Classifying station areas in Greater Manchester using the node-place-design model

A comparative analysis with system centrality and green space coverage

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Abstract

Transit-oriented development (TOD) is receiving increasing attention from planners and policymakers as an essential strategy for addressing urban travel inequalities and air pollution. As an analytical method based on the conceptual construct of TOD, The Node-Place-Design Model (NPD) is utilised by researchers to assess the level of development of TOD in urban public transport systems. However, current research focuses more on local perspectives of station development and lacks the identification of the functions of stations at the system level. Not only that, but with the urban densification and the covid-19 crises, there is a growing demand for healthy living close to green space, yet few TOD-related analyses consider the ecological aspects of cities. This study used an NPD model to evaluate the TOD development at rail stations in Greater Manchester. We also incorporated extended indicators of systemic importance and a green space indicator in our analysis to provide additional insight into the model. We firstly found a low level of TOD integration around stations in Greater Manchester and some differences in development level around train stations and Metrolink stations. Secondly, a comparison with the extended system importance indicators revealed that there could be significant differences in the NPD index and system importance indicators of stations, pointing to some stations that have the potential to take on new routes and some areas that are worthy of transit-oriented development. Finally, by comparing the green space indicator, we found a specific negative correlation between the NPD index and the green space indicator, which indicates that the TOD model sacrifices green space to a certain extent and demonstrates the importance of including ecological indicators in the TOD assessment. Overall, this study provides additional insight into the node-place design model by introducing expanded systems and ecological indicators.

Declaration

I, Lingwei Zheng, hereby declare that this dissertation is all my own original work and that all sources have been acknowledged.

The processed data and part of the experimental code in Python and R can be found at:

https://github.com/Lingweiz1998/2020_CASA_Dissertation

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Secondly, due to the pandemic, I completed all my courses in an online format. As an interdisciplinary student, I was very concerned about the difficulty of learning programming and spatial analysis in an online format. However, the quality of the courses provided by CASA allowed me to gain a lot of knowledge and experience. I want to thank all the staff at CASA for their various efforts in providing high-quality teaching during this time.

Finally, I would also like to thank my family and my girlfriend for their encouragement and support during this time.

List of Acronyms and Abbreviations

TOD Transit-Oriented Development

NP Node-Place

NPD Node-Place-Design

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1. Introduction

Urban managers have long valued public transport systems. Public transport provides mobility and access to employment, community resources, health care and recreation, and it benefits those who choose to use public transport and those who have no other options (Lee and Averous, 1973; Stuart et al., 2000). It also helps reduce road congestion and travel times, air pollution, and energy and oil consumption, from which anyone can benefit (Levine, Grengs and Merlin, 2019). In addition, public transport is vital for evacuation and shelter in emergencies (Miller, 2019).

In recent years, establishing environmentally friendly and sustainable cities has become an important goal worldwide to mitigate climate crises. As a result, the importance of public transport systems is increasing, and the idea of public transport-oriented land use and development has become more popular. This idea, known as Transit-Oriented Development (TOD), was first proposed by Peter Calthorpe (1993) and called for forming urban centres by developing land within a particular area centred on a railway or bus station. It refers to a dense, mixed-use, pedestrian and cycling-friendly land development oriented towards public transport and not just development next to rail and bus stations (VTPI, 2019).

Transit-oriented development has many benefits. It has promoted economic activities in communities and reduced urban sprawl (Chorus and Luca Bertolini, 2011). Furthermore, development through public transport can foster a sense of community and enhance neighbourhood safety and security (Levine, Grengs and Merlin, 2019). There are already many successful examples of TOD worldwide, such as in Singapore, Canada and Hongkong (Jones and Ley, 2016; Loo, Chen and Chan, 2010; Tan and Yi, 2021). In Hong Kong, 45% of the population is within a 500-metre living circle of an MTR line station, especially in Kowloon and Hong Kong Island, where the proportion is as high as 65% (Loo, Chen and Chan, 2010). Moreover, many more new projects and policies are in the pipeline (Chorus and Luca Bertolini, 2011; City of Bellevue, 2018; City of Shoreline, 2016; Miller, 2019; MRSC, 2021; Zhang, Marshall and Manley, 2019).

As a model created for TOD, the Node-Place (NP) model has been used by researchers to assess the level of TOD of urban public transport system stations. This model evaluates the level of development and characteristics of stations through a combination of indicators of both transit development and land use around the station. So far, the Node-Place Model has had many applications, and many improvements have been made. The current improvements focus on three aspects, the selection of station observation areas, the expansion of the indicator list, and new dimensions. For example, based on the well-established bike-sharing infrastructure and high usage rate in Seoul, scientists increased the observation range of stations from 400 m to 3 km in the earlier study (Jun et al., 2015). Another study added the distance from the station to the city centre to the indicator list based on the monocentric urban character of Tokyo (Chorus and Luca Bertolini, 2011). More recently, Vale (2015) and Lyu (2016) expanded the model to a third dimension, the Node-Place-Design (NPD) model, which attempts to provide a more comprehensive assessment of TOD development in cities by adding observations on the extent of the pedestrian-oriented design.

However, the current model cannot observe the function of a station in the overall rail system and its importance. The NP model's node indicators focus more on station attributes such as frequency, connectivity to bus systems or motorways, and the capacity of parking spaces within the station (Bertolini, 1999). However, these indicators lack a measure of the station's different functions due to its location in the rail system. Although many studies have added observations on the number of lines carried by a station, they still lack an understanding of its position in the system (Chorus and Luca Bertolini, 2011; Monajem and Ekram Nosratian, 2015; Vale, 2015). In simple terms, we do not know whether the station is located at the front of the end of the rail system and how it is positioned to other stations. This information indicates the transport capacity that the station is expected to carry in the rail network (Dou, Wang and Dong, 2021). Despite having lower transit connections or service frequencies, some stations will have higher transport importance in the system due to their location close to the centre or other transit stations. Such a view has been confirmed in several studies. However, this cannot be observed with current NP models (Derrible, 2012; Jayasinghe et al., 2019; Vale, Viana and Pereira, 2018; Wang and Fu, 2017; Zhang, Marshall and Manley, 2019).

Scientists in transportation have been attempting to apply network analysis to traffic analysis (Derrible, 2012). The use of network analysis in transportation has become popular in recent years due to the close match between the characteristics of network graphs (graphs consisting of nodes and edges) and the characteristics of various transportation systems (Zhang, Marshall and Manley, 2019; Zhong et al., 2014). Network centrality is a metric to assess the importance of nodes in a network, and many algorithms have been developed to calculate the importance of nodes in different aspects. Among these algorithms, closeness centrality and betweenness centrality are two algorithms frequently used in analysing rail transit systems (Derrible, 2012; Dou, Wang and Dong, 2021). closeness centrality measures the proximity of a node to the centre of the network, which helps us identify the geometric centre of the network, which in transport studies generally represents the city's core area. Betweenness centrality measures the frequency with which a node acts as the shortest transit between all other nodes, that is, the importance of acting as a 'bridge' between any nodes (Wang and Fu, 2017). Both algorithms are important for understanding the importance of stations at the system level in TOD assessment.

Furthermore, few TOD studies have looked at the issue of urban green space coverage. Many studies have pointed out that urban densification can create a shortage of green space (Cervero and Sullivan, 2011). However, as a development pattern of densification, TOD, and research on TOD, has paid little attention to this aspect of the crisis. This problem can be seen in the refinement of NP models by scientists, as few studies have so far attempted to analyse NP models in combination with ecological indicators (Chorus and Luca Bertolini, 2011; Dou, Wang and Dong, 2021; Vale, Viana and Pereira, 2018; Zhang, Marshall and Manley, 2019). However, in the post-epidemic era, the importance of green space has been raised repeatedly. Many studies have shown that areas with more green space during the epidemic had lower infection rates and higher well-being (Ciupa and Suligowski, 2021; Hubbard et al.) Therefore, establishing a TOD development pattern with sufficient green space is a future trend, and combining TOD and green space concepts is a valuable research direction. With this in mind, we attempt to gain more insight by including green space observations in TOD studies applying the NP model.

In summary, we hope to enhance the model by combining the nodal place design model with expanded indicators of system centrality and green space coverage to gain more insight into the model. Our study area is the Greater Manchester area. Our study seeks to answer the following questions:

1. What is the level of TOD of the transit system stations in Greater Manchester? What are its characteristics?

2. What information do the expanded system centrality and green space indicators tell us?

3. Does the comparative analysis of the expanded indicators and models give us more valuable information?

The dissertation is structured as follows: in Chapter 2, we review the history of urban modelling of transport and land development and highlight the changes, characteristics and shortcomings of the nodal place model. We also review studies related to network analysis as well as green space. Chapter 3 describes the study area, the data used, the analysis process, and its algorithms. Chapter 4 collates the study's findings and translates them from numerical values to practical meanings. In Chapter 5, we discuss the conclusions, verify the validity of the improved analytical framework with more insightful findings, and make recommendations in the context of policy. In the Final Chapter, we conclude the whole study and suggest possible future research directions.

2. Literature Review

2.1 Integrated transport and land use model

Assessing the extent and effectiveness of transport and land development in an area can be an essential reference for future land planning in that area. The development and use of integrated land use and transport models to assess cities can be traced back to the Lowry model of 1964 (Lowry, 1964). Depending on the type of theory on which the model is based, there are three broad models: integrated models based on spatial interaction/gravity models, economic theory models, and micro-simulation models.

The original Lowry model was based on a spatial interaction/gravity model that used classical economic theory to simulate basic urban patterns by assessing work and household activities (Lowry, 1964). This comprehensive model was easy to obtain data for but was too simplistic in its description of urban behaviour. Since then, many scholars have improved or built new models, such as the IRPUD model by Wegener (1982), the LILT model by Mackett (1983) and the ITLUP model by Putnman (2007).

Researchers have begun to use these models to model discrete locational distributions and travel patterns with the emergence of economic models such as discrete choice theory and consequent utility theory (Cascetta, 2009a; Ennio Cascetta, 2009b; Quillian, 2015; Train, 1993). The TRANUS model developed by de la Barra et al. (1984), for example, is a regional economic model that has been widely used around the world. The MEPLAN model developed by Echenique et al. (1990) adds an economic assessment module to the Input-Output model, which treats travel as a derived demand and predicts travel patterns. Furthermore, the PECAS model developed by Hunt and Abraham (2003) is a regional economic model that incorporates micro-simulation and can assess and forecast activity-based travel.

Microscopic models are a relatively recent area of research that uses theories like cellular automata, activity-based and multi-agent systems to effectively simulate the microscopic behaviour of individual decision-makers in land use and transport development, such as MASTER, SLEUTH, CLUE-S models (Mackett, 1990; Silva and Clarke, 2002; Verburg and Overmars, 2009). The MASTER model examines population growth and changes in household structure (Mackett, 1990), while the SLEUTH model uses the principle of meta-automata to simulate urban change patterns and can model the transformation of land from non-urban use (forest, farmland) to urban land use (Silva and Clarke, 2002). Silva and Clarke, 2002).

Many Land-use and Transport models have been developed based on different theories and for various purposes. Although some of these models are well developed, their purpose is not in line with the TOD concept, which encourages public transport, cycling and walking in areas where private car travel is discouraged (Calthorpe, 1993). Some of these Land-use and Transport models are more concerned with the economic benefits of the city, some are more concerned with population or land-use change, and some include public transport systems but do not emphasise the importance of public transport travel (Mackett, 1990; Putnam, 1983; Silva and Clarke, 2002). Therefore, they can hardly reflect the “transit-oriented” concept of TOD.

2.2 Node-Place Model

Bertolini (1999) first proposed the Node-Place model following the introduction of public transport-oriented development models. The Node-Place model is an analytical model that evaluates both public transport and land-use nodes based on the land-use transport feedback cycle theory (Wegener, 2004). As shown in the figure, the x and y axes of the original Node-Place model represent the transport value of a transport hub (rail station, bus station, or even bicycle sharing station) as a transport node and the human activity value as a place node. Such an approach allows multiple sites to be positioned in the same two-dimensional plane to describe and compare their development. It is worth noting that the value of a node and the value of a place are difficult to describe adequately in terms of a single indicator, and therefore these two indicators are usually expressed as a linear combination of a series of related indicators.

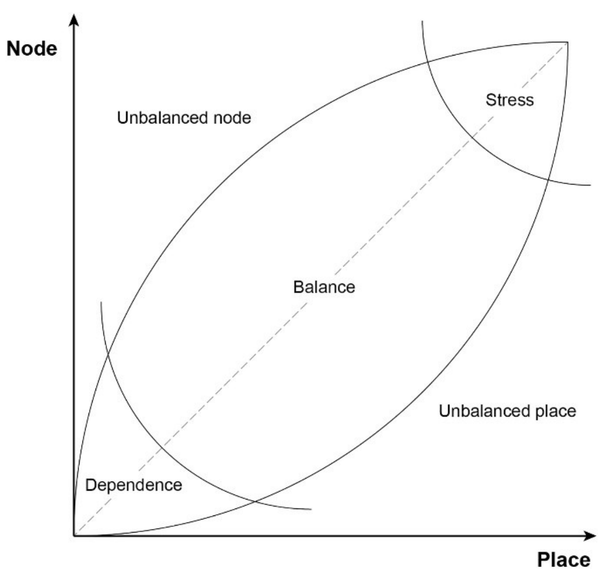


Figure1：The Node-Place Model (Bertolini, 1999)

Bertolini (1999) defines the Node-Place model as describes two imbalances and three balance states at different levels (see Figure 1). The three states along the diagonal are the stress zone, the balance zone and the dependency zone, which express a more balanced public transport and land use development for these sites. Conversely, the zones in the top left and bottom right corners are the imbalanced node zone and the imbalanced place zone, respectively, which have less balanced development patterns and are more oriented towards separate functions (nodes or places). The nodes that balance characteristics of Place and Node are considered more successful in the TOD model. The Dependency Zone is considered to be balanced with low levels of development. The Stress Zone indicates that the area is balanced in public transport and land development, but both are very high and may be overdeveloped. The Imbalanced Node Zone and Imbalanced Place Zone need to be focused on representing their possible development potential.

Based on the theoretical foundations of the Node-Place model, different frameworks based on different lists of indicators have been developed to assess the TOD around nodes based on different cases. The studies cover various cities around the world. At first, the research was mainly conducted in European cities such as Amsterdam (Bertolini, 1999), Brussels (Caset et al., 2019), Flanders (Caset et al., 2020), Lisbon (Vale, 2015; Vale, Viana and Pereira, 2018), London (Zhang, Marshall and Manley, 2019), and Rotterdam (Groenendijk, Rezaei and Correia, 2018). In recent years, Node-Place models have started to gain popularity in studies of Asian regions, such as in Tokyo (Cao, Asakura and Tan, 2020; Chorus and Luca Bertolini, 2011), Shanghai (Chen and Lin, 2015; Gui, Zhang and Wang, 2021; Li et al., 2019), Shenzhen (Su et al., 2021), and Beijing (Gui, Zhang and Wang, 2021; Lyu, Bertolini and Pfeffer, 2016). The vast majority of studies have used clustering analysis to classify a series of nodes into subcategories with different functions and levels of exploitation. In some cases, to facilitate clustering analysis, researchers eliminate insignificant indicators from the index list by principal component analysis (Austin et al., 2010; Zhang, Marshall and Manley, 2019).

While applying the Node-Place model to assess the TOD, researchers have made different improvements to the model, focusing on three main areas: 1. selecting the station boundary; 2. improving the list of indicators; 3. the addition of dimensions.

Firstly, in early studies, a radius of 400-800 meters was frequently used to determine an area of interest around each transport node. However, most of the early studies were conducted on railway stations and more recently, the scope used by researchers has changed based on different types of transport nodes (Bernick and Cervero, 1997; Zhao et al., 2003). For example, in a study in South Korea, researchers suggested that the observation range for metro nodes should be extended to 3 km due to the popularity of bike-sharing, while the observation range for BRT nodes was suggested to be 500 m (Lee, Choi and Leem, 2015). Not only that, when assessing the TOD of the Lisbon urban metro system, Vale et al. suggest an observation range of 500 m by comparing other studies (Jun et al., 2015; Vale, 2015; Vale, Viana and Pereira, 2018).

Secondly, improvements to the list of indicators for the Node-Place Model have also been an important area of research. The original Node-Place Model has 15 normalised indicators, nine of which point to node value and six to place value, with the final node value and place value being their equally weighted mean values, respectively (Bertolini, 1999). The list of indicators has then been abridged or added to in subsequent studies due to data limitations or various other reasons (Chorus and Luca Bertolini, 2011; Monajem and Ekram Nosratian, 2015), such as proximity to city centres and public transport accessibility (PTAL) (Chorus and Luca Bertolini, 2011; Kamruzzaman et al., 2014).

Finally, the current discussion on adding a new dimension is related to ‘pedestrian-oriented design’, where Node and Place nodes can describe the traffic development and land development in the vicinity of a site but do not represent the ‘Oriented Development’ TOD well. Development (Lyu, Bertolini and Pfeffer, 2016; Vale, 2015; Vale, Viana and Pereira, 2018). For example, some poorly designed pedestrian paths may reduce people’s enthusiasm to get to public transport nodes. The lack of assessment of pedestrian-oriented design has led researchers to include other indicator series. In the Lisbon metro system study, Vale (2015) proposes a new ‘Design’ dimension for the value of public transport orientation, looking at the public transport orientation of the area through the ratio of pedestrian sheds on the street. Similarly, Lyu (2016), in his evaluation of TOD in Beijing, incorporates proximity indicators into a new dimension named ‘oriented’ to observe the orientation.

2.3 Network Analysis in Urban Research

Although scientists have improved many aspects of the Node-Place model, the current model still has many shortcomings. Firstly, the current Node-Place model focuses more on estimating the area’s development around each node and neglects to consider the region’s land use and transport planning. In other words, the current Node-Place model ignores the node’s position in the whole public transport system. Researchers have found that many TOD-related initiatives are challenging to promote and implement due to the limitations of administrative boundaries and the competition for development priority between TOD projects near each other that are not part of the same local authority (America, 2007). A successful TOD project needs to go beyond the confines of individual stations and understand the role of each community and station area in a public transport oriented regional network, which is the basis for the concept of some of the more recent projects known as Regional TOD (Anderson, 2011). The current model assesses the value of a node as a transport node by observing the number and frequency of its connections to other nodes and other public transport systems. This kind of estimation is a local perspective rather than a system perspective, as it does not take the node’s position in the topological network into account. Due to their more central position in the topological network, some stations may have more transit potential despite having fewer connections and should be developed earlier in the system. Several studies have confirmed such a view, but the current Node-Place model cannot capture this point (Derrible, 2012; Jayasinghe et al., 2019; Vale, Viana and Pereira, 2018; Wang and Fu, 2017; Zhang, Marshall and Manley, 2019). Therefore, we need to assess the value of stations in the entire network to the model.

Network centrality has a long history of research, with graph theorists having studied networks since 1735 (Berkeley, 1735). The concept of network centrality has been mentioned in social science research since 1950 (Bavelas, 1948; Leavitt, 1951). However, only at the beginning of the 21st century was the concept of network science taken out of other disciplines, considered a separate discipline, and widely applied in various fields (Barabási, 2013). In network science, centrality is an indicator of the importance/influence of nodes in a network (Barabási, 2013). For example, a fundamental task in social network analysis is identifying which individuals in a group are more influential than others, thus helping us understand the role they play in the network (Barabási, 2013).

Network centrality already had some applications in the transport field, with some scientists using network analysis to study the relationship between land use and transport (Curtis, 2011; Derrible, 2012; Zhang, Marshall and Manley, 2019). In these studies, network centrality was used to find key transport nodes and design systems to distribute passenger flows rationally. Scientists have developed many centrality algorithms, such as degree centrality, closeness centrality, betweenness centrality, eigenvector centrality and PageRank (Barabási, 2013; Zhong et al., 2014).

Among these, betweenness centrality and closeness centrality are essential for transport studies, with betweenness centrality represents the importance of a node as a transit node between any other nodes (Derrible, 2012). It calculates all the shortest paths of any two nodes in a network, and if any of these shortest paths pass through a node, then it is essential because it is likely to take on the function of acting as a 'bridge' to many other nodes (Freeman, 1978). This algorithm, which represents the 'transport' characteristic, is well suited to the study of transport systems, particularly the study of the transport capacity of rail systems. In a railway system, a node with a high betweenness centrality brings benefits and drawbacks. On the one hand, for the node itself, a high betweenness centrality means that it carries an important transport function in the overall system. However, on the other hand, if there are only a few nodes with extremely high betweenness centrality in a network, then if these nodes are disrupted, it can be a severe blow to the whole railway system. Several studies researching the resilience of rail systems have also frequently used betweenness centrality to identify critical stations (Chopra et al., 2016; Jin et al., 2014; Zhang et al., 2018). It is formulated as

$$C_B(i) = \sum_{k \neq i \neq j \in N} \sigma_{kj}(i)/\sigma_{kj}$$

Here, σ_{kj} represents the sum of the shortest paths between v_k and v_j, and $\sigma_{kj}(i)$ is the count of the shortest paths through v_i. Thus, a node i on the shortest path between many nodes will have a higher betweenness centrality.

The closeness centrality, like the betweenness centrality, uses the characteristics of the whole network, that is, the position of a node in the whole structure. If the shortest distance to any other node is small, its closeness centrality is high. Closeness centrality is closer to the geometric centre of a network. Simply put, it allows for better identification of the geometric centre of the system (Dou, Wang and Dong, 2021). For many cities, this centre is generally at the city's core, especially in monocentric cities. This feature also has important implications for urban research, which many studies have observed in relation to the degree of TOD development and distance from the city centre (Chorus and Luca Bertolini, 2011; Zhang, Marshall and Manley, 2019). The closeness centrality is the reciprocal of the average shortest distance from this node to all other nodes in a given network (Sabidussi, 1966). The formula for the closeness of node i is

$$C_C(i) = \frac{n-1}{\sum_{v_j \in V_i i \neq j} d_{ij}}$$

Although many applications of network centrality in research on public transport systems already exist (Jayasinghe et al., 2019; Vale, Viana and Pereira, 2018; Wang and Fu, 2017; Zhang, Marshall and Manley, 2019; Zhong et al., 2014), among the relevant studies using the Node-Place model for assessment, few studies attempt to incorporate network centrality into the model's assessment framework. Therefore, we introduce the metric of network centrality in this study to enhance the value of the Node-Place model from a systems perspective.

2.4 Green Space in Urban Research

Furthermore, most of the current research on TOD has focused on optimising transport systems, high-density land use and pedestrian-friendly design (America, 2007; Anderson, 2011; Lyu, Bertolini and Pfeffer, 2016; Su et al., 2021). However, there is a lack of attention to ecological and environmental aspects, which has also been pointed out in several studies (Ali et al., 2021; Cervero and Sullivan, 2011; Huang and Wey, 2019). Of these, we are particularly concerned about the neglect of urban green space.

The World Health Organisation defines urban green space as 'urban land with vegetation cover' (WHO, 2018). It can be a human-made facility or a natural landscape and is generally open to the public (WHO, 2018). It is a vital part of the urban ecosystem, improving air quality and positively impacting mental and physical health. Greenery can reduce temperatures by 2 to 8 degrees Celsius, mitigate the heat island effect (Shishegar, 2014; Zhang, Murray and Turner, 2017). Evidence suggests that living in a greener environment can promote and ensure good health and help recovery from disease and poor health habits (Public Health England, 2020). Moreover, during the covid-19 pandemic, many studies have found the importance of an excellent urban ecology for people's physical and mental health. A study in London noted that areas with more green space had lower rates of covid-19 infection (Pan, Bardhan and Jin, 2021). This pattern has also been confirmed in studies in Beijing and Melbourne (Astell-Burt and Feng, 2021; Zhu and Xu, 2020). In addition, these studies also indicate that green space increases the well-being of residents and has a beneficial effect on people's psychological well-being (Astell-Burt and Feng, 2021; Pan, Bardhan and Jin, 2021; Zhu and Xu, 2020).

However, studies have shown that TOD, a representative pattern of urban densification, has been developed at the expense of green space (Haaland and van den Bosch, 2015; Khoshkar, Balfors and Wärnbäck, 2018). This results in a shortage of green space in densified cities and indirectly affects people's quality of life and health (Bell et al., 2014; Kondo et al., 2018).

Current research on urban green space focuses on two main areas. Some studies used remote sensing and machine learning techniques to detect and identify urban green space (Chen et al., 2018; Kuang and Dou, 2020; Luo, 2021; Shahtahmassebi, Amir Reza et al., 2021; Xu et al., 2020).

Some studies assessed the impact of green space on people and construct related indicators (Gupta et al., 2012; Knobel et al., 2021; Schindler, Texier and Caruso, 2018; Wang et al., 2019). Although some studies have proposed the concept of green TOD based on the combination of green urbanism and TOD, these articles focused on the design concept of integrating green spaces with architectural planning, and few studies have included the assessment of green spaces in the evaluation framework of TOD (Ali et al., 2021; Cervero and Sullivan, 2011). Therefore, in this research, we combined the concept of TOD with green urbanism and introduced the evaluation of urban green space coverage in this study.

The WHO (2018) emphasises in its recommendations that the area of green space per capita in cities should be between 10 and 15 square metres. Many studies have also used the area of green space per capita as an evaluation indicator rather than simply the area of green space coverage (Arshad, Hafiz Syed Hamid and Routray, Jayant Kumar, 2018; Badiu, Denisa L et al., 2016; Lin et al., 2019; Shahfahad et al., 2019). This is because there are areas where, despite few green spaces, there are few or no residents at all, so more green space can be allocated per capita instead. Therefore, the green space per capita ratio was also chosen as a comparative indicator in this study. The formula is:

$$\text{Green Space Ratio} = \frac{\text{Area of green space within the catchment area}}{\text{The resident population within the catchment area}}$$

After calculating the green space per capita ratio for the evaluation areas, we also calculate whether their coverage is up to standard. According to WHO (2018), ideally, everyone should have no more than 300 metres of green space from their home, and the ratio of urban green space should be 10-15 square metres per person. Following this principle, we judge whether an area's green space is 'up to standard' based on 15 square metres per person. However, due to data limitations, it is not possible to observe the accessibility of green space, which will be discussed later as a limitation.

In summary, as a representative analytical framework for assessing transit-oriented land development patterns, the Node-Place model still has some shortcomings, even though many studies have been conducted to apply and improve it. The main issues are the neglect of the function of nodes at the whole system level and the neglect of the urban green space evaluation. Therefore, this study aims to extend the assessment framework of the Node-Place model by focusing on two aspects:

1. Introducing system centrality index (network centrality).

2. Introducing index for green space (green space ratio per capita)

3. Methodology

Chapter 2 introduced the transit-oriented development pattern and explained the history, shortcomings and ways to improve the NP model associated with TOD. This chapter will explain the methodology used in the study, which aims to inform the future direction of land development by extending the indicator system of the NP model and assessing TOD development in Greater Manchester from a network system and ecological perspective.

3.1 Study Area

The study area for this research is the rail system in the Greater Manchester area. The system consists of two components: the Metrolink system in Manchester and the commuter train system in the Greater Manchester area, as shown in Figure 2. The two rail systems are considered together because Transport for Greater Manchester has long defined Metrolink as "complementary to the rail system within the city", and both systems make a significant contribution to people's commutes (TFGM, 2017). In the future, it is planned that the two systems will interact more and even have shared lines (TFGM, 2021b). Therefore, it is more comprehensive to assess the two rail systems as one system.

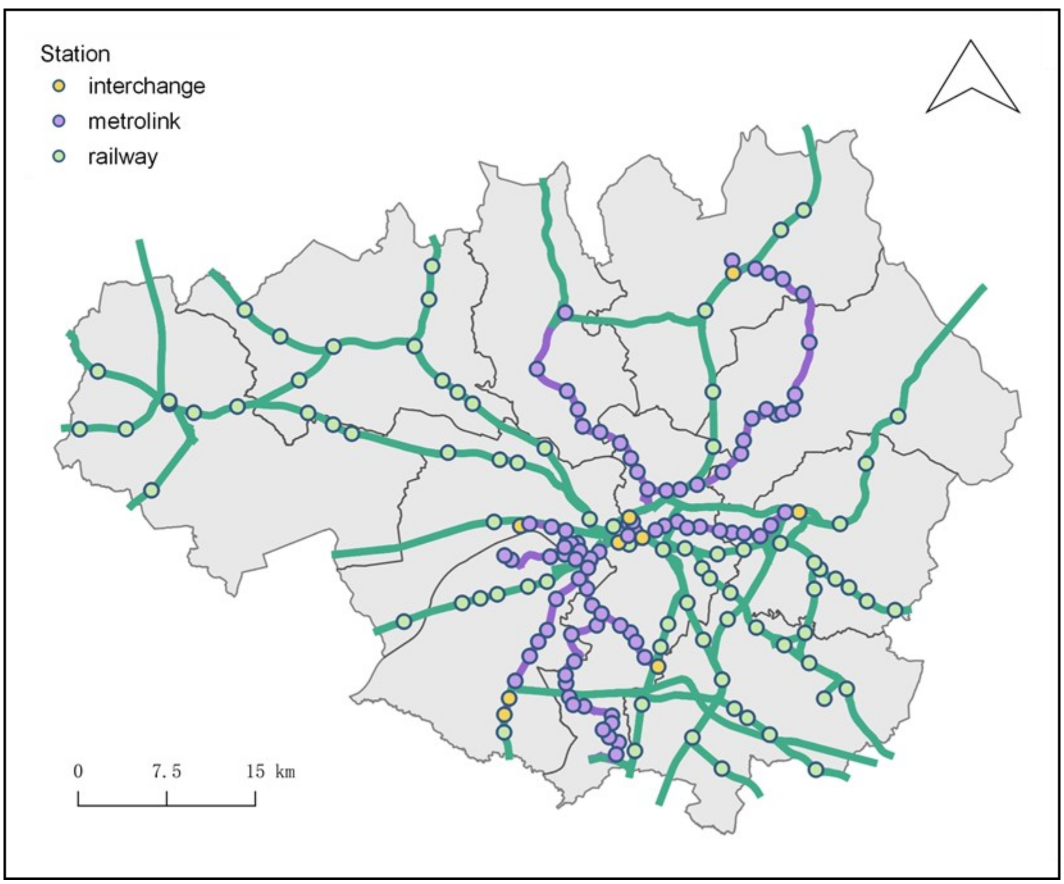


Figure 2: Train System in Greater Manchester.

Greater Manchester's rail network consists of 198 stations, leaving 177 stations after combining metro-rail interchange stations, football stadium stations that are only open during matches and Manchester Airport stations. According to publicly available statistics from TFGM and related businesses, people in Greater Manchester usually walk between 680m and 730m to get to a station (Moovit Insights, 2020; TFGM, 2017). We, therefore, set the catchment area to be a circle with a radius of 700 m centred on stations. The majority of catchments area does not overlap or has minor overlap, with only a proportion of stations in Manchester city centre having overlap. Also, based on the stations and track lines, we constructed a travel time-weighted undirected weighted graph with 177 nodes. We chose to use travel time weighted edges because the speed of a commuter train is not the same as that of a Metrolink, and travel time is more of a concern for passengers than geographic distance (Gustafson, 2012; Holz-Rau, Scheiner and Sicks, 2014). Therefore, travel time weighting is a better indicator of the operation of the rail network than weighting by geographical distance.

3.2 The List of Indexes

Our NPD model metric framework is based on the classic NP model and the new dimension 'Design' proposed by Vale (2018) and Lyu (2017), focusing on pedestrian-oriented design. We also introduced the network indicators and green space indicators for comparative analysis with the NPD model. Table 1 shows the list of indicators for the NPD model and additional indicators for comparison. As shown in the table, the NPD model contains seven indicators representing the node dimension, four indicators representing the place dimension and three indicators representing the design dimension. The indicators for the model and the variables used for comparison were collected from a 700m radius catchment area and checked for normality. As commuter trains have seven to eight times more carriages than Metrolink carriages, the frequency of commuter railway train departures was weighted to ensure equity in the demonstrated transport capacity (TFGM, 2017). The reasons for using the 'Bike Capacity' variable in node metric and the 'Design' dimension are explained in detail here, as the other variables have been extensively used and studied in the past NP literature not be repeated here.

Index	Indicator	Calculation	Main Data Source
Node	N1=Number of stations within 20 min of travel	number of stations reachable within 20 min by metro	TfGM, 2021
	N2=Number of directions served by metro	number of metro services offered at the station	TfGM, 2021

	N3=Daily frequency of metro services	number of metro departing from the station on a working day	Manual input according to schedule (TfGM, 2021)
	N4=Number of directions served by other public transport	number of public transport services offered at the station	TfGM, 2021
	N5=Number of car parking spaces	distance to the nearest motorway access	TfGM, 2021
	N6=Bike Parking Capacity	number of bikes that can be parked at the station	TfGM, 2021
	N7=Distance from the closest motorway access	number of car parking spaces at the station	TfGM, 2021
Place	P1=Number of residents	number of residents within 700 m	ONS, 2013
	P2=Number of workers	number of workers within 700 m	ONS, 2013
	P3=Land use mix	Degree of the functional mix (Vale, 2015)	OSM, 2021
	P4=Number of POIs	number of points of interest (POIs) within 700 m	OSM, 2021
Design	D1=Intersection density	the density of intersections per hectare	TfGM, 2021
	D2=Accessible network length	length of the accessible network (metres)	TfGM, 2021
	D3=Pedshed Ratio	Pedestrian shed ratio (Vale, 2015)	TfGM, 2021
Comparative indicators	Nc=Closeness Centrality	Closeness centrality of the station	TfGM, 2021

Nb=Betweenness Centrality	Betweenness centrality of the station	TfGM, 2021
G1=Green Space Ratio per capita	Average green space allocated per resident in a 700m radius catchment area	Ordnance Survey, 2021

Table 1: the Node-Place-Design Indicators list and Comparative Indicators

Although Bertolini (1999) included bicycle-related indicators in his original list of NP indicators, researchers have in the last decade largely stopped focusing on this aspect due to urban characteristics, insufficient bicycle penetration and inadequate bicycle infrastructure (Chorus and Luca Bertolini, 2011; Kamruzzaman et al., 2014; Zemp et al., 2011). However, with the development of technology, many cities now have well-developed bike-sharing systems with stations, and several studies have found combined modes of travel for bike-sharing and other public transport (metro, bus) (Flamm, 2013; Lin et al., 2018; Martin and Shaheen, 2014; Zhang and Zhang, 2018). Not only this, but in Greater Manchester, cycling is a mode of travel that the government is actively promoting, and in 2018, Chris Boardman, the Cycling and Walking Commissioner, launched the Bee Network project, which aims to change travel patterns across the city region and make active travel the preferred option for travel (TFGM and Sustrans, 2019). In recent years, this has manifested itself by providing fully segregated cycle and walking routes on busy roads and the construction of cycle centres to provide temporary storage and loan of bicycles (TFGM and Sustrans, 2019). In total, there are 108 cycling and walking schemes in development by 2021, with a total value of over £500 million (TFGM, 2021a). Therefore, in addition to looking at the connectivity between stations and buses, it is important that we also consider the connectivity between stations and bikes.

Furthermore, this research adds a ‘design’ dimension to the model based on Vale (2015) and Lyu (2016) research. Although other applications of this new dimension are currently limited, several previous studies confirm the importance of pedestrian-oriented design in TOD (Kamruzzaman et al., 2014; Lyu, Bertolini and Pfeffer, 2016; Vale, 2015; Zhang, Marshall and Manley, 2019). Vale (2018), in his study, synthesised previous research on the ‘design’ dimensions of intersection density, walkway length, and pedestrian shed ratio and confirmed the reliability of these indicators. Therefore, our model incorporates the ‘design’ dimension to provide a more comprehensive assessment of TOD development in Greater Manchester.

3.3 Data

There are four primary sources of data for this study, the first of which is geographical data on railway stations and bus stops and road network data provided by Transport for Greater Manchester (TfGM) on the UK government’s public data website (data.gov.uk) (TfGM, 2021).

The station data is used to construct maps and visualisations and obtain node indicators such as the station's number of routes and the connectivity to bus stops. The road network data is used to construct road network layers on ArcGIS to obtain data for the design indicators. The second is the 2011 Lower Super Output Area level census data provided by the Office for National Statistics (ONS) (ONS, 2013). This data was used to get place indicators for the residential and working population around the stations. The third is the Shapefile for Greater Manchester from OpenStreetMap (OSM), which includes different categories of points of interest (OSM, 2021). It is used to calculate the land-use mix around the stations and the number of POIs. The fourth is a Shapefile provided by the Ordnance Survey covering a range of green spaces in urban and rural areas of the UK, including playing fields, sports facilities, play areas and allotments (Ordnance Survey, 2021). This data was used to calculate the green space ratio per capita with the stations' demographics.

A basic visualisation of the list of NPD indicators and the extended indicators is shown in Figure 3. In order to facilitate the observation of the variables, we have kept only stations in it and discarded the presentation of lines. The data distributions in this study were primarily skewed, so log transformations of the data (see Appendix 1) was required to convert the data to normal distributions. However, there are zero values in the data, which leads to null values when performing the usual log transformation. Therefore, we followed Zhang, Marshall and Manley (2019) process and log-transformed the data by log(x+1). As shown in the second set of histograms in Appendix 1, the distribution of the transformed data was essentially normal, satisfying the conditions for follow-up analysis.

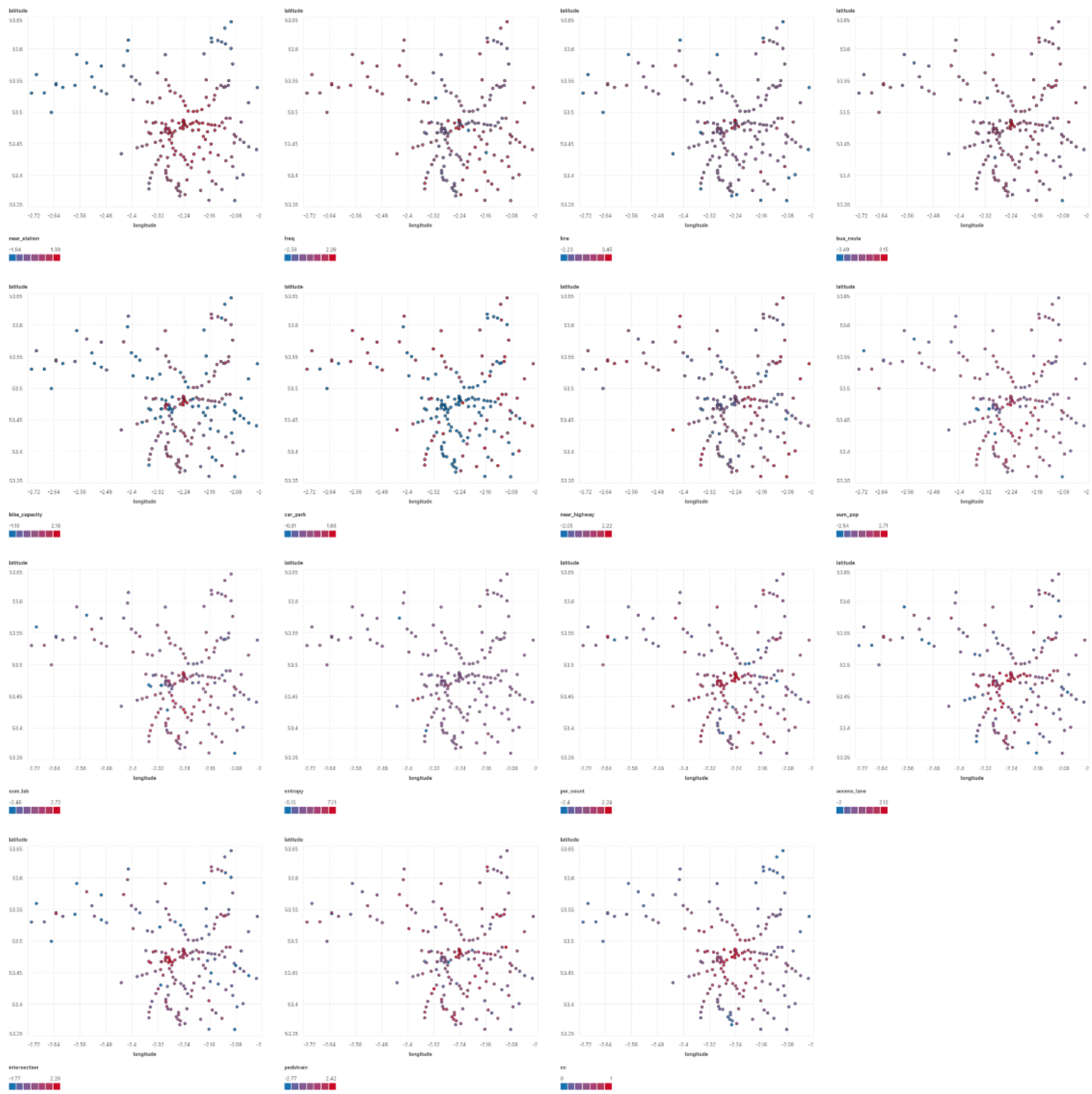


Figure 3: Simple Plot for indicators

3.4 Ethical Statement

The four data sources used in this study are all from open data platforms. We have used these data following their licensing requirements, namely the Open Data Commons Open Database License (ODbL) and the Open Government License. Although neither license restricts the distribution of the data, for security reasons, the authors declare that the data used in this paper will only be used for this research and that the authors will not distribute the original data privately.

3.5 Research Framework

The general flow of the experiment is shown in Figure 4. We first cleaned and integrated the data obtained from the data sources using the R and Rstudio platforms (R Core Team, 2020; RStudio Team, 2020). We then used QGIS's toolbox to count the metrics within a 700m radius of each station. It is worth noting that for some of the data, such as frequency of rail services or frequency of public transport, we used timetables up to 2020 in the hope of avoiding errors caused by the lockdown of cities during the Covid epidemic. Also, we have entered these data manually as we do not have access to the old timetable data via the API. At the same time, the closeness centrality and Betweenness centrality of each station was calculated using an undirected weighted network graph created from the railway system, a step that used the R igraph package (Gabor Csardi and Tamas Nepusz, 2006).

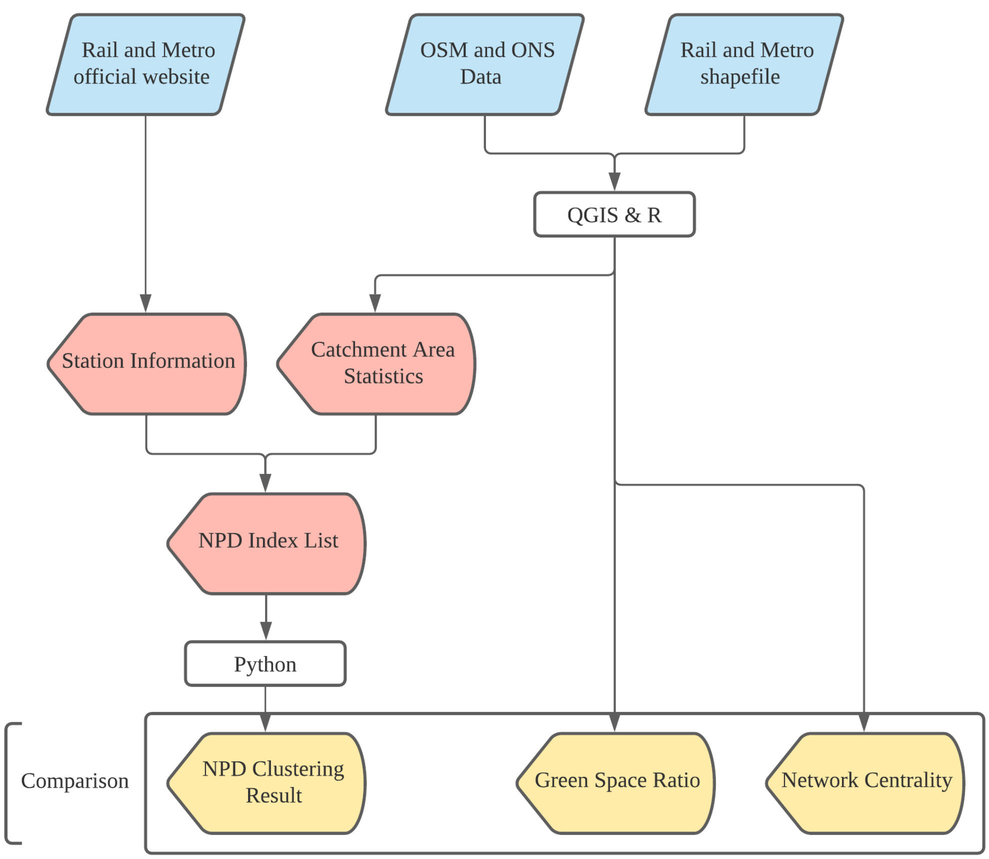


Figure 4: Experiment Flow Chart

Before conducting the cluster analysis, we first calculated node, place and design metrics through the variables in the list of indicators. According to Bertolini (1999) and Vale (2018), we assigned the same weight to each variable. Next, we determined the optimal number of clusters by calculating the average silhouette method and the elbow method, followed by a cluster analysis of the metrics to identify the TOD characteristics of the station areas in the Greater Manchester area. We used the K-means++ algorithm from the Scikit-learn package in Python (Lloyd, 1982; Pedregosa et al., 2011). After completing the clustering analysis of the stations and defining the characteristics of the clusters, we compared the results with the extended metrics. In the context of the policies proposed in the various public transport and land development documents compiled for the Greater Manchester area, we sought to assess TOD development in Greater Manchester from a network system and ecological perspective and discuss detected problems and the potential for model expansion.

4. Result

4.1 Clustering

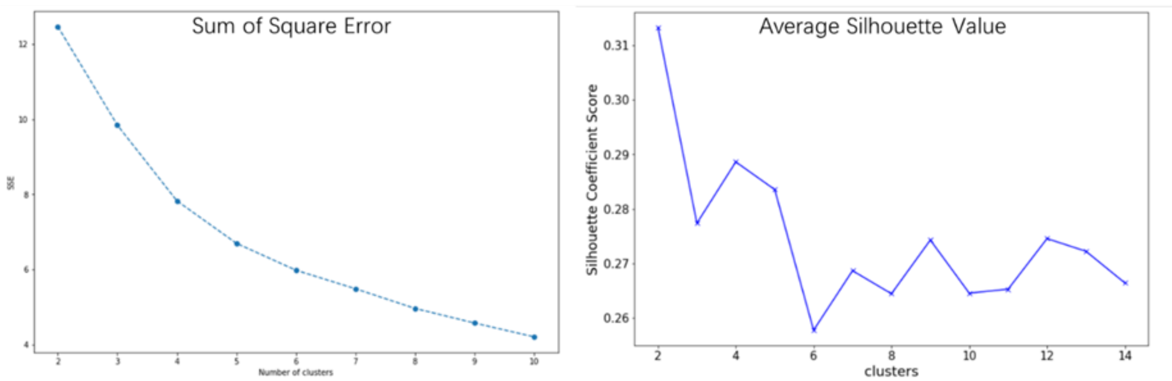


Figure 5: Selection of Clusters

Following the approach of Vale (2018), we assigned the same weight to each variable to calculate the NPD index. After generating the indexes, we used the elbow and average contour method to select the optimal number of clusters, as shown in Figure 5. The average silhouette method results in 2 clusters being the optimal number of clusters (right-hand graph), as the Average Silhouette Value is highest at 2 clusters. However, a clustering number of 2 did not provide enough valuable information, and after trying this, we chose to use the sub-optimal value of 4 clusters (Ding and He, 2004). The clustering results are shown in Figure 6 and Figure 7. Figure 6 shows the distribution of the 4 clusters on the map, and Figure 7 shows the distribution of the mean values of node, place and design index for the 4 clusters. This visualisation is referenced from Vale (2018). Figure 8 shows a scatter plot demonstrating the relationship between the node, place and design indexes. We have also named the various categories of stations according to the recommendations of Vale (2018) and Lyu (2016).

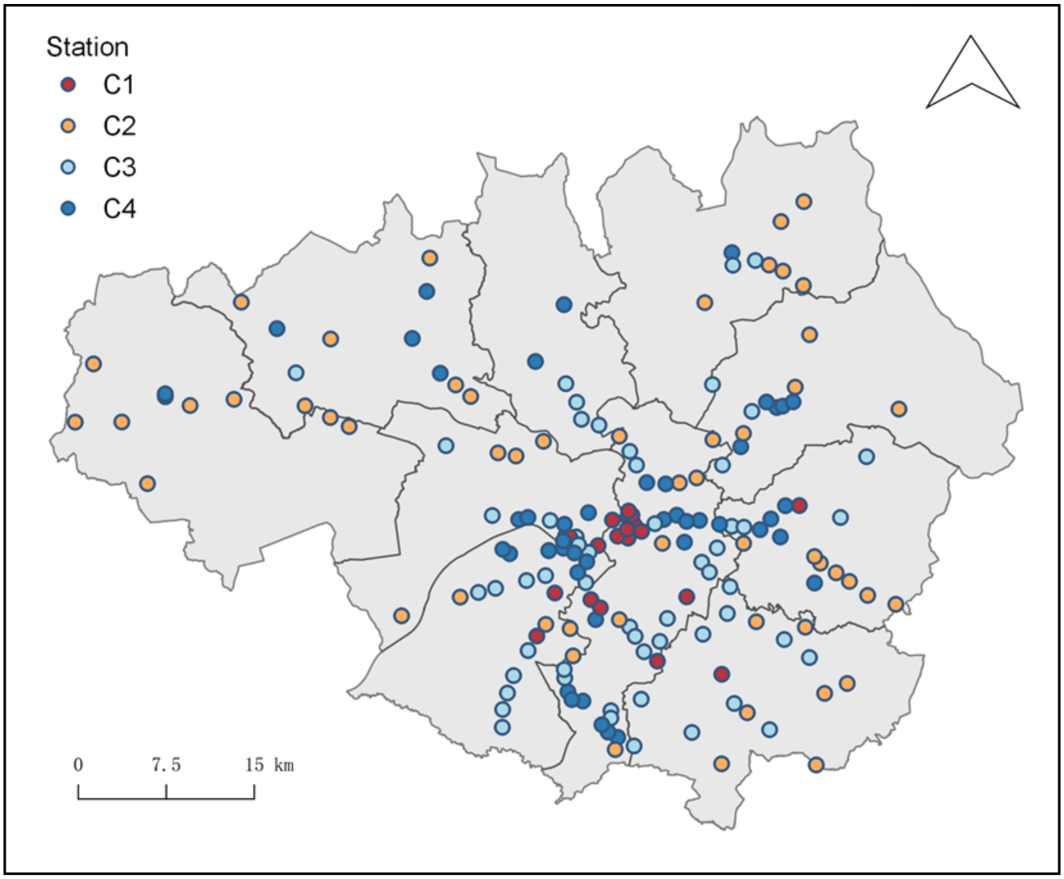
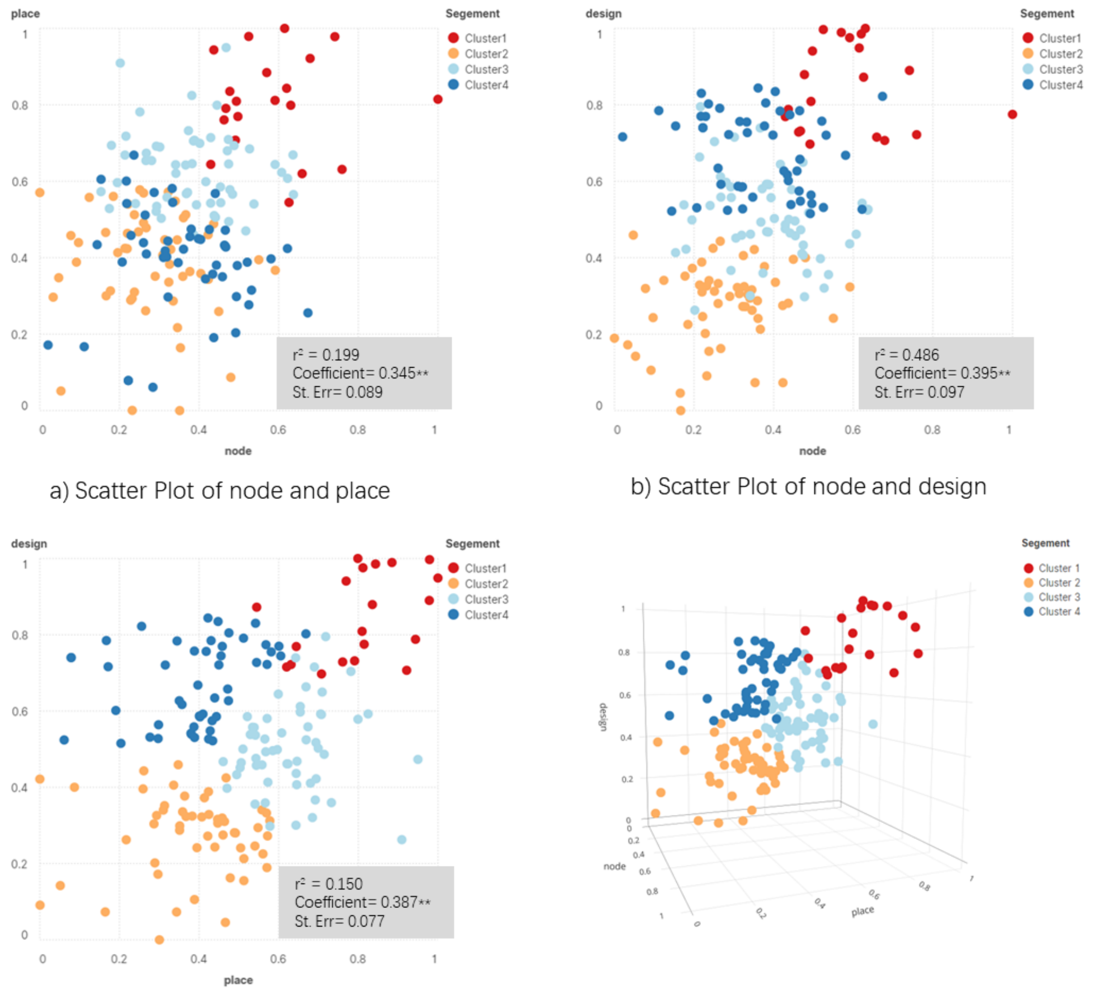


Figure 6: the Classification of station areas in Greater Manchester based on the Node-Place-Design Model.

Figure 7: Average values of node, place, and design indexes for each TOD category



a) Scatter Plot of node and place

b) Scatter Plot of node and design

c) Scatter Plot of place and design

d) Scatter Plot of node, place and design

Figure 8: Scatterplot of Greater Manchester Station in the node-place-design model from a 2D and 3D perspective

C1: Urban TOD

Cluster 1 has the highest average node, place and design values (0.59, 0.8, 0.85). Some of these stations are located in the Manchester City Centre area, and some are located on the South Manchester Line and Airport Line. For example, Wythenshawe Town Centre and Chorlton are two stations on the airport line, close to Wythenshawe city centre, with shops, libraries and the Wythenshawe Forum (a mixed-use building of restaurants, entertainment and fitness centres) nearby. The vast majority of Cluster 1 stations are Metrolink stations or Metrolink-train interchanges, with a few train stations in different city centres like Stockport and Manchester Oxford Road.

C3: Balanced TAD and C4: Unbalanced TOD

Cluster 3 and Cluster 4 have relatively similar average NPD indices, the difference being that Cluster 3 has a relatively low design index (0.48) and a relatively high place index (0.65), while Cluster 4, in contrast, has a shallow place index (0.33) and a high design index (0.68). This result indicates that Cluster 3 has good transit and land use development around its stations but lacks oriented design. Cluster 4 has good transit development and pedestrian-oriented design but lacks sufficient land development and human activity. These findings imply that there is potential for development around the stations of Cluster 3 and Cluster 4. The stations in these two clusters are primarily located in the urban area of Manchester and the first half of the line extending out from the city. A few exceptions are located in the town centre areas of the Greater Manchester Borders, such as Wigan Wallgate and Wigan Northwestern stations in Wigan city centre, and Rochdale Railway station in Rochdale city centre. It is worth noting that while most of the stations on the Manchester-Airport line close to the centre are Cluster 1, which has a relatively high nodal place design index, some stations around there are under the management of Trafford Local Authority, such as Old Trafford and Wharfside, are Cluster 4. This finding may point to the potential for development in some areas.

C2: Future TOD

Cluster2 has a low average NPD index and is predominantly located at the end of the rail network, although there are some exceptions. Clifton Railway Station, for example, is located at the junction of Manchester and Salford. Although in its early years, Clifton Station served as a transit point for two lines and a means of commuting for local factory workers, the station gradually lost its usefulness due to the abandonment of the line, the closure of factories and the already inadequate quality of service and advertising (R V J Butt, 1995; Wright and Young, 2011). The station was also built on an elevated site, which may have contributed to the unpopularity of Clifton station, as people had to climb a hill and pass a factory to get to the station (Wright and Young, 2011).

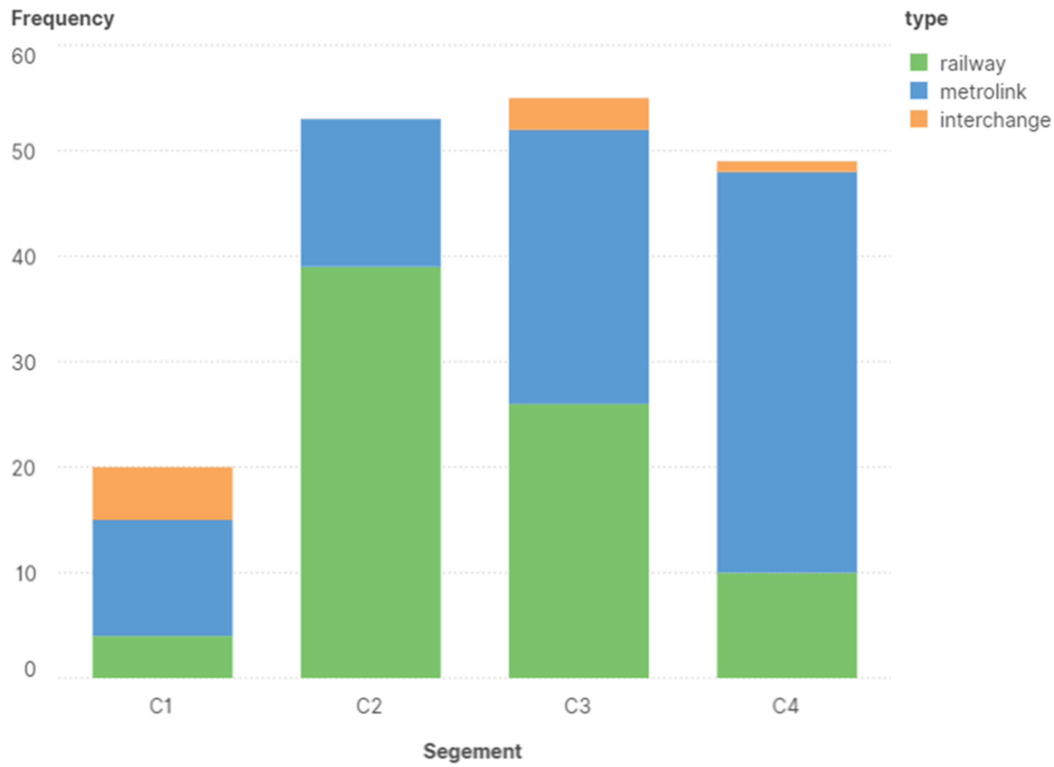


Figure 9: Types of Greater Manchester stations in different clusters

In addition, when classifying stations, we also looked at their station type, as shown in Figure 9. The most evident phenomenon is the large number of railway stations that fall into Cluster 2, possessing a relatively low nodal place design index, suggesting a difference in the development of commuter train and Metrolink systems.

We also explored the relationship between each component, as shown in Figure 8. Overall, Greater Manchester stations have a relatively balanced NPD index (8-d), with a few exceptions for stations located in shopping centres, sports centres or tourist attractions such as The Trafford Centre and Barton Dock Road, which have relatively low node-place indexes and relatively high design index. These two stations are located five miles west of Manchester city centre on the Trafford Park industrial estate, a campus that includes The Trafford Centre, a large indoor shopping centre and leisure centre that is the third-largest retail scale commercial centre in the UK and attracts a large number of visitors to the area every year (Statista, 2018). As a large shopping centre, the Trafford Centre has a good design index as it has a large number of indoor and outdoor pedestrian routes linking the various buildings. However, like many other shopping centres, it is a ‘ car-oriented ’ mall, with no residents living within 700 metres of the Trafford Centre, and a low place index due to the monotonous land use pattern of the entire area being covered by the shopping centre. Despite having over 3,000 parking spaces at Trafford Centre, Trafford Centre Station and Barton Dock Road, the last two stops on the Trafford Park line do not have many service routes or high frequency of service. This also contributes to the lower node scores.

Furthermore, the correlation between node, place and design is significantly different in Greater Manchester: the correlation between the node and design indexes is positive (coefficient=0.4) and relatively high (r^2=0.49), implying that stations with better public transit development in Greater Manchester also have better pedestrian accessibility design. On the other hand, the correlations between node and place and place and design indexes are low, especially for place and design (r^2=0.15), which means that the land-use patterns of stations in the Greater Manchester area are not well integrated into the pedestrian-oriented design. Not only that, a correlation analysis after filtering the station categories revealed a strong correlation between node and design (r^2 = 0.52) for the train stations, while the correlation between node, place and design was weaker for the Metrolink stations (r^2 < 0.1). This suggests a difference in the degree of integration of transit and land development between the two systems. Combined with previous findings when looking at the station clusters, we can find that the Metrolink system has a relatively high NPD index and a low TOD integration, while the train system has a relatively low NPD index and a somewhat higher TOD integration.

4.2 Network Centrality

Although the NPD model analysis assessed the degree of integration of land use and public transport at stations in Greater Manchester and the Classification of stations, it was unclear how vital stations were to the overall rail system. We, therefore, measured the importance of stations in the system by using two network centrality algorithms (closeness and betweenness).

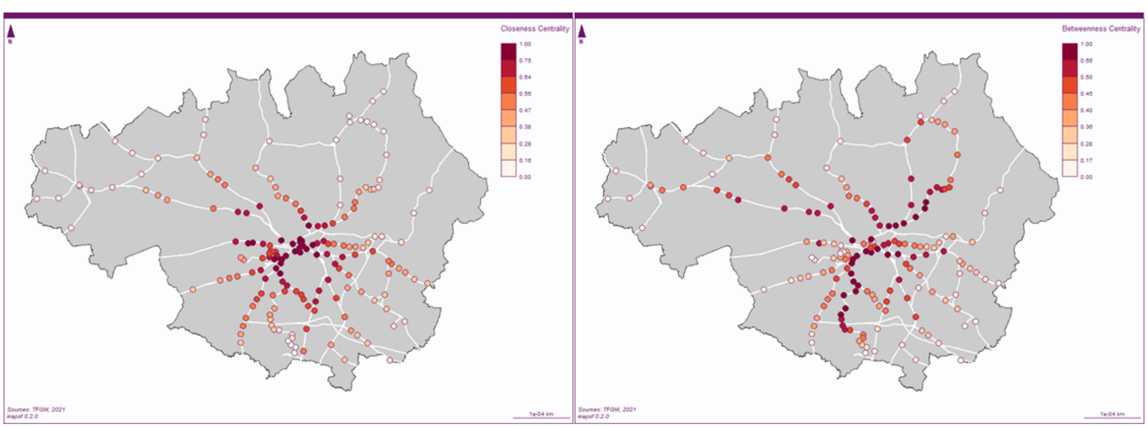
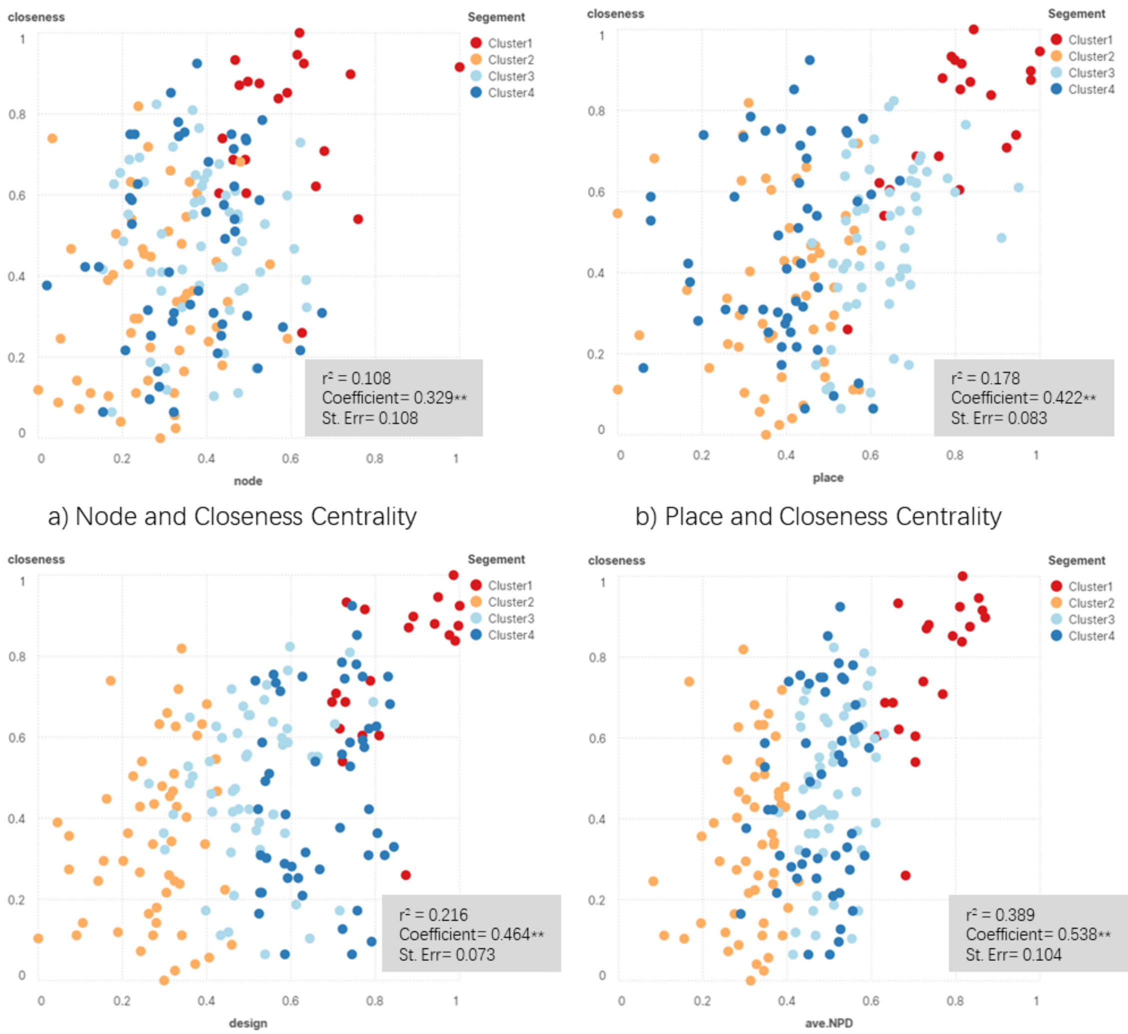


Figure 10: Closeness Centrality (left) and Betweenness Centrality (right) of Manchester Station



a) Node and Closeness Centrality

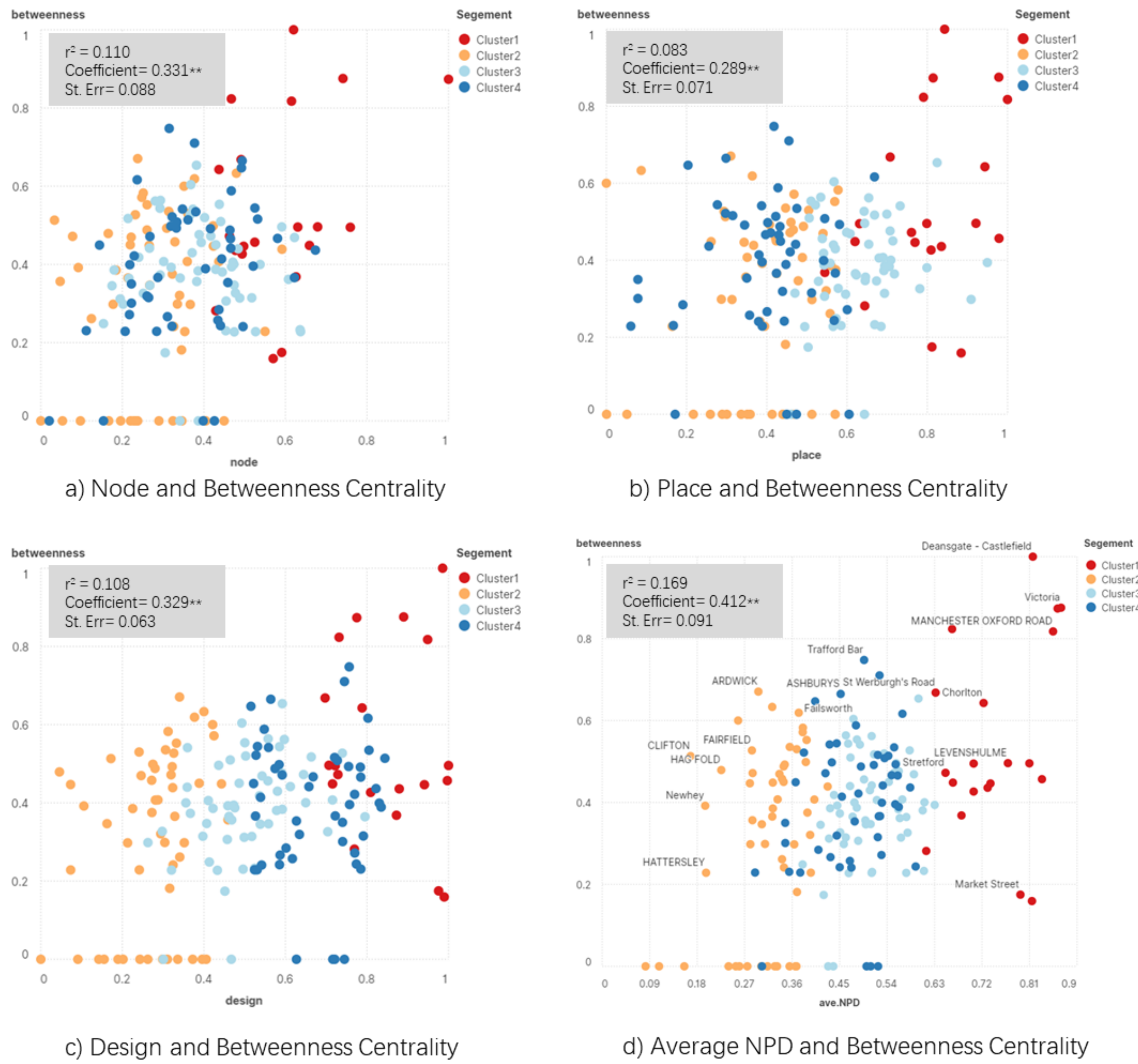
b) Place and Closeness Centrality

c) Design and Closeness Centrality

d) Average NPD and Closeness Centrality

Figure 11: Scatterplot of station closeness centrality and NPD criticality

The results of Closeness Centrality are shown in Figures 10 and 11. Closeness Centrality is more reflective of the geometric centrality of the stations in the system. We can see that the stations with high centrality are concentrated in Manchester's city centre, radiating from high to low in all directions. A comparative analysis with the NPD index (Figure 11) reveals a low correlation strength between closeness centrality and the NPD indexes. Comparatively, the correlation between the average NPD index and closeness centrality is somewhat higher (r^2 = 0.39). This suggests a relationship between the TOD development around the stations and the distance of the station from the centre of the rail network. This finding is similar to Chorus and Bertolini (2011) and Kamruzzaman (2014) in Tokyo and Brisbane.



a) Node and Betweenness Centrality

b) Place and Betweenness Centrality

c) Design and Betweenness Centrality

d) Average NPD and Betweenness Centrality

Figure 12: Scatterplot of station betweenness centrality and NPD criticality

The results for betweenness centrality are shown in Figures 10, 12. betweenness centrality better reflects the importance of the station as a transit hub in the network. As shown in Figure 12, unlike closeness centrality, a node at the centre of the system does not represent a higher level of centrality. For example, Anchorage and Habour City stations are not as crucial in the network as the slightly more distant St. Werburgh's Road station for transmission. Anchorage and Habour City stations have only one service line and few stations, whereas St. Werburgh's Road station carries two Metrolink lines. In a comparative analysis with the NPD index (Figure 13), we find that the correlation between betweenness centrality and node, place, design and average NPD index is weak ($r^2 < 0.2$). Combined with the previous weaker correlations between NPD indexes and closeness centrality, these two findings suggest that TOD development at Greater Manchester stations rarely considers the criticality of stations in the network.

We have also detected some stations with a high NPD index but very low betweenness centrality, such as MediaCityUK, located in Salford's Media Park, a sub-centre of the city and a focal point for local civic and economic activity. However, it is only one station on a relatively short line on a system level and does not serve as an interchange or multi-line function. Also, Market Street and Shudehill stations in central Manchester share similar characteristics in terms of NPD index and betweenness centrality. This suggests that these stations can be considered candidates for new lines or new interchange stations in the future.

4.3 Green Space Ratio

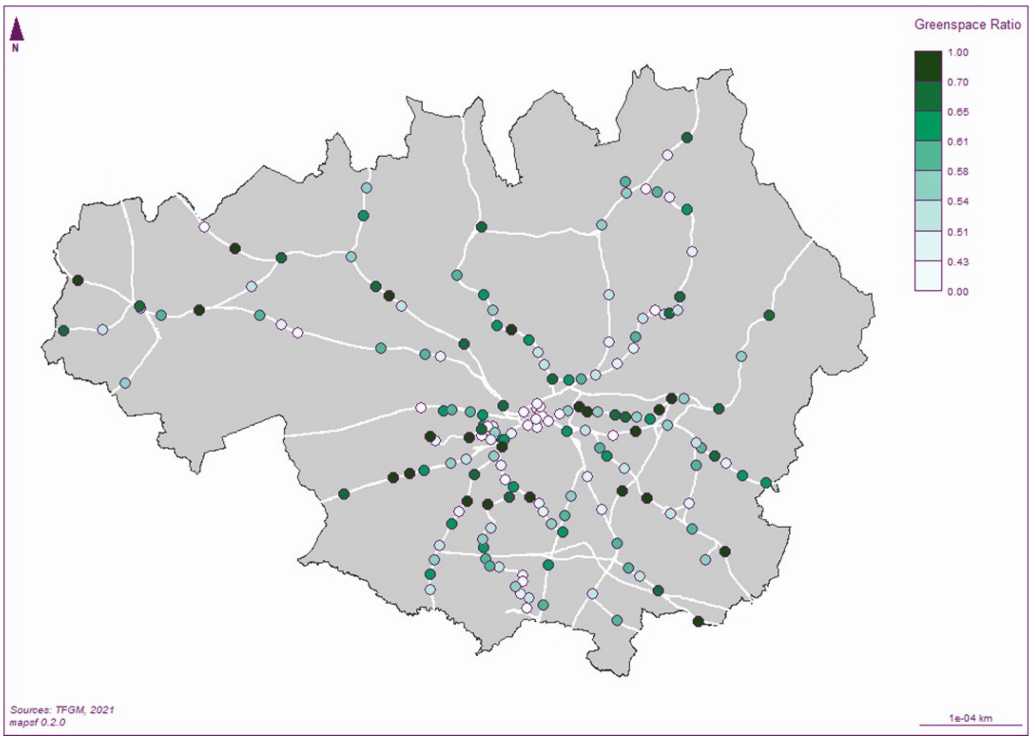
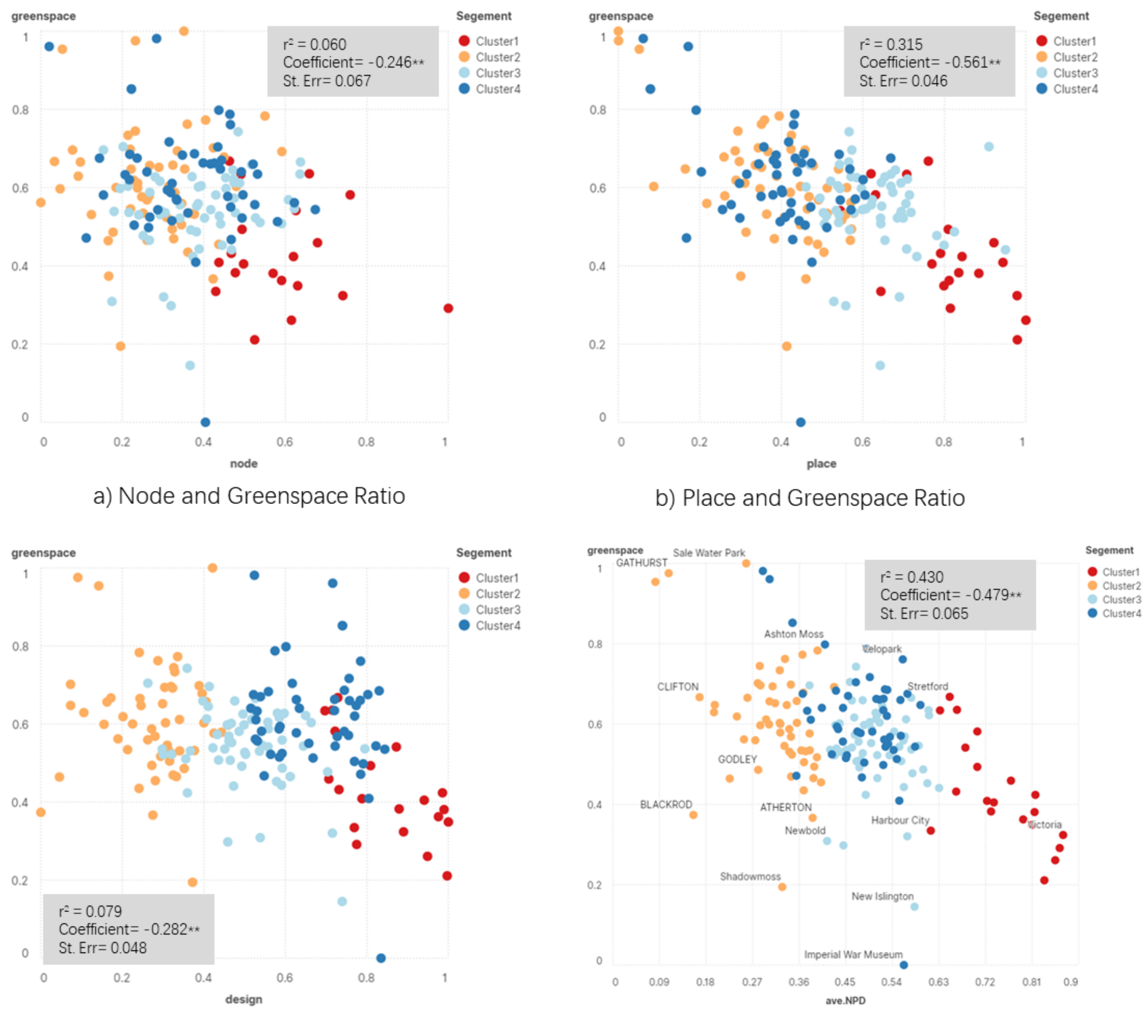


Figure 13: Green Space Ratio of Greater Manchester Station Area

In response to the neglect of ecological aspects of the NPD model, we have introduced a green space ratio (per capita) to measure the ecological integration of land development in Greater Manchester. As shown in Figure 13, although it is difficult to observe a pattern of green cover in terms of geographical distribution, we can find that the stations in the central areas of Manchester all have very low green space ratios per capita. The scatter plot of the NPD model and the green space ratio per capita (Figure 14) show a negative correlation between the place indicator and the average NPD indicator and the green space ratio per capita (r^2=0.32, r^2=0.43). This suggests that Transit-Oriented Development in Greater Manchester will somewhat sacrifice the green space coverage of the city. Furthermore, the summary of attainment stations (T) and non-attainment stations (F) according to the WHO (2018) classification of green space per capita standards (Figure 15) shows that although the majority of stations in Greater Manchester meet the standard in terms of green space per capita around them, more than half of the stations in Cluster 1, a cluster with a relatively high nodal place design index, do not meet the standard. This phenomenon also corresponds to the low green space coverage observed in Manchester city centre regarding geographic distribution, indicating a significant shortage of green space in Manchester city centre.



a) Node and Greenspace Ratio

b) Place and Greenspace Ratio

c) Design and Greenspace Ratio

d) Average NPD and Greenspace Ratio

Figure 14: Scatterplot of station area’s Green Space Ratio and NPD criticality

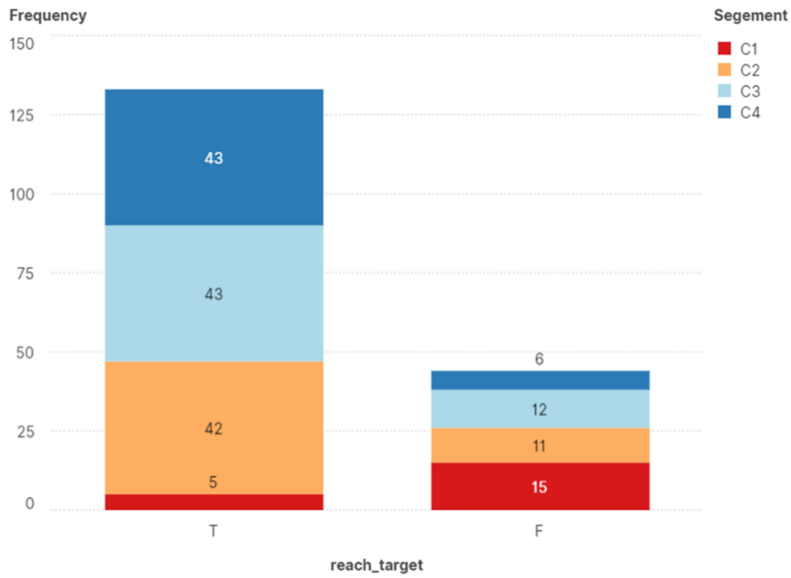


Figure 15：Stations in Greater Manchester that meet the green space standard

5. Discussion

This chapter explains and elaborates on the analysis results presented in Chapter 4. It seeks to answer the question of what characteristics of Transit-Oriented Development exist around rail stations in Greater Manchester and whether introducing indicators of system centrality and green space ratios can bring additional insight into NPD models.

5.1 TOD in Greater Manchester

After calculating the node, place, and design indexes and performing cluster analysis, the results show that four types of TOD can be identified for the Greater Manchester area stations. These were 'Urban TOD' with high node, place and design metrics; 'Future TOD' with low node, place and design metrics; Balanced TAD' (transit adjacent development), which has high node and place metrics but low design metrics; and 'Unbalanced TOD', which has a high node and design metrics but low place metrics. These characteristics can inform the planning direction of TOD. For example, 'Balanced TAD' stations can be designed to capture local land-use values through improved pedestrian-oriented design. The area around the 'Unbalanced TOD' stations could be seen as a potential allocation area for future population growth in Greater Manchester. It has a reasonable allocation of transport capacity and pedestrian-oriented design but lacks sufficient intensity of land activity.

Through correlation analysis, we found that the station areas in Greater Manchester are not very well integrated. There is a degree of integration between transit development and pedestrian-oriented design, but transit and pedestrian-oriented design are not well integrated into land use development patterns. These findings are contrary to Zhang (2019) and Vale (2015) in other cities, suggesting that different development characteristics exist in different cities and need to conduct more case studies. Taken together, the train system in Greater Manchester has better TOD integration but generally low NPD metrics, while the Metrolink system has lower TOD integration and generally high NPD metrics. The reason for the phenomenon in Greater Manchester may be the difference in the level of development and geographical location of the train and Metrolink stations in the rail system under study; the two rail systems in Greater Manchester are operated by Northern Rail and Paris Mass Transit, respectively, and therefore may differ in their strategic approach to development. Also, Metrolink is mainly located in the thriving Manchester metropolitan area, and it is not easy to access its services in other parts of Greater Manchester. This issue has been taken up by Transport for Greater Manchester (TfGM). In recent years TfGM has been trying to promote Tram-train services, a shared line service where conventional trains and Metrolink can share lines (TFGM, 2021b). The TfGM hopes this integration will allow the two systems to be combined to compensate for the lack of capacity during peak hours and to plan and manage both systems in an integrated manner.

Another reason for the poor integration level is that TOD was not the planning approach at the beginning in Greater Manchester. As an old metropolis, Greater Manchester started with a highway-oriented development pattern, like many cities of the time (TfGM, 2015). This can also be seen in the Manchester region's nation-leading number of motorways (TfGM, 2015). Although the rail system was introduced in Greater Manchester at an early age, it was not as popular as it is today and the dominant means of travel at the time was the car (TFGM, 2017). As the concept of sustainable development gained popularity and the TOD model spread across the UK, the Manchester region gradually adapted its planning approach. In 1993, Manchester introduced the Metrolink system as a light rail system that could operate within the city, complementing the traditional train system's lack of routes (Department for Transport, 2009). This was the beginning of Manchester's gradual transformation into a transit-oriented city. Recent examples of TOD in Manchester include the redevelopment of the Salford Quays area, where the introduction of Metrolink into the Salford Quays area, combined with the construction of business districts such as MediaCityUK, has resulted in a significant increase in the number of residents in the Salford Quays area (Urban Transport Group, 2019). Between 2016 and 2017, house prices in the Salford area increased by 8.4%, faster than most places in the Manchester area (Urban Transport Group, 2019). This is due to the TOD development at Salford Quays, which has helped improve employment opportunities and increase transport links, contributing to property prices. In addition, more TOD areas are planned for the Greater Manchester area in the future. The Draft Greater Manchester Spatial Framework highlights the need to deliver 227,200 new homes of different types and tenures by 2040 (Manchester City Council, 2021). The draft states that "the density of residential development should reflect the relative accessibility of walking, cycling and public transport, enabling more people to live in the most convenient places" (Manchester City Council, 2021).

5.2 A more insightful analytical framework

A comparative analysis of the NPD model and closeness centrality reveals a significant positive correlation between the two. This suggests that the degree of TOD development of a station is influenced by the distance from the centre of the rail system (Manchester city centre). Other studies have also demonstrated this (Chorus and Luca Bertolini, 2011; Kamruzzaman et al., 2014; Zhang, Marshall and Manley, 2019). Furthermore, comparing the NPD model and betweenness centrality reveals how stations function at the system and local levels. These results provide a valuable policy reference. We suggest that policymakers assess stations' local and system-level criticality when developing TOD modes for rail systems, which can help identify potential TOD stations worth developing and improving. Stations with low system-level value but high NPD values (e.g. MediaCityUK) serve as a focal point for economic business activity locally but assume lower transit importance on the system. These stations could be candidates for future rail network planning as well as interchange stations. Stations with high system-level value but relatively low NPD values (e.g. Central Park and Ardwick) are also of interest and could be considered candidates for the future urban transit-oriented development project.

In the comparative analysis of the model and the green space per capita ratio, we found a slight negative correlation between the TOD development pattern and the green space ratio per capita. This implies that TOD development patterns in Greater Manchester sacrifice green space to some extent, which corresponds to the findings of other cities that have found that intensification of development causes a reduction in green space (Haaland and van den Bosch, 2015; Khoshkar, Balfors and Wärnbäck, 2018). This also points to the importance of including an assessment of green space coverage in our evaluation of TOD's, as a development approach that only focuses on TOD's transit, land use, and pedestrian-oriented design can have severe consequences for ecology. Not only that, but we detected a significant lack of green space in central Manchester, which points to a possible over-intensification of development in Manchester city centre. Although Manchester has not been an early adopter of TOD, and this overdevelopment may not be related to TOD, the crisis of insufficient green space per capita in the city centre points to the need for Manchester planners to act on this.

5.3 Limitation

Although our comparative analysis provides more insights into NPD models, our study still has many shortcomings. Firstly, our network centrality provides a limited reference because our network graph is only based on a railway system setting. Insufficient understanding of actual passenger flows prevented us from perfectly exploiting the network centrality, for example, even though Market Street, which was found to have low betweenness centrality on the system in the analysis, is the third most used station in Manchester and has high passenger flows. Such misunderstanding points to a strong need to introduce new types of patronage data to construct network graphs in the future. Many studies in recent years have combined network analysis with new types of data, such as smart card data, to provide a more accurate picture of public transport systems in cities by analysing people's travel patterns (Zhang, Marshall and Manley, 2019; Zhong et al., 2014). In the future, we can add smart card data to our study to provide a more comprehensive system-level reference for TOD assessment.

Moreover, the green space indicators selected for our study are too simple and correspond to only part of the requirements set out in WHO (2018). In the WHO (2018) recommendations, the existing indicators only reflect "15 square metres of green space per capita" and do not reflect "green space areas within 300 metres of the home". This implying that we need to improve the green space indicators. Benton (2021), in his latest study, proposes to judge the degree of green space coverage through three indicators, namely:

1. Green space coverage.

2. People's ease of access to green space (green space accessibility).

3. People's visibility of green space (green space visibility).

A more comprehensive and accurate assessment of green space can be obtained by including all three green space indicators in the analysis framework in future studies.

6. Conclusion

Transit-oriented development (TOD) patterns are receiving increasing attention from planners and policymakers as an important strategy for addressing urban travel inequalities and global air pollution. While the Node Place Model, an urban model based on the TOD concept, is often adopted by researchers to assess the extent of TOD in urban public transport systems, this model lacks the identification of the system-level functions of the public transport network. Meanwhile, as urban densification advances, there is an increasing demand for a green and healthy life closer to nature, which is difficult to detect by the Node-Place model.

This study builds on Vale's (2015) and Zhang's (2019) refinement of the NP model and uses the node-place design model, extended network centrality indicators, and green space coverage indicator to explore the TOD characteristics around rail system stations in the Greater Manchester area. This study detected four types of TOD stations in the Greater Manchester area and identified differences in the level of development of the train and Metrolink systems. Overall, transit development at stations in Greater Manchester is not well integrated with land use. In addition, we identified significant differences in some stations' systemic and local importance through comparison with network centrality, pointing to the potential for development that may exist at some stations. Finally, the comparative analysis detects a negative correlation between the NPD indicator and the green space index and a significant lack of green space cover in Manchester city centre. This firstly demonstrates the importance of TOD analysis in conjunction with ecological indicators and points to an ecological crisis in the Manchester city area. These findings confirm that system centrality and green space indicators can provide additional insight into the model. It also provides a reference for future planning of rail transport in Greater Manchester. The importance of betweenness centrality is highlighted here, which identifies the transport importance of a station at a system level, and by comparing this with the NPD model, stations that have potential and those that need to be enhanced can be identified.

This research can be seen as an enhancement to the NPD model, providing more insight into the model by introducing two perspectives (system perspective and ecological perspective). Future research could consider improvements from two aspects. Firstly, we need to incorporate new data types such as smart card data in the system-level analysis to provide a more comprehensive and accurate reference for the model. Secondly, improving the green space indicators by adding accessibility, visibility, and other related indicators expands the green space index framework as a "fourth dimension" of the model. This paper emphasises the significance and importance of combining the TOD model with green ecology and calls on policymakers to pay more attention to the coexistence of green space and urban densification. "Urban green space is an important investment that local authorities can make on behalf of citizens and their well-being" (WHO 2018, p. 3). The neglect of green space by transit-oriented development has long contributed to the deterioration of urban ecology. We believe that a TOD model that incorporates green ecological development will be the key to sustainable, equitable and attractive urban development in the future.

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Appendix 1

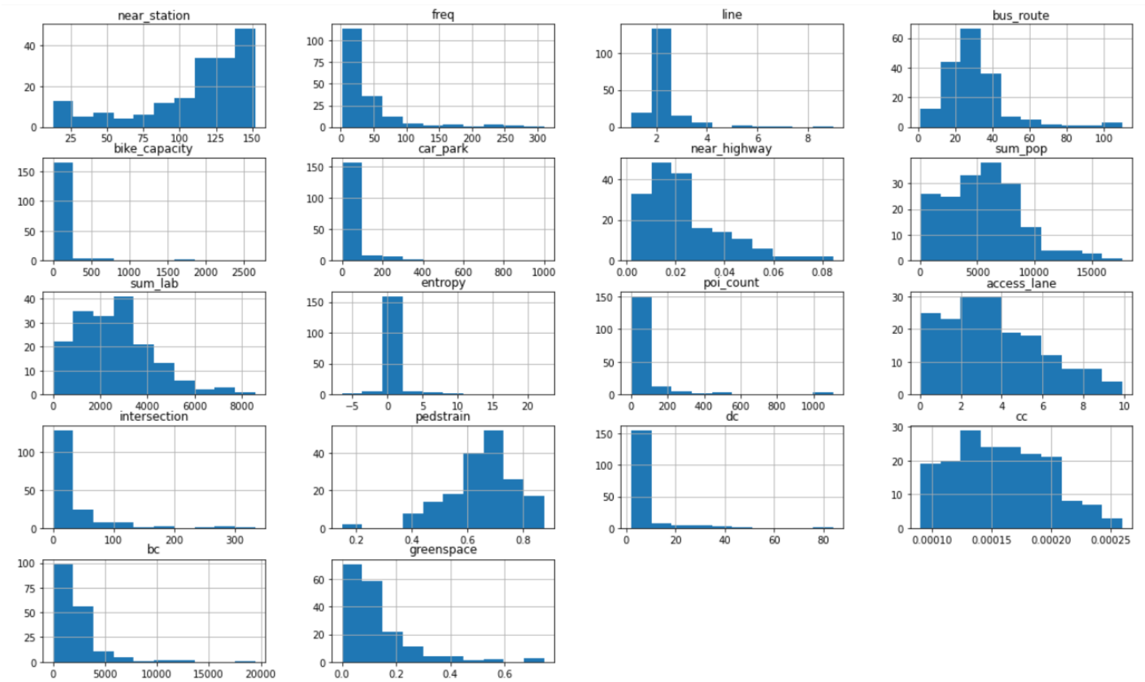

Figure1: Data distribution before log transformation

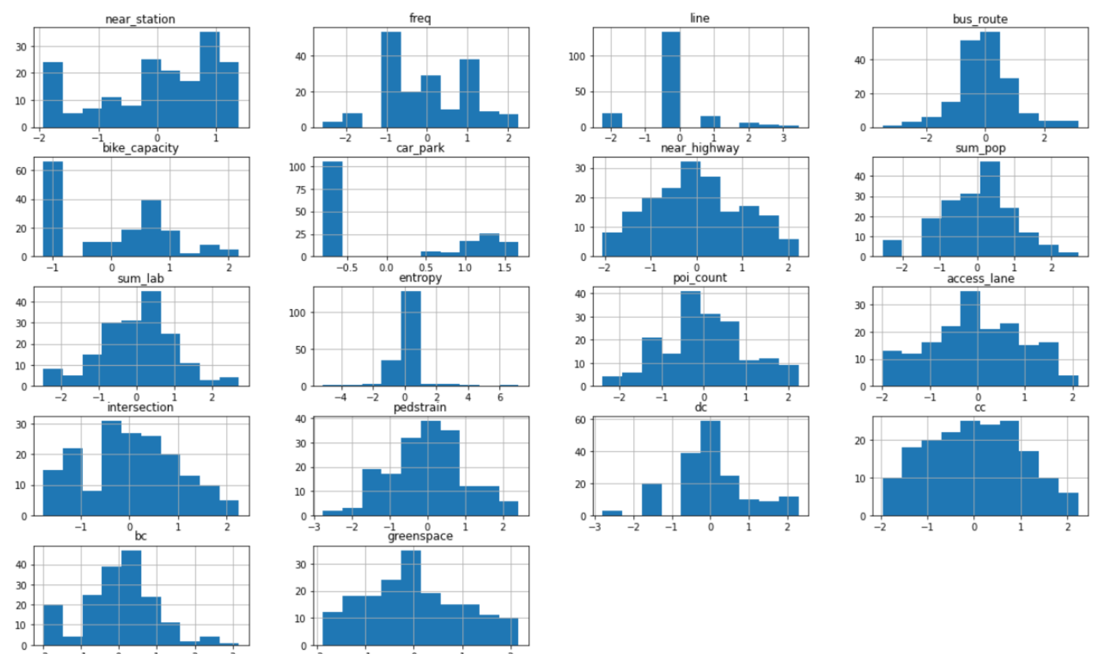

Figure2: Data distribution after log transformation