0.01 °C	22.76 °C	22.81 °C	22.86 °C	0.03 °C	22.81 °C	2.20 °C
	G	20.52 °C	20.53 °C	20.55 °C	0.01 °C	22.13 °C	22.30 °C	22.46 °C	0.10 °C	22.41 °C	1.80 °C
	G1	20.43 °C	20.45 °C	20.47 °C	0.01 °C	21.69 °C	21.73 °C	21.81 °C	0.03 °C	21.95 °C	1.34 °C
	H	20.20 °C	20.25 °C	20.31 °C	0.03 °C	21.22 °C	21.28 °C	21.33 °C	0.03 °C	21.66 °C	1.05 °C
	I	20.15 °C	20.15 °C	20.16 °C	0.00 °C	20.97 °C	21.04 °C	21.10 °C	0.04 °C	21.52 °C	0.91 °C
	J	20.09 °C	20.12 °C	20.13 °C	0.01 °C	20.89 °C	20.91 °C	20.92 °C	0.01 °C	21.50 °C	0.89 °C
	K	19.97 °C	20.00 °C	20.04 °C	0.02 °C	20.74 °C	20.79 °C	20.86 °C	0.04 °C	21.49 °C	0.88 °C
	L	19.92 °C	19.94 °C	19.96 °C	0.01 °C	20.64 °C	20.68 °C	20.70 °C	0.02 °C	21.46 °C	0.85 °C
	M	19.88 °C	19.89 °C	19.90 °C	0.01 °C	20.49 °C	20.53 °C	20.59 °C	0.03 °C	21.39 °C	0.78 °C
	M1	19.83 °C	19.85 °C	19.86 °C	0.01 °C	20.49 °C	20.52 °C	20.54 °C	0.01 °C	21.46 °C	0.85 °C
	N	19.77 °C	19.79 °C	19.81 °C	0.01 °C	20.47 °C	20.50 °C	20.54 °C	0.02 °C	21.52 °C	0.91 °C
	N1	19.72 °C	19.74 °C	19.75 °C	0.01 °C	20.40 °C	20.42 °C	20.43 °C	0.01 °C	21.52 °C	0.91 °C
	O	19.70 °C	19.71 °C	19.71 °C	0.00 °C	20.38 °C	20.40 °C	20.42 °C	0.01 °C	21.58 °C	0.97 °C
May 30, 2021 | 8:00 PM | R^2 = 0.98 E - Moderately Stable	A	20.50 °C	20.51 °C	20.52 °C	0.00 °C	20.98 °C	21.01 °C	21.02 °C	0.01 °C	20.95 °C	0.45 °C
	A1	20.48 °C	20.50 °C	20.51 °C	0.01 °C	21.04 °C	21.12 °C	21.23 °C	0.06 °C	21.12 °C	0.63 °C
	B	20.45 °C	20.46 °C	20.48 °C	0.01 °C	21.38 °C	21.51 °C	21.60 °C	0.07 °C	21.57 °C	1.07 °C
	B1	20.40 °C	20.41 °C	20.42 °C	0.01 °C	21.60 °C	21.60 °C	21.61 °C	0.00 °C	21.74 °C	1.24 °C
	C	20.37 °C	20.38 °C	20.39 °C	0.01 °C	21.46 °C	21.52 °C	21.57 °C	0.03 °C	21.72 °C	1.23 °C
	D	20.33 °C	20.35 °C	20.36 °C	0.01 °C	21.36 °C	21.40 °C	21.42 °C	0.02 °C	21.65 °C	1.16 °C
	E	20.27 °C	20.29 °C	20.32 °C	0.01 °C	21.25 °C	21.31 °C	21.34 °C	0.03 °C	21.63 °C	1.13 °C
	F	20.20 °C	20.22 °C	20.25 °C	0.01 °C	21.21 °C	21.22 °C	21.23 °C	0.00 °C	21.60 °C	1.10 °C
	G	20.13 °C	20.15 °C	20.17 °C	0.01 °C	20.96 °C	21.04 °C	21.12 °C	0.05 °C	21.50 °C	1.00 °C
	G1	20.07 °C	20.09 °C	20.10 °C	0.01 °C	20.68 °C	20.74 °C	20.82 °C	0.04 °C	21.26 °C	0.76 °C
	H	19.93 °C	19.95 °C	19.97 °C	0.01 °C	20.33 °C	20.38 °C	20.43 °C	0.03 °C	21.03 °C	0.53 °C
	I	19.80 °C	19.83 °C	19.87 °C	0.02 °C	20.23 °C	20.26 °C	20.29 °C	0.02 °C	21.00 °C	0.50 °C
	J	19.73 °C	19.75 °C	19.78 °C	0.01 °C	20.03 °C	20.10 °C	20.17 °C	0.05 °C	20.89 °C	0.39 °C
	K	19.69 °C	19.70 °C	19.72 °C	0.01 °C	20.02 °C	20.02 °C	20.02 °C	0.00 °C	20.89 °C	0.39 °C
	L	19.64 °C	19.65 °C	19.67 °C	0.01 °C	19.94 °C	19.98 °C	20.01 °C	0.02 °C	20.91 °C	0.41 °C
	M	19.55 °C	19.59 °C	19.62 °C	0.02 °C	19.82 °C	19.85 °C	19.89 °C	0.02 °C	20.84 °C	0.34 °C
	M1	19.46 °C	19.49 °C	19.52 °C	0.02 °C	19.80 °C	19.81 °C	19.82 °C	0.01 °C	20.86 °C	0.37 °C
	N	19.38 °C	19.40 °C	19.43 °C	0.01 °C	19.79 °C	19.80 °C	19.82 °C	0.01 °C	20.91 °C	0.42 °C
	N1	19.31 °C	19.33 °C	19.36 °C	0.01 °C	19.79 °C	19.80 °C	19.80 °C	0.00 °C	20.96 °C	0.47 °C
	O	19.26 °C	19.28 °C	19.30 °C	0.01 °C	19.76 °C	19.76 °C	19.77 °C	0.00 °C	20.99 °C	0.50 °C

Appendix VII: Building in Argyle Street, parallel to point B1