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Multilevel Multimodal Network Modelling

The Spatial Impacts of The Public Transport on Urban Systems

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ABSTRACT

Transportation plays an essential role in supporting people and freight movement in cities and regions. The physical infrastructure of the transport network is usually embedded as a part of urban structure to link spaces and cover a significant amount of ground. However, accessibility studies, especially the space syntax theory and measurements, mainly focus on modelling and analysing the street network without concerning the public transport network. Although space syntax methodology has been proved to successfully examine the configurational urban form and the related effects on the pedestrian and vehicular flow within the street network, the effect of rail-based public transport is still missing in most space syntax studies. Therefore, this study applied a synthetic methodology to examine the multilevel multimodal network by combining railways and streets into a united network model. An Integrated Urban Model (IUM) has been developed to uncover the network and land use accessibility in cities and regions. This study further explored the distance cost in Depthmap by adopting time-cost distance for every segment based on the speed of transport modes for multimodal travelling. The results indicated that the multilevel multimodal model could provide a new vision of the network centrality. The study demonstrated that the concept of time-cost distance, along with metric distance and angular cost, could be a new approach for measuring the accessibility of the multilevel network in cities and regions.

KEYWORDS

Public Transport, Multilevel Network, Network Modelling, Integrated Urban Model, Time-cost distance

1 INTRODUCTION

Sustainable urban development has become the top priority for most countries and regions with increasing population and city expansion. We are facing the challenges of implementing urban infrastructure and delivering better urban development plans to meet the necessity of everyday life and, at the same time, ensure economic growth and protect the environment. In 2013, the European Commission proposed Sustainable Urban Mobility Plans (SUMPs) that could and should be adapted to urban transport planning in EU countries. SUMPs is a strategic and integrated approach for dealing with the complexities of urban transport in a more effective manner. The central goal of SUMPs is to improve the accessibility of urban areas and provide high-quality transport services by achieving a shift towards sustainable mobility (UN-Habitat, 2013; Rupprecht Consult, 2019).

Moving toward a greener environment and reducing greenhouse gas emissions, local authorities are enforcing the restriction on the vehicles to replace gas cars with electric ones. However, to mitigate travel demand and congestion, private cars might not be ideal for all the cases. Encouraging the modal shift toward active, efficient, and sustainable transport modes (walking, cycling, and public transport) might be the long-term solution for the cities and regions.

According to Transport for London, travel demand in London grew from 25.1 million trips per day in 2010 to 27.0 million in 2019 – an increase of 7.6 per cent. The share of trips made by walking, cycling and public transport increased from 59.6 per cent in 2010 to 63.2 per cent in 2019. Compared with all other modes, public transport is 35.8 per cent in 2019 (Transport for London 2021). That being said, public transport plays a significant role in the transportation and daily commute in London. Therefore, a more efficient and convenient public transport system is needed to facilitate the movement and accessibility to jobs and activities in cities and regions.

To enhance mobility is a matter of developing transport infrastructure and providing efficient services as well as overcoming the social, economic, political, and physical constraints to movement. Thus, to ensure effective, sustainable transport and urban development, sustainable urban mobility planning is required. It must coordinate policies across all sectors of transport, land use, environment, economic development, social policy, health, safety, and energy, to provide an integrated development for the sustainable mobility solution. The goal of transport development should extend beyond gaining access to destinations, activities, services, and goods to focus on how people could reach opportunities for employment, education, and leisure more easily and efficiently. Consequently, urban transport development should emphasise how to bring people and places together by creating an urban transport system that enhances accessibility, rather than simply building more transport infrastructure or increasing the movement of people and goods.

Improving mobility and accessibility requires a holistic and integrated approach to incorporate socio-economic, urban, and transport planning. A sustainable mobility plan has to establish a link between urban form (in terms of shape, structure, function, and demographics) and urban transportation systems. It has been widely accepted that the urban transportation system involves all forms of mobility, including walking, cycling, private vehicles, and public transport. An integrated urban transport system is considered to reduce travel distance and frequency and lower the environmental impact in terms of energy consumption and congestion by encouraging the modal share of public transport and non-motorised transport, which could eventually reduce private motorised transport. That being said, all forms of public transport, particularly high-capacity public transport systems that are well integrated with a multi-modal network, are the backbone of the accessibility-based urban mobility plan.

Therefore, this study aims to develop a synthetic methodology by integrating space syntax network analysis with GIS land use datasets. It ought to uncover the transport mobility and the characteristic of the urban form in the notion of a multilevel network system that consequently influences the social-spatial development in the cities and regions. Unlike most space syntax studies, this study applies a multilevel multimodal network model, which joins the additional layer of the rail network to the street network, for the spatial accessibility analysis. This study further explores the distance cost of the network model by applying the time-cost of multiple transport modes instead of the metric distance, which is commonly used in space syntax research. The result could provide a better understanding of the network and land use accessibility and suggest that the spatial analysis space syntax and the land use accessibility measurements by the Integrated Urban Model would be able to evaluate the public transport development.

Following the introduction, this paper will describe the gap in knowledge and previous related studies in the literature review chapter and then present the datasets and methods developed and used in this study. Finally, this paper will discuss the results, followed by the limitations and potential future research.

2 LITERATURE REVIEW

2.1 Transport Study and Modelling

Studies in transport planning constantly apply simulation modelling to examine and emulate the traffic flow or capacity in the urban system. To create the transport model and simulate the performance of the street network movement, an immense amount of information and network input datasets are required. Assumptions and information such as streets, junctions, vehicle types, signals, directions, service frequency, etc., must be collected or predefined before the analysis is executed. Besides the topology and connectivity of the network or other information within the urban system, transport modelling particularly focuses on trip cost as the main determinant for studying travel behaviour and movement patterns. Transport modelling software such as

MATsim and Urbanism, usually adopts Gravity Model (Masucci et al., 2013), Agent-Based Modelling (ABM) (Batty, 2013), and Cost-Benefit Analysis (CBA) (Hanley and Spash, 1993; Boardman, 2001) to investigate the network equilibrium at the prevailing costs to the users, where the system is considered as dynamic network (Bell and Iida, 1997; Daganzo, 1997).

Nevertheless, the distribution of the trip frequency within the transport network will mainly depend on the trip cost in the notion of economics when compared with different transport modes, and the results of the movement pattern will highly rely on the traffic volume and the speed. This approach makes the characteristics of the topological and the geometric spatial layout of the street network difficult to be reflected in the simulation results. Even though the Geographic Information System (GIS) is widely adopted in transport analysis (Haynes et al., 2004), most of the transport simulation models could only predict the patterns within the predefined system as a whole, instead of demonstrating the multidimensional multimodal flow in different parts of the urban system. The network accessibility of spatial effect, which is related to the urban form in multi-scale, is usually missing.

2.2 Space Syntax Approach

Space syntax methodology has proved that the configurational urban form determines the pedestrian and vehicular flow within the street network (Penn et al., 1998). The simplified physical components with the constant time spent and equal weight segments between all spaces to all other spaces are the features of the geometric network analysis in space syntax (Law et al., 2012). The spatial layout of the urban tissue could inform the urban function of the city and settlement, as well as the social-spatial activities taking place inside the urban areas. Although it is unnecessary to acquire considerable traffic information to perform space syntax measurements, it could present the immediate result of the urban patterns for the overall understanding of an urban system. The relative accessibility for the location of the transport infrastructure for the street network is still without concerning the sense of the geographic properties of the non-street transport network between places (Jiang, 1999; Batty 2004). Therefore, space syntax analysis could only partially capture the flow of people in the city by the geometric composition of the street network and somehow lose the sense of the public transport network, which has been heavily used in daily commutes for jobs and opportunities.

There is a gap between transport study and space syntax study. It requires a different approach to combine the geometric analysis of space syntax with the geographic and cost-benefit analysis of transport modelling. Transport study needs to involve the spatial effect of urban form, whereas space syntax analysis requires attention to travel time and speed to inspect the multimodal network. In order to provide a synthesis methodology for applying accessibility as a tool to identify the spatial interaction of the multilayer multiscale network in the cities and regions, linking space and time patterns with the human behaviour related to transport network and developing an integrated urban model is, therefore, a reasonable approach to accomplish this study.

2.3 Public Transport in Space Syntax Studies

The well-known space syntax spatial analysis of the London Kings Cross Station neighbourhood in the Natural Movement study (Hillier et al. 1993) has demonstrated that the infrastructure of railway stations would affect urban street networks in connectivity and accessibility, which could enhance or disrupt the pedestrian movement patterns. The study of railway terminus neighbourhoods in London also suggested that the development of railway structures would impede the pedestrian movement by their locations and spatial characteristics of the stations over time (Bolton, 2015). The embeddedness of the stations with the existing urban environment has been inspected by space syntax analysis with socio-economic variables and identified that spatial conditions might determine the land use distribution and the walkability around station neighbourhoods (Mulders-Kusumo, 2005: Dhanani and Vaughan, 2016). Studies in the neighbourhoods of London Underground stations also revealed that the global and local spatial configuration of the station catchment area could facilitate the local economic and socio activities (Chen and Karimi, 2017; Chen and Karimi, 2019).

Another study has examined the accessibility effect of the London Underground stations and indicated that the ridership within the public transport system might follow the topological effect of the network. However, the commuters' travel pattern still corresponds to the angular or metric characteristics of the street network (Chiaradia, 2005). The same phenomenon has been found in a larger scale railway system study (Schwander, 2007). A previous multiscalar study in North Holland (Van Nes and Stolk, 2012) has applied the space syntax method with the Node Place model to investigate to what extent the degree of railway station could affect the place value in terms of urban functions such as offices, dwellings, shops, etc. The result indicated that the diversity of the urban functions and the frequencies of the railway services seems to depend on the spatial configuration of the street network around stations. High regional accessibility of the station degree along with high local accessibility of the angular choice and integration would strengthen the Node Place value to enhance the movement of people and the local economy. Studies have further examined the network centrality in multimodal network analysis, which integrated the public transport network with the urban street network (Gil, 2012; Gil et al., 2012; Gil,2014; Law et al., 2012) and indicated that the additional layer of rail network could affect accessibility significantly other than the centrality of the street only network.

Many space syntax studies have investigated the spatial factors of the station neighbourhoods, but few studies focused on the global phenomenon of the public transport system, and on how public transport services could affect the network centrality in the cities and regions. This study intends to discover the multilevel effect of the public transport network in the global urban system and the local scales of station catchments by assessing land use and station datasets.

3 DATASETS AND METHODS

This study developed and applied the Integrated Urban Model to investigate the urban network system within London M25, including the street network and public transport rail network, namely TfL London Underground, Overground, DLR, and National Rail. The Integrated Urban Model and the related datasets are introduced in the following sessions.

3.1 Integrated Urban Model

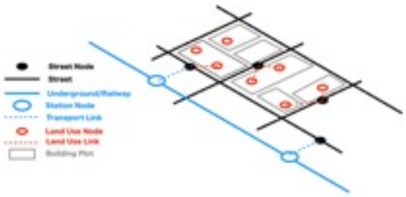
In this study, an Integrated Urban Model (IUM) has been built to adopt the multilevel multimodal network model and link land use dataset for spatial analysis and land use accessibility. The IUM is based on the concepts and methodologies from previous multimodal network studies (Law et al., 2012; Gil, 2016) and advanced space syntax and land use modelling literature (Karimi et al., 2015; Acharya et al., 2017). The IUM is a geospatial modelling representation of multimodal urban networks which is capable of accessing the network analysis and linking with the urban dataset. Unlike axial or segment models, the multimodal network model, which has been created within the IUM, could measure the network accessibility not only by taking the metric or angular cost into account but also by assessing the travelling speed by the time-cost of different transport modes for each segment. With the information on the road classification, which is inherited in the multimodal network model, IUM could uncover both the configurational network effect and time-based network accessibility by merging the topo-geometric properties with geographic properties. Furthermore, by linking the urban dataset, IUM would be able to estimate the land use accessibility by the catchment analysis. Therefore, IUM could potentially improve the traditional approach of space syntax and transport modelling by calculating and comparing the geometric urban network and the land use accessibility.

3.2 Network Datasets

The primary network model of the IUM is the combination of the street network and rail network. The street network model is derived from the Road-Centre Line model (Turner, 2005) from Ordnance Survey Open Roads and MasterMap Highways Network – Path, whereas the rail network model is converted from the Transport API GTFS dataset, which is a universal format for public transport network including the information of the routes, services, and schedule. These two network layer is joined by creating links from the station nodes to the street.

3.3 Land Use Datasets

IUM adopted five urban land use datasets from multiple sources, including OS Addressbase Point, NHS digital data, and School data from GOV.UK, OS Open Greenspace, and NaPTAN stops/stations from the Department of Transport. These datasets have been georeferencing into data points and linked systematically to the network model in the IUM by the street name and urban point reference number (UPRN). A series of spatial query functions based on SQL (Structured Query Language) has been applied in developing the IUM to transform and link the urban network and land use data in the geodatabase. It allows IUM to be able to perform the spatial query and analysis in terms of network accessibility measurements (space syntax) and land use catchment analysis, but also could link the result of accessibility variables with land use distribution and density together for statistical evaluation. Figures 1,2 and table 1 could explain the structure of the IUM in more detail regarding the network model and land use.



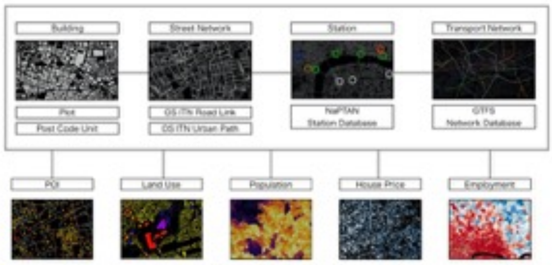


Figure 1 (left): Diagram of IUM

Figure 2 (Right): The dataset structure of the geodatabase.

Dataset	**Modelling Representation**	**Geometry Type**	**Data Source**
Road-Centre Line	Street Network	Polylines	OpenStreetMap (OSM)
Transport API GTFS	Tube/Rail Network	Vector Lines	Department of Transport (DfT)
OS AddressBase Point	Land Use	Points	Ordnance Survey
NaPTAN	Station Node (Land use)	Points	Department of Transport (DfT)
NHS Services	Health Facilities (Land use)	Points	NHS Digital
School	Schools (Land use)	Points	GOV.UK
OS Open Greenspace	Greenspace entrance (Land use)	Points	Ordnance Survey

Table 1: Network and land use datasets

4 RESULTS AND DISCUSSION

4.1 Network Centrality of the Multilevel Network Model

A series of scenario tests have been designed to reveal the spatial network effect with and without public transport networks in Greater London. Space syntax analysis has been processed to understand the global impact of the multilevel model with the TfL services and Rail services on the network centrality in four scenarios (Figure 3): 1. Street-Only Network, 2. Street + Metro Network (TfL Services), 3. Street + Metro + Rail Network (Within M25), and 4. Street + Metro + Rail + Crossrail (Open in 2022) Network. Angular cost and metric distance constraints have been applied in the tests to provide an overall understanding of the potential shift movement with the additional rail network layer.

According to the graph result, the pattern of global integration in scenario 1 simply indicated that the places with high accessibility are distributed more to the north of the River Thames but rarely extend to the South. The graph result in scenario 2 suggested that North London benefits from the higher density of TfL services with the global centrality moving toward the North region. The value of accessibility measurements in Table 2 also supports the graph result that the segments with top 50% integration are decreased proportionally in the South when only taking the TfL services into account for the multilevel model. The result of scenario 3 from both the graph representation and segment value of global integration indicates that the Rail services enhance the network centrality significantly in the South from 13% to 70% of the area. Finally, the result from scenario 4 demonstrates that network centrality is boosted in most of the fringe areas with all types of public transport services, including Crossrail, which will begin its service in the coming years.

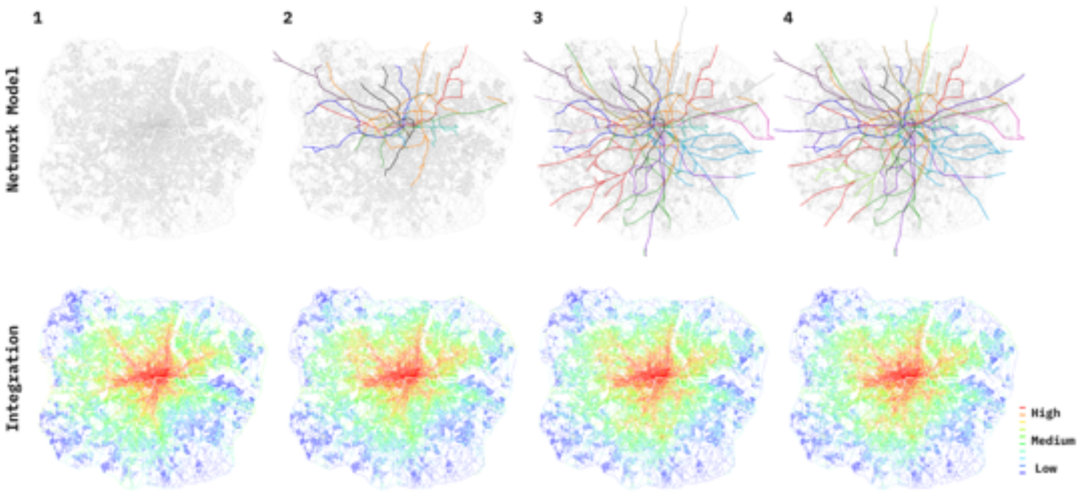


Figure 3: 4 Scenarios and global integration.

Scenarios	Top 50% Integration			Integration Increase Over 20% (Compare with the street network)		
Area	Greater London	South	North	Greater London	South	North
Street	46%	31%	58%	-	-	-
Street+Metro	45%	28%	59%	17%	13%	20%
Street+Metro+Rail	46%	36%	54%	67%	70%	64%
Street+Metro+Rail+Crossrail	46%	35%	54%	76%	77%	76%

Table 2: Multilevel Integration Variance in 4 Scenarios.

It is clearer to present the variance of accessibility from the graph representation of the network model within the London M25. Comparing the degree of global integration changes in percentage between street-only and multilevel networks, the graph in figure 4 (left) demonstrated that the TfL services enhanced network accessibility in the west, east fringes, and partially south London. Following the graph result of Figure 4 (right), the integration increase in the multilevel network with both TfL and Rail services indicates that the accessibility enhanced significantly in the South where the Rail system is serving as the major public transport for the region. This result could suggest that people who live in the South might rely on Railway services more than TfL or other public transport services for daily commute between Central London and the South suburban area.

Figure 4. (Left): Integration increase percentage between scenario 1 and 2, (Right): Integration increase percentage between scenario 1 and 3.

4.2 Multilevel Network Effect and Land Use Accessibility

Previous London Jubilee Line station neighbourhood studies (Chen and Karimi, 2017; Chen and Karimi, 2019) have indicated that the land use distribution, especially the retails, is dominated by the spatial configuration of the street layout within a certain catchment distance around stations. This study further examined the catchment area for all the TfL and Rail stations located within London M25. A multilevel network model has been used to calculate the integration and choice in various radii. Instead of metric distance constraint, time-cost distance has been applied for the network analysis to address the configurational effect of public transport in this case study. The land use accessibility calculated by the IUM time catchment analysis has also been used for the statistical analysis (figure 5). A list of the space syntax measurements and the IUM land use types could be found in table 3.

The initial correlation result between space syntax measurements and land use accessibility shows that integration has a higher correlation with most of the land use accessibility variables than choice. The correlation matrix in figure 6 demonstrates that high correlations could be found from the integration in 400m to 1200m radius in the London M25 model with most land use types, especially the restaurant (r~0.62), retail activities (r~0.64), and services (r~0.63). The results could suggest that the multilevel network accessibility mostly affects the distribution of the economic activities around the station within 1200m. The highest correlation usually happens at radius 800m might mean that the distance within a 10-minute walk or 10-minute ride with public transport from the station might be the most comfortable and acceptable distance for the residents. Comparing the correlation matrix in figures 6 and 7, the result indicates that the multilevel network model could predict the land use distribution better (with the r-squared from r~0.6 to r~84 for most of the active land use) within 1200m catchment around the station.

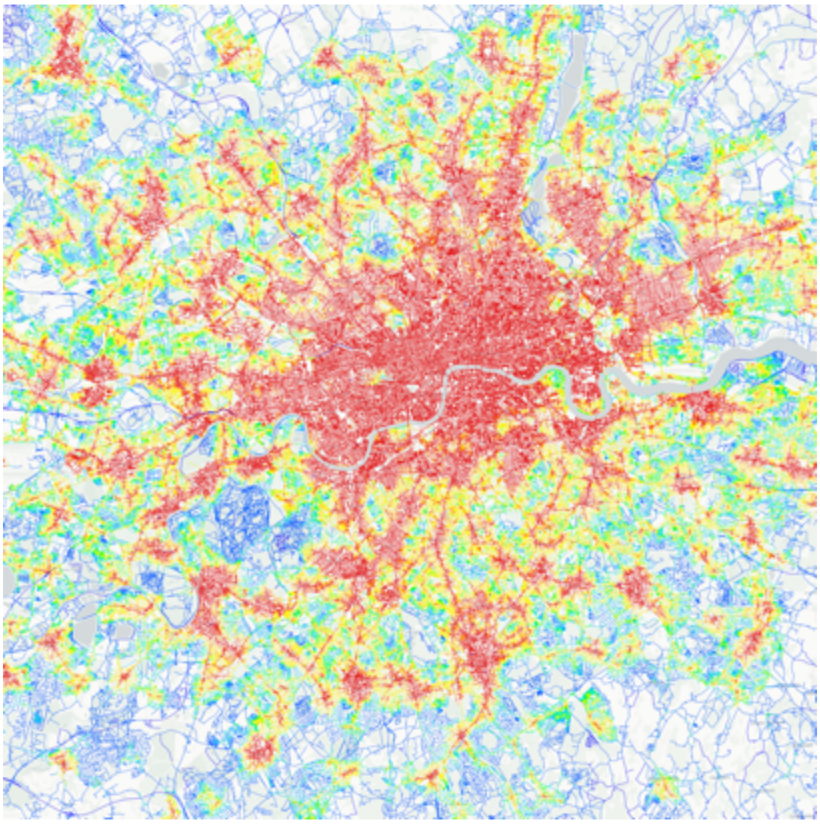


Figure 5: IUM land use accessibility.

Names	Column name
Commercial	Index_gb_cmrl_gnl
Restaurant/Cafe	Index_gb_fd
Greenspace	Index_gb_grn
Leisure	Index_gb_lesr
NaPTAN Stops/Stations	Index_gb_naptan
NHS facilities	Index_gb_nhs_services
Office	Index_gb_ofic
Retail	Index_gb_rtl
School	Index_gb_schl
Shops	Index_gb_shp
Services	Index_gb_srv

Table 3: List of IUM land use catchment.

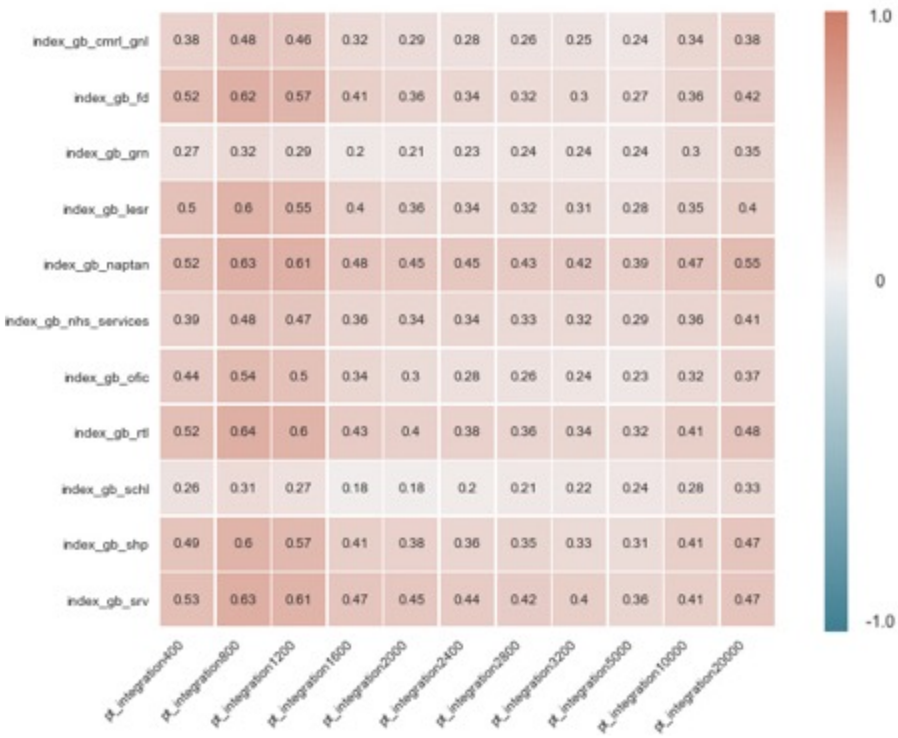


Figure 6: Correlation matrix for London M25 model -IUM land use accessibility (Y) VS multilevel network accessibility (X).

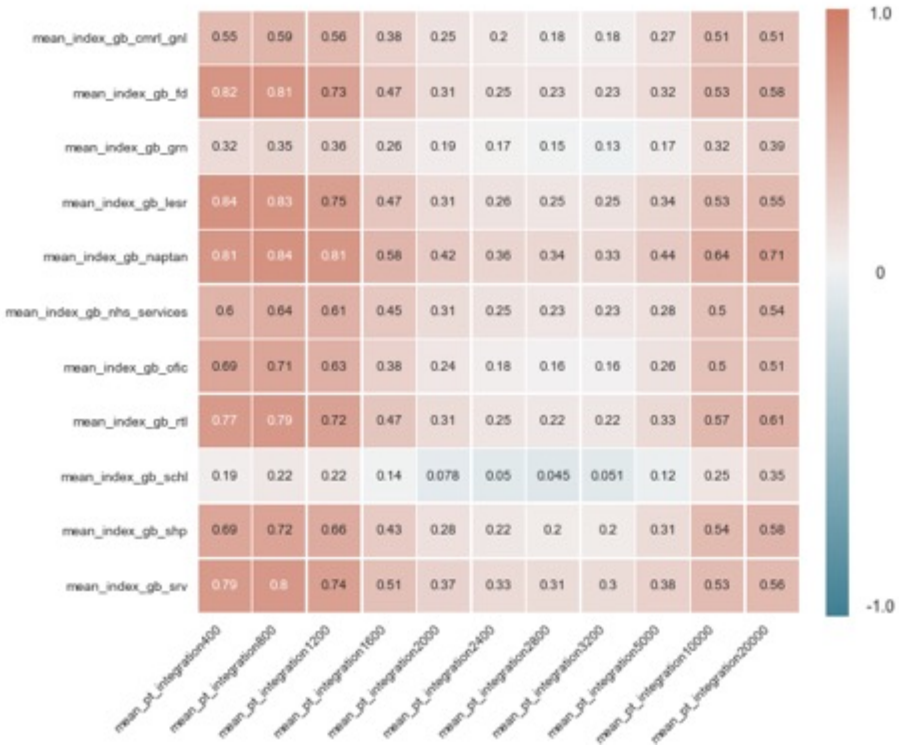


Figure 7: Correlation matrix for station catchment model (M25) -IUM land use accessibility (Y) VS multilevel network accessibility (X).

4.3 Station Usage

This study further examines the London TfL and Rail station entry and exit numbers in 2019 with a multilevel network and land use accessibility. The station usage dataset is from the open data source of TfL transport API and the Office of Railroad (ORR) data portal. This dataset has been imported to the IUM geodatabase for referencing and transferring to the station points. In figure 8, some of the land use types and integration on a local scale are just above r~0.50 for the correlation with station usage. However, the level of the correlation is not good enough to assume the station usage is affected by the land use or spatial accessibility.

Nevertheless, the result somehow indicated that the multilevel network accessibility would influence more on the station neighbourhood in the local radius within 1200m rather than larger radii. When the radius of distance increases to around 3km to 5km, the network effect would ultimately diminish but become stronger again on the global scale of 10km and 20km radius. The result could explain that the network accessibility supports the local economy in the station neighbourhoods within 15 minutes by walk, whereas the global centrality is the factor to make the local station area become one of the city centres which would attract more socio-economic activities and provide more opportunities for jobs.

Regarding the land use accessibility, the analysis indicated that station usage would potentially be affected by the location and distribution of retail, restaurant, shop, and public transport stops/stations. The outliers have heavily disturbed the results, which could be identified from the linear regression test (figure 9). The outcomes suggested that some of the stations might already be located near the shopping centre or high street with above-average retail numbers to skew the dataset sample. Further machine learning and investigations are required to clarify these outliers' stations and to understand how the land use and network accessibility influence the usage of the public transport system.

Apart from the result of all the stations within the London M25 network, this study has also conducted the correlation matrix of the station usage with the network and land use accessibility variables for individual public transport services in Underground, Overground, Dockland Light Rail (DLR), and National Rail. No significant result could be addressed except the DLR station catchment model. The entry and exit numbers correlate well with the land use accessibility for most of the land use types from r~0.64 to r~0.73 (figure 10). The result could suggest that the light rail system could potentially embed better than other types of service. Neighbourhoods and local centres might benefit from the light rail system with easier access and a high frequency of services to improve the local movement with a shorter distance between stations. Unlike other TfL or National Rail services and stations, which usually link the suburban to the city centre from a relatively long distance, DLR is connecting the local residential area to the Canary Wharf as a CBD and Stratford as the shopping and transport hub within 15 minutes of travel, which might be the reason that the usage could reflect the development of the surrounding area near stations.

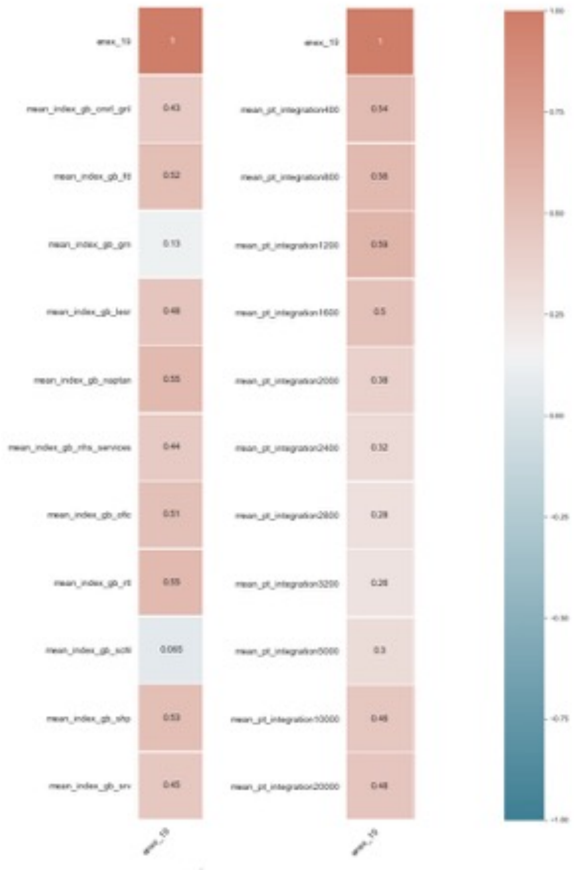
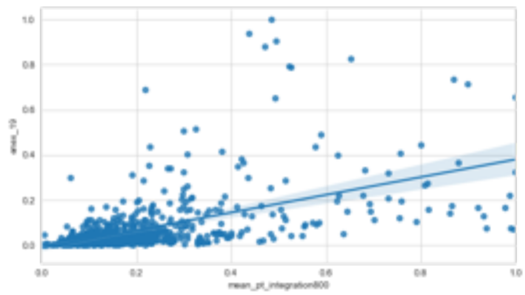


Figure 8: Correlation results for all the stations (within London M25) entrance and exit numbers with land use accessibility (left) and integration (right).



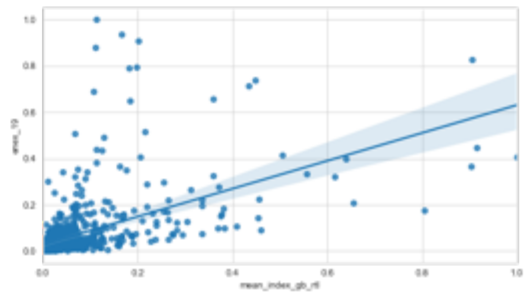


Figure 9.1 (Left): Station entrance numbers (Y) against multilevel integration 800m(X).
Figure 9.2 (Right): Station entrance numbers (Y) against multilevel retail accessibility(X).

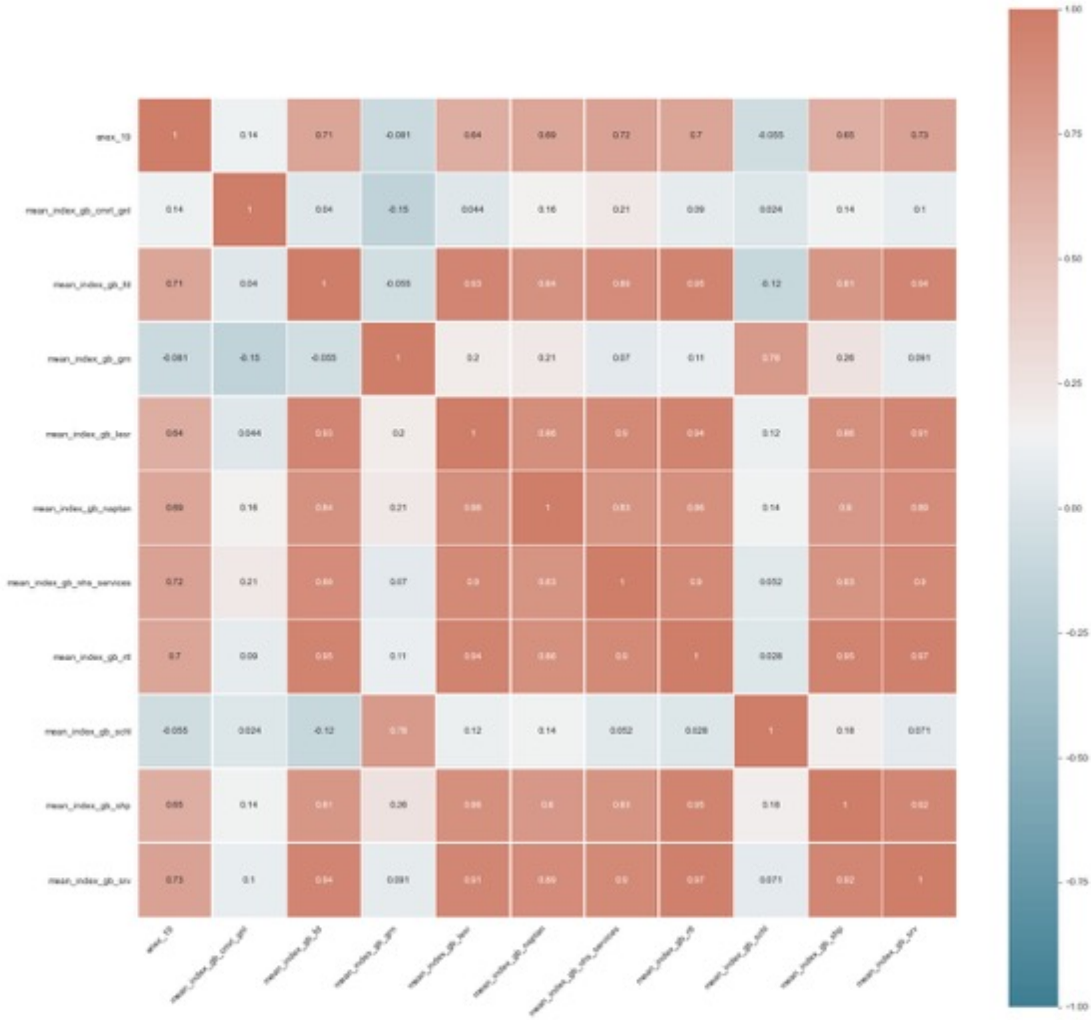


Figure 10: Correlation matrix for Dockland Light Rail stations entrance and exit numbers with land use accessibility (left) and integration (right).

4.4 Multiple Regression Model

This study further tested the multiple regression analysis for all the land use accessibility against the multilevel network accessibility within 400m catchment of stations. The initial finding is that multilevel integration in 800m and 1200m correlates well with land use accessibility. Therefore, this study applies IUM land use accessibility as dependent variables to examine the correlation with 800m and 1200m multilevel integration. The result shows that about 52% to 65% of economic land use could be predicted by the multilevel network accessibility of 800m and 1200m. Adding one choice local measurements or integration global measurement to the regression model might increase the percentage to just over 70% for specific land use, but the result is not significant. Further examination in machine learning is required to understand the phenomenon.

Names	R-squared	P for integration 800	P for integration 1200
Commercial	0.397	0.000	0.677
Restaurant/Cafe	0.654	0.000	0.000
Greenspace	0.154	0.015	0.184
Leisure	0.685	0.000	0.000
NaPTAN Stops/Stations	0.685	0.000	0.231
NHS facilities	0.393	0.000	0.816
Office	0.519	0.000	0.000
Retail	0.633	0.000	0.000
School	0.067	0.037	0.798
Shops	0.547	0.000	0.001
Services	0.605	0.000	0.036

5 CONCLUSIONS

The aim of this study was to develop a methodology to apply space syntax measurement for transport-related research. The approach this study took is to examine the multilevel multimodal network by building an Integrated Urban Model, which could assess the network connectivity as well as the urban dataset to better understand the network centrality and its relation with the land use distribution and station usage. The scenario tests of the multilevel model and the global integration suggested that the influence of the public transport network might change the accessibility patterns significantly, which could not be discovered through the street-only network model. The city fringes, which were thought to be spatially segregated from the city centre, benefit from the public transport services to become closer to the rest of the region in terms of network accessibility.

The results indicated that the multilevel network could be a better representation of the network model for the space syntax analysis, especially for transport-related studies. The multilevel network model of the IUM not only could identify the shift of global centrality but also could validate the local land use distribution influenced by the stations. Based on the results and findings, this study suggests that space syntax together with the IUM could be a useful tool and methodology to investigate the network effect and land use accessibility from the local scale of the towns to the global scale. The methodology could also become the assessment tool for future transport and urban development projects for cities and regions.

Future studies are required to fully capture the movement difference between rail network and street network by applying the combination of topological and angular cost in the algorithm of segment analysis. Other demographic datasets could also be used for machine learning to identify if there is any significant correlation that exists with station usage, for example, working population, car ownership, travel to work population, etc.

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