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Impact of urban morphology on Urban Heat Island in Manchester's transit-oriented development

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ABSTRACT

This study delves into the relationship between urban morphology and the Urban Heat Island (UHI) effect in Manchester's transit-oriented development (TOD). Using various analytical methods, including context analysis, remote sensing, SPSS correlation and the Sankey analysis, the research examines both weekday and weekend data of Manchester Piccadilly and East Didsbury TODs. Remote sensing analysis reveals Manchester Piccadilly TOD as a UHI hotspot due to concentrated human activities and low Normalised Difference Vegetation Index (NDVI). East Didsbury TOD, on the other hand, experiences lower UHI intensity because of its lower building and population density. The findings highlight the significant impact of land use and urban morphology on UHI intensity. The paper highlights how TOD-generated commercial and entertainment activities contribute to UHI levels in different locations in Manchester. Factors such as high population density and a higher percentage of workers exacerbate the UHI effect in TODs. The relationship between building heights and UHI challenges the conventional assumption of a positive correlation between floor area ratio (FAR) and UHI. These insights are crucial for TOD planning, emphasising the need to carefully consider land use, population density, and building characteristics in shaping the TOD locations. Implementing measures such as reducing heat emissions from commercial and entertainment activities can lessen the UHI intensity. Providing effective shading in TOD streets and shortening the distance to transit stations can encourage sustainable transportation modes like walking and cycling. Ultimately, this paper enhances understanding of the intricate connections between urban morphology and UHI, facilitating the development of environmentally friendly TOD.

1. Introduction

Climate change intensifies, underscoring the urgency of implementing measures to foster sustainable urban growth and alleviate its repercussions, as specified in the Sustainable Development Goals (SDGs): Goal 11, which pertains to establishing sustainable cities, and Goal 13, dedicated to climate action (Koley, 2020; SDG, 2022; UN, 2015). Despite these aspirations, the environmental situation remains challenging, marked by increasingly frequent extreme weather events and unprecedented temperature levels (EEAA, 2021; El Raey, 2004; Wade et al., 2013). Focusing on the United Kingdom, the country has been witnessing a significant rise in temperature records since 1984, with 2022 breaking the record as the warmest year at an average annual temperature of 10.03 °C, surpassing the previous high of 9.88 °C in 2014, according to the Met Office (BBC, 2022; Met Office, 2022). These circumstances raise pertinent questions regarding the effectiveness of Sustainable Urban Development (SUD) strategies and their ability to deliver anticipated benefits (see Fig. 1).

Monitoring the environmental impact of SUD strategies becomes crucial to evaluating performance, identifying inefficiencies, and proposing guidelines for improvement. Among the SUD strategies, Transit-Oriented Development (TOD) stands out, emphasising the importance of integrating urban development and transportation. TOD promotes the creation of residential neighbourhoods around transport stations, enabling easy access to work, community services, and activities within a 600-m radius, fostering walkability, cycling, and public transportation usage, and reducing car dependency (Fig. 2) (Dittmar and Ohland, 2004; Paul and Taylor, 2021; Uddin et al., 2023).

TOD planning and design rely on two essential characteristics: density and diversity of land use. These aspects are instrumental in enhancing TOD efficiency and viability and facilitating various activities such as services, amenities, employment, and housing (Calthorpe, 1993;

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Higgins and Kanaroglou, 2018). However, the environmental impact of such TOD benefits warrants consideration. High-density urban forms tend to retain solar heat emissions, elevating urban temperatures. The mixed land use in a TOD may also contribute to higher air temperatures if it lacks green open spaces and shading features while accommodating excessive human activities. Consequently, TOD areas could be susceptible to the intensified effects of Urban Heat Islands (UHI) (Fig. 4).

UHI is a phenomenon characterised by urban areas storing more heat than their surrounding rural counterparts, leading to noticeable temperature disparities (Fig. 3). Studies have demonstrated temperature differences ranging from a few degrees Celsius in smaller cities to over 10 °C in large metropolises. The consequences of UHI vary, ranging from localised effects such as increased energy demand and human discomfort to broader impacts like water scarcity and severe respiratory diseases (Fig. 4) (Elmarakby et al., 2020; Kamruzzaman et al., 2018; Santamouris, 2020).

Moreover, condensed TODs lacking verdant open space render them more susceptible to the UHI effect because of a decreased Normalised Difference Vegetation Index (NDVI) (Wang et al., 2023). NDVI holds significant importance in the study of urban heat islands (UHIs) in TOD, where it serves as a critical tool for evaluating the health and distribution of vegetation in urban environments, which is essential for mitigating the warming effects of UHIs through the cooling and shading properties of greenery (Grover and Singh, 2015; Zhang et al., 2012).

However, existing literature frequently neglects the potential environmental implications of TOD, notably the formation of UHI. Since UHI is highly associated with dense urban morphologies, the high-density urban form of TOD would represent a risk of exacerbating the UHI in urban areas, putting TOD's environmental impact under consideration. Therefore, this paper is dedicated to investigating the influence of TOD urban morphology on UHI formation to establish correlations between TOD's urban morphology parameters and UHI intensity and offer evidence-based recommendations for mitigating the UHI effect within the context of TOD.

This paper is divided into five sections, tackling diverse TOD typologies in Manchester City, UK.

The first section examines existing literature on various TOD typologies, their design characteristics, and their contribution to UHI intensification. Section two presents the case study selection and the research methodology. The third section presents the analysis findings and subsequent discussion. Finally, the fourth and fifth sections summarise the impact of TOD urban form on UHI in the study areas and propose potential recommendations for mitigating UHI effects in TOD.

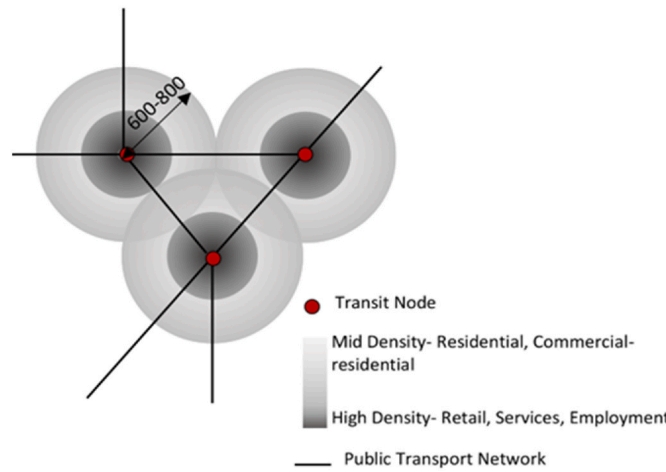


Fig. 2. Transit-oriented development connected nodes.
Source: Author

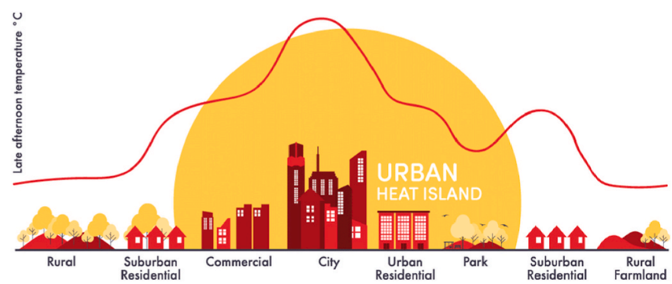


Fig. 3. The urban heat islands effect.
Source: Author

1.1. TOD typologies

Transit-oriented development (TOD) promotes compact mixed-use urban development around public transport stations, encouraging walking, cycling, and reliance on public transportation (Benfield, 2019;

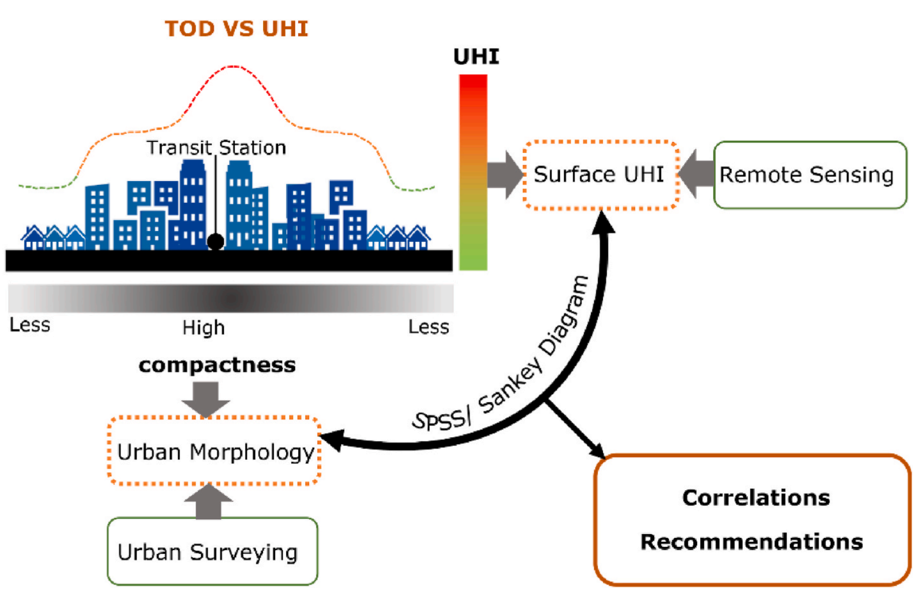


Fig. 1. Graphical abstract illustrates the papers' aim and methodology.

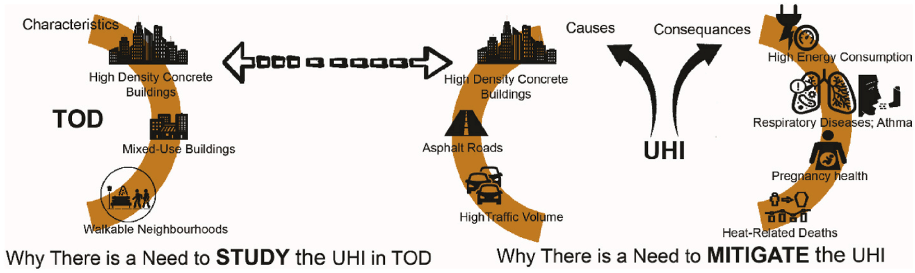


Fig. 4. Potential impact of the TOD characteristics on the UHI.
Source: Author

Braswell, 2013; Gerald et al., 2021; Phani Kumar et al., 2020; Thomas and Bertolini, 2017; Zhang et al., 2019). The TOD neighbourhoods are structured as a network of interconnected nodes, with each node centred around a public transport station (Fig. 2) (NIUA, 2016). These nodes vary in scale, context, and transit mode, encompassing centre TOD, district TOD, and corridor-oriented TOD (NIUA, 2016).

Center TOD is situated around major transit hubs, accommodating regional and community-level residential, commercial, and retail activities. It includes the Regional Center, Urban Center, Suburban Center, and Transit Town Center TOD (NIUA, 2016). District TOD, on the other hand, revolves around local transit stations and incorporates a mix of local and residential community activities. Examples of district TOD include Urban Neighborhoods, Transit Neighborhoods, and Special Use/Employment districts (NIUA, 2016). Corridor-oriented TOD, as the name suggests, is aligned along transit corridors such as light rail or bus rapid transit lines. It features a blend of mixed-use economic, community, retail, civic, and cultural activities (NIUA, 2016).

While each type of TOD possesses distinct characteristics, they share the common goal of creating vibrant, walkable living areas that are easily accessible through public transportation and interconnected across different urban scales (Braswell, 2013; Thomas and Bertolini, 2017). By promoting TOD, cities can foster sustainable and livable communities (Singh et al., 2017).

1.2. TOD design characteristics

Since the rise of the TOD concept in 1993 Peter Calthorpe introduced the TOD term, the TOD design principles have been varied to be more inclusive to include density, mixed-use, walkability, and accessibility (Calthorpe, 1993; CapMetro, 2021; ITDP, 2017; Thomas and Bertolini, 2017). Ewing and C (2010) proposed a five-dimensional scheme, including Density, Diversity, Design, Destination, and Distance to Transit, as critical indicators for TOD design (R. Ewing and Cervero, 2017).

- Density: Urban Density is a crucial principle in TOD planning, attracting urban growth around transit stations and supporting mixed-use activities (Huang, 2018). Different TOD types exhibit varying densities based on the urban scale they serve. The TOD density is usually referred to as the Population density, reflecting the number of residents, and building density, represented by the Floor Area Ratio (FAR). Both the population and building densities play a significant role in the TOD's density evaluation (R. Ewing and Cervero, 2017; NIUA, 2016; Sohoni et al., 2017).
- Diversity: Promoting diverse land uses within TODs enhances accessibility and reduces the need for commuting. To achieve diversity in the TOD, the land uses should include a varied pattern, comprising residential, commercial, employment, and public areas, and ensuring a minimum of 50% mixed-use street frontage (CHEN, 2010; Kristianto et al., 2020).
- Design: TOD does not only target embedding the transit in the proximity of dense and diverse land-use areas; it is a step toward reducing the dependency on the car and improving the quality of life, which eventually enhances the environment (Mehta et al., 2021; NIUA, 2016). The design dimension is commonly related to street network design, including street enclosure and sidewalk design (Huang, 2018).
  - Street enclosure refers to how well-defined and visually enclosed streets and public spaces are due to the presence of buildings, walls, trees, and other vertical elements. It is assessed using the canyon ratio, which compares buildings' height to the street's width (H/W). To ensure the creation of walkable streets, it is recommended that at least 50% of all street frontages within the TOD have a minimum building height-to-street-width ratio of 1:3.(AUDRC, 2017; Huang, 2018; NIUA, 2016).
  - Sidewalk design is crucial for enhancing walkability in TOD. The width of sidewalks varies depending on traffic volume and the type of movement, accommodating pedestrian-only or shared use with cyclists. In TOD, sidewalks should not be narrower than 5 feet (~160 cm). Street furniture, bicycle parking, trees, and other amenities also influence sidewalk width (MinneapolisMN, 2018).
- Destination: This dimension refers to the accessibility to daily needs destinations. It could be achieved by offering activities within walking distance. In the TOD, local destination s to the accessibility to the nearest retail service (Huang, 2018). Accordingly, destination accessibility depends on the land-use mix and walkability, as the more mixedness between residential, commercial, and other land uses occurs, the more the destination could be reachable by walking or cycling (Braswell, 2013; Dittmar and Poticha, 2004).
- Distance to transit: It is a crucial consideration in TOD because it can impact the success and effectiveness of the development. The TOD goal is to make it easy for residents and workers to access public transportation, reducing reliance on cars and promoting sustainable, environmentally friendly modes of transportation. Distance to transit dimension indicates how the transit station is reachable within 10 min of walking distance. It could be assessed by calculating the distance from each building to the nearest station (Braswell, 2013; Dittmar and Poticha, 2004).

But the intriguing question is how all these characteristics impact the UHI effect in the TOD. Do they exacerbate the UHI intensity by reducing car dependency and, therefore, the heat emissions associated with them? Or do they just add more thermal burden on the cities due to their high-density characteristics?

1.3. TOD characteristics and UHI effect

The relationship between TOD urban morphology and the Urban Heat Island (UHI) effect is essential to understanding their impact on UHI spatial and temporal patterns. Specific characteristics such as density, diversity, and street design directly influence UHI, while others like sidewalk design, destination accessibility, and distance to transit are influenced by UHI (Table 1) (Deilami and Kamruzzaman, 2017; Kamruzzaman et al., 2018; Santamouris, 2020).

Table 1
Ewing and Cervero 5 Design dimensions for TOD design.

5D	Component	Parameter	UHI Impact
Density	Population Buildings density	Population Density* Residents to Employment Density* Building Heights* FAR*	- Positive: The compact urban form generates shade and lessens the exposure to solar heat. - Negative: Increasing the heat generated by concrete buildings, asphalt roads, and vehicles in proximity.
Diversity	Mixed-use pattern	Land Use* Mixed-use Street Front*	- Positive: mixed-use development can encourage people to walk or use low-emission transportation options, reducing vehicle-generated heat. - Negative: The concentration of the uses that could generate heat, such as restaurants, transport stations, and parking lots. - However, to increase pedestrian comfort and encourage walkability in the TOD, the 50% of mixed-use street fronts filled with activities should be considered when designing shaded streets.
Design	Street Design	Street Enclosure (Canyon Ratio) * Sidewalk Design*-	- Close and tall buildings relative to the width of the space between them could create a "canyon" effect that traps heat and exacerbates UHIs. - Sidewalks should be designed to be comfortable for pedestrians and cyclists.
Destination Distance to Transit	Accessibility Distance to transit*	Walkability/ cycling*	- It should be connected and supported by shading features to reduce the UHI intensity to create a more walkable TOD area while achieving thermal comfort for the people, whether they walk or cycle to their destination or the public transport nodes. - Distance to transit needs to be shortened in case of an intense UHI effect.

*Affects the UHI.
*Affected by the UHI.

The compact urban form of TOD can positively and negatively affect UHI intensity. The concentration of tall buildings, infrastructure, and transportation in high-density urban areas increases heat absorption and emission, mainly from materials like concrete and asphalt. However, careful design of the compact urban form, including mid-rise buildings, narrow streets, and shaded sidewalks, can help mitigate the UHI effect (Elmarakby et al., 2020, 2022).

The TOD's mixed-use urban form could also positively and negatively impact the UHI. Mixed-use development involves a combination of residential, commercial, and/or employment land uses in a single area, which can increase the UHI due to the high heat generated by buildings and vehicles in close proximity. When facilities that generate heat uses, such as restaurants, are close together, they can trap heat and create a heat island effect, especially if there is a lack of green open spaces (Elmarakby et al., 2022; Yu et al., 2019). Thus, land use mainly affects the UHI spatial and temporal pattern, which differs according to, for instance, the working hours. However, diverse land uses could encourage people to walk or use low-emission transportation options, reducing vehicle-generated heat.

TOD design considerations include street enclosure and sidewalk design, which UHI influences differently. High street canyon ratios can increase solar radiation absorption by buildings and surfaces, leading to higher temperatures (M'Saouri El M'Saouri El Bat et al., 2021). Conversely, Sidewalk design should account for UHI's impact by providing shading and a comfortable pedestrian network to promote walking and cycling, even in hot weather (Yu et al., 2019).

The destination dimension of TOD focuses on providing access to various destinations, emphasising walkability and cycling. While most literature focuses on achieving walkability for daily needs, work, and public transportation, thermal comfort is crucial to encourage walking. If people do not feel comfortable walking or cycling, they may opt for other modes of transportation, such as private cars, undermining the concept of a walkable TOD (Ollivier et al., 2021; Polyzoides, 2011; Tse, 2020). Therefore, Understanding UHI patterns within TOD can inform the adoption of suitable techniques, such as shading elements, to enhance the thermal comfort of pedestrians and cyclists.

The UHI effect directly influences the distance to the transit dimension. Hot weather can make the 10-min walking distance to transit seem long, particularly for vulnerable groups. Therefore, understanding the UHI patterns in TOD is crucial for making walking to transit more convenient and appealing to achieve TOD goals (Cervero and Murphy, 2004; Ibraeva et al., 2020).

This paper aims to establish correlations between urban morphology parameters (5D) and the UHI effect in TOD areas. By examining the exact influence of TOD's urban morphology on UHI, this analysis provides evidence for identifying effective UHI mitigation strategies and enhancing sustainability goals within TOD.

2. Materials and methods

This paper aims to investigate how the urban morphology of TOD affects the UHI effect. The city's strategic location within the Greater Manchester metropolitan area in the UK makes it an ideal case study (Fig. 5). With a population of 552,000 and 45 square miles (116 square km), Manchester City is the second largest city in the UK after London. The Pennines area surrounds it to the north and east, Cheshire Plain to the south, and Salford City to the west (Symons et al., 2002). This study focuses on two specific TOD types: Center TOD and District TOD. The selected areas for analysis are Manchester Piccadilly (Regional Centre TOD) and East Didsbury (Urban Neighbourhood TOD), as shown in Table 2.

Manchester Piccadilly (MP) is the central transport hub in Manchester's Central Business District (CBD), connecting the city centre with local and regional destinations (Manchester City Council, 2019). It offers a range of public transportation options, including railways, trams, buses, and a proposed high-speed tram. The CBD encompasses diverse land uses, such as employment, retail, community activities, and residential areas (Hakimian, 2022). Therefore, MP serves as an ideal case study for examining the impact of the urban structure in a regional centre TOD on UHI (Table 2) (Manchester City Council, 2019; Hakimian, 2022).

On the other hand, East Didsbury (ED) is located in the Didsbury villages, approximately 5 miles (8 Km) south of Manchester city centre. Despite its distance, ED is a significant transportation hub due to its train station, connecting the village with Manchester Piccadilly, Manchester Victoria, and neighbouring cities like Leeds and York. Local public transport networks, such as buses, serve the area. The vicinity of the train station represents the city centre of ED, characterised by a mix of retail, employment, and community services catering to local needs. ED represents the District Neighbourhood TOD, allowing for a comparative analysis with the Regional Center TOD, MP (Table 2) (Cox and Wilkinson, 2023).

This study employed a range of analytical methods to evaluate UHI performance within the TOD study areas, MP and ED, while also

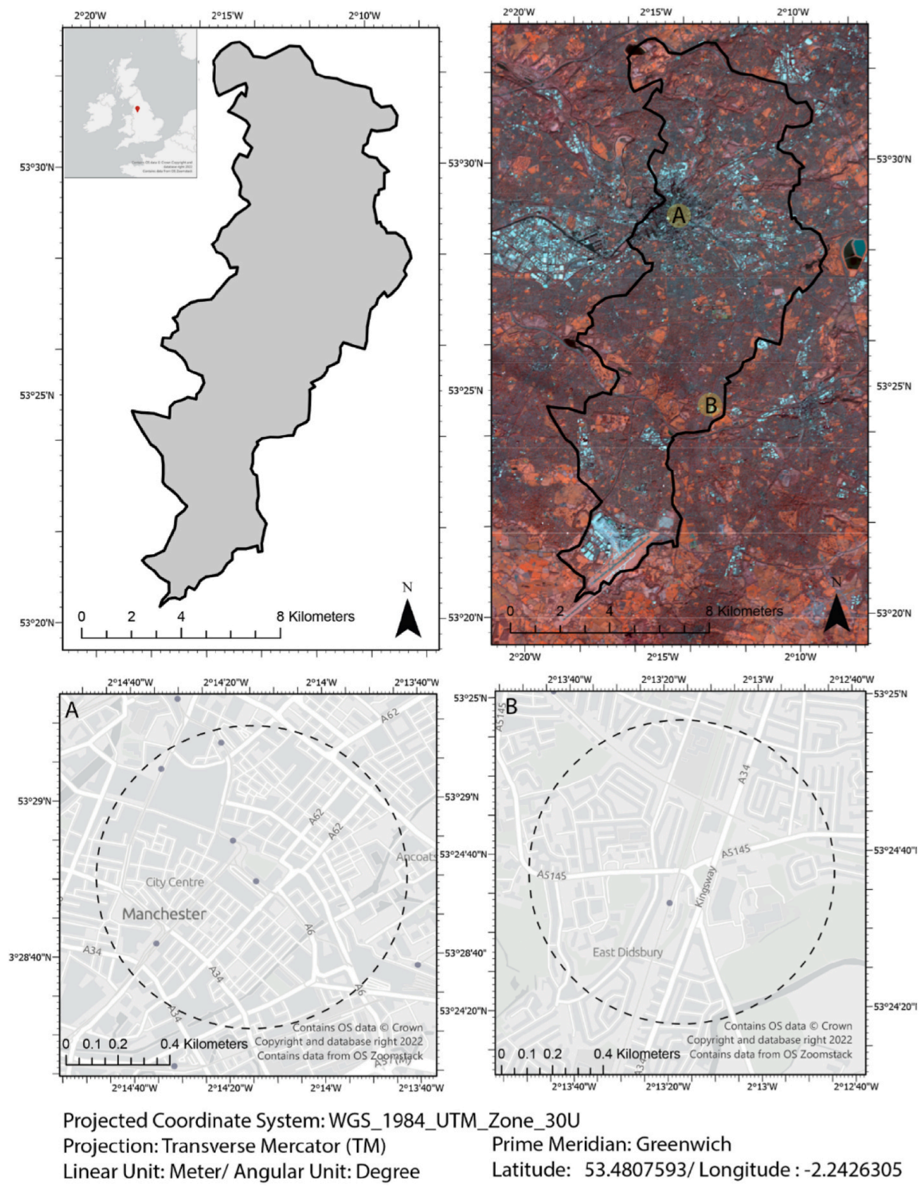


Fig. 5. Manchester City's geographical location. The satellite image is a false colour composite of Landsat 9 acquired on the 6th and April 29, 2023. (Manchester Piccadilly (B) East Didsbury. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

exploring the impact of urban morphology on UHI. These methods included a contextual analysis involving shadow and incident radiation analysis, remote sensing, statistical analysis using SPSS, and the utilisation of Sankey diagrams. Each technique has significant importance in delivering part of the research for framing the comprehensive outcome of the paper. For instance, the context analysis and shadow and incident radiation analysis offer valuable insights into the contextual environmental factors contributing to UHI. Remote sensing provides a means of assessing UHI at the regional and local scales, while SPSS allows for statistical analysis of correlations. Moreover, using the Sankey diagram is instrumental in visualising the complex relationships between urban morphology parameters and the UHI intensity. These methods collectively contribute to a more comprehensive understanding of UHI dynamics with the TOD for mitigating its effects, thus advancing the field of UHI research (Figs. 6 and 7).

2.1. 3D solar analysis: shadow and incident radiation

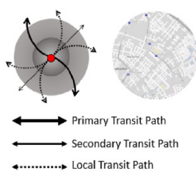
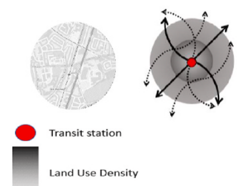
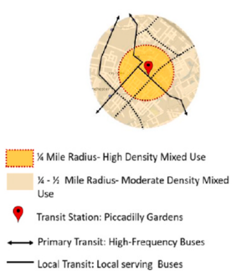
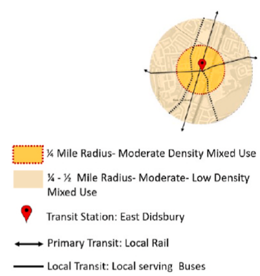
To comprehensively analyse the UHI phenomenon, an initial assessment was conducted to map the incident radiation and shadows in the study areas.

This assessment aimed to gain insights into the urban context of the study area and evaluate the heat performance during the UHI detection period on April 6th and 29th, 2023.

Incident radiation refers to solar radiation reaching the Earth's surface and significantly influencing the UHI effect. Urban areas, characterised by impervious and dark surfaces such as concrete buildings and asphalt roads, absorb more incident radiation. Consequently, these areas trap more heat, intensifying the UHI effect compared to rural regions with more vegetation. Hence, incident radiation plays a pivotal role in the UHI effect by influencing heat absorption and reflection by urban surfaces (Yuan et al., 2021).

Shadows can also impact the UHI by modifying the incident radiation urban surfaces receive. In areas exposed to direct sunlight, shades provide relief from the heat by reducing the radiation received by permeable surfaces. This mitigation mechanism can alleviate the UHI effect by decreasing the heat absorbed by urban surfaces (Elmarakby et al., 2020; Kamruzzaman et al., 2018; Santamouris, 2020).

Table 2
The selected TOD study areas in Manchester: typologies and characteristics.

Type	Regional Centre	Urban Neighbourhood
Area Characteristics	Core and primary centre of economic and community activities at the regional level	Residential districts surrounded and supported by one or more regional or subregional centres with high accessibility
Transit Mode	- Primary transit, such as high-frequency and capacity regional railways and buses. - Local serving bus transport. - < 5 min off-peak frequency.	- Served by local public transportation such as subway, rail, monorail, light rail, local buses, or tram. - From 5 to 10 min peak frequency with 20mins off-peak.
Land use/ Density	- High-density mixed-use residential, commercial, cultural and employment activities - Regional-serving retail destination	- Few economic and community activities support residential areas. - Densities are moderate to low. - Primary Local-serving retail destination, integrated with other surrounding community services.
Housing	High-rise to Mid-rise mixed-use housing (Multifamily Loft).	Commonly, mid to low-rise townhouses.
Study Area/ Morphology	Manchester Piccadilly 	East Didsbury 
Analysis		

However, shadows contribute to the UHI effect by impeding air circulation in urban areas. Buildings and structures casting shadows create stagnant air pockets that trap heat and pollutants, resulting in elevated temperatures in these areas (Yu et al., 2019).

Consequently, this study utilised Rhinoceros 3D and Grasshopper, computer-aided design (CAD) and computational design software to calculate the absorbed incident radiation and map shadows in the MP and ED areas. The incident radiation was calculated using the Ladybug Tools, a collection of open-source software plugins for environmental analysis. The obtained study provided a comprehensive understanding of the UHI drivers in both Transit-Oriented Development (TOD) areas, which will be further linked to the 5D characteristics in subsequent analysis.

The effectiveness of Rhino and Grasshopper software in shadow and incident radiation analysis is evident in their adaptability to architectural and environmental simulations. Grasshopper's parametric modelling facilitates the manipulation of design variables, complemented by seamless integration with Rhino for precise 3D representation of real-world environments (Bellia et al., 2014; Roudsari and Pak, 2013). However, it's essential to acknowledge the inherent limitations and assumptions accompanying using Rhino, Grasshopper, and Ladybug Tools in such analyses. These include the reliance on accurate geospatial data, potential inaccuracies due to outdated information, and reliance on weather and climate data that may not always reflect real-time variations. Spatial resolution constraints, assumptions about building geometry accuracy, and the impact of cloud cover should also be considered (Kim et al., 2019; Roudsari and Pak, 2013).

In addressing these limitations, a meticulous approach was adopted for this analysis. High-precision data sourced from the University of Edinburgh's EDINA, specifically the Digimap collection, was employed to eliminate any assumptions related to urban surveying. This dataset offered precise, vector-based information about heights and urban structures, significantly enhancing the analytical accuracy (Table 4) (EDINA, 2021).

Furthermore, careful consideration was given to selecting analysis days, favouring those characterised by predominantly sunny weather and minimal cloud cover. This decision was instrumental in minimising the potential impact of cloud cover on the analysis (Roudsari and Pak, 2013). Notably, on cloudy days, Rhino and Grasshopper would generate results as if the sky was clear with total sun exposure. At the same time, remote sensing data would faithfully represent the prevailing weather conditions. Thus, aligning analysis conditions became paramount, ensuring consistency and preventing data disparities from varying sun exposure in differing weather conditions. This approach proved invaluable in achieving precise and consistent assessments of the Urban Heat Island (UHI) effect related to shadow and incident radiation.

2.2. Remote sensing analysis: land surface temperature (LST) and urban heat islands effect (UHI)

To accurately assess and project UHI effects, climate models need to capture the complex interactions between urban settings and the atmosphere. However, state-of-the-art climate models often face challenges in representing urban climates due to the intricate interplay of weather variables, such as humidity and wind (Doan and Kusaka, 2018; Nogueira et al., 2020).

For addressing the urban heat islands, remote sensing offers an efficient and cost-effective method for investigating UHI in a specific geographic area. Moreover, Remote sensing plays a crucial role in capturing local variability in weather variables like humidity and wind,

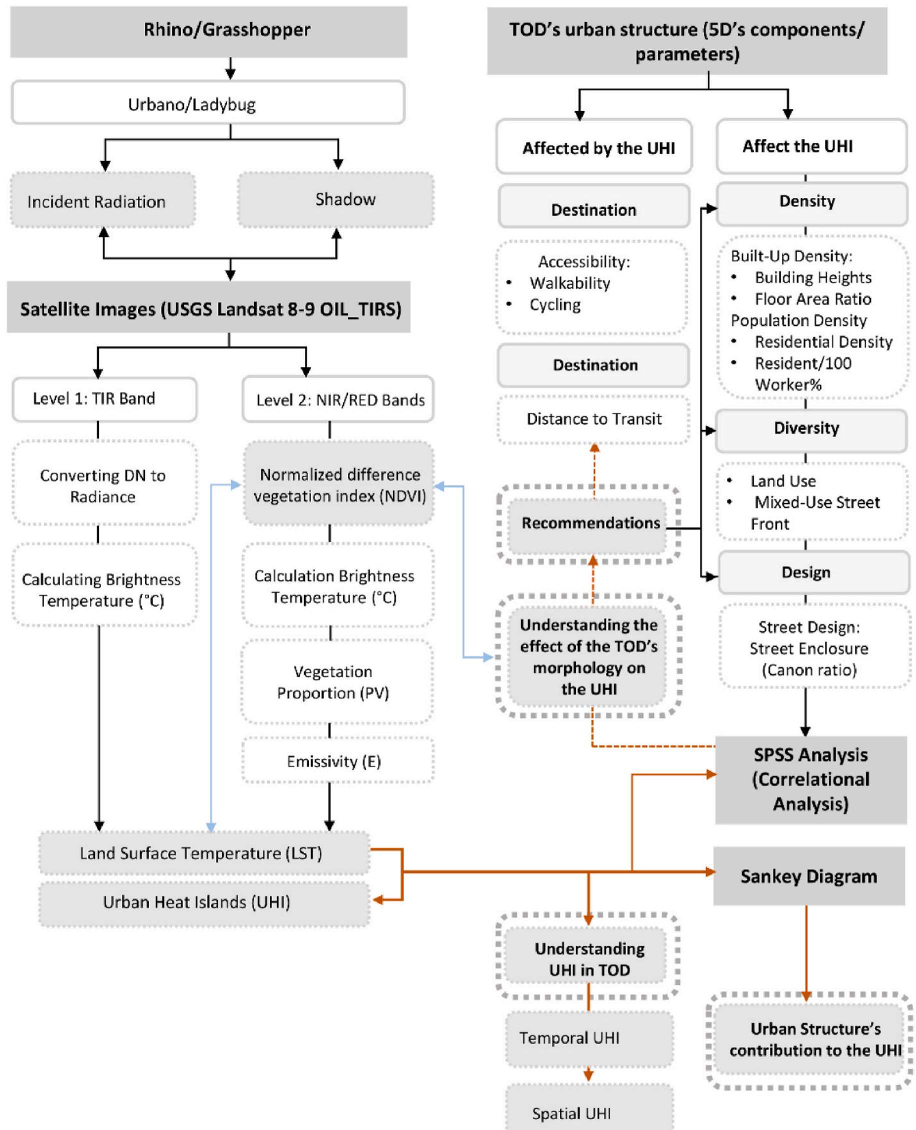


Fig. 6. Research methodology.

which are vital for understanding Urban Heat Island (UHI) dynamics (Diem et al., 2023). Through sensors that operate in thermal infrared bands, remote sensing provides high-resolution information on temperature gradients based on emissivity changes, soil moisture, wind patterns, and atmospheric conditions within urban areas (Kustas and Anderson, 2009; Tomlinson et al., 2011).

This approach involves analysing satellite imagery to quantify Land Surface Temperature (LST). In this study, researchers utilised Earth-Explorer, an accessible platform, to obtain relevant digital data from the United States Geographical Survey (USGS), including satellite imagery, digital aerial photographs, and map products. Specifically, Landsat 8–9 OLI/TIRS Collection 2 Level-2 and Landsat 8–9 OLI/TIRS Collection 2 Level-1 images were employed to identify LST and the UHI effect in the study area.

To identify LST and the UHI effect in the study area.

Two distinct satellite images of Manchester City were selected to represent weekdays and weekends, enabling an examination of temporal and spatial patterns of UHI occurrence during these periods. Manchester Piccadilly (MP) and East Didsbury (ED), the two Transit-Oriented Development (TOD) study areas, were cropped for statistical analyses to evaluate the correlation between urban structural elements and the UHI effect. To ensure reliability, satellite images were filtered based on a cloud coverage threshold of less than 20% within a given Worldwide Reference System (WRS) scene, minimising the potential influence of cloud cover on the results (Table 3). The selected satellite images have been chosen in the spring to avoid the extreme effect in the summer and the diminished UHI effect in the winter. Avoiding the fall is returned to the high cloud cover the satellite image experiences during this season.

Using ArcGIS Pro, the selected satellite images went through the analysis process. In the beginning, two levels of the data were processed (de Almeida et al., 2021; P. Kumar et al., 2018; Kustas and Anderson, 2009; Tomlinson et al., 2011).

- Level 1: Band 4 Red (0.64–0.67 μm) 30-m and Band 5 Near-Infrared (0.85–0.88 μm) 30-m
- Level 2: Band 10 TIRS 1 (10.6–11.19 μm) 100-m

The processing process for obtaining the LST and the UHI followed the below steps (P. Kumar et al., 2018; Tomlinson et al., 2011).

For the level 1 analysis, the Digital Numbers (DN) were converted to Spectral Radiance using the following equation (Agam et al., 2008; Hall et al., 2012; P. Kumar et al., 2018; Kustas and Anderson, 2009):

$$TOA\ (L) = ML * Qcal + AL \quad (1)$$

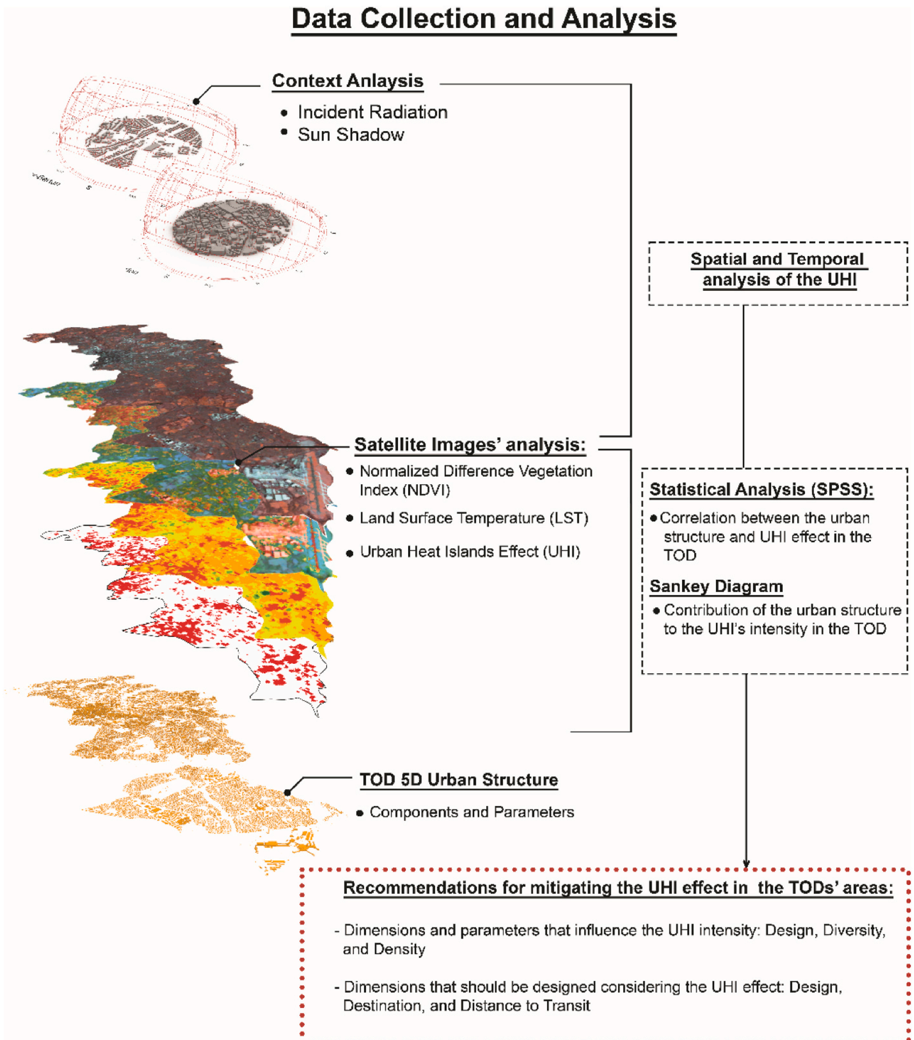


Fig. 7. The research's layers of analysis and outcomes.

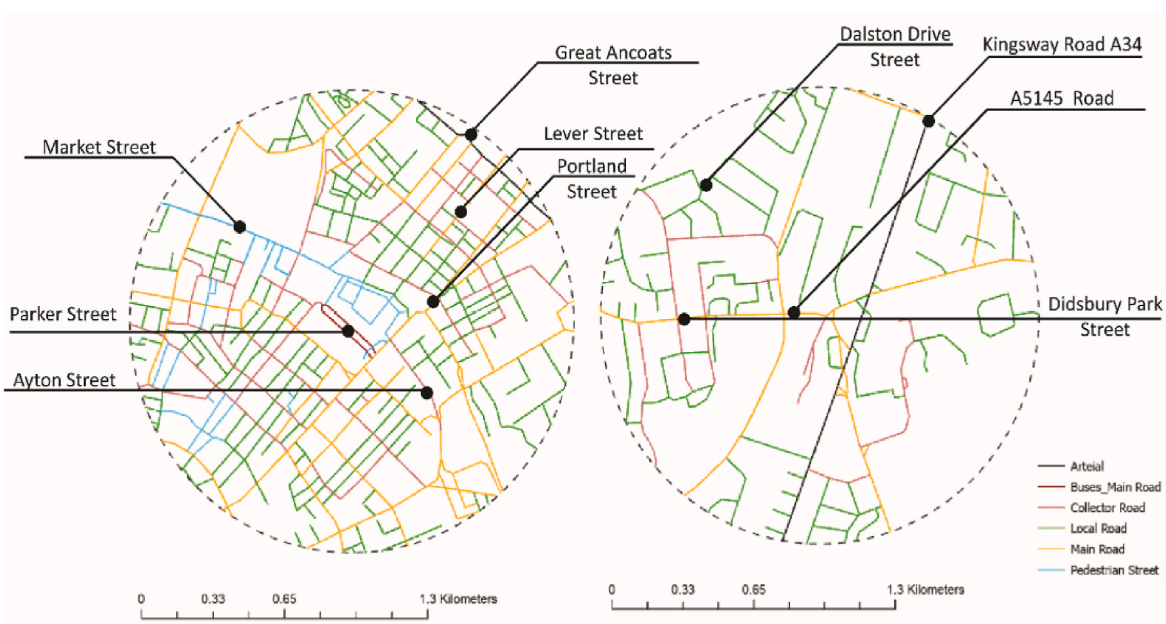


Fig. 8. The selected roads for the section analysis based on the hierarchy in MP and ED.

Table 3
The selected satellite images' metadata.

Satellite	Sensor	Path/Row	Spatial Resolution	Acquisition Date	Day	Acquisition Time (Z)[a]	Acquisition Time (BST)[a]	Cloud Cover
Landsat 8–9	OIL_TIRS	204/023 203/023	30	29.04.2023 06.04.2023	Saturday Thursday	11:04:35 11:10:25	12:04:35 12:10:25	15.17 15.17

[a] **Z: Zulu time is generally used as a term for Universal Coordinated Time (UCT) which is converted to British Summer Local Time (BST).**

Table 4
TOD Urban Structure Characteristics and their Data Sources.

5D	Components	parameter	Data Source	Analysis Method
Density	Population	Residential density	Plumplot based on the Office of National Statistics, 2020	ArcGIS Pro, Spatial mapping, Residents/ Km2
		Residents to Employment density		Statistical Analysis, Residents/ 100 Workday People
	Buildings density	Building heights	Digimap, EDINA, the University of EDINA, 2021	ArcGIS Pro, Spatial mapping, Building heights
		FAR		Statistical Analysis, Gross floor area to land size
Diversity	Mixed-use pattern	Land Use	Andrew Taylor's Manchester City Centre Maps, The University of Manchester City Council, 2019	ArcGIS Pro, Spatial mapping, Land use mapping
		Mixed-use street front	Digimap, EDINA, the University of EDINA, 2021	ArcGIS Pro, Statistical Analysis, Street Length to Activity (SLA) analysis
Design	Street Design	Street Enclosure	Digimap, EDINA, the University of EDINA, 2021	ArcGIS Pro, Spatial mapping, Canyon ratio analysis
		Sidewalk design	OpenStreetMap Instant Google Street View	Section Analysis, Street Design Spatial mapping, Cycling Network
Destination	Accessibility	Walkability /Cycling	https://www.walkscore.com/	Spatial mapping, Length of the walking routes to destinations
Distance to Transit	Distance to Transit		Digimap, EDINA, the University of EDINA, 2021	ArcGIS Pro, Network Analysis, Closest Facility

Where: TOA (L) is the Top of Atmospheric spectral radiance from the metadata, ML is the radiance multiplicative scaling factor from the metadata, Qcal is band 10, and AL is the radiance additive scaling factor.

Then the sensor brightness temperature BT is calculated in degree Celsius using the following formula (Agam et al., 2008; de Almeida et al., 2021; Dousset and Gourmelon, 2003; Hall et al., 2012; Hulley et al., 2019; Imhoff et al., 2010; P. Kumar et al., 2018; Kustas and Anderson, 2009b; Tomlinson et al., 2011; Weng and Fu, 2014):

$$BT\ (C) = (K2 / (\ln (K1 / L) + 1)) - 273.15 \tag{2}$$

Where k1 and K2 are the Band-specific thermal conversion constants obtained from the metadata, and L is the spectral radiance (TOA).

Level 1 of the analysis ends with calculating the Brightness Temperature (BT), while Level 2 calculates the LST corrected by Emissivity (°C) using the following steps. Firstly, the Red and NIR bands (bands 4 and 5) were used to calculate the Normalised Difference Vegetation Index (NDVI) using the following equation (Agam et al., 2008; de Almeida et al., 202):

$$NDVI = (Band\ 5 - Band\ 4) / (Band\ 5 + Band\ 4) \tag{3}$$

Calculation of the NDVI is essential for obtaining the Emissivity (ε) from the below equation (Dousset and Gourmelon, 2003; Hall et al., 2012; Hulley et al., 2019; Imhoff et al., 2010) depending on the calculated Vegetation Proportion (PV) as follows:

$$Pv = Square\ ((NDVI - NDVImin) / (NDVImax - NDVImin)) \tag{4}$$

$$\varepsilon = 0.004 * Pv + 0.986 \tag{5}$$

Finally, the LST is calculated based on the output of Level 1 and Level 2 analysis as follows equation (P. Kumar et al., 2018; Kustas and Anderson, 2009b; Tomlinson et al., 2011; Weng and Fu, 2014):

$$LST = (BT / (1 + (\lambda * BT/\rho) * Ln(\varepsilon))) \tag{6}$$

LST is the Land Surface Temperature (°C) corrected by the Emissivity calculated from Level 2's analysis. BT is the Brightness Temperature obtained from Level 1's analysis. ρ = h*c/r (1.438*10–2 m K), r = Boltzmann constant (1.38*10–23 J/K), h = Planck's constant (6.626*10–34 J s), c = velocity of light (2.998 *108 m/s).

$$\rho = h*c/r \tag{7}$$

The UHI is calculated as the spectral areas with a temperature of 0.5 or more standard deviation above the mean temperature. Where μ is the mean LST, and σ is the standard deviation (de Almeida et al., 2021). Retrieving the UHI allowed the researcher to conduct a statistical analysis to find the correlation between the 5D parameters and UHI in the study areas.

$$UHI \geq \mu + 0.5\sigma \tag{8}$$

2.3. NDVI and urban heat islands in manchester TODs

Remote sensing techniques can accurately compute NDVI using as outlined in equation (3) in section 2.2. By incorporating NDVI alongside the monitoring of UHI formation, it becomes possible to assess the environmental impact of urban landscapes in terms of their natural vegetation cover compared to impermeable surfaces (Gandhi et al., 2015).

Using a single pixel-based satellite image to derive both NDVI and Urban Heat Island (UHI) data presents an opportunity for integrating these two analytical layers into a unified dataset, encompassing UHI and NDVI values. This integration facilitates the application of SPSS correlational analysis, enabling the evaluation of the degree of significance in the relationship between these two variables within the study areas: Manchester Piccadilly and East Didsbury.

In addition, NDVI undergoes dynamic changes influenced by seasonal variations and weather conditions. Seasonal fluctuations in NDVI are intricately linked to the life cycle of vegetation. Additionally, short-term weather conditions have an impact on NDVI values. Factors such as rainfall and cloud cover can lead to rapid fluctuations. Rainfall, for instance, acts as a catalyst for plant growth and can trigger a substantial increase in NDVI during wet periods (Gandhi et al., 2015). Conversely, prolonged cloud cover can obstruct the satellite's view of the Earth's surface, potentially affecting the accuracy of NDVI measurements (Boegh et al., 1999; Gandhi et al., 2015; B. P. Kumar et al., 2020). These interactions between seasonal variations and transient weather events highlight the intricate nature of NDVI and its sensitivity to environmental dynamics.

Hence, given that this paper is analysing the relationship between NDVI and UHI on both a weekend and a weekday during the same season while also selecting days with low cloud cover and proximity in temperature, it aims to mitigate the potential impact of these variables on the reliability of the analysis.

2.4. Addressing the TOD characteristics in the study area

This paper applies the 5D framework proposed by Ewing and C (2010) to examine the urban structure of Transit-Oriented Development (TOD) areas (R. Ewing and Cervero, 2017). The framework includes dimensions of Density, Diversity, Design, Destination, and Distance to Transit. The analysis investigates the correlation between Urban Heat Island (UHI) intensity and the parameters associated with these 5D characteristics.

The 5D dimensions are categorised into those influenced by the UHI and those affecting the UHI. Density, land-use diversity, and street design enclosure influence the UHI. Sidewalk design and street enclosure are parameters that UHI influences.

Population and built-up density are measured for density, including residential density, residents-to-employment ratio, building heights, and Floor Area Ratio (FAR) (EDINA, 2021; ONS, 2021). Land use mapping assesses land use diversity, identifies mixed-use patterns, and calculates the percentage of mixed-use street frontage to measure TOD vitality (Taylor, 2021). Regarding street design, street enclosure influences the UHI, and street enclosure influences the UHI. Street enclosure refers to the building height-to-width ratio (H/W), called the canyon ratio. The canyon ratio determines the exposure of the streets and the open spaces to the sky (sky-view factor) and, therefore, the potential heat exchange. A higher canyon ratio suggests lower sun exposure, reduced heat exchange, and an increased UHI effect (M'Saouri El M'Saouri El Bat et al., 2021). Although these characteristics primarily pertain to the physical configuration and design of the TOD urban structure, which influences the UHI, dimensions such as sidewalk design, distance to transit, and destination are influenced by the UHI, necessitating UHI mitigation strategies.

Road hierarchy maps were developed for the study areas (MP and ED) to analyse street design, classifying roads into arterial, main, collector, local, pedestrian, and public transport-only categories. Section analysis was conducted on selected streets from each category, providing insights into their preparedness to mitigate the UHI.

The destination dimension focuses on the accessibility of TOD services through walkable networks or cycling paths, evaluating the integration and distribution of these services. Accessibility is studied by analysing the walkability and cycling coverage areas within the TOD boundary using the Walkscore website (R. ; C. R. Ewing and C, 2010; R. Ewing and Cervero, 2017).

The dimension of distance to transit considers the spatial extent and time required to reach transit stations. Minimising the distance to transportation hubs becomes crucial, particularly in the presence of significant UHI. Geographic Information Systems (GIS) and network analysis were employed to determine the length to transit, incorporating road networks, public transport stations, and building centroids (ITDP, 2023).

2.5. Urban structure influence on the UHI using SPSS

SPSS was employed for correlational analysis between TOD 5D parameters (representing urban structure) and the UHI. Urban structure data, including building heights, density, land use, and UHI measurements, were collected for Manchester Piccadilly and East Didsbury on Thursday, April 6, 2023, and Saturday, April 29, 2023. Descriptive statistics were initially performed to assess variable distribution, identify outliers, and address potential issues affecting the correlational analysis.

Bivariate correlational analysis, specifically Spearman's rho analysis in SPSS, was utilised to determine the correlation coefficient between urban structure parameters and the UHI. Spearman's rho analysis was chosen due to the following considerations: (1) the variables being continuous, (2) the non-normal distribution of the Land Surface Temperature variable despite the absence of outliers in the data (Mircioiu and Atkinson, 2017). The correlation coefficient (r) in Spearman's Rho ranges from −1 to 1, indicating positive or negative correlations, with values close to 0 representing weak or no correlation. The p-value derived from Spearman's rho analysis determines the statistical significance of the observed correlation, with lower p-values indicating more substantial evidence of a significant correlation, typically below a predetermined significance level (<0.05) (Mircioiu and Atkinson, 2017).

2.6. Quantifying UHI contributions of urban structure components: Sankey Diagram

A Sankey diagram analysis was employed to quantify the UHI effect associated with urban structure components, visualising the contributions of different parameters to the overall UHI effect [62], [63]. The UHI effect was expressed as a percentage, representing the temperature differential attributed to each component or parameter. Key parameters, including mixed-land use diversity, residential population, residents-to-worker ratio, building heights, floor area ratio (FAR), and canyon ratio, were visualised in the Sankey diagram, highlighting their contributions to the UHI effect (Riehmann et al., 2005).

By integrating remote sensing analysis and land surface temperature (LST) data on weekdays and weekends, the Sankey diagram illustrated the relative influence of each parameter in the TOD context. The chart, created using a designated visualisation tool, depicted the normalised values of urban structure elements as source flows, with connections leading to the UHI effect as the sink. The width of each flow indicated the respective element's contribution to the UHI [62], [63]. The UHI was categorised into three intensity grades based on temperature increase to understand the role of each urban structure parameter in exacerbating the UHI effect. Negative and non-UHI values were excluded from the analysis to focus only on the active UHI triggering parameters.

Three temperature-based UHI grades were established: grade 1 (0.2–0.4 °C UHI), grade 2 (>0.4–0.6 °C UHI), and grade 3 (>0.6–0.99 °C UHI), representing different levels of UHI severity within the study area. Weekend data was compared to weekday data to explore temporal variations in the UHI and the contributions of urban structure to the UHI.

By incorporating SPSS analysis and insights from the Sankey diagram, this research provided valuable insights into the contributions of various design dimensions to the UHI. It recommended urban structure parameters to mitigate the UHI in Manchester TODs.

The utilisation of Sankey diagrams for assessing complex relationships and contributions in the context of the Urban Heat Island (UHI) study brings valuable insights. Still, it is essential to acknowledge certain limitations associated with this visualisation technique. First, Sankey diagrams simplify intricate relationships by representing them in a linear, one-way flow. In reality, urban environments are dynamic and multifaceted, with interactions between various parameters often being multidirectional and nonlinear. Sankey diagrams may oversimplify these complexities by assigning fixed percentages to contributions, potentially masking relationship nuances (Cuba, 2015).

Sankey diagrams, though simplifying complex relationships, offer distinct advantages in this UHI study compared to alternative visualisation techniques. While they may oversimplify intricate interactions, their clear and intuitive representation of the relative contributions of urban structure parameters to the UHI effect is invaluable. These diagrams facilitate the quick identification of critical contributors, facilitating focus on mitigation strategies. They also enable straightforward comparisons between parameters and across periods, aiding in understanding temporal variations. Moreover, Sankey diagrams bridge data analysis and effective communication, making them preferable for conveying complex UHI insights to a broader audience. In summary, despite their limitations, the benefits of clarity, comparability, and communication make Sankey diagrams a valuable tool in addressing UHI challenges in Transit-Oriented Developments (TODs).

3. Discussion and results

Each level of the five levels of analysis, context analysis, remote sensing, SPSS Correlation, and Sankey diagram analysis. It revealed an insightful aspect of the UHI situation in the study area (Figs. 6 and 7).

3.1. Context analysis: shadow and incident radiation in the TOD

Shadow analysis using Rhino and Grasshopper software in MP and ED revealed distinct patterns during specific timeframes. Observations on Thursday, April 6, 2023, and Saturday, April 29, 2023, at 11:00 a.m., represented weekdays and weekends, respectively (Table 5). In Piccadilly, most streets were covered in shadow, except for Piccadilly Garden, which had incident radiation levels ranging from 0.005 kWh/m^2 to 0.01 kWh/m^2. About 32% of the area experienced incident radiation levels between 0.04 kWh/m^2 and 0.05 kWh/m^2, while the remaining 68% had levels ranging from 0.01 kWh/m^2 to 0.04 kWh/m^2, indicating relatively low incident radiation exposure.

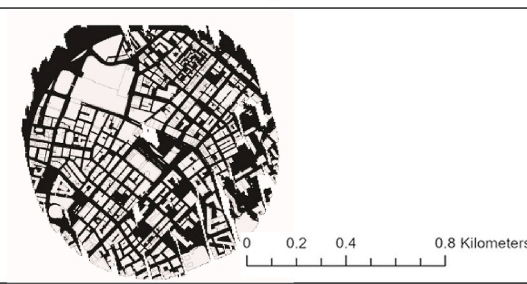
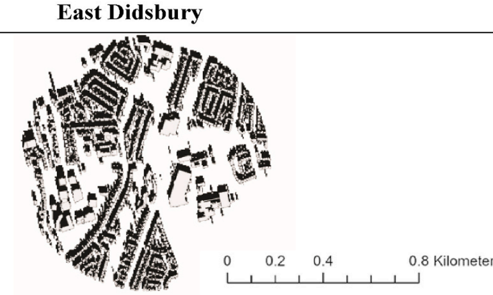
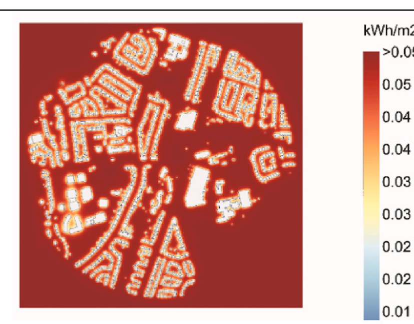
In contrast, East Didsbury, characterised by a transit-oriented development area with shorter building heights than Piccadilly, had limited shadow coverage. In East Didsbury, 93.07% of the region received incident radiation levels ranging from 0.04 kWh/m2 to 0.05 kWh/m^2, indicating greater sunlight exposure. Only 6.93% of the area had incident radiation levels between 0.001 kWh/m^2 and 0.004 kWh/m^2, suggesting minimal shadow coverage. This difference is attributed to the varying building heights between the two areas, with Piccadilly having taller buildings compared to East Didsbury. These findings offer insights into shadow distribution and incident radiation in urban areas, highlighting the influence of urban structure on shadow patterns and sunlight exposure.

3.2. Land surface temperature, urban heat island, and the impact of NDVI in Manchester's TOD

The analysis of land surface temperature (LST) and urban heat island (UHI) using remote sensing techniques provided valuable insights into the spatial distribution of UHI effects in the city (Fig. 9). On Thursday, June 4, 2023, it was found that approximately 26.99% of the city exhibited UHI effects. This coverage increased slightly to 29.21% on Saturday, April 29, 2023. Notably, during weekdays, the UHI effect appeared to be more scattered across the city, whereas, on weekends, it became significantly concentrated in the city centre. This observation suggests that the city centre attracts more commuters during weekends compared to weekdays, resulting in increased traffic and subsequent heat emissions from vehicles. As UHI effects are known to be associated with the urban structure and traffic-related heat emissions, the concentration of UHI in the city centre can be attributed to increased traffic and condensed urban activity during weekends.

A focused analysis was conducted on two specific study areas: MP and ED. During weekdays, MP experienced a substantial UHI effect,

Table 5
MP's and ED's incident radiation and shadow analysis using Rhino and Grasshopper.

	Manchester Piccadilly	East Didsbury
Shadow		
Incident Radiation		

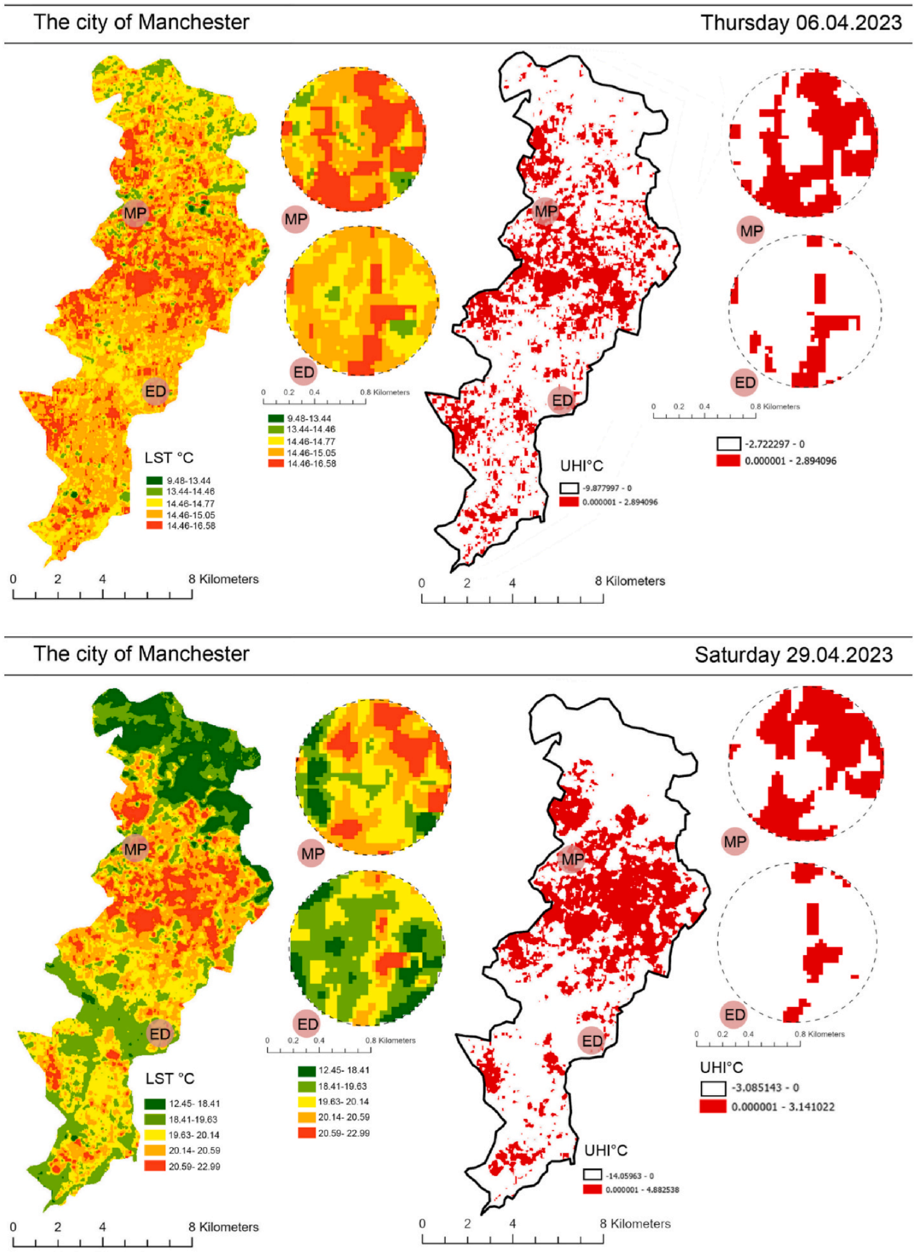


Fig. 9. Spatial distribution of the UHI intensity in Manchester with a focus on the two studied TOD: MP and ED.

covering 52.14% of the area, while ED exhibited a lower UHI coverage of 16.50%. Similarly, during weekends, MP showed a UHI coverage of 51.19%, whereas ED had a more inadequate UHI coverage of 11.40%. These findings indicate that Manchester Piccadilly is more susceptible to UHI effects compared to East Didsbury.

The present findings serve to underscore the thermal dynamics ramifications associated with variations in shadow coverage and incident radiation levels between MP and ED. Despite the considerable shadow extent and diminished incident radiation observed in MP, it demonstrates a greater capacity for heat accumulation compared to ED, which exhibits a lesser degree of shadowing and a susceptibility to a more pronounced incident radiation spectrum. These empirical findings firmly establish the substantial impact exerted by urban structure on the UHI phenomenon. To further understand the influence of urban structure on these UHI percentages, correlation analysis using SPSS was conducted between transit-oriented development (TOD) urban structure parameters and UHI effects. The results of this analysis will be discussed in the subsequent section, shedding light on the relationship between specific urban structure elements and the occurrence and intensity of UHI in the study areas.

Mapping the Normalised Difference Vegetation Index (NDVI) in Manchester's selected TOD study areas unveils a significant disparity. The analysis revealed that weekends exhibited lower NDVI values than weekdays in Manchester, possibly due to the heightened influx of commuters and increased human activities on weekdays.

The NDVI values in Manchester Piccadilly (MP) are notably lower than those in East Didsbury (ED) on weekdays and weekends (Fig. 10). This discrepancy serves as a clear justification for the widespread presence of the UHI effect in MP compared to ED. The limited vegetation cover in MP suggests a dearth of the cooling and shading benefits typically conferred by verdant green spaces or water bodies within the study areas. These findings underscore MP's heightened vulnerability to the UHI effect, elucidating one of the principal factors contributing to the exacerbated UHI impact witnessed in MP relative to ED.

The analysis of NDVI in conjunction with UHI facilitated a correlational study to determine the direction and significance of the

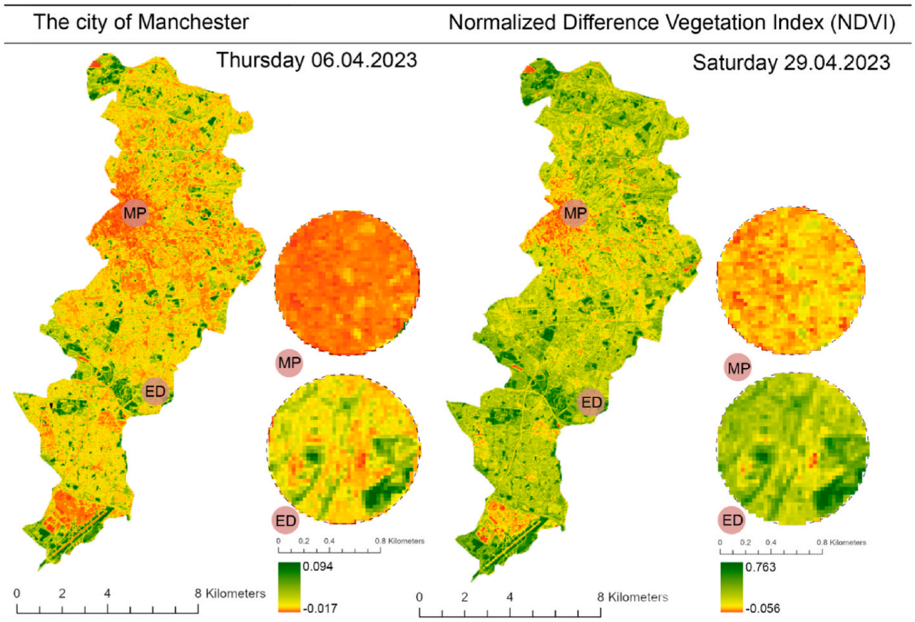


Fig. 10. NDVI levels in the study areas on a weekday and a weekend.

relationship between these two variables. In this analysis, UHI was considered the dependent variable, while NDVI served as the independent variable. The results unveiled a negative correlation between NDVI and UHI during weekdays and weekends, demonstrating a consistent inverse linear association: as NDVI values increased, UHI decreased. Specifically, on weekdays, the correlation coefficient was $r = -0.232$; $p=<0.001$; on weekends, the correlation coefficient was $r = -0.260$; $P=<0.001$ (Fig. 11).

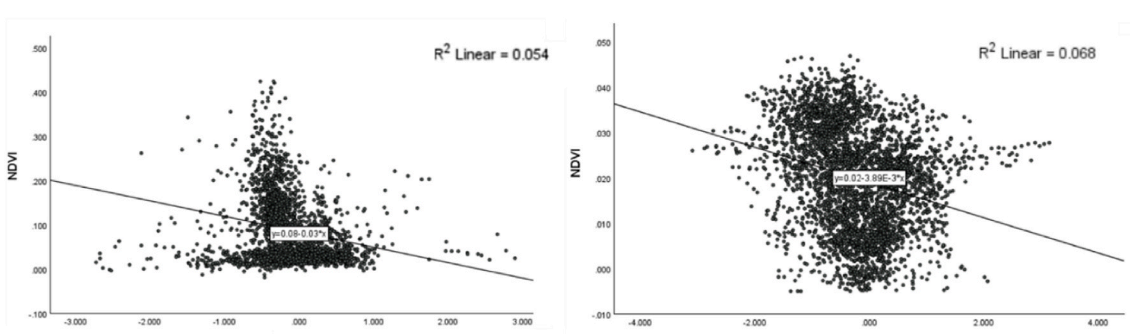
3.3. SPSS correlational analysis of the TOD urban structure and the UHI effect

SPSS analysis examined correlations between urban structure parameters (Fig. 12) in transit-oriented development (TOD) and the urban heat island (UHI) effect (Table 6). The first dimension studied was land use diversity and mixed-use street front. Specific land uses contributed more to UHI, with notable contributions observed during weekdays and weekends. Commercial residential, residential, commercial, and entertainment sectors showed significant contributions to the UHI effect. East Didsbury (ED) had a substantially lower presence (46.12%) of commercial land uses compared to Manchester Piccadilly (MP) (89.15%). Additionally, ED had a 33.33% mixed-use street frontage with exclusively day working hours services, while MP encompassed a significant 88% of mixed-use street frontages, with 12.7% offering 24-h services. This finding justifies the higher intensity of spatial UHI in MP compared to ED.

In the context of the density dimension, building height emerged as a noteworthy factor influencing the Urban Heat Island (UHI) effect in MP compared to ED. The analysis, employing Spearman's rho correlation, revealed intriguing insights. During weekdays, there was a statistically significant positive correlation coefficient between UHI and building height ($r = 0.114$; $p < 0.001$). However, this correlation strength decreased during weekends ($r = 0.069$; $p = 0.012$). This observation implies that taller buildings in MP exhibited a more pronounced UHI effect, particularly during weekdays.

However, the analysis also unveiled a negative correlation between UHI and floor area ratio (FAR) for both weekdays ($r = -0.256$, $p < 0.001$) and weekends ($r = -0.160$, $p < 0.001$). This negative correlation suggests that the UHI effect decreased as the density of built-up floor area increased.

What makes this finding particularly intriguing is the expectation of a more straightforward relationship between building heights and FAR



R2 linear= 0.054
Correlation Coefficient (r)= -0.232**
Sig. (2-tailed) =<0.001

R2 linear= 0.068
Correlation Coefficient (r)= -0.260**
Sig. (2-tailed) =<0.001

Fig. 11. Scatter plot of UHI by NDVI in Manchester TOD study areas: MP and ED.

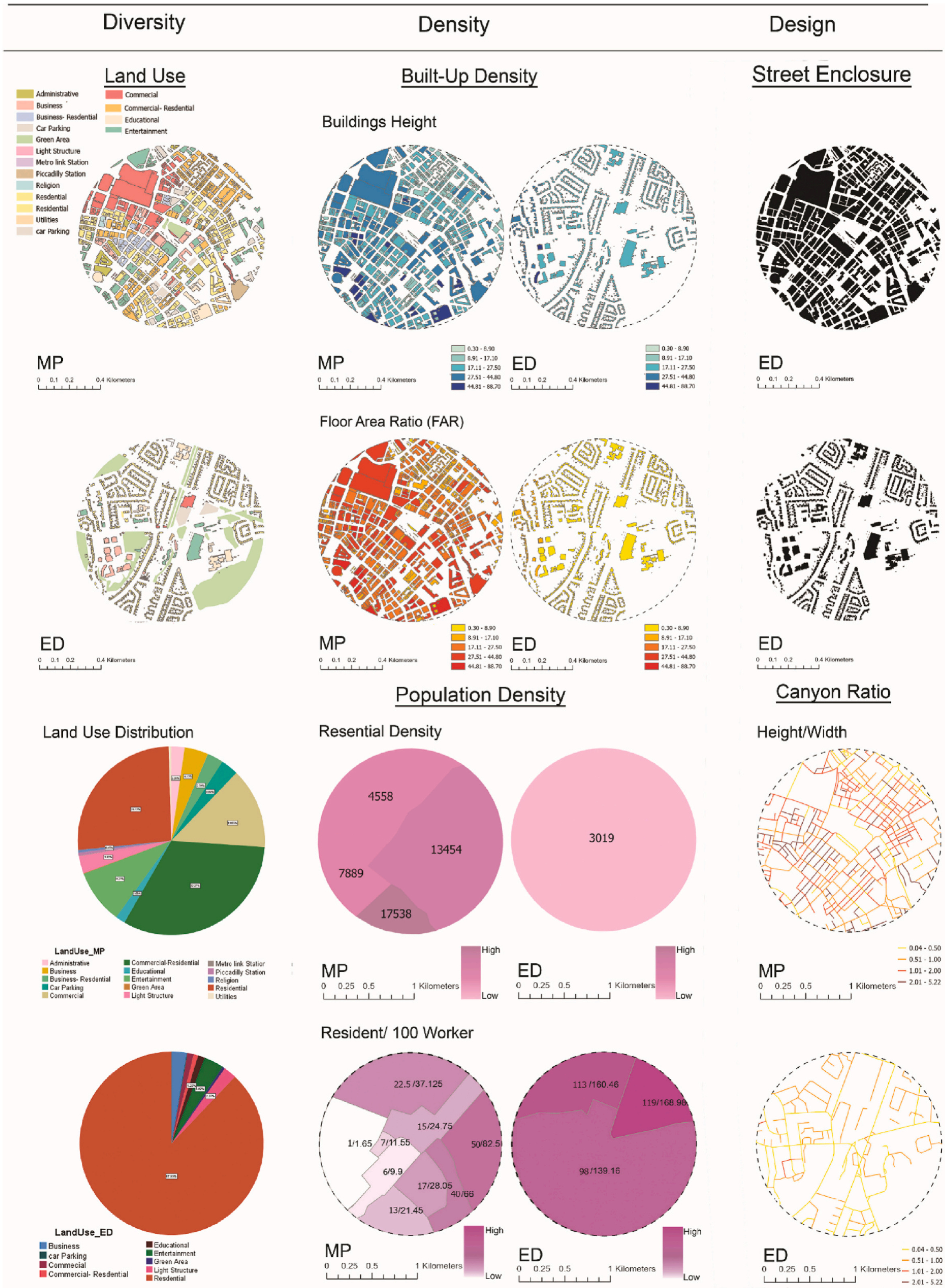


Fig. 12. Urban surveying of the TOD morphological parameters that influence the UHI effect.

in their impact on the UHI effect. Typically, one would anticipate a positive correlation between building heights and UHI (meaning taller buildings contributing to a more significant UHI effect) to align with a similar trend for FAR. However, this research uncovers a more complex scenario.

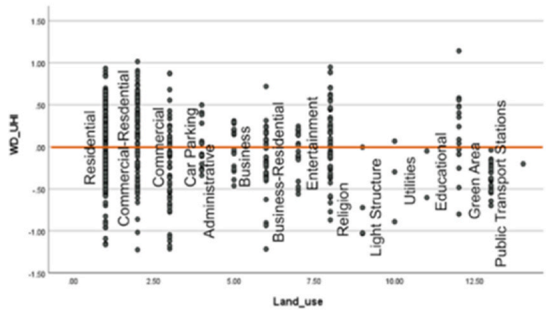
This complexity is rooted in the influential role of shadows. The analysis of incident radiation and shadows provides further support for these findings. It demonstrates that the MP study area experiences significantly reduced exposure to incident radiation due to shading caused by closely packed buildings with higher FAR. This shading

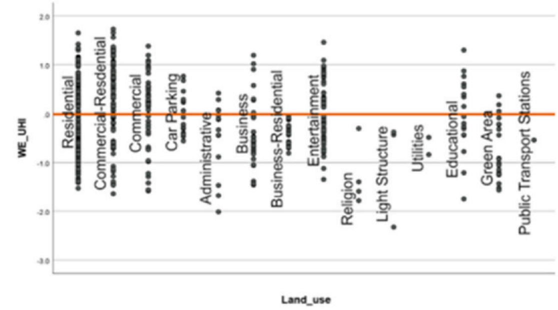
Table 6
SPSS correlational analysis; TOD's urban structure and UHI intensity.

Diversity

Land Use

Weekday	Weekend

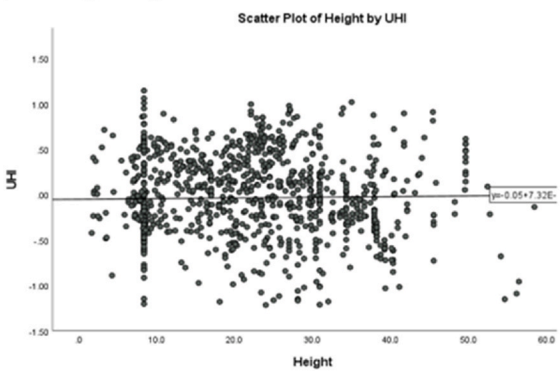




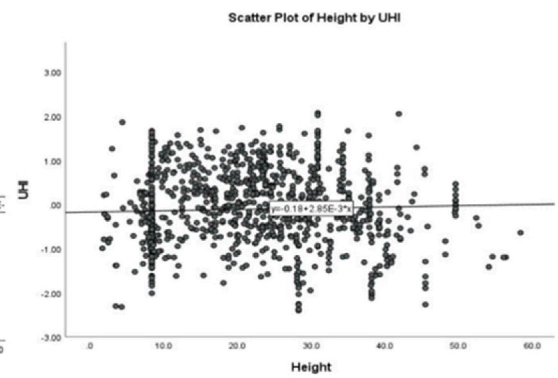
Density

Built-Up density

Buildings Height

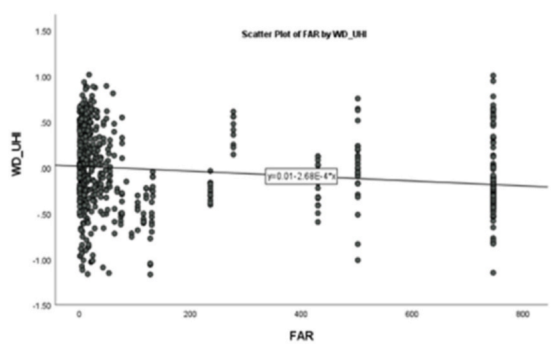


R2 linear = 0.002
Correlation Coefficient (r) = 0.114**
Sign. (1-tailed) (P) = <0.001

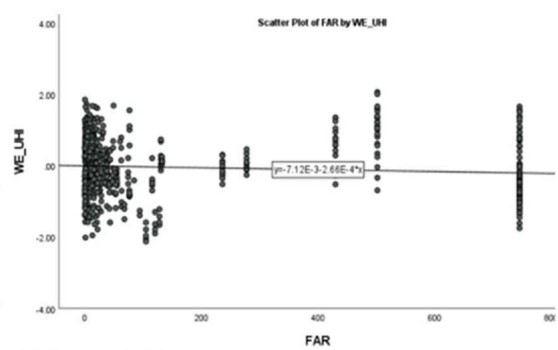


R2 linear = 0.069
Correlation Coefficient (r) = 0.69*
Sign. (1-tailed) (P) = 0.12

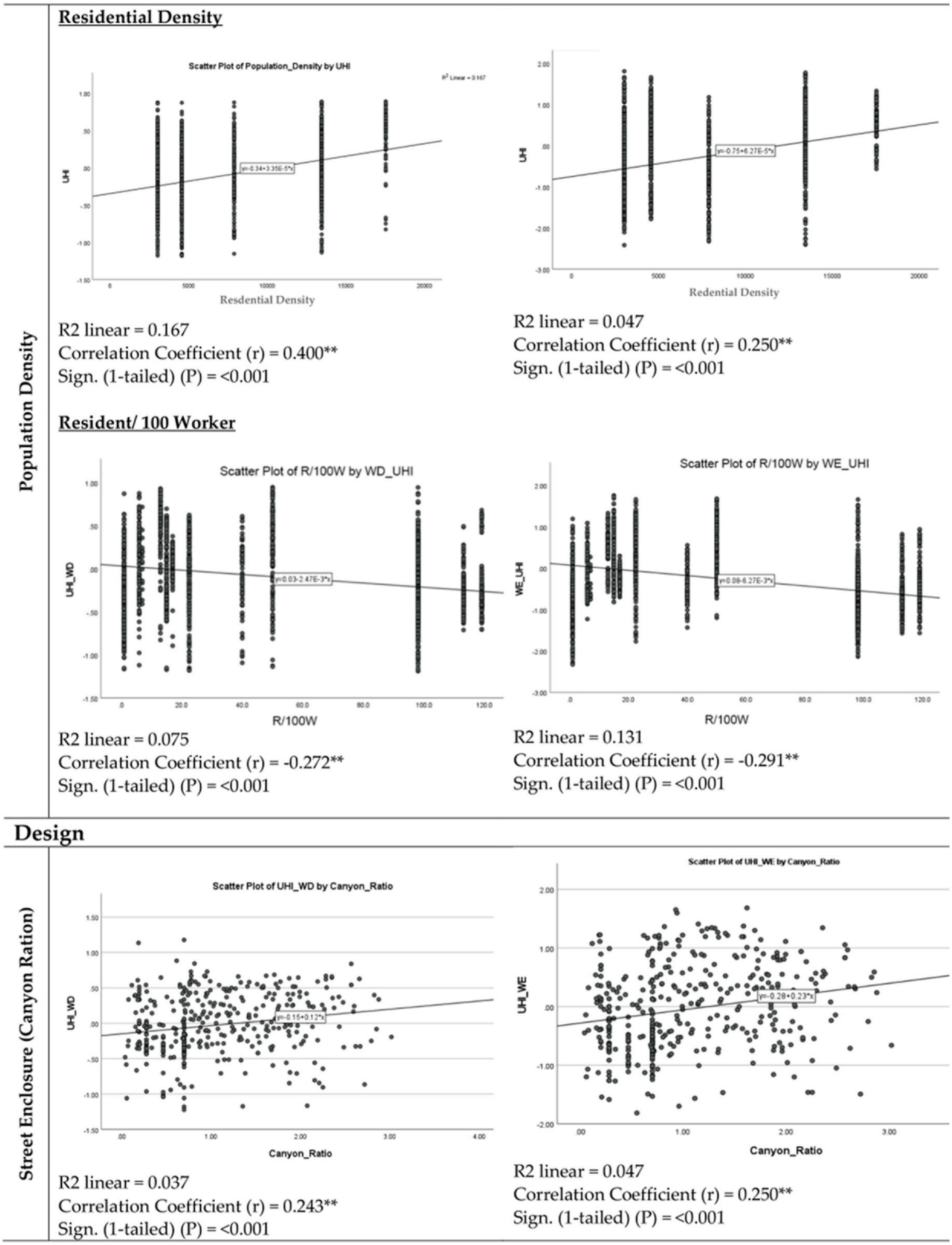
Floor Area Ratio



R2 linear = 0.035
Correlation Coefficient (r) = -0.256**
Sign. (1-tailed) (P) = <0.001



R2 linear = 0.01
Correlation Coefficient (r) = -0.160**
Sign. (1-tailed) (P) = <0.001



phenomenon, resulting from the urban morphology characterised by taller buildings and increased FAR, contributes to the reduction in the UHI effect, contrasting the expected positive correlation between building height and surface UHI. Therefore, these intricate relationships between building characteristics, incident radiation, and shadows underscore the multifaceted nature of the UHI phenomenon and the importance of considering factors beyond mere building height in UHI mitigation strategies.

Regarding the density dimension, building height significantly influenced UHI in MP compared to ED. Spearman's rho analysis demonstrated a significant positive correlation coefficient between UHI and building height during weekdays ($r = 0.114$; $p < 0.001$). The correlation strength decreased during weekends ($r = 0.69$; $p = 0.012$). Interestingly, floor area ratio (FAR) exhibited a negative correlation with UHI ($r = -0.256$, $p < 0.001$ on weekdays and $r = -0.160$, $p < 0.001$ on weekends), indicating that as FAR density increased, UHI decreased.

While the heights of buildings and the floor area ratio (FAR) are expected to have a similar impact on the urban heat island (UHI) effect, where a positive correlation with UHI for one should correspond to a similar trend for the other, intriguingly, this research indicates a complex scenario. It reveals a potential complication arising from a positive correlation between building heights and a negative correlation with FAR. This complication can be attributed to the influential role of shadows. Analysis of incident radiation and shadows supports this finding, demonstrating that the study area in Manchester Piccadilly experiences significantly reduced exposure to incident radiation due to shading caused by closely packed buildings with higher FAR.

To delve into the relationship between Floor Area Ratio (FAR), building height, and Urban Heat Island (UHI), it is essential to indicate that this relationship is complex and controversial. FAR is intricately linked to building height, which has a polarising impact on UHI. Taller buildings expose more concrete surfaces to solar heat, absorbing and trapping heat, thus intensifying the UHI effect. Conversely, tall buildings can provide shade, reducing the UHI impact. A case-by-case analysis is necessary to determine which of these effects dominates, as it is challenging to anticipate the predominant impact.

In the context of this research, the analysis reveals a negative correlation between FAR and UHI, while a positive correlation exists between building height and UHI. This suggests that, within the study area, it would be beneficial to adopt a mid-rise urban form that incorporates shaded streets and green spaces to mitigate UHI and reduce its impact.

Population density analysis demonstrated that increased residential density led to increased UHI effect due to heightened human activities. Spearman's rho analysis indicated a positive correlation between UHI and residential density during weekdays ($r = 0.400$; $p < 0.001$) and also a positive correlation during weekends ($r = 0.250$; $p < 0.001$). Additionally, the ratio of residents to workers showed that UHI increased as this ratio decreased, indicating a higher proportion of workers compared to residents. The coefficients were $r = -0.272$, $p < 0.001$ during weekdays and $r = -0.291$, $p < 0.001$ during weekends.

Regarding the design dimension, the analysis revealed a positive correlation between the canyon ratio and UHI. As the canyon ratio increased, UHI also increased, with $r = 0.243$ during weekdays and $r = 0.250$ during weekends ($p < 0.001$ for both days). While MP suffered from low shadow cover and high exposure to incident radiation, the broad street canyon allowed heat transfer, increasing UHI.

The interplay of TOD dimensions—density, diversity, and design—profoundly influences the UHI effect. While categorised separately for UHI assessment in TOD areas, these dimensions exhibit strong correlations directly between each other's impacting UHI patterns.

High-density TOD, MP, characterised by tall buildings and transportation hubs, inherently absorbs and emits heat from materials like concrete and asphalt. However, compact urban design elements can be practical UHI mitigation strategies, including mid-rise buildings, narrow streets, and shaded sidewalks. Conversely, green open areas like ED may alleviate UHI intensity, reflecting on the importance of conscious land use planning that considers the importance of greenery.

Mixed-use TOD urban development presents a complex relationship with UHI. Combining entertainment, commercial, and employment land uses can contribute to heat generation, especially from establishments like restaurants. Diverse commercial and entertainment land uses can potentially promote pedestrian activity in TOD. However, they heighten the UHI impact, influencing the UHI spatial and temporal patterns.

TOD design elements, like street enclosure and sidewalk design, are influenced by UHI differently. For example, higher street canyon ratios in MP increase solar radiation absorption, resulting in elevated temperatures. Understanding the interconnectedness of density, diversity, and design in TOD areas is crucial for a comprehensive understanding of their collective impact on UHI, informing effective mitigation strategies.

3.4. UHI Sankey Diagram analysis

The present study employed Sankey diagrams to investigate the contributions of different urban structure dimensions of transit-oriented development (TOD) to the UHI effect on weekdays and weekends. Results indicated substantial variations in the contributions of the TOD morphological parameters to the UHI.

On weekdays, the diversity dimension, represented by mixed land use diversity, contributed 61% to the UHI effect. The density dimension, including built-up density and population density, accounted for 31%, with built-up density contributing 16.2% and population density contributing 14.8%. The design dimension, specifically the street enclosure component, made an 8% contribution to the UHI effect (Fig. 13).

Analysing specific urban structure parameters within the TOD context revealed that commercial land use exhibited the highest contribution of 9.5% to the UHI effect. Entertainment land use followed at 8.13%, while residential, educational, commercial, and parking areas collectively accounted for significant contributions ranging from 7.99% to 7.3%. Administrative, business, business residential, and light structures had relatively lower impacts, ranging from 4.5% to 1.1%. Considering their heat generation nature, these findings indicate positive correlations between commercial and entertainment activities and the UHI effect.

In terms of the density dimension, both floor area ratio (FAR) and building height equally contributed 8% to the UHI effect. For population density, residential density and residents per 100 worker ratio made similar contributions of 7% each. These results underscore the influence of FAR and building height on the UHI effect.

Regarding the design dimension, the Sankey diagram illustrated that the canyon ratio significantly contributed ~8% to the UHI effect between the other parameters.

During weekends (Fig. 14), the diversity dimension contributed 55.9% to the UHI effect, while the density dimension became more prominent, contributing 35.04%. Within the TOD, Commercial and Commercial Residential land uses had the highest contribution of 10.34% to the UHI effect. Entertainment and business land uses were 8.33% and 8.21%, respectively.

Similar to weekdays, FAR and building heights played significant roles, contributing 8.97% and 8.77% to the UHI effect. Population density, represented by residential density and residents per 100 worker ratios, made relatively equivalent contributions of 8.48% and 8.77%, respectively. The Sankey diagram emphasised the substantial contribution of the canyon ratio (9.06%) to the UHI effect during weekends.

In the SPSS analysis, the correlation analysis between building height and UHI showed a positive relationship during both weekdays ($r = 0.114$, $p < 0.001$) and weekends ($r = 0.69$, $p < 0.001$). However, the correlation between FAR and UHI was negative during both weekdays ($r = -0.056$, $p < 0.001$) and weekends ($r = -0.160$, $p < 0.001$), challenging the conventional assumption of a positive impact of FAR on UHI. However, when conducting the Sankey diagram analysis where all the negative values of the UHI were excluded to emphasise only the active triggers of the UHI, the study showed a strong influence of the FAR on the UHI with a contribution value ranging between 8 and 9%, contributing to grade 3 of the UHI intensity classification. That means that FAR has a strong influence on the UHI. However, this analysis put the correlation between the buildings' heights and the FAR in a controversial situation where further in-depth analysis is required.

The previous results highlight the significant impact of TOD's urban structure on UHI in the studied areas. As a regional TOD, Manchester Piccadilly particularly suffers from the UHI effect due to the high density of human activities attracting residents and commuters. Elements of TOD structure, such as building height, FAR, population density, and

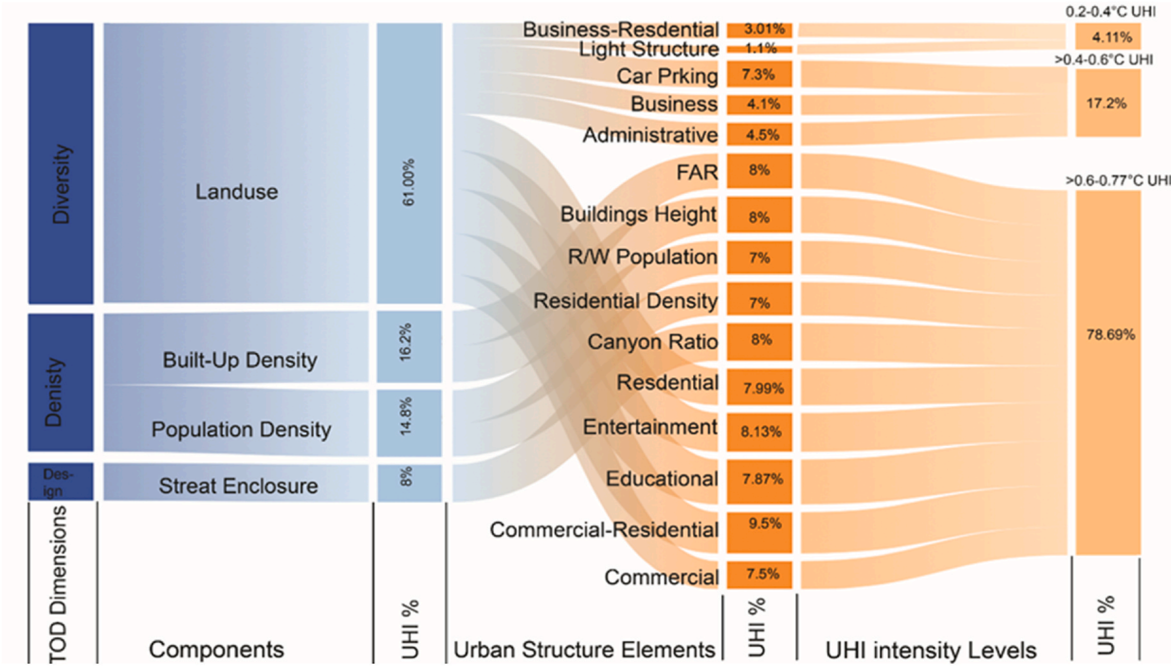


Fig. 13. Sankey Diagram representing the contribution of each urban morphology parameter to the UHI with the TOD on the weekday of 06.04.2023.

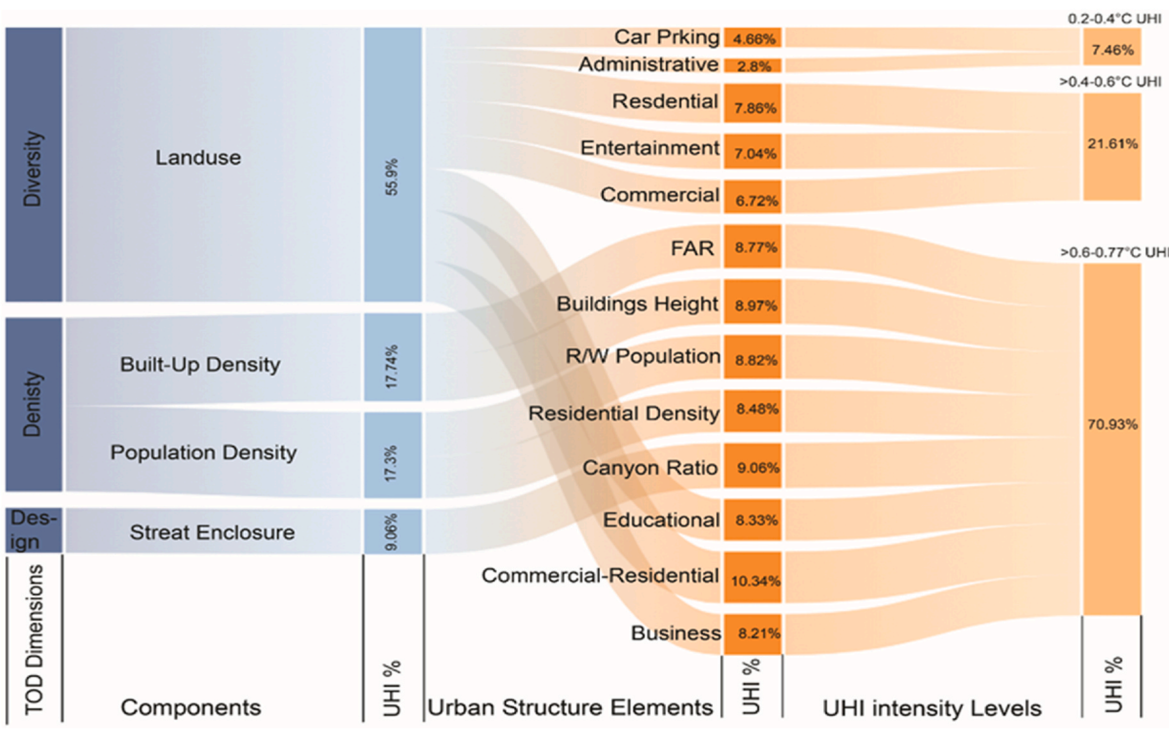


Fig. 14. Sankey Diagram representing the contribution of each urban morphology parameter to the UHI with the TOD on the weekend of 29.04.2023.

resident-to-worker ratio, contribute to the UHI.

Commercial and entertainment land uses were found to contribute significantly to UHI intensity. High population density and a higher percentage of workers relative to residents were identified as triggers for UHI intensity within TODs. Building height also contributed to the UHI effect, although its dual impact on UHI presents some confusion. The relationship between floor area ratio (FAR) and UHI showed contradictory results, warranting further investigation.

3.5. Mitigating the UHI effect in the TOD: dimensions that affected the UHI

Although this paper showed insightful findings about how TOD urban morphology influences the UHI effect, it is also interested in studying the characteristics affected by the UHI (Table 1). Those characteristics are sidewalk design, destination and distance to transit. For the sidewalk design, the research studied the sidewalks in the selected streets (Fig. 8) in the two study areas using section analysis (Figs. 16 and

17).

The analysis revealed insufficient shading features and street furniture in Manchester's TODs, Manchester Piccadilly and East Didsbury (Figs. 15 and 16). These findings underscore the critical need to address the lack of shading infrastructure and resting amenities in TOD areas affected by UHI. Improving the walkability and cycling experience by incorporating suitable shading features and street furniture becomes essential to enhance these areas' overall comfort and attractiveness. Future urban planning and development efforts should prioritise integrating such elements to mitigate the adverse effects of UHI and promote sustainable and enjoyable modes of transportation within TODs.

The accessibility dimension in TOD emphasises the promotion of cycling and walking as viable modes of transportation for reaching destinations. Assessing the walking and cycling ranges in Manchester Piccadilly and East Didsbury revealed that both areas can be conveniently covered within a radius of 600 m, allowing for a cycle ride or walk of less than 10 min (Fig. 15). This indicates the presence of a well-established cycling and pedestrian network within the TOD regions.

However, it is essential to recognise that such analyses typically rely on two factors: the distribution of daily necessities like restaurants, shops, and pharmacies within the areas and the physical existence of suitable pedestrian and cycling infrastructure. Nevertheless, these conventional analyses appear inadequate and potentially misleading when considering the UHI effect. As temperatures increase in an area, the comfort and feasibility of walking and cycling decrease. Taking Manchester Piccadilly as an example, a TOD area where the UHI affects over 50% of the area on both weekdays and weekends, it becomes evident that the walkability and cycling range need to be carefully considered. Specifically, providing adequate shading features and restful street furniture is crucial to alleviate the discomfort caused by the UHI effect.

The accessibility dimension of TOD prioritises cycling and walking. Both Manchester Piccadilly and East Didsbury have well-established cycling and pedestrian networks, with convenient coverage within a 600-m radius (Fig. 15). However, conventional analyses overlook the impact of UHI on walking and cycling comfort, necessitating the inclusion of shading features and resting amenities. In Manchester Piccadilly, the average distance to transit was approximately 01:57.6 min, with a maximum walking time of 08:80 min. The average time required to reach a transit station in East Didsbury was approximately 04:65.4 min, with a maximum walking time of 16:36 min. This maximum walking time exceeds the recommended 10-min walking distance to the nearest transit, indicating a potential deficiency in the allocation of transit stations in East Didsbury, disregarding the impact of the urban heat island (UHI) effect.

Considering the Urban Heat Island (UHI) effect, it becomes evident that the design of Manchester Piccadilly prioritises minimising the need

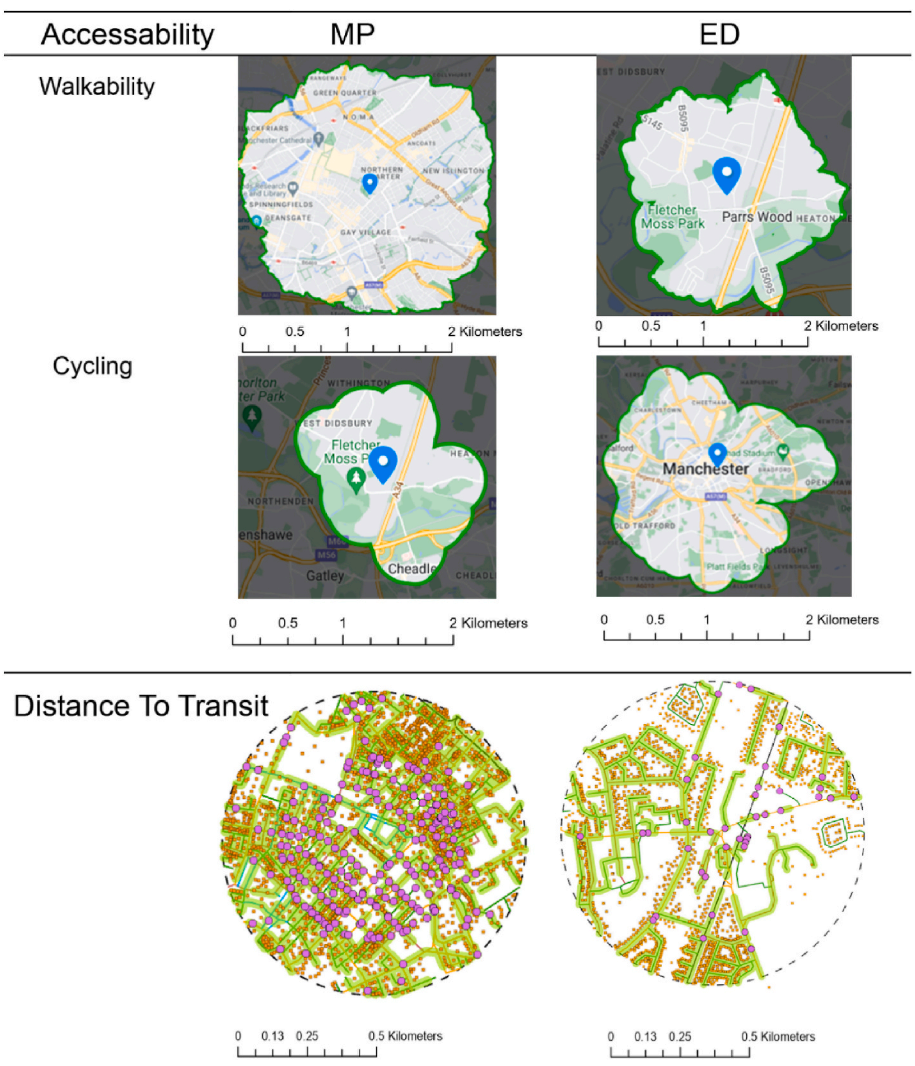


Fig. 15. The Analysis of Accessibility (Walkability and cycling within a 10-min distance) and Distance to transit in Manchester Piccadilly and East Didsbury using GIS Network analysis.

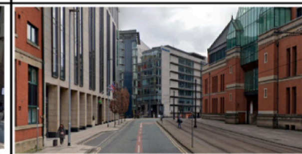
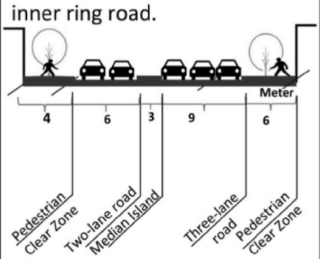
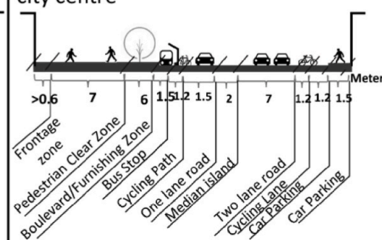
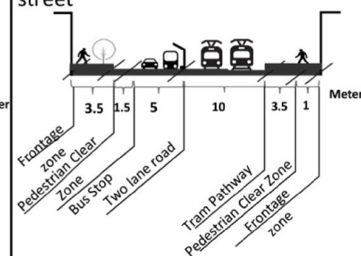
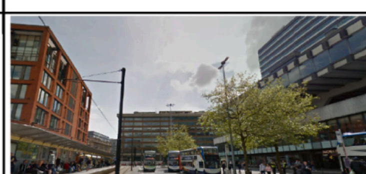
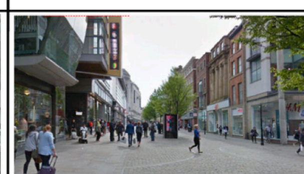
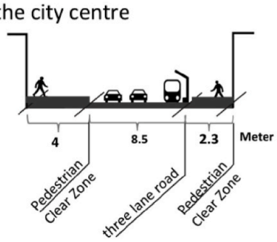
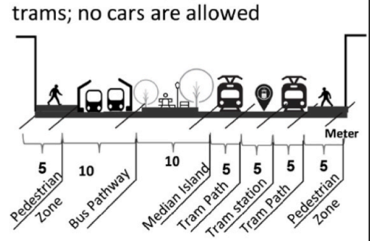
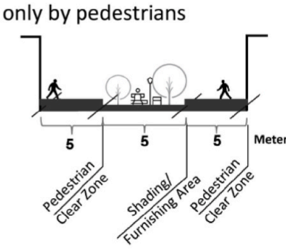
Name	Great Ancoats Street	Portland Street	Ayton Street
Type	 **Arterial Road (CR=0.71)** Great Ancoats Street is a street at the eastern border of the city centre, in Ancoats, Manchester. It forms one of the stretches of the city's inner ring road.	 **Main Road (CR=1)** Portland Street is a major (main) street in the Manchester Piccadilly TOD area, extending from Piccadilly at its junction with Newton Street downward to the southwest of the city centre	 **Collector Road (CR=1.2)** Ayton Street is a collector road in Manchester that funnels traffic from the perpendicular east-south and West-south streets to Portland street
Street/ sidewalk Design	 - No street furniture on either both sidewalks or median islands - Sidewalks width aligns with the 5 min. Mixed-Use Regional Connector width) - No shedding features on the right sidewalk	 - No Furnishing Zone on the right sidewalk - The right sidewalk width < 4.8- 5.4 (min. City core width) - Lack of shading features on both sides	 - No Furnishing Zone on both sides - The left sidewalk width < 4 (min. Urban Neighbourhood streets width) - Lack of shading features on both sides - No cycle lanes. Cyclers are utilising the pedestrian zones
Name	Lever Street	Parker Street	Market Street
Type	 **Local Road (CR=1.01)** Lever Street is a local street in the Northern Quarter, east Manchester Piccadilly. It serves the residential area North-East the city centre	 **Local Road: Public Transport only (CR=0.44)** Parker Street is a street in the heat of the Piccadilly garden. It is accessible only by buses and trams; no cars are allowed	 **Pedestrian Street (CR=1.2)** Market Street is a retail street that's packed full of shopping opportunities and cafes. This part of the street is accessible only by pedestrians
Street/ sidewalk Design	 - The right sidewalk width < 4 (min. Urban Neighbourhood streets width) - Lack of shading features at the both sides - No cycle lanes. Cyclers are utilising the pedestrian zones	 - Median island is occupied by bus stops covering whole Manchester - Shading features and street furniture are significantly existing - No defined cycle lanes	 - Wide pedestrian street with significant existence of shading features such as trees and street furniture such as seats

Fig. 16. Manchester Piccadilly streets and sidewalks' design.

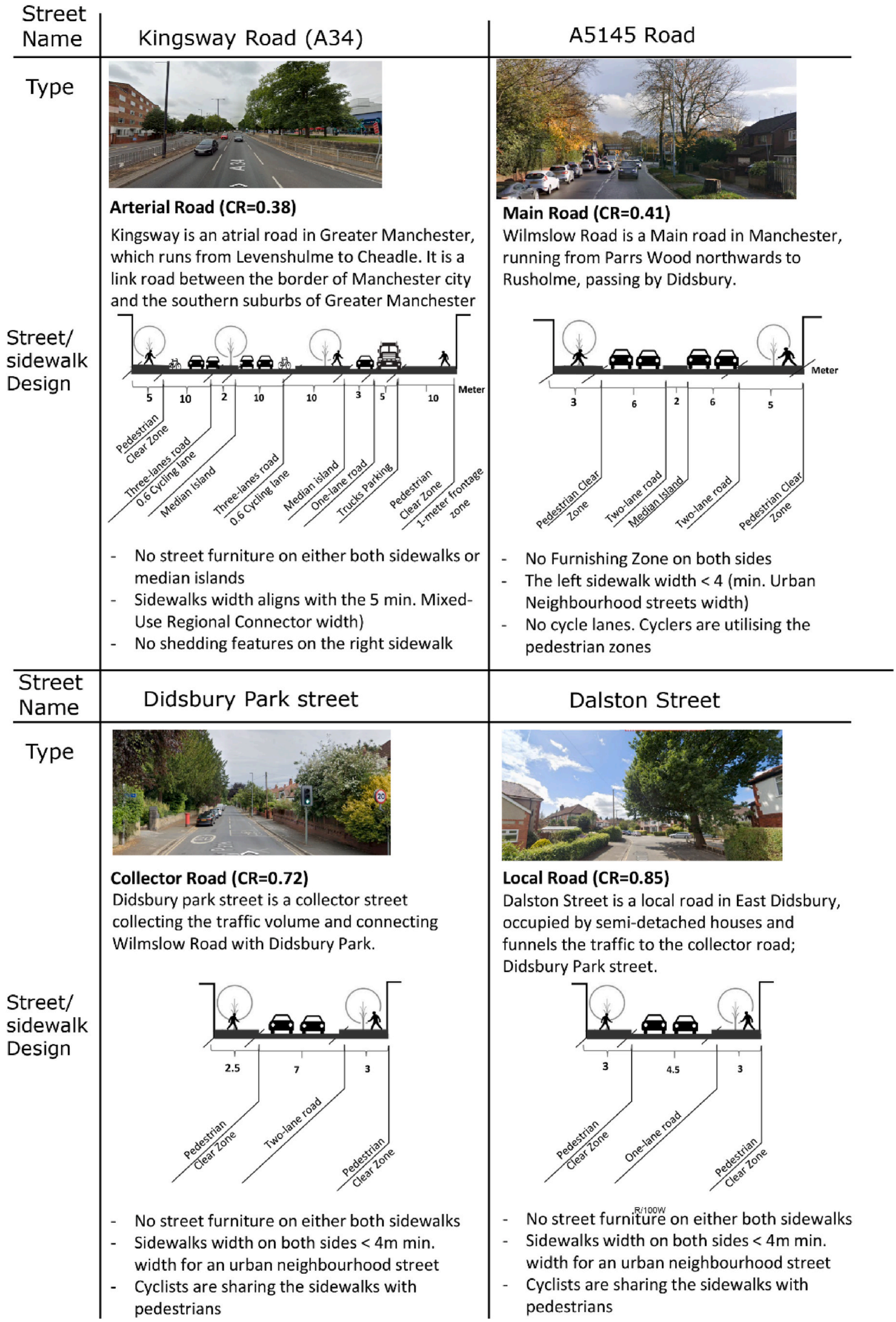


Fig. 17. East Didsbury streets and sidewalks' design.

for commuting to transit stations and actively encourages walking. This approach contrasts with East Didsbury, which faces challenges in optimally allocating transit stations to ensure that the maximum walking distance to the nearest station falls within the recommended 10-min timeframe without considering the UHI effect that might affect the efficiency of the 10-min walk in extreme weather events.

These findings underscore the critical importance of factoring in both distance to transit and walking time in the planning and design of Transit-Oriented Development (TOD). They highlight the necessity for enhanced strategies in transit station allocation, especially in regions like East Didsbury, aiming to ensure accessibility and promote sustainable transportation practices. Moreover, these results emphasise the potential impact of TOD design on UHI mitigation, suggesting that well-planned and easily accessible transit stops can significantly contribute to reducing the UHI effect by encouraging walking and reducing dependence on private vehicles. This comprehensive approach contributes to creating a more sustainable and UHI-resilient urban environment, which also underscores the importance of designing convenient, shaded streets and pedestrian networks as part of TOD planning and development to provide pedestrians with comfortable and sheltered pathways, further encouraging walking and mitigating the UHI effect.

4. Conclusion

This study aimed to assess the impact of urban morphology in Manchester's TOD areas on the UHI effect, considering weekday and weekend scenarios. Through a comprehensive analysis using various methodologies, including context and remote sensing analysis, SPSS correlation analysis, and Sankey diagram analysis, the study investigated the contributions of different dimensions and parameters of TOD to UHI in Manchester Piccadilly and East Didsbury areas. Key findings highlight the influence of land use diversity, population density, and building height on UHI intensity. Notably, a negative correlation between floor area ratio (FAR) and UHI challenges the conventional assumption. As a regional TOD, Manchester Piccadilly exhibits high UHI intensity due to dense human activities, while East Didsbury shows relatively lower UHI intensity. These findings have implications for urban planners and policymakers, emphasising the need for careful dealing with mixed land uses and building characteristics to mitigate UHI in TODs. The findings of this research could be summarised as follows.

1. This paper showed that UHI effect in the city of Manchester is significant, affecting over 25% of the city during weekdays and weekends. The intensity of UHI in Manchester City is higher at the city scale during weekends, particularly concentrated towards the city centre, possibly due to increased traffic and private vehicle usage by commuters for weekend entertainment.
2. On the contrary, TOD study areas, Manchester Piccadilly and East Didsbury, experience significant UHI during weekdays compared to weekends.
3. The Manchester Piccadilly TOD study area (600-m TOD) demonstrates a high UHI effect during weekdays and weekends, covering more than 50% of the area on both days. Factors contributing to this may include high concentrations of heat-generating human activities such as commercial and entertainment sectors, attracting outsider commuters with their traffic. The low resident-to-worker ratio and dense residential occupancy in tall buildings with a high Floor Area Ratio (FAR) and narrow street canyon also contribute significantly to the UHI effect.
4. In contrast, the East Didsbury TOD (600-m TOD) exhibits low UHI coverage despite the lack of shading and high exposure to incident radiation. This is attributed to the limited diverse activities limited to local-scale services, resulting in a significantly higher resident-to-worker percentage compared to the Manchester Piccadilly study area. The low residential density, with occupation primarily in low and mid-rise buildings and wide canyon streets, further contributes to the lower UHI effect.
5. Both Manchester Piccadilly and East Didsbury TODs lack adequate shading features in their streets, along the different streets' hierarchies, rendering them susceptible to intense UHI effects.
6. There is a significant NDVI disparity between Manchester Piccadilly (MP) and East Didsbury (ED) during weekdays and weekends, highlighting an evident Urban Heat Island (UHI) effect in MP due to its limited vegetation. Weekdays show lower NDVI, possibly due to increased human activity. The negative NDVI-UHI correlation underscores the importance of urban greening to mitigate UHI effects. Thus, green urban planning is vital for climate resilience and liveability, especially in MP and similar urban areas.
7. TOD accessibility in terms of walking and cycling range extends across both study areas. However, these measures typically consider the availability of daily needs and the presence of pedestrian and cycling networks without accounting for the UHI effect on human discomfort and the walking and cycling limit. Applying uniform standards to all TODs is unsuitable, considering the varying susceptibility to UHI between Manchester Piccadilly and East Didsbury.
8. The study of distance to transit reveals that the average distance to transit in both areas is relatively appropriate and even less than the 10-min walking distance. However, East Didsbury shows a maximum walking distance of 16:36 min to the nearest transit station, which should be considered to improve TOD efficiency.
9. A comprehensive multidimensional approach is necessary to understand the UHI effect's complexity comprehensively. Relying on a singular method or parameter may provide incomplete insights into the dynamics of the phenomenon.
10. In general, TOD areas should be designed with limitations on high-density tall buildings and uses that attract outsider residents. Emphasis should be placed on creating green open spaces to reduce UHI effects and providing adequate shading in streets to promote walking and cycling while reducing transit distance.

In conclusion, the findings of this study emphasise the significance of considering multiple dimensions and parameters when examining and mitigating the UHI effect in transit-oriented developments. The results also highlight the necessity of considering temporal variations and urban activities in developing effective strategies to reduce the UHI effect and promote sustainable urban environments.

5. Future directions for UHI mitigation in Manchester's TOD

Two critical focus areas should guide future research on Urban Heat Islands (UHI): developing tools and methods for UHI detection and implementing mitigation strategies to reduce its impact. To effectively address both directions, forthcoming investigations should emphasise utilising diverse models capable of capturing the intricate interactions between urban environments and the atmosphere (Kaloustian et al., 2016).

While remote sensing represents a valuable, efficient, and cost-effective method for examining UHI within specific geographic regions, future studies must diversify the models employed. This diversification ensures the validity and reliability of remote sensing findings.

Following the comprehensive analysis conducted in this study to assess the impact of urban morphology on the Urban Heat Island (UHI) effect in Manchester's Transit-Oriented Developments (TODs), it is evident that there is a need for a more in-depth exploration of specific urban planning and design recommendations tailored to the unique characteristics of Manchester's TODs. While this research has provided valuable insights into the factors influencing UHI intensity, further investigation is essential to formulate practical strategies for UHI mitigation. Specifically, future research could delve into the following areas.

- Urban Greening Strategies: Given the significant negative correlation between the Normalised Difference Vegetation Index (NDVI) and UHI observed in Manchester Piccadilly (MP), exploring and recommending specific urban greening strategies is crucial. This may include the introduction of green roofs, vertical gardens, and increased tree canopy coverage in MP to counteract the UHI effect.
- Mixed Land Use Planning: The findings suggest that mixed land use contributes to higher UHI intensity, particularly in commercial and entertainment sectors. Investigating zoning regulations and land use policies that encourage a balanced mix of activities while minimising heat-generating uses can aid in UHI mitigation.
- Shading and Building Design: Since both TODs lack adequate shading features, there is an opportunity to explore innovative building designs that incorporate shading elements to protect streets from direct sunlight. Furthermore, building heights and orientation guidelines could be developed to reduce the shadowing effect that exacerbates UHI.
- Transit-Oriented Development (TOD) Guidelines: Tailored TOD guidelines can be developed to address UHI's specific challenges in Manchester's TODs. These guidelines should consider the unique characteristics of each TOD, such as the resident-to-worker ratio, building density, and land use mix.
- Public Space Design: Enhancing public spaces within TODs by integrating green areas, shaded seating, and pedestrian-friendly pathways can create more liveable environments while mitigating UHI. These designs should promote outdoor activities.
- Temporal Variations: Future studies should continue to monitor temporal variations in UHI and how they relate to changes in urban activities. This understanding can help in adjusting strategies based on daily and seasonal patterns.

In summary, a more detailed exploration of urban planning and design recommendations, considering the specific characteristics of Manchester's TODs, would provide practical guidance for urban planners, architects, and policymakers. These recommendations can contribute to the creation of sustainable, climate-resilient urban environments that prioritise human comfort and well-being while addressing the challenges posed by the UHI effect.

6. Research limitation and future work

The limitations of this study included.

- Generalisability: Findings are specific to Manchester's Piccadilly and East Didsbury TODs and may not apply directly to other cities or TODs with different characteristics.
- Scope: The study focused on specific dimensions (5D) and parameters within the TOD context, necessitating further research to explore additional factors and develop comprehensive strategies.
- Temporal Variation: Analysis compared the UHI effect between weekdays and weekends, but did not consider seasonal or annual variations, requiring future research to understand long-term dynamics.
- Dependency on remote sensing: The study utilised remote sensing techniques for addressing Surface Urban Heat Islands (SUHI) which did not account for climatic variables such as wind.
- Traffic influence: The study highlighted the importance of studying traffic patterns in understanding temporal changes in spatial UHI associated with traffic.

Despite these limitations, the adopted methodologies in this study, including context analysis, remote sensing analysis, SPSS correlation analysis, and Sankey diagram analysis, demonstrate their efficiency in investigating the relationships between urban structure and UHI in the TODs. The comprehensive approach allows for a multidimensional understanding of the UHI effect and provides valuable insights for urban planners and policymakers in developing strategies to mitigate UHI in TODs.

CRediT authorship contribution statement

Esraa Elmarakby: Conceptualization, Literature Review, Methodology, Writing, Data Collection, Data Analysis, Writing – original draft, Preparation. **Hisham Elkadi:** Conceptualization, Supervision, Writing – original draft, Preparation.

Declaration of competing interest

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

The authors do not have permission to share data.

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