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Examining the impact of urban canyons morphology on outdoor environmental conditions in city centres with a temperate climate

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ABSTRACT

The concept of future-proofing cities seeks to minimise environmental impacts by utilising various mitigation and adaptation techniques, specifically by improving urban fabric. Studies on urban forms and parameters have been extensively conducted in hot, arid and humid climates while they have been less investigated in temperate climates. In the UK, the current local urban design guides meet the needs of designers and urban planners, however, they are still considered descriptive and lack in-depth environmental assessment. This study aims to investigate the recommended threshold values in the National Model Design Code against real sites with different urban canyons morphologies to examine their impact on outdoor environmental conditions. The study used quantitative methods by conducting a review study, a survey on UK urban design guides and modelling using simulation via RayMan and IESVE. The study targeted pre-selected sites in Cardiff and Bristol that were identified as zones with urban heat stress. The results showed that the Aspect Ratio and Sky View Factor (SVF) in two cities have significantly impacted outdoor environmental conditions in urban areas subsequently affecting the Physiological Equivalent Temperature (PET). The results showed that the recommended values have a significant impact on the outdoor thermal performance of the pre-selected urban canyons. The findings demonstrated that modifying the width of streets and changing the Aspect Ratio and SVF resulted in achieving a positive impact during summer when both factors have a direct relationship. However, when the Aspect Ratio and SVF have an inverse relationship, the results demonstrated extreme cold stress during winter. Therefore, maintaining a direct relationship between the Aspect Ratio and SVF would help to improve outdoor conditions.

1. Introduction

With the rapid climatic changes and the rise in global temperatures, cities face challenges to provide comfort for outdoor spaces that consider a pressing issue. Urban microclimate research has become essential in the last few decades due to global warming and temperature escalation among other factors, affecting the quality of outdoor urban environments. Despite the vast amount of theoretical research available, limited studies were translated into practical actions that resulted in a gap between research and application [1,2,3]. Nazarian et al. [4] stated that there are limitations in supporting architects, planners, and decision makers on strategies that cover the performance of outdoor spaces in terms of thermal comfort. Matos Silva and Costa [5] stated that diminishing the gap between theory and practice could inform a better design of outdoor urban environments in times of drastic climate change. Also, it could improve the prediction of future climatic projections that would provide a basis for quantifiable data.

Future-proofing cities are developed by using different techniques in the form of passive and active solutions as strategies for environmental mitigation [6]. Different approaches to attain future-proofing would lead to re-ecologising the built environment by reducing carbon emissions and increasing energy efficiency. Using active/hybrid technologies to produce green energy to achieve carbon-neutral close to zero-toxic consider important in the built environment. For instance, utilising biofuels in the form of algae from photobioreactors represent an effective mitigation strategy [7,8]. Also, assessing construction and retrofitting stages as well as using photovoltaic panels deem practical approaches[9]. Furthermore, controlling air pollution in areas with traffic and vehicle movements, particularly by understanding travel movements and pedestrian behaviour demonstrate feasible ways [10,11,12]. Capturing CO_2 and sequestration is gaining popularity based on various methods, which represent an effective solution to mitigate climate change[13]. These concepts help in shaping strategies for decarbonization in the built environment to improve outdoor conditions and help in providing ways for carbon capture and storage [14,15].

On the other hand, future-proofing strategies based on passive techniques could be demonstrated by understanding the relationship between urban parameters and microclimatic data. Hirashima et al. [16] corroborated this by expressing the need for an in-depth under-

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standing of urban climatology and its effects on enhancing outdoor urban environments to be used at different times of the year. Santos Nouri and Costa [17] argued that implementing a triangulation process that covers climate change, urban design and user-based approaches could help to achieve successful outdoor urban environments.

Taleghani et al. [18] stated that different urban forms and parameters have been extensively investigated in hot, arid and humid climates, however, they have been less studied in temperate climates. Given the projected impacts of climate change, the UK government has identified the need for anticipating and planning for the effects of these changes through funding a series of projects. Despite the availability of such projects and urban microclimate research in the UK context [19,20,21], it is yet considered limited in comparison to available research in hot, arid and humid climates. In the UK, collaborative research on Urban Heat Islands (UHIs) examined the topic in depth within multiple metropolitan cities to deduce effective mitigation initiatives to reduce the impact of climate change [21]. Thus far, research has found that UHIs develop in areas with low wind speeds. Additionally, UHIs have a stronger correlation with minimum temperatures rather than maximum temperatures during summer. Specifically, within the UK, researchers found that there is a 7°C difference in air temperatures between urban and rural areas [22]. Furthermore, a study by Taher et al. [21] examined UHI effects in the city of London, it was concluded that the city will face an increase of 9°C in air temperature compared to its surroundings. On the other hand, a study by Chowienczyk et al. [20] examined multiple metropolitan cities within the UK, including Cardiff, and found that within the Cardiff metropolitan area UHIs intensity strongly correlates with maximum temperatures rather than the usual minimum. Overall, the research infers that urban geometry parameters and their effects on Urban Heat Islands have been widely researched within the UK, however, outdoor thermal comfort requires further research.

The effects of urban geometry parameters extend beyond thermal comfort, into a much larger phenomenon that shapes Urban Heat Islands (UHIs) [20]. Nowadays, rapid urbanization has replaced green spaces with buildings and roads which massively affected the conditions of local climates. Thermal comfort was initially intended for indoor spaces, however, with the rising issues of rapid urbanization, climate change and global warming, it has become applicable to outdoor spaces [23,24]. Liu et al. [25] argued that the heat transfer between a human body and its surrounding environment is a result of multifactorial effects concerning both physical and non-physical parameters. Physical parameters include clothing, physical activities and urban geometry, whereas non-physical parameters include solar radiation, air temperature, air speed, humidity and cloud cover. Due to the complexity of climatological parameters, heat transfers between a human body and the surrounding environment are considered unstable and changeable according to time, place and season [26]. Studies suggested that there are seasonal differences in preference and thermal neutrality in outdoor spaces such as the tendency to prefer higher temperatures in winter and lower temperatures in summer. Hence, the concept of outdoor thermal comfort is vital in climate responsive urban design to establish the boundaries of optimum climatic conditions [17]. Therefore, it is vital to study both physical parameters in the form of urban geometry and non-physical parameters in the form of solar radiation, air temperature, air speed, humidity and cloud cover and their effects on human beings using a thermal index .

The integrated effect of urban parameters and microclimatic data can be evaluated using an array of thermal indices. Thermal indices include the Universal Thermal Climate Index (UTCI), Standard Effective Temperature (SET), Predicted Mean Vote (PMV) and Physiological Equivalent Temperature (PET). PET index was originally introduced by Hoppe in 1999 and is defined as 'the equivalent temperature to the air temperature at which, for a typical internal situation, the thermal balance of human does not change, considering the same core and skin temperatures in the original situation'. Tseliou et al. [27] stated that for the calculation of PET a group of climatological factors is needed such as air temperature, relative humidity, mean radiant temperature and wind speed alongside individual-related factors. Furthermore, the index originally had no reference ranges but has since been frequently used in investigating outdoor thermal comfort and mitigation techniques [3]. Chow and Heng [28] incorporated a comparison of 10 major cities' neutral PET ranges, as well as multiple studies that examined urban geometry in improving outdoor urban environments within the wide scope of research available [16,17,21]. PET index provides a clear and accurate indication of thermal comfort and an assessment of the climatological effects on human health and well-being [2]. Hence, the PET index has been used repeatedly in research and provides an indication and understanding of thermal comfort for both researchers and people [29].

To fully assess the outdoor thermal comfort in urban design; spatial distributions and temporal variabilities are vital to represent [30,4]. In an urban environment, net radiation is the main source of energy that is constituted by incoming solar, reflected solar, atmospheric radiation and surface radiation. Generally, the amount of solar radiation and net radiation varies based on the season, time of day, altitude, azimuth and solar position. Consequently, an array of climatological parameters should be examined to comprehend the thermal balance in urban environments, most importantly solar radiation.

To understand thermal comfort, it is equally important to fully comprehend the urban microclimate and the urban climatology layers. Oke [31] categorised the urban volume layers into three: the Urban Air Dome Layer which is the mesoscale climatic conditions, Urban Boundary Layer which incorporates the Inertial Surface Layer, an envelope for urban roofs, and lastly the Urban Canyon Layer which is the microscale climatic conditions. Studies argued that detailed mapping of the urban environment under the Inertial Surface Layer considers the key to understanding the parameters that could be adapted or mitigated to enhance outdoor thermal comfort by assessing its impact [32,33]. Grimond and Oke [34] proposed a set of Local Climate Zones (LCZ) based on roughness, Aspect Ratio and built percentage that was later simplified by Oke [35]. Various studies stated that well-designed urban canyons play a key role in creating thermally comfortable and pleasant urban microclimates [36]. Streets otherwise known as urban canyons have been categorised by capacity and character in the Urban Design Compendium; a document published by Partnerships and Housing CORP [37] to provide guidance on good urban design. According to Urban Design Compendium, street categories are classified in width as Mews (7-12 m), Residential Street (18-30 m), High Street (18-100 m) and Boulevard (27-36 m). Studies in the field suggested that as urban canyons become narrower heat exchange problems arise leading to discomfort. Urban canyons are widely researched spaces that are used as routes and resting areas for pedestrians, as a result, these canyons demonstrate multiple thermal concerns due to the surrounding buildings, density, materials and vegetation.

In general, cities have begun to 'future-proof' their urban fabric by utilizing integrated mitigation and adaptation techniques such as enhancing urban ventilation and solar orientation by studying the effects of urban geometry parameters [33]. Past research showed that the most influential urban geometry parameters include Aspect Ratio (H:W), Sky View Factor (SVF), Orientation, Vegetation and Materiality.

Aspect Ratio is described as the height to width ratio; the height of the buildings (canyon walls) to the width of the street (canyon width). As shown in Fig. 1, urban canyons are categorised into three typologies: deep, shallow and uniform [38]. Maharoof et al. [32] indicated that the Aspect Ratio is a determining factor in outdoor thermal comfort as it dictates the level of openness irrespective of orientation. Ketterer and Matzarakis [39] studied the effect of Aspect Ratio and orientation in Stuttgart-Germany during summer and its effect on PET values. The study suggested that shallow urban canyons with lower Aspect Ratio experience higher heat stress during the daytime which results in discomfort, but lower PET values at night. Furthermore, it was deduced that an ideal configuration of northwest-southeast or north-south orientation with an Aspect Ratio of 1.5 minimum results in enhanced thermal com-

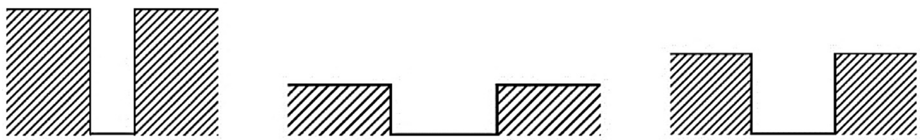

Fig. 1. Urban canyon typologies with different Aspect Ratio (H:W), from left to right: deep, shallow and uniform.

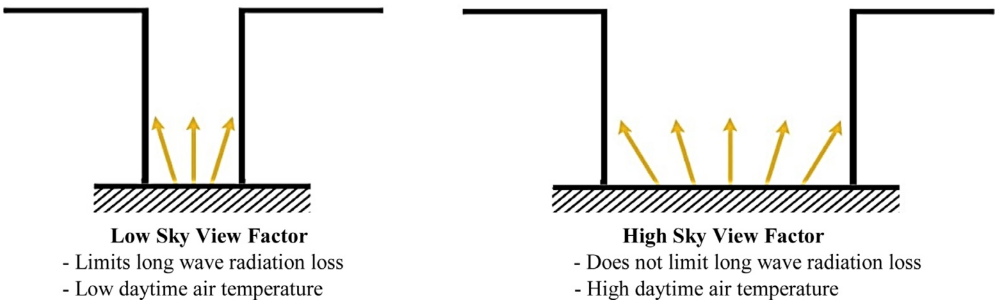

Fig. 2. Low and high Sky View Factor.

fort conditions and increased solar access all year long in mid-latitude cities.

Various studies examined the effect of the Aspect Ratio on solar radiation, airflow and air temperature. A study conducted in Glasgow-Scotland established that building height variations and Aspect Ratio have significant effects on the urban wind environment [40]. While studies argued that increasing building heights lead to higher Aspect Ratio values and deeper canyons cause thermal discomfort. Berardi and Wong [41] investigated the effects of high-rise buildings on an open space in Toronto-Canada, the study showed an increase in wind speed at the pedestrian level which resulted in lower air temperatures. Although the Aspect Ratio is a determining factor in outdoor thermal comfort, it is often insufficient to study it on its own. Thus, multiple researchers examined the correlation of orientation and Aspect Ratio collaboratively on outdoor thermal comfort.

Orientation has evident contributions to the energy balance and heat storage in urban canyons as it affects solar access due to the positioning of the sun, wind exposure and surface temperatures in the urban morphology [17]. However, wind speed and wind direction are unpredictable; hence difficult to anticipate, unlike the sun's path which is known all-year round. Taleghani et al. [18] examined five urban forms in the temperate climate of the Netherlands and corroborated that East-West canyons are exposed to solar radiation for almost 12 hours a day in contrast to 4 hours a day in North-South orientated canyons that are found to be of a cooler microclimate. Studies agreed that the E-W orientation is the most inadequate in any geographical context, due to the prolonged periods of solar radiation [42]. Therefore, orientation is a key factor in addressing heat stress as it provides in-depth knowledge of solar radiation and wind flow within an urban environment.

Sky View Factor (SVF) is a dimensionless parameter that ranges from 0 to 1 and is defined as the amount of sky that can be seen at any given point on a surface (Fig. 2). SVF mainly controls solar radiation and wind speed which is considered context based. Thus, optimal SVF values are suggested on a case-by-case basis. Yang et al. [43] argued that lower SVF values cause cooler thermal environments during daytime due to the shading effect of the urban morphology however trapped radiation is released during night-time. The effects of SVF irrespective of Aspect Ratio are discussed by Santos Nouri and Costa [17] that suggested higher SVF values correlate with higher solar radiation exposure. Chatzipoulka and Nikolopoulou [19] stated that it is vital to understand how SVF is related to urban geometry specifically density. SVF values are lower in highly dense areas that cause obstructions to the amount of sky. Additionally, the study suggested that by adjusting urban morphology in horizontal and vertical ways and creating more open spaces on the ground level, outdoor thermal comfort would be enhanced. Generally, SVF is used as an indication of solar radiation, cloud cover and built obstructions.

Recent research has shown that vegetation is a key element to the adaptation and mitigation techniques in existing urban environments and greatly aids in enhancing outdoor thermal conditions and overall urban microclimate. Vegetation greatly affects evapotranspiration and shade in any urban environment. Santos Nouri [44] discussed vegetation's ability to shield outdoor spaces in summer from direct solar radiation by providing shade; thus leading to reducing air temperature, while still being able to allow for much-needed solar radiation in winter. Additionally, Karakounos et al. [45] stated that vegetation and water surfaces have a significant effect on wind conditions and air temperature within an urban environment when a 0.9°C decrease was observed in Greece. Introducing vegetation into an urban environment increases evapotranspiration causing a reduction in heat loads and providing adequate shade. Hence, achieving a higher decrease in PET values during the daytime makes it thermally comfortable for pedestrians but releases trapped heat during night-time [18].

In addition to vegetation being a prominent technique to enhance outdoor thermal comfort in existing urban environments, studies validated cool material as a potential strategy. Cool material is defined as a material with high solar reflectance (albedo) and high infrared emissivity that causes a decrease in surface temperatures and enhance outdoor thermal conditions [46]. The albedo of cool material is influenced by colour and roughness [47], where lighter colours and smoother surfaces are of a high albedo value. García-Solórzano et al. [48] indicated that cool material has a positive impact on night-time surface temperature which leads to less heat release. Similarly, research has suggested that the use of 'cool material' could have adverse effects affecting pedestrian comfort and building energy balance, such as increasing thermal indices, increasing surface temperatures of surrounding buildings and inducing surface glare [1]. Lopez-Cabeza et al. [49] examined the albedo of cool materials against the vegetation, which indicated that vegetation has lower albedo values than cool materials coated in a light colour but still leads to decreased radiation and enhanced heat stress. Despite, materiality being an important factor in addressing outdoor thermal comfort and its mitigation techniques, it is insufficient to examine the effect of cool material on its own but should be examined collaboratively with Sky View Factor [45]. Studies often examine the effect of two or more urban geometry parameters on urban microclimates and outdoor thermal comfort as it provides critical understanding (Table 1).

Finally, this study aims to investigate the recommended threshold values in the National Model Design Code against real sites with different urban canyons morphologies to examine their impact on outdoor environmental conditions. The study seeks to provide clear and

Table 1
Studies on the effects of urban geometry parameters in temperate climates.

Research	Urban Area	Method	Geometry Parameters
Yan et al. [63]	Beijing - China	Empirical measurements	Sky, Building and Tree View Factors (SVF, BVF, and TVF)
Athamena [64]	Tripode and Bottiere Chenaie - France	Numerical and Simulation	Urban Sub-Configurations (open city block, semi-open city block and intermediate horizontal city block)
Maharoof et al. [32]	Glasgow- Scotland	Simulation	H:W, SVF, Orientation, Materials and Vegetation
Chatzipoulka and Nikolopoulou [19]	London- UK Paris- France	Simulation	SVF, H:W and Density
Karakounos et al. [45]	Serres- Greece	Empirical measurements+ Simulation	SVF, Materialsand Vegetation
Chatzidimitriou and Yannas [1]	Thessaloniki - Greece	Empirical measurements	SVF, Materials, Albedoand Vegetation
Cheung et al. [65]	Manchester- UK	Simulation	SVFand Orientation
Santos Nouri [44]	Auckland- New Zealand	Empirical measurements	Materials, Albedoand Vegetation
Taleghani et al. [18]	Netherlands	Empirical measurements + Simulation	Orientation, SVFand Vegetation
Ketterer and Matzarakis [39]	Stuttgart-Germany	Simulation	H:W, SVFand Orientation
Muller et al. [66]	Oberhausen-Germany	Simulation	Materials, Albedoand Vegetation
Kruger et al. [67]	Glasgow-Scotland	Empirical measurements + Simulation	SVFand Materials

measurable outcomes by understanding the relationship between design theory/guidelines and environmental practice to support architects, urban designers, and planners. The novelty of this study is demonstrated in utilising quantifiable measures to examine the impact of suggested threshold values in urban design guidelines on environmental impacts. The rationale of this study would help to pave the way for sustainable future-proofing to reduce emissions and increase energy efficiency in urban areas using passive strategies.

2. Urban design guidelines in the UK

In the past decade, several policy documents and guidelines have been released by governmental authorities to guide the urban design and planning process within the UK. The Ministry of Housing, Communities and Local Government is responsible for most policy documents and guidelines that are utilised by local authorities to derive their own local urban design guide or planning document. In addition, several professional bodies such as the English Partnership-Housing Corporation and the Design Council aid the government with supplementary material to aid the urban design and planning process (Fig. 3).

Among the numerous documents available, the national design guide, living with beauty [50], the manual for streets 1 [51] and manual for streets 2 [52] have been the focus of local authorities' own guides. The previous documents act as a guide and produce rule-of-thumb descriptions of various issues within the urban design and planning field, such as built form, movement, public spaces, homes and buildings, etc. Despite the purpose of the documents, they remain descriptive and diagrammatic in nature and open to interpretation by local authorities; specifically, in areas that need quantitative numerical values such as the Aspect Ratio. Furthermore, the policy documents hardly mentioned climate change and the need for more sustainable and environmentally friendly designs when addressing public spaces.

National Design Guide [53] stated that a new policy document will be published as *"a baseline standard of quality and practice across England which local planning authorities will be expected to take into account when developing local design codes and guides and when determining planning applications"*. Furthermore, in the Building Better, Building Beautiful Commission's document; living with beauty [50]; *"Policy Proposition 7: localise the National Model Design Code which will function as a template for local authorities to develop, their own codes in accordance with local needs and preferences and to support better urbanism and mixed use."* outlines the need for codes that local authorities can utilise as a template to develop their own codes.

In 2021, the National Model Design Code accompanied by a guidance notes document was published based on the recommendation of the aforementioned policy documents, which outlined quantitative numerical values for multiple aspects in the Urban Design and Planning field and addressed the climatic aspect of urban design and planning. Within the area of public spaces, proper and reviewed categorisation of streets in conjunction with movement hierarchy was suggested with numerical values for the Aspect Ratio (Fig. 4).

The suggested street categorisation provides a deeper insight into street types, area types and functions. In addition to the suggested categorisation, accompanying diagrams showcase ideal designs of different street types in different areas which are offered as a rule of thumb. Local authorities such as County Councils, District Councils, Unitary Authorities, Metropolitan Districts and London Boroughs produce their own local urban design guides that are used to inform local development documents that in turn deduce core strategies and area action plans. The focus of these local urban design guides is mainly on city and town centres with key themes relating to the nature of the city.

In Cardiff, a Liveable Design Guide [54] was published in May 2015, the guide highlights the main focus of the local council's vision for the city, that being to create 'people-friendly places and streets', convenient and fast travel, easy access to amenities and community sharing and meeting cores. The document is descriptive in nature and merely provides guidance to developers and professionals through a masterplan checklist to ease the understanding of the process and what should be required. Similarly, Urban Living SPD as guidance to the policies contained management maintenance plans within the Bristol Local Plan [55] and 'City Centre Framework'; published in 2018 and 2020 respectively, both focus on preserving the historic nature of Bristol while advocating for improved movement, new developments and enhancing the public realm within the highly dense urban fabric. The documents moderately discuss climatic aspects in relation to pedestrian level winds and sunlight/daylight, which are descriptive and diagrammatic providing guidance to current and new developments within the city.

Despite the current local urban design guides being well-organised and functional, they are yet considered descriptive and lack environmental assessment. Therefore, examining the threshold values in the National Model Design Code and guides by modelling and testing different environmental aspects will enable developers and professionals to understand the impact of design on outdoor spaces. These improvements would help to implement effective retrofit decisions to enable developers and professionals to enhance the public spaces and public realm simultaneously. The impact of current work on the industry would open opportunities to consider energy efficiency measures for the installa-

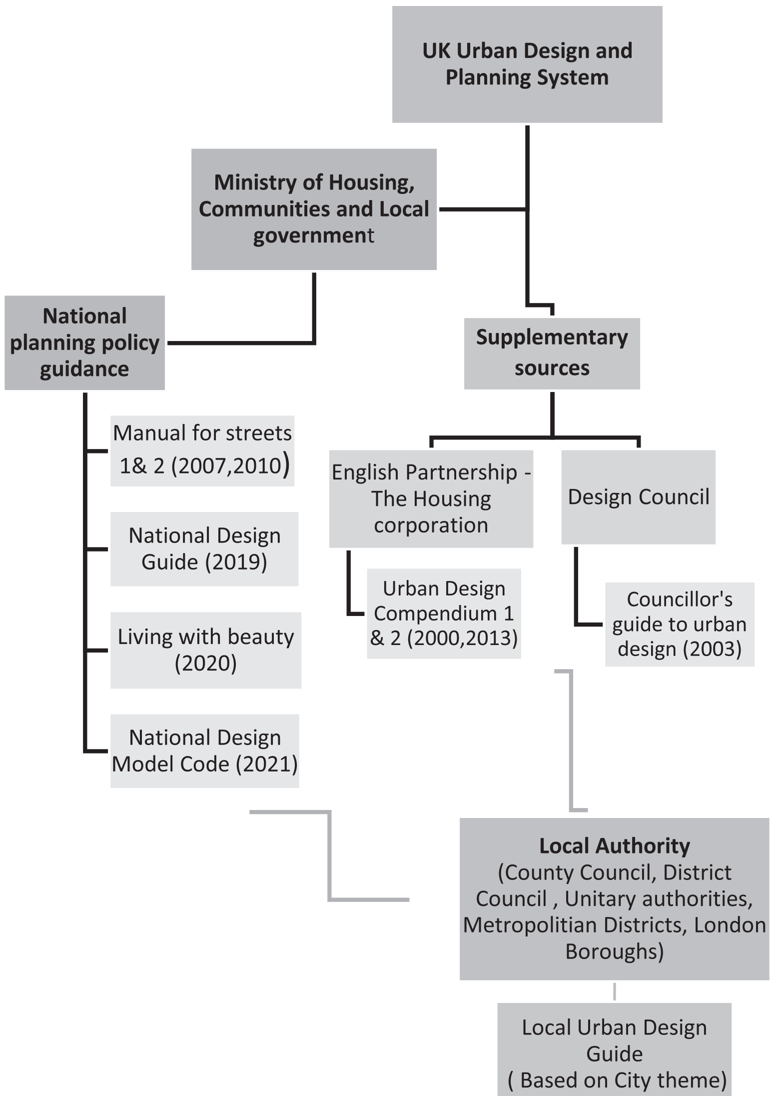

Fig. 3. Urban design and planning hierarchy in the UK.

tion of energy-saving materials such as solar panels, insulation and heat pumps as well as further technologies e.g. for energy distribution and consumption within the existing infrastructure or meet the emerging objectives of rapid reductions of carbon footprints.

3. Case studies

Cities are comprised of multiple Local Climate Zones (LCZ), ranging from compact high rise, industrial, suburbs and city centres. Research in the field has indicated that the most climatically troubled zones are those characterised by high density, narrow streets and little vegetation much like city centres nowadays where solar radiation is restricted and airflow is decelerated and diverted [33]. As a result, for the purpose of this research two city centres in the UK were examined; Cardiff and Bristol due to being located at similar geographical latitudes (51.4815°N and 51.4545°N respectively) as shown in Fig. 5 and streets orientations (N-W) that face similar climatic conditions but different urban forms and densities.

The climatic context of the UK is known as a Maritime temperate climate (Cfb), as classified by Köppen-Geiger. The maritime temperate climate is characterised by significant precipitation during all seasons, where the average maximum temperatures range from 16 – 20°C during summer and 2.5 – 8.5°C during winter [56]. Furthermore, two high streets in each city were considered. Both are route and resting spaces for pedestrians and within the walkable catchment areas and activity nodes of Cardiff and Bristol city centres (Fig. 6).

3.1. Cardiff

Cardiff's city centre area consists of a highly dense urban fabric and a loose grid street layout with most streets in the N-W and S-E orientation with close proximity to the River Taff and the main road that connects the city centre to the M4 motorway. Climatic conditions in Cardiff vary year-round, but on average, the temperatures range between 2.3°C to 13.8°C during winter and 11.0°C to 21.7°C during summer with wind speed and direction ranging from 1.8 m/s to 11 m/s from the NW and SW. Cardiff has 149 days of rainfall per year and varying cloud cover and humidity levels depending on the month. Within Cardiff city centre, Saint Mary Street and The Hayes are considered the main high streets and have high occupancy rates (Fig. 6). The street widths are 28.42m and 24.69m respectively with average building heights ranging from 9m to 18m on Saint Mary Street and 9m to 21m on The Hayes making the Aspect Ratio of both streets of a wide nature (Fig. 7). Saint Mary Street consists of both pedestrian and vehicular functions with no vegetation available, whereas The Hayes is a pedestrian zone with vegetation in the middle of the street.

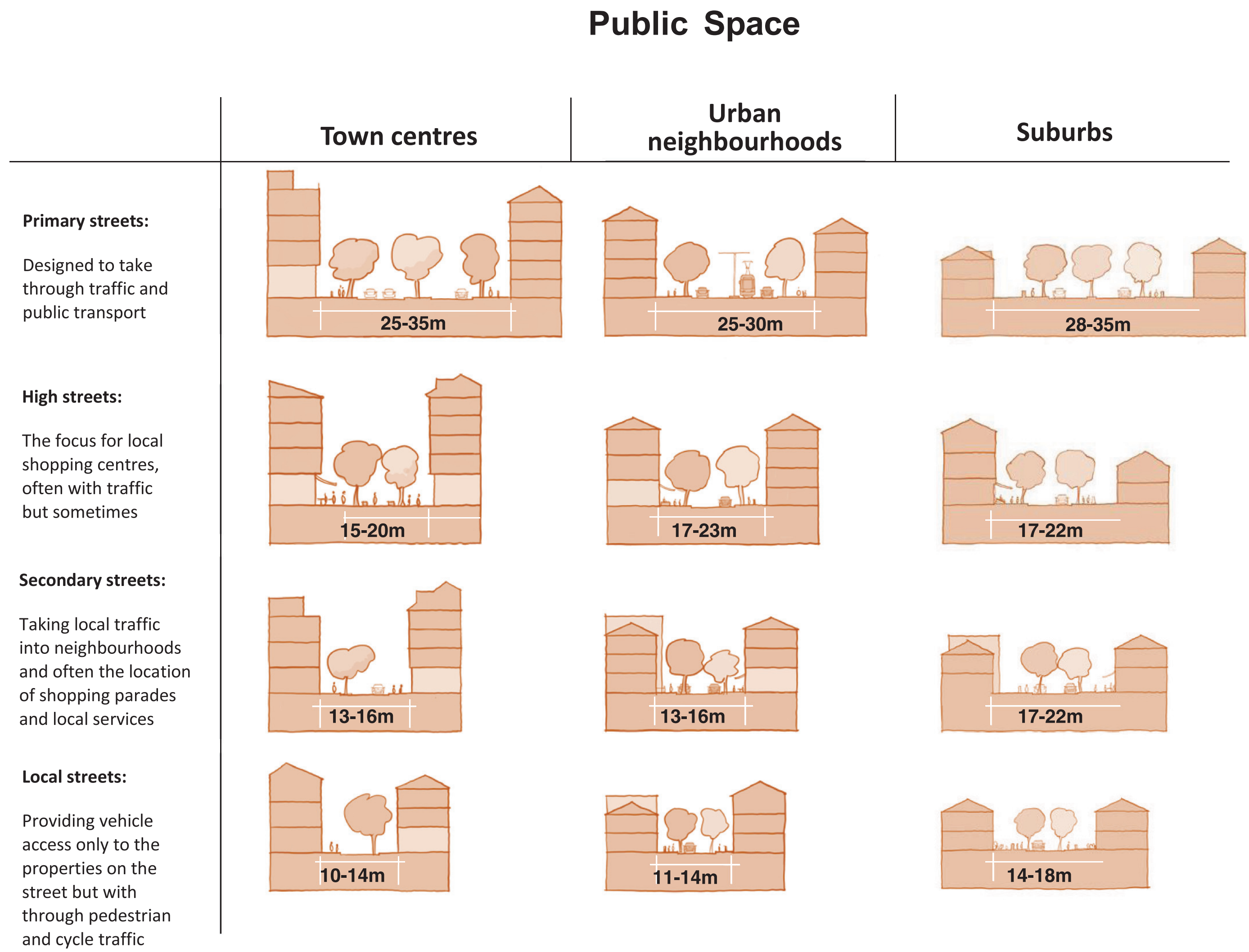

Fig. 4. Street categorisations by area [57].

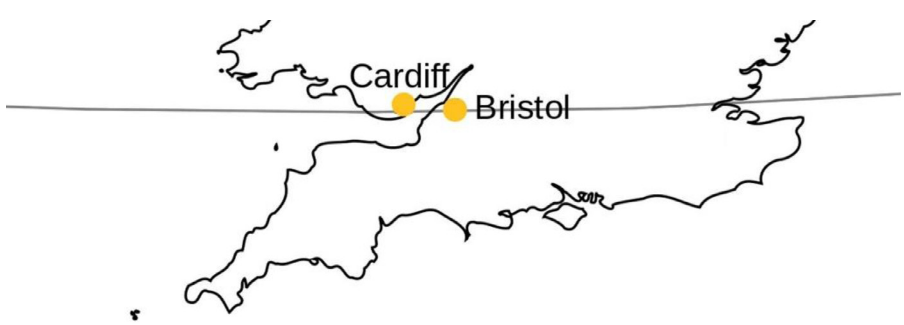

Fig. 5. Locations of Cardiff and Bristol within the UK.

3.2. Bristol

Bristol's city centre area is of a highly dense urban fabric and is comprised of an organic grid street layout with most streets in the N-W and S-E orientation with close proximity to the River Avon and an expressway that runs all the way to the North of England (Fig. 6). On average the climatic conditions in Bristol are similar to that of Cardiff, with temperatures ranging between 2.2°C to 13.3°C during winter and 11.1°C to 21.5°C during summer with wind speed and direction ranging from 1.8 m/s to 11 m/s from the WSW and W. Bristol has 123 days of rainfall per year and varying cloud cover and humidity levels depending on the month. Broad Street and Merchant Street are considered the main high streets and have high occupancy rates. The street widths are 10.61m and 18.01m respectively with average building heights ranging from 6m to 25m on Broad Street and 9m to 15m on Merchant Street making the Aspect Ratio of a narrow and wide nature respectively (Fig. 8). Broad Street consists of both pedestrian and vehicular functions, whereas Merchant Street is a pedestrian zone with both streets lacking vegetation.

4. Methods

From a positivist perspective, the study used quantitative methods in the form of review, survey and simulation. For review, the study investigated design guidelines and documents by exploring the relation-

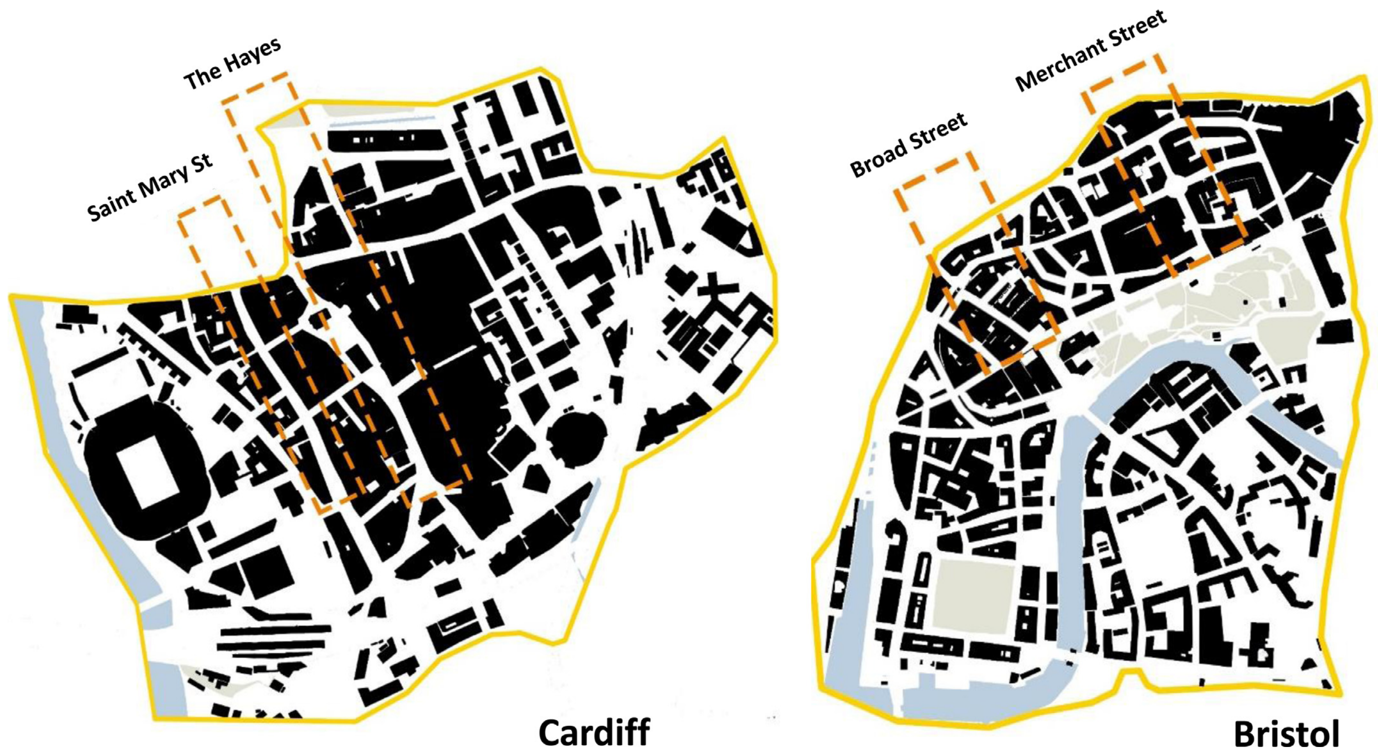

Fig. 6. Cardiff and Bristol's city centre cores and case studies.

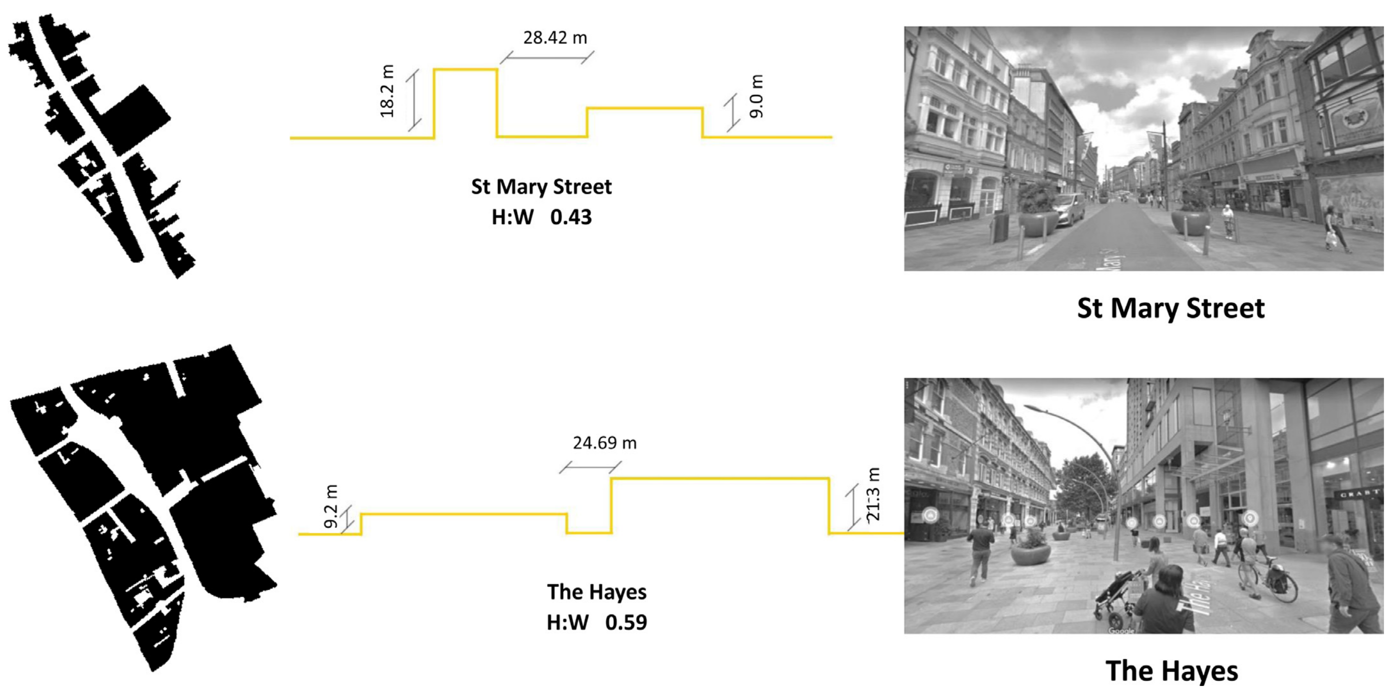

Fig. 7. Urban fabric and geometry of Saint Mary Street and The Hayes in Cardiff City Centre.

ship between urban design guides and threshold values and identified the overall direction of existing literature. For the survey and simulation, the study examined environmental factors using threshold values proposed in the National Model Design Code [57] against outdoor environmental conditions in pre-selected sites. The study examined 2 high streets in the city centre of Cardiff and Bristol. The study analysed the pre-selected canyons in their original state and then modified cases to comply with urban design codes for Aspect Ratio and street widths for High Streets within Town Centres as shown in Fig. 4.

The pre-selected urban canyons in Cardiff and Bristol city centres were based on a survey using site visits, satellite imagery and 3D buildings on Google Earth and Digimap, and background research helped determine the selected urban canyons according to density, orientation and street functions. Thereafter, weather data for each city were collected from weather stations nearby the streets with a distance of 500m in Cardiff and about 900m in Bristol. The data were obtained from Climate.OneBuilding.Org, a repository of free climate data for building performance simulation which enabled the researchers to thoroughly study

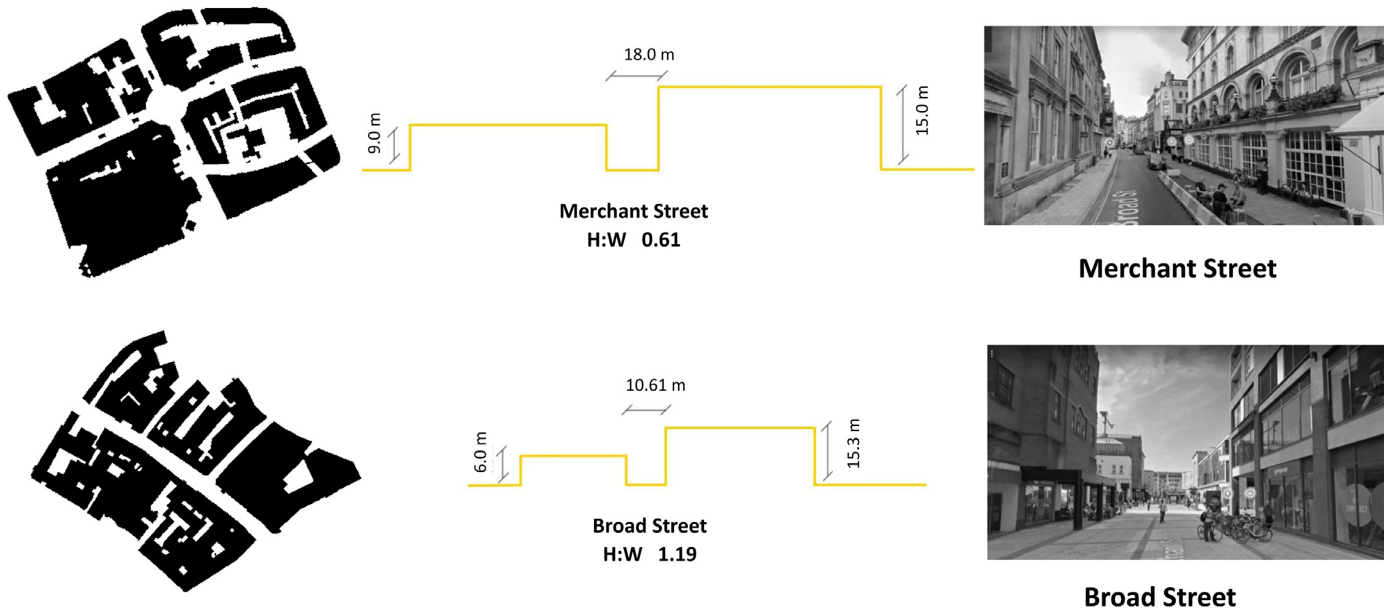

Fig. 8. Urban fabric and geometry of Broad Street and Merchant Street in Bristol City Centre.

the climatic conditions of both cities. The chosen dates and times were June 21 (summer solstice) and December 21 (winter solstice) at 12:00 pm for the purpose of this research, as these dates mark the longest and shortest daylight periods in a year. To examine the urban geometry of each urban canyon including building density and height, DWG files were generated from CADMAPPER, an application that transforms data from OpenStreetMap into CAD files and validated through Google Earth and OpenStreetMap 3D viewer powered by WebGL. The survey from Digimap, OpenStreetMap, Google Earth and DWG files enabled the researchers to determine average building heights and street widths and then calculate Aspect Ratio values for all four streets in their original state. Fig. 9 shows the process for conducting this research to assess outdoor environmental conditions and test National Model Design Code. Thereafter, an informed decision on the street widths to comply with the National Model Design Code was made. The street widths were modified to attempt to achieve an Aspect Ratio of 1:1 and within the 15- 20m range that is presented as Case 2 - Modified.

4.1. RayMan

RayMan is an urban climate software developed by Andreas Matzarakis that calculates PET, Tmrt and SVF values. It is a validated software and used by several studies to calculate thermal comfort conditions [58,59]. First, the study assessed weather information to collect the climatic data; air temperature, relative humidity, wind velocity and cloud cover for June 21 and December 21 at 12:00pm for both Cardiff and Bristol. Afterwards, the climatic data were imported into RayMan along with specifying the geographical longitude and latitude, date and time. Furthermore, Rayman has a pre-set of personal data, clothing and activity values that are set according to standards to measure PET values. For the purpose of this research, the clothing values (clo) were specified as 0.50 for June 21 and 1.00 for December 21. The Bitmap files for Case 1 and Case 2 in Cardiff (Saint Mary Street and The Hayes) and Bristol (Broad Street and Merchant Street) were individually imported into the software to produce the buildings in 3D format with correct heights. Finally, the software helped to calculate and provide data for SVF, Tmrt and PET values, in addition, it created obstacle files and fish-eye diagrams for each street in the two different scenarios.

Table 2
Standard PET values [62].

Temperature Scale	Climate Condition	Heat Stress
Below 4°C	very cold conditions	extreme cold stress
4°C - 18°C	slightly cool to cold	slight to strong cold stress
18°C - 23°C	comfortable conditions	absence of heat stress
23°C - 41°C	slightly warm to hot	slight to strong heat stress
Above 41°C	very hot conditions	extreme heat stress

4.2. IESVE

IESVE is a building performance analysis software that enables designers to examine passive solutions, solar impact and wind flow using Computational Fluid Dynamics (CFD) among other features. IESVE is a validated software that was used by various studies to study outdoor thermal conditions [23,60]. The study imported the generated DXF files into IESVE using ModellT application to create the buildings in 3D format with the correct heights and materials. Then, using the Apache application, the location data and weather data were specified for Cardiff and Bristol. The SunCast application was used to assess the solar radiation impact on the buildings and most importantly the urban canyon. The SunCast simulation was run for all four streets in two different cases and in the selected days; June 21 and December 21 at 12:00pm, as a result, visual simulation images were produced and used for comparison and analysis. Similarly, MicroFlo, a CFD simulation application in IESVE, was used to examine the average wind flow within the pre-selected urban canyons in Cardiff and Bristol, in two different cases; the original and the modified. Within MicroFlo a group of settings was added to ensure simulation results. The settings include wind direction, exposure and turbulence model using k-e model that calculated turbulent viscosity for each grid cell and grid settings. The analysis of CFD model used a height of 1.5 m from the ground to analyse the flow [61,23].

Finally, the findings were evaluated using a thermal index in the form of the Physiological Equivalent Temperature (PET). Table 2 demonstrates the standard PET values in the form of temperature, climate conditions and heat stress scale that were used to compare against the generated outputs based on Matzarakis et al. [62].

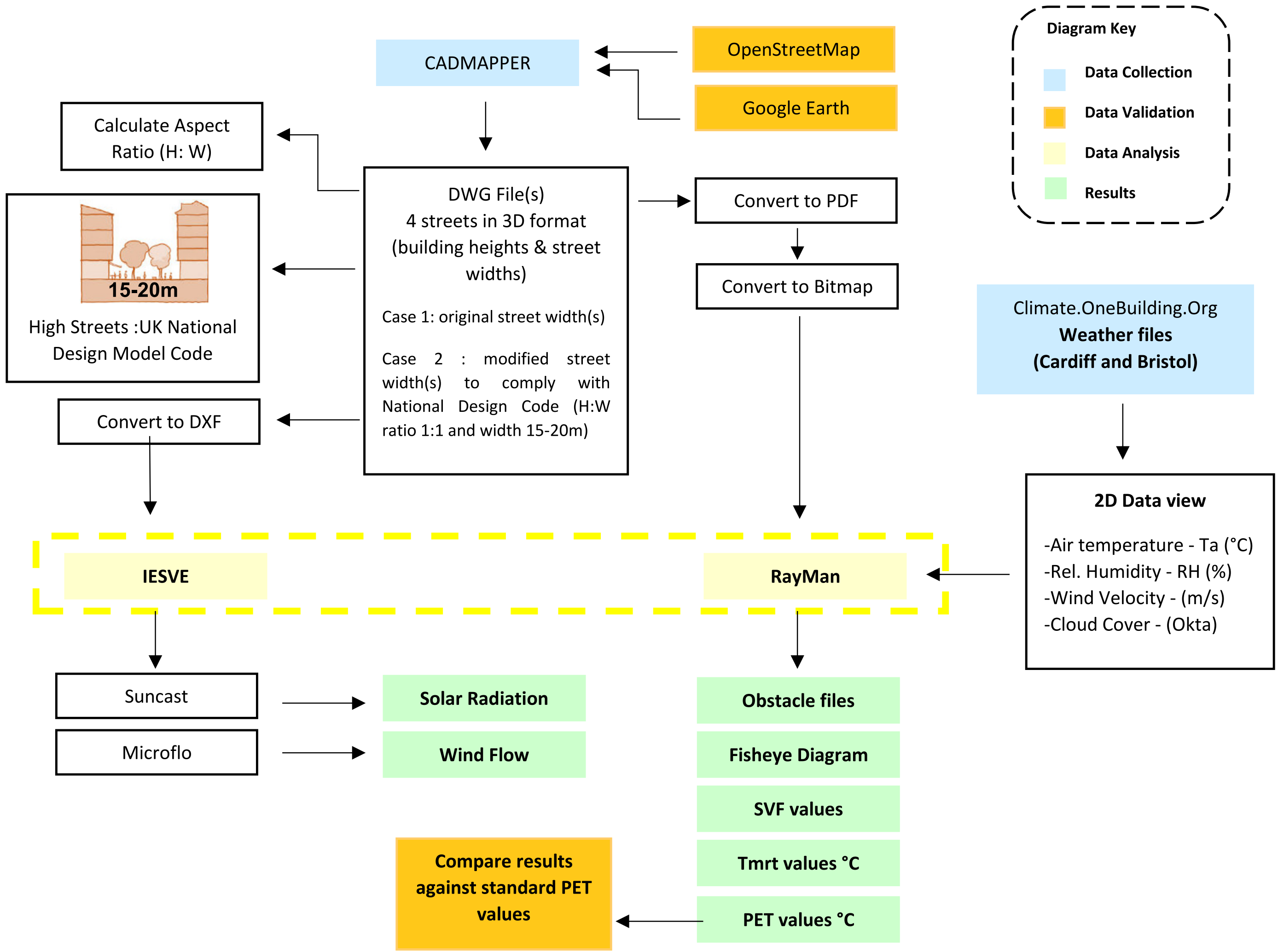

Fig. 9. Flowchart of research steps.

5. Results and discussion

The findings from reviewing the design guides in section 2 showed that most guidelines were mainly descriptive and lack critical assessment in the form of quantitative values to support the examination of environmental urban models. The National Model Design Code [57] has set codes for Aspect Ratio and street widths for different types of streets and local zones and has stated that these are merely a guide and that the Local Councils should deduce its own values derived from the general codes. The comparison between the two guides revealed that in Bristol's local guide, the Aspect Ratio or building heights are not mentioned, whereas Cardiff's local guide, vaguely mentions building heights. Furthermore, the review found that both guides lack the climatic aspect of Urban Design that has recently been integrated into the National Model Design Code's features for a well-designed place. Hence, there is a need for each council to derive their own codes and local guides and incorporate sustainable or climatic sensitive attributes into their guides and checklists. After surveying the National Model Design Code's guidance on high streets in town centres and carefully reviewing the two conditions: Aspect Ratio of 1:1 and street width between 15-20 m, the Aspect Ratio for Case 1 was calculated. Subsequently, the street width for Case 2 was modified accordingly, the results are shown in Table 3 and Fig. 10. It is important to highlight that in St Mary Street, Broad Street and Merchant Street a 1:1 Aspect Ratio could not be achieved as the street width values would fall below the recommended street width of 15-20m by the National Model Design Code. Hence, the research attempted to increase or decrease the Aspect Ratio valued to a close proximity of the 1:1 recommendation within the 15-20m range.

Table 3
Streets widths for four streets in cases 1 & 2.

Street Name		Street Width(s) Average Building Heights (m)	Case 1-Original (m)	Case 2-Modified (m)
Cardiff	**St Mary**	12	28	15
	The Hayes	15	25	15
Bristol	**Broad**	13	11	15
	Merchant	11	18	15

Fig. 10 shows that the analysis of the Aspect Ratio in modified streets increased at St Mary Street, The Hayes and Merchant Street by about 0.86%, 66% and 19.67%. However, the ratio decreased at Broad Street by 48.75%. The values of the Aspect Ratio for modified streets according to the National Model Design Code for St Mary Street, The Hayes, Merchant Street- and Broad Street are 0.8, 1, 0.73 and 0.8, respectively.

The results in Figs. 11 and 12 indicated that SVF values increased in The Hayes, Broad Street and Merchant Street while they decreased at St Mary Street affecting the amount of sky visibility at the central point of all four streets. The analysis showed that the increment of SVF at The Hayes, Merchant Street and Broad Street was 43.75%, 25% and 176%,

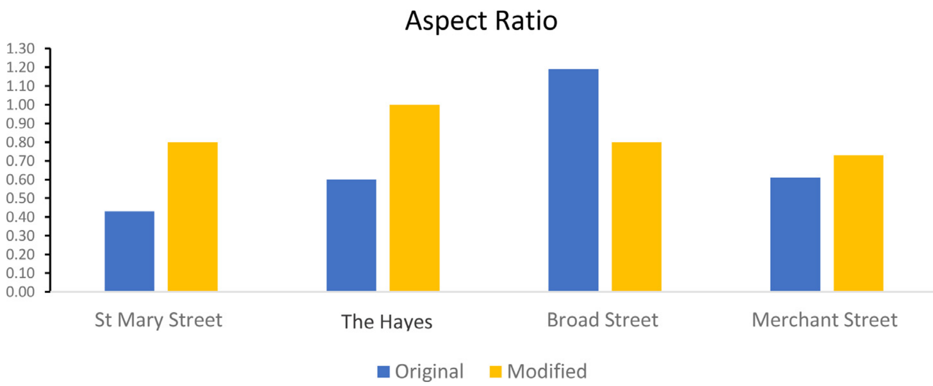

Fig. 10. Values of Aspect Ratio for four streets in cases 1 & 2.

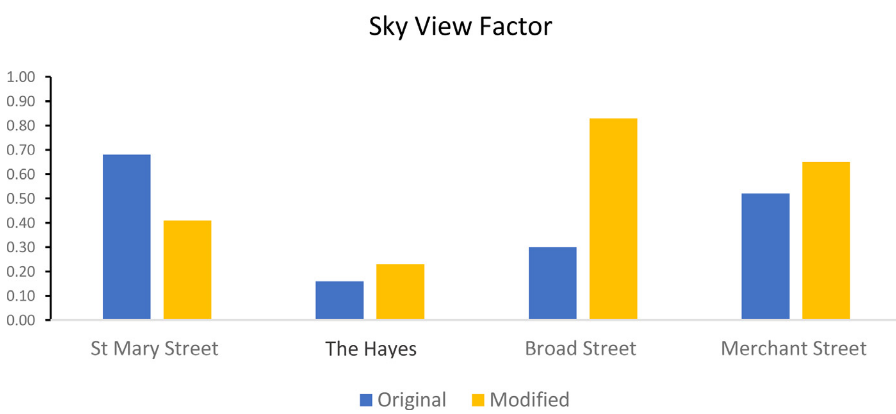

Fig. 11. SVF values for both cases in all streets.

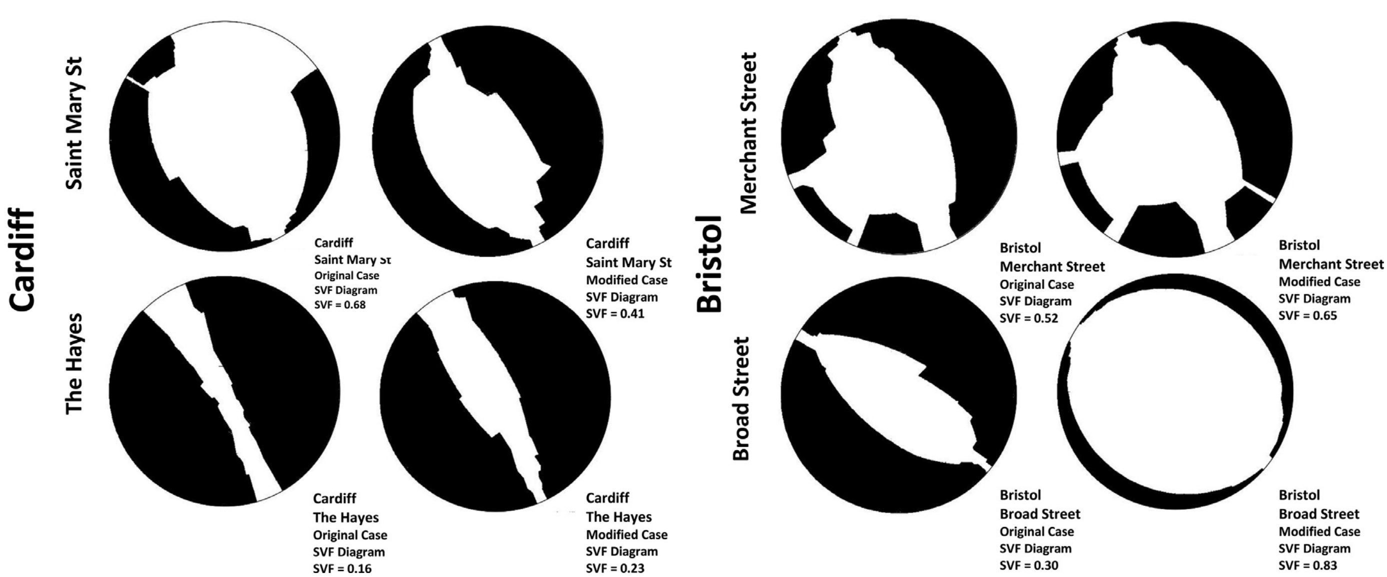

Fig. 12. Fisheye diagrams and SVF values for four streets in cases 1 & 2.

respectively. However, Saint Mary Street experienced a decrement of about 65.85%. The SVF values for modified streets according to the National Model Design Code for St Mart Street, The Hayes, Broad Street and Merchant Street are 0.41, 0.23, 0.83 and 0.65, respectively.

Fig. 13 demonstrates the results of PET values for four different streets on June 21 and December 21. The values showed that on June 21, the temperatures with original conditions at St Mary Street and The Hayes in Cardiff were 18.6°C and 24.4°C which are higher than Broad Street and Merchant Street in Bristol which were 11.3°C and 12.1°C. However, on December 21, the temperatures with original conditions at St Mary Street and The Hayes in Cardiff were 6.7°C and 7°C while Broad Street and Merchant Street in Bristol were 4.1°C and 3.5°C. The differences represent a consequence of the street widths, context and climatic conditions in Cardiff compared to Bristol. These differences showed a critical demonstration to understand the impact of Aspect Ratio and SVF in environmental urban design. On the other hand, the modified models showed a considerable reduction in Cardiff on June 21, the reduction at St Mary Street and The Hayes was 0.7°C and 2.1°C. However, the temperatures were slightly increased in Bristol due to the effect of increasing and decreasing street widths, the readings showed a rise in Broad Street and Merchant Street by 0.4°C and 0.2°C. In contrast, on December 21, the temperature at St Mary Street significantly dropped

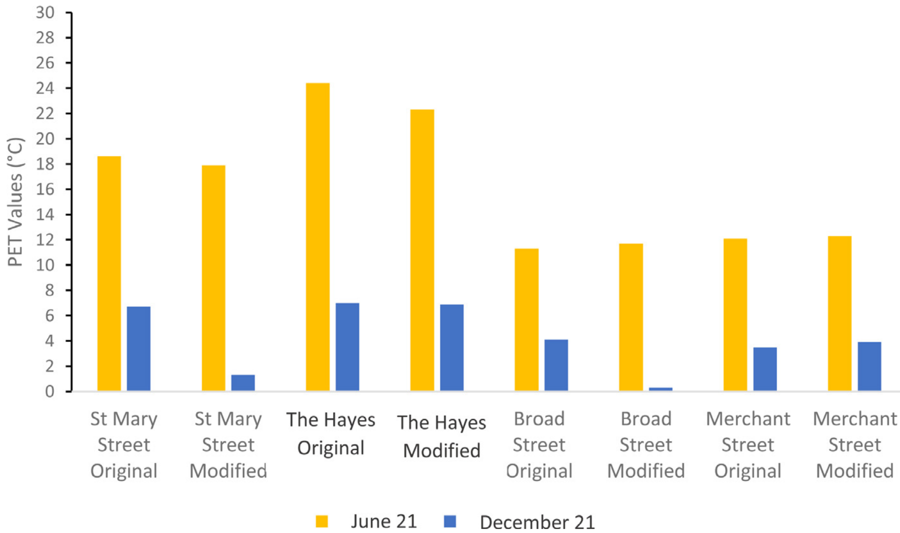

Fig. 13. PET values for four streets in cases 1 & 2.

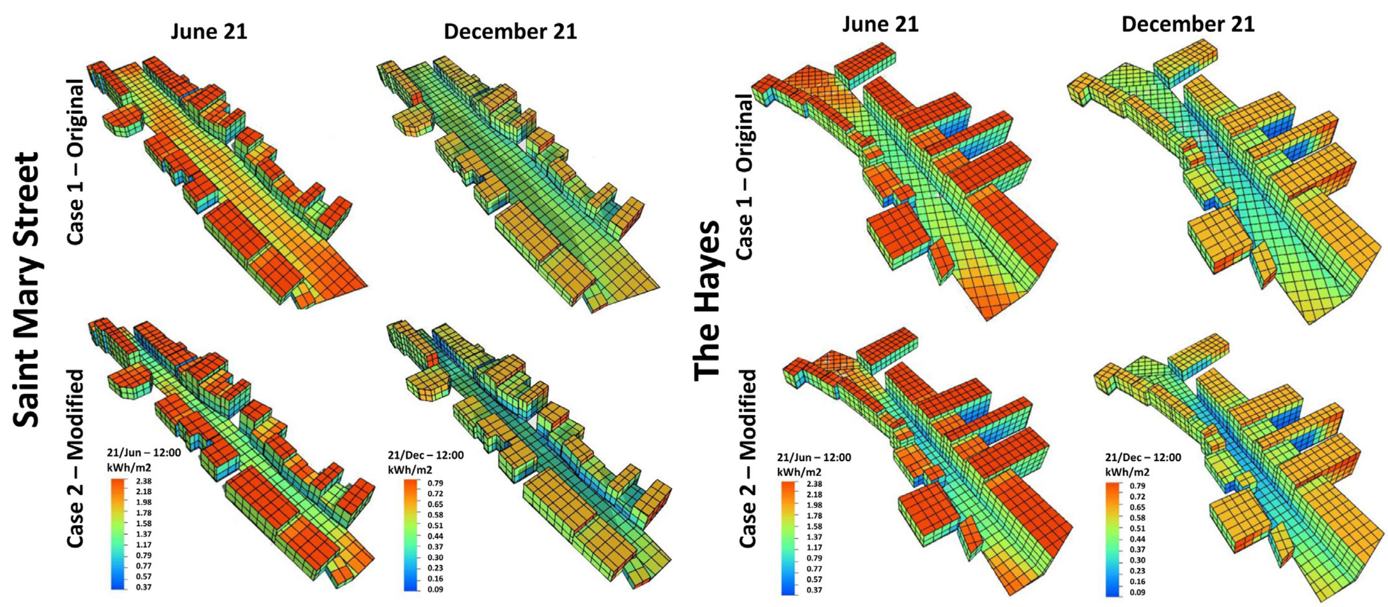

Fig. 14. Solar radiation analysis for Saint Mary Street and The Hayes in cases 1 & 2.

by 5.4°C, however, it slightly dropped by 0.1 at The Hayes. On the other hand, the temperature at Broad Street notably dropped by 3.8°C due to the significant increase in SVF by 176% that causing a considerable reduction in temperature, however, at Merchant Street, the temperature increased by 0.4°C.

Fig. 14 demonstrates the analysis of solar radiation exposure at St Mary Street and The Hayes in Cardiff. The analysis showed that with original conditions on June 21, the results ranged between 1.37 - 2.38 kWh/m^2 and 1.17 - 2.18 kWh/m^2, respectively. While on December 21, the findings ranged between 0.372 - 0.582 kWh/m^2 and 0.162 - 0.578 kWh/m^2, respectively. However, the modified models showed a reasonable reduction on June 21 that ranged between 1.17 - 1.58 kWh/m^2 and 0.97 - 1.98 kWh/m^2 while on December 21, the findings ranged between 0.302 – 0.512 kWh/m^2 and 0.092 - 0.549 kWh/m^2, respectively. The analysis indicated that modified models in Cardiff managed to reduce peak solar exposure during June 21 by 50.63% at St Mary Street while it was less by 10% at The Hayes. While on December 21, the peak solar exposure reduced by 13.67% and 5.28%, respectively.

Fig. 15 demonstrates the analysis of solar radiation exposure at Broad Street and Merchant Street in Bristol. The analysis showed that with original conditions on June 21, the results ranged between 0.97 - 1.37 kWh/m^2 and 1.17 – 2.38 kWh/m^2, respectively. While on December 21, the findings ranged between 0.092 - 0.440 kWh/m^2 and 0.301 – 0.580 kWh/m^2, respectively. Alternatively, the modified models at Merchant Street showed a reasonable reduction on June 21 and December 21, the results ranged between 0.77 – 2.18 kWh/m^2 and 0.162 – 0.510 kWh/m^2, respectively. However, the modified models at Broad Street demonstrated an increase in solar exposure due to the impact of the significant rise in SVF by 176%. The results on June 21 and December 21 were 1.17 - 1.78 kWh/m^2 and 0.301 - 0.510 kWh/m^2. The analysis indicated that modified models at Merchant Street managed to reduce peak solar exposure on June 21 by 9.17% while it increased by almost 30% at Broad Street. While on December 21, the peak solar exposure decreased by 13.72% at Merchant Street but increased by 15.9% at Broad Street.

Figs. 16 and 17 show the analysis of wind flow in two cities. According to Beaufort Scale, air speed ranged between 0 – 6.1 m/s (< 0.3 / Calm, 0.3 - 1.5 / Light air, 1.6 - 3.3 / Light breeze, 3.4 - 5.4 / Gentle breeze, 5.5 - 7.9 / Moderate breeze). The analysis showed that within the original context in Cardiff and Bristol, the airflow was unbalanced and fluctuated along the streets. The range of airspeed in Cardiff was

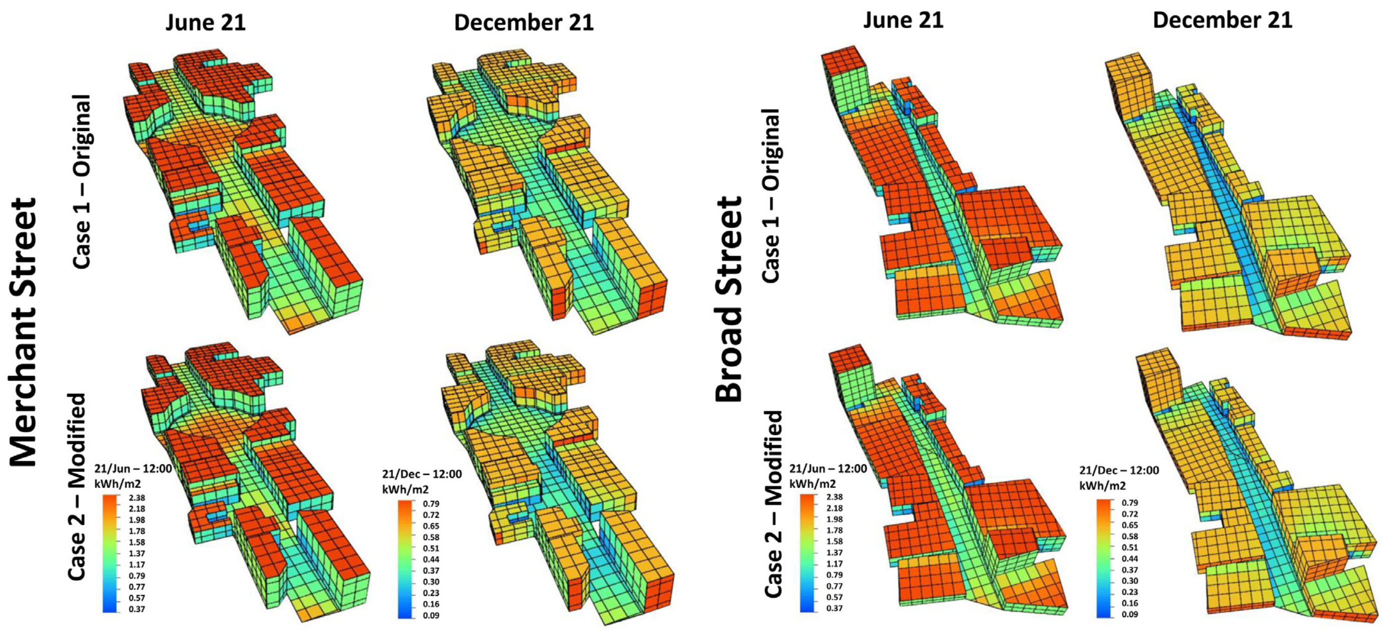

Fig. 15. Solar radiation analysis for Broad Street and Merchant Street in cases 1 & 2.

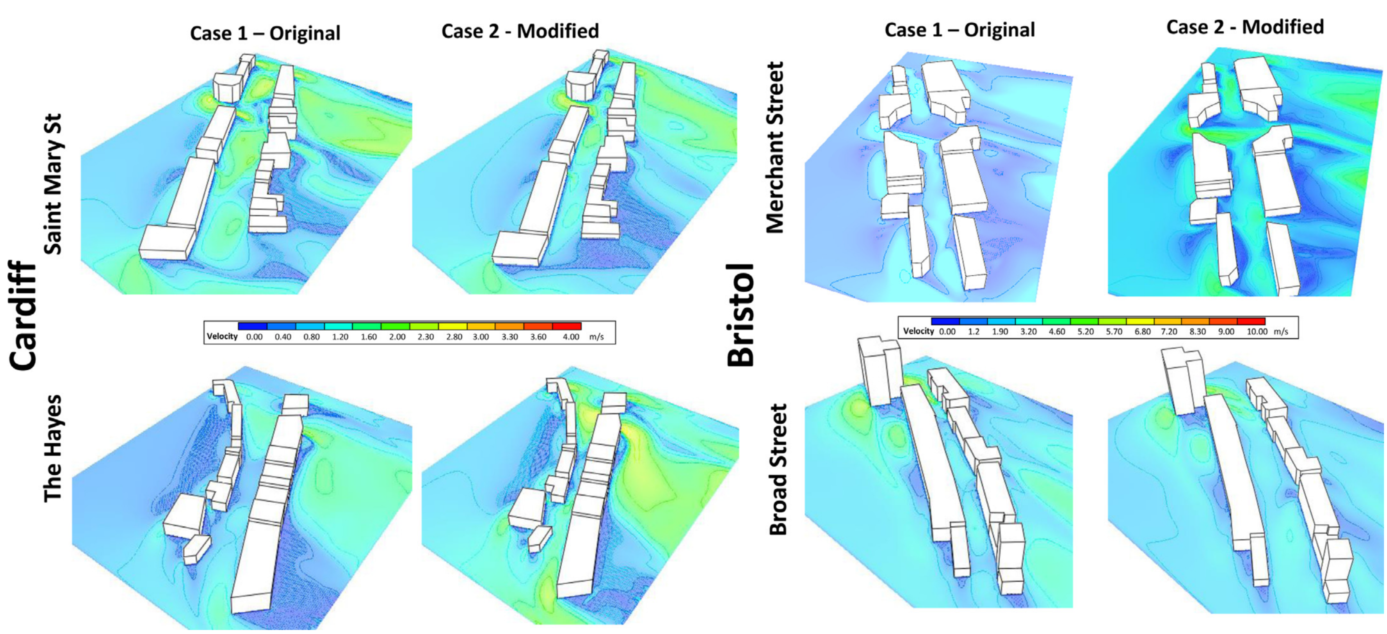

Fig. 16. Wind flow analysis for four streets in cases 1 & 2.

between 0.4 and 4 m/s while in Bristol was between 1.2 and 6.16 m/s. Interestingly, the modified models showed a steady movement and even distribution of airflow within four streets. In Cardiff, the results showed that narrower street widths compared to the original helped to provide constant airflow. The airflow ranged between 0.4 and 2.4 m/s on both streets. In Bristol, the findings showed that the airflow ranged between 1.1 and 5.7 m/s on both streets.

Finally, the results indicated that the modifications of street widths were evident and the mitigation techniques managed to control heat stress levels for all four urban canyons (Table 4). These results corroborate Lin et al. [40] and Santos Nouri and Costa [17] findings that low SVF values provide cooler environments whereas high SVF values cause higher solar radiation exposure, hence more heat stress. Conversely, the results contradict Ketterer and Matzarakis [39] finding that shallow canyons with low Aspect Ratio values cause higher heat stress and thermal discomfort. As in St Mary Street case 1, the Aspect Ratio was of 0.43 value, which is considered a shallow canyon but had a PET value of 18.6°C which is considered thermally comfortable and characterised by the absence of heat stress. Overall, the results revealed that the proposed threshold values recommended by the National Model Design Code when they are compared to real sites have a positive effect on the outdoor thermal comfort of the urban canyons on June 21, however, they have a negative effect on December 21 if an inverse relationship exists between the Aspect Ratio and SVF.

6. Conclusions

The study investigated the recommended threshold values in the National Model Design Code against real sites with different urban canyons morphologies to examine their impact on outdoor environmental condi-

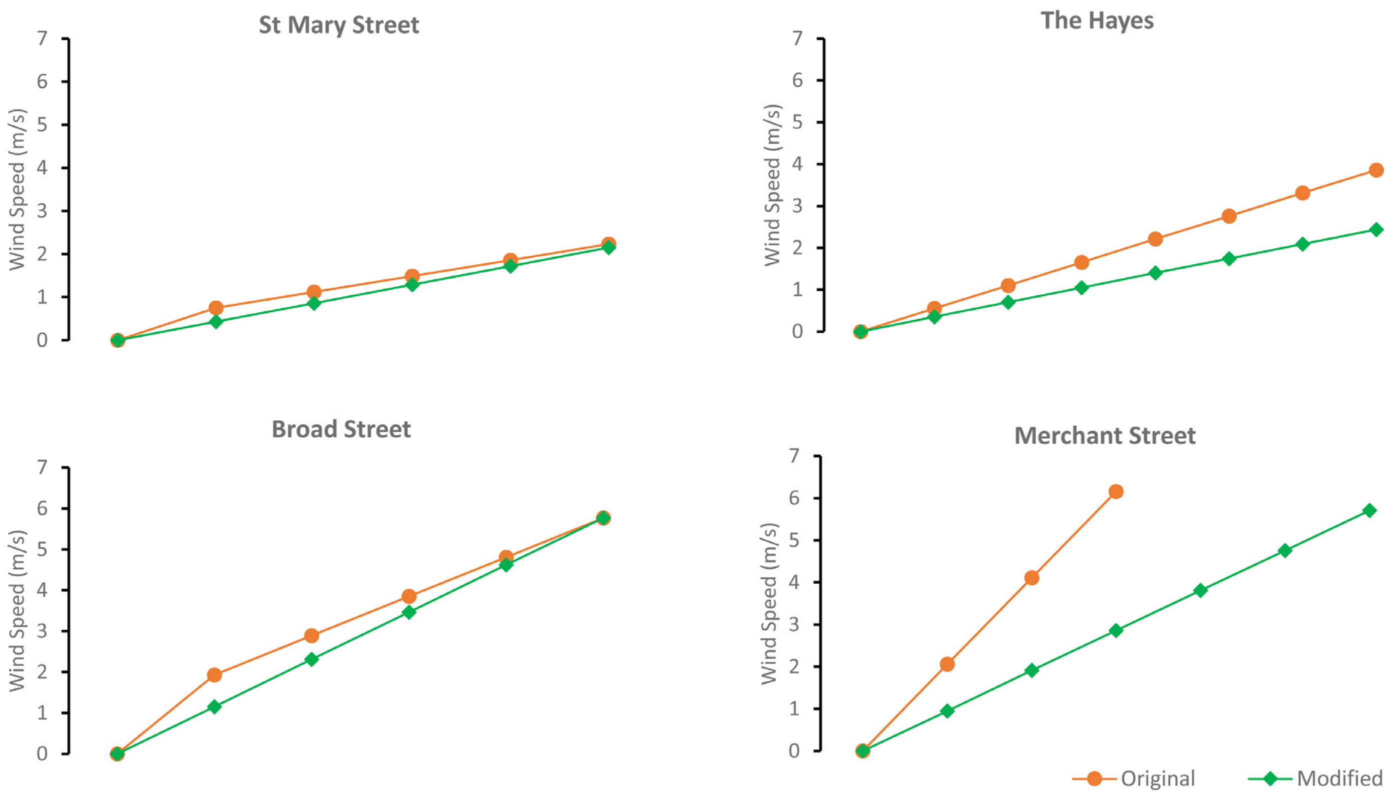

Fig. 17. Wind flow results for all four streets in cases 1 & 2.

Table 4
Summary of main PET values against the temperature scale.

Street Name	Street Width	Aspect Ratio	SVF	PET June 21	PET Temperature Scale	PET December 21	PET Temperature Scale
St Mary (Original)	28 m	0.43	0.68	18.6°C	Comfortable conditions	6.7°C	Slightly cool to cold
St Mary (Modified)	15 m	0.80	0.41	17.9°C	Comfortable conditions	1.3°C	Very cold conditions
The Hayes (Original)	25 m	0.60	0.16	24.4°C	Slightly warm to hot	7.0°C	Slightly cool to cold
The Hayes (Modified)	15 m	1.00	0.23	22.3°C	Comfortable conditions	6.9°C	Slightly cool to cold
Broad (Original)	11 m	1.19	0.30	11.3°C	Slightly cool to cold	4.1°C	Slightly cool to cold
Broad (Modified)	15 m	0.80	0.83	11.7°C	Slightly cool to cold	0.3°C	Very cold conditions
Merchant (Original)	18 m	0.61	0.52	12.1°C	Slightly cool to cold	3.5°C	Very cold conditions
Merchant (Modified)	15 m	0.73	0.65	12.3°C	Slightly cool to cold	3.9°C	Very cold conditions

tions. The research presented quantitative techniques to understand the relationship between design theory/guidelines and environmental practice. Using modelling, the research demonstrated measurable outcomes that would help design specialists to enhance public spaces in temperate climates. The main findings and contributions are summarised below:

- The review of local guides for Bristol and Cardiff showed that both documents need further developments to integrate the climatic aspects of urban design. Hence, there is a need for each council to derive its own codes and local guides and incorporate sustainable and climatic-sensitive attributes into their guides and checklists.
- The simulation analysis showed that the recommended values have a significant impact on the outdoor thermal performance of the preselected urban canyons. The findings demonstrated that modifying the width of streets and changing the Aspect Ratio and SVF resulted in controlling solar radiation exposure and wind flow and speed.
- The analysis revealed that within the original contexts, the airflow was unbalanced and fluctuated along the streets. Interestingly, the modified models showed a steady movement and uniform distribution of airflow within four streets. The results showed that narrower street widths compared to the original helped to provide constant airflow in both cities.
- The results indicated that by minimising street widths compared to their original sizes to meet the thresholds of the National Model Design Code, the amount of visible sky decreased causing a reduction

in solar radiation exposure on the canyon and neighbouring building facades, consequently affecting temperature values. As a result, PET values showed a reduction that could mitigate heat stress in summer.
- The study found that the proposed threshold values have a positive impact on the pre-selected urban canyons with larger areas during summer, as deduced by the generated PET values.
- The analysis revealed that when Aspect Ratio and SVF have a direct relationship and a similar pattern resulted in providing stable PET during winter. However, when the Aspect Ratio and SVF have an inverse relationship, the obtained results generated low temperatures during winter.

Generally, the assessment provided an approach to developing local design guides. However, the study was limited to specific dates and times, walkable streets, streets of N-W orientation, simulation methods and cities with similar geographical latitudes, making generalization difficult as comfort condition is a case-by-case assessment. The study recommends that further investigations should be conducted using empirical measurements specifically during the winter season to further validate the impact of the proposed threshold values on urban canyons. Additionally, in old city centre cores, building heights are lower than in new build, hence compliance to the two proposed threshold values with an Aspect Ratio of 1:1 and a street width of 15-20 m are difficult to achieve. It is recommended to investigate new strategies such as planning High Streets in Old Town cores or altering the recommended widths to have a lower or minimum value.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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