

TOWARDS A MULTI-MODAL SPACE SYNTAX ANALYSIS. A case study of the London street and underground network

AUTHOR: **Stephen LAW**
University College London and Space Syntax Limited, United Kingdom
e-mail: stephenlawdesign@gmail.com

Alain CHIARADIA
Cardiff University, United Kingdom
e-mail: ChiaradiaAJ@Cardiff.ac.uk

Christian SCHWANDER
Kunstakademie Stuttgart, Germany
e-mail: christian.schwander@gmx.net

KEYWORDS: *Multi-Modal Network Analysis, Underground Rail Network, Space Syntax, Pedestrian Flows, Accessibility Analysis*

THEME: Methodological Development and Modeling

Abstract

In an age where citizens are connected in an endless city of intertwining social, transport and communications networks, there is a need for space syntax analysis to look beyond the street network in exploring how different networks impact upon today's society. Through the use of Depthmap (Turner, 2007) and geographic information system, this study continues previous space syntax research on public transport network analysis such as London Underground network (Chiaradia, 2005) and the National Railway network. (Schwander, 2007) The study develops a bi-modal network model of London within the M25 that combines the street and the Underground network as a proof of concept for a multi-modal space syntax network analysis. This model is validated through a statistical analysis with empirical data of station usage in Underground stations. (TfL, 2008) The results suggest that an integrated bi-modal network analysis is able to capture more accurately the spatial advantage of town centres that are well connected by non street-based modes of transport than a traditional space syntax street-only network analysis. This provides an extra layer of understanding London, where the advancement of communication and transportation technology allows for the emergence and growth of the metropolis. In parallel with the latest space syntax research on origin and destination weighting and place syntax accessibility analysis, the study continues the dialogue between geometric analysis of space syntax and geographic accessibility analysis. (Jiang, 1999)

1. INTRODUCTION

Space syntax research suggests that there is a strong relationship between the configuration of the road network and vehicular and pedestrian flows (Penn, Hillier, Bannister, Xu 1998). Research shows that angular distance (angular costs) in measuring accessibility provides a more accurate representation of pedestrian movement distribution than metric distance and topological distance (Hillier and Iida, 2005). The analysis is not only valid on a local scale in dense urban areas, but also on a global scale for large urban agglomerations (Chiaradia, 2007). It had also been suggested that angular distance conforms to global scale route choices and metric distance conforms to local scale agglomerations (Hillier, Yang, Park, Turner 2007). Space Syntax measure of accessibility had also been tested on station usage levels (Chiaradia, 2005) and railway networks. (Schwander, 2007) This study differs from previous research in rather than isolating each network (streets and underground network), it integrates the two networks within one analysis. The objective of the research is to explore this integrated modelling approach through a bi-modal network as a proof of concept for a multi-modal space syntax network analysis in the future.

The space syntax approach to accessibility fundamentally contrasts with the geographical science approach. Accessibility in geographical science measures the ease of opportunities in an environment (Weibull, 1980) for either individuals or place as a function of attractiveness between origins and destinations and generalized travel cost as a function of journey time, frequency, reliability, comfort and economic costs. (Miller 2000, Kwan 1998) In Space Syntax, accessibility commonly known as integration in the literature, is a measure of shallowness or closeness centrality from every space to every other space within the network where the cost is calculated as a function based on the configuration or geometry of the grid. This measure is often times related to pedestrian flow where higher accessibility is related to higher pedestrian flows and lower accessibility is related to lower pedestrian flows.

This highlights both a characteristic and a concern of space syntax, where a constant or zero speed on its network and equal weight between origin and destination are assumed. Holding the aforementioned parameters constant, space syntax allows for the isolation of geometric properties of networks. As a result, the analysis accounts for the geometric continuity of the grid but through the density of nodes only partially account for the geographic properties of the transport network and attractions between destinations. As a result, the analysis partially captures the comparative advantage between locations where the network exhibits heterogeneous distribution of attractions, density and speed through additional non street-based transport connections, such as railway or underground stations.

This concern had previously been highlighted and there is a need to compare and possibly combine the geometric analysis of space syntax with the geographic analysis of traditional transportation accessibility models (Jiang, 1999 and Batty, 2004). Recent development in space syntax research, such as the use of road centre line models (Turner, 2007), origins and destinations attraction weighting and place syntax analysis (Marcus, 2000) provide a bridge in combining the two approaches. One of the objectives of this paper is to continue the dialogue between traditional space syntax geometric accessibility and geographic accessibility analysis.

In a global city such as London, where the decrease in travel time and advancement in communication technology allowed for the emergence of a metropolis, global multi-modal hubs play an important role for the spatial economy with higher volume of pedestrian activity, land use intensity and specialization that cannot be explained by assuming a pure configuration street-only network. An obvious example is Canary Wharf which does not rely on its immediate neighbors but instead relies upon global connections such as

dual carriageways, the London Underground Jubilee line, the Docklands Light Railway, future Cross-rail station, high speed communication networks and close proximity to clients and stakeholders. These hubs being highly integrated over multiple transportation and communication networks allows the area to emerge as an important global financial centre in less than 20 years. In an age where citizens are connected in an endless city of intertwining social, transport and communications networks (Castell, 1996), there is a need for space syntax analysis to look beyond the street network in exploring how transportation as well as communication networks impact upon today's society. In the same instance analyzing through space syntax's topo-geometric approach (Hillier, 2007) could provide great insights in understanding cities and visualizing its impact within the field of urban studies, urban planning and urban economics.

As a result, we have developed an integrated bi-modal network model of London within the M25 that combines the street network and the London underground. We compare this bi-modal network with the street-only model and analyse to what extent they both conform, and where the bi-modal model reveals an uplift in areas with outstanding non street-based transport connections. As a continuation of previous research on London underground network (Chiaradia, 2005), we would compare the results between the integrated spatial model presented in this study with the multiple component approach from previous study. The results suggest that integrating non street-based modes of transport as an integrated model in space syntax analysis provides an additional layer in understanding London's global network and its agglomeration. In order to explore the bi-modal integrated space syntax analysis as a proof of concept for a multi-modal space syntax analysis, the paper is divided into four sections.

- The first part of the paper explores the concept of a bi-modal network on the basis of a notional network and explores the spatial differences between a bi-modal and a street-only network using Space Syntax analysis.
- The second part compares a bi-modal network model of London with a street-only model and correlating underground station usage from Transport for London using OLS regression analysis
- The third part draws a comparison with previous research specifically with the multiple component approach developed in the underground pedestrian study (Chiaradia, 2005)
- The fourth part draws the conclusion of the study and suggests next steps to tests a multi-modal network to include the national rail and bus networks.

2. METHODOLOGY

This part of the paper describes the methodology to construct a simple variation of the multi-modal network and explores the spatial differences in network attributes to a traditional street-only network.

In transport modeling, research in multi-modal transport is comprehensive and applied. This type of modeling requires information on transfer time, speed, density and travel information between different modes. These factors are commonly applied in transport modelling using software such as Vissim. (<http://www.ptvag.com/research/cooperative-systems/>)

Conversely, there had been limited research in studying the construction of a multi-modal network in space syntax analysis. Christian Schwander studied station usage for the Southeast Railway system using a topological railway network model weighted by frequency with various network centrality measures from graph theory. (Schwander, 2007) Alain Chiaradia studied station usage of the London underground network using space syntax configuration analysis through a multiple-component approach. (Chiaradia, 2005) Chulmin Jun studied using the concept of topological depth as transfer cost on the bus-metro network of

Seoul in application to a public transport accessibility model calibrated through origin and destination data. (Jun, 2008) This paper would not focus on optimising the modeling parameters of a multi-modal network analysis, but instead would study the evidence for an integrated multi-modal model in space syntax analysis.

A simplified approach is chosen for the configuration analysis: Two independent networks (street and underground) are developed and linked at exit and entry points. This approach is explained on a simplified notional network.



Figure A. Two notional network models: street-only (A) and multi-modal (B) with a fast link (red)

In figure A, two simple notional networks are shown. Model A on the left consists of three network clusters interconnected by one link between them. Links are assumed to have constant speed where each cluster represents an agglomeration of nodes. Model B on the right describes the same three clusters with the only difference of an additional high speed link between two of the clusters, shown in red. The link is drawn approximately between 75-90 degree to the street model illustrating the angular and metric cost of entering the station. This linkage between the station to the street network is constant for all the stations. For future research, case specific economic, angular or metric costs should be implemented for each station according to its station layout and price.

To compare the spatial attributes of the two models, three general measures of accessibility commonly used in space syntax analysis are explored through Depthmap. (Turner, 2007):

- Step depth,
- Node count,
- Integration (closeness centrality).

The first analysis compares metric step depth, angular step depth and travel time step depth analysis (figure B). The analysis calculates the catchment area from an origin at the centre of the northern cluster (black circle) according to metric distance (how far could you get to in 400 metres?), angular (how far could you get to in 90 degree?) and time steps. (how far could you get to in five minutes ?)

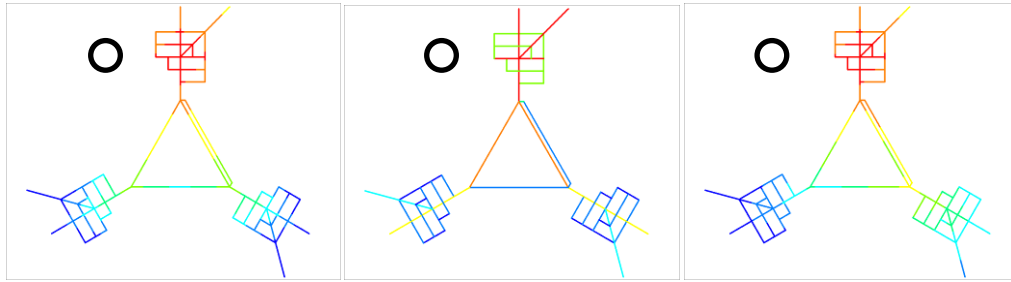


Figure B. step depth comparison between metric step depth (left), angular step depth (centre) and topological time step (right)

- In terms of metric step depth, the northern cluster is equally far from the eastern and western cluster.
- In terms of angular step depth, the distance from the northern cluster to the others is reduced due to the direct connections with a low degree of angular change, but they are still equally far apart.
- In terms of time step depth, the northern cluster is closer to the eastern one in time due to the high speed link.

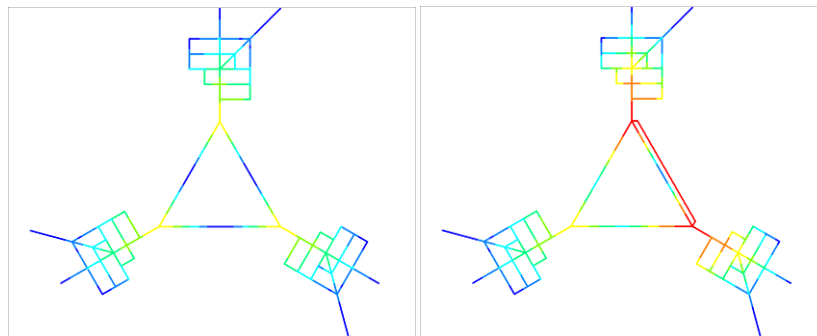


Figure C. Space Syntax node count measure for model A on left and model B on right

The second analysis measures the node count accessibility by calculating from every space, how many destinations or opportunities could be reached up to a certain constraint. In this case, it is up to five minutes. (400 metres in walking speed, 1,000 metres in the higher speed network)

- In model A (street-only) the three clusters have an equal node count within five minutes.
- In model B (multi-modal) the additional high speed link between the northern and the eastern cluster increase the node counts within five minutes in these two clusters. This suggests that the high speed link brings the two clusters closer to each other while isolating the third.

The third analysis calculates *space syntax angular segment integration* which measures the closeness centrality C_c of a graph as the reciprocal function of the sum of the shortest path between every origins (i) to every destinations. (k) (Sabidussi, 2005 as mentioned in Iida and Hillier, 2005)

$$C_c(P_i) = (\sum_k d_{ik})^{-1}$$

The higher is the integration, the more central and nearer is the space to all spaces within the network. As opposed to previous research on axial integration normalization, recent research from Hillier suggests different functional form of node count analysis could be used in the normalization of the integration measure. Previous research suggests the integration measure of accessibility exhibit a strong relation with pedestrian movement (Hillier and Iida, 2005), vehicular movement (Chiaradia, 2007) and property value. (Chiaradia, Hillier, Barnes, Schwander, 2009). The measure of closeness centrality had previously been calculated for topological steps, angular and metric steps. (Hillier and Iida, 2005) In this study, closeness centrality would also be calculated in travel time step depth.

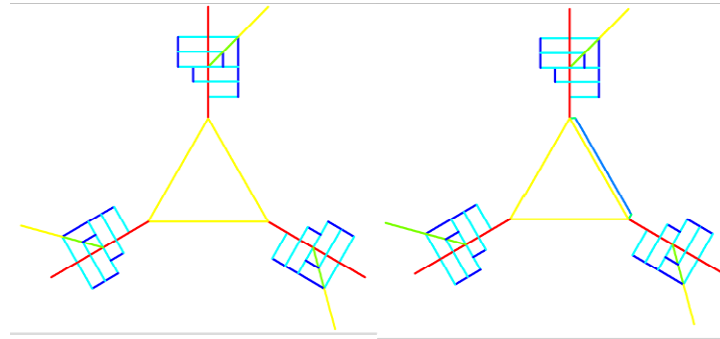


Figure D. Space Syntax segment angular closeness measure

Figure D shows integration value calculated by segment angular analysis for the two models. The diagram suggests similar distribution of integration values between the three clusters for both systems as the high speed link (blue) has much higher angular change from the northern cluster than the direct link (yellow). This might be true between two closely located underground stations where there is higher cost in taking the underground link than to stay on the street level. In a more complex network such as a city, centres are often connected not as a straight line on the street level which would allow the connection of the railway network to be more continuous than the street network. In such circumstances, segment angular closeness for locations near high speed network would exhibit spatial advantage compare to locations away from high speed networks.

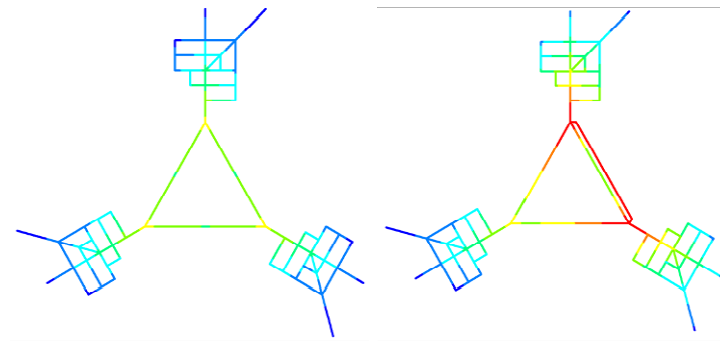


Figure E. Space Syntax segment time steps closeness measure

Figure E shows integration value calculated by the segment time step closeness measure for the two models. The three clusters in model A (street-only) exhibit similar integration values while in model B (multi-modal) the northern cluster and eastern cluster have higher integration values compared to the western cluster. Travel time closeness centrality illustrates spatial differences between a street-only and a multi-modal model for the notional grid. This section illustrates key spatial differences between the two models under Space Syntax accessibility analysis. To further explore the value of an integrated model in space syntax, a case study of London is presented in the following section.

3. LONDON CASE STUDY

“London became a greater and still greater accumulation of towns.” (Rasmussen, 1934)

The quote above best describes the dynamic process of how London became a metropolis, where villages that vary in scale, size and character agglomerate over time to form an interdependent network. The decrease in travel time through faster modes of transport, such as the underground, allows for a further accumulation of towns and the emergence of the metropolis. Underground stations emerge as multi-modal hubs with high volumes of pedestrian activity, land use intensity and specialization. They play an important role for the spatial economy and shift town centres from their original location. There are many examples of this spatial process in London: The centre of Clapham, for example, shifted from the historic village centre, Clapham Old Town, which is only integrated on a local scale, to the location of the underground station, Clapham Common. This process cannot be fully captured by a traditional space syntax street-only analysis, where the effect of multi-modal nodes is underestimated. The main objective of this case study is therefore to explore the significance of the multi-modal network for space syntax analysis. As a proof of concept study for a multi-modal spatial model, a bi-modal spatial model was constructed and analyzed in the following case study. Two initial examinations, a comparison between the integrated approach and multiple component approach as well as an initial temporal graph analysis of the London Tube network were conducted.

3.1 Bi-modal network of London

A bi-modal network model of London was constructed on the basis of the London street segment network (Space Syntax Ltd) and the London underground network.



Figure F. London M25 segment model (Space Syntax Ltd)

The UK ordinance survey was used as a basis for the London M25 street segment model. The model was drawn and edited as a least angular segment model which involves thinning, segmentation and junction simplification. Further manual editing was applied to include walking paths in the central area such as the Thames path. Future iteration of the network model should include the new walking path layer from Ordnance Survey or the Open Street Maps layer.

The basis of the London underground network model is constructed in GIS from Transport for London open source location data of underground stations. (<http://data.london.gov.uk/datastore/package/tfl-station-locations>) Assuming passengers traveling on the underground network along the same line to be relatively less sensitive to distance and angular change, we propose a topological network model similar to previous study on National Railway networks (Schwander, 2007) where each station is directly linked between stations that are geographically referenced. Stations that are physically close or along the same line have low or no marginal angular costs (angular change) between them and stations that are on a different line have higher marginal angular costs (angular change) between them. As the Underground network is highly continuous, the angular cost is lower along the same line as when it is connected to another line.

The multi-modal network is created by linking the underground network and the street network at the location of the stations through a perpendicular link segment, which accounts for the cost of level change between the street and the underground level. These preliminary assumptions would need to be formally examined in future studies and further adjusted to individual locations where transfer time, complexity of transfer and travel information would be considered in travel cost or depth cost. Figure G illustrates the integrated multi-modal network combining the London street and underground network.

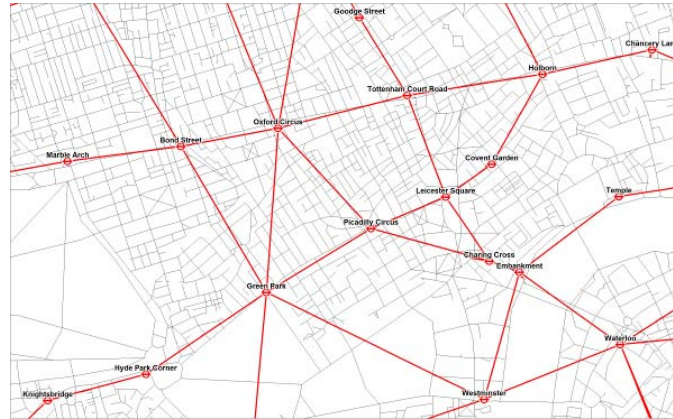


Figure G. 2008 London multimodal

3.2 London Underground movement data

To compare station usage as a function of street and tube model and as a street model, rather than comparing pedestrian movement at a local scale within a local area (Hillier&lida, 2005), we would use station entry and exit data from Transport for London. The dataset is freely available from the customer information matrices and includes entry and exit figure from the different peak times for every station in London on both weekday and weekend. <http://www.tfl.gov.uk/tfl/corporate/modesoftransport/tube/performance/> Figure H illustrates a sample of the pedestrian movement matrix from the Transport for London website. The data includes pedestrian movement data from 2000 – 2010 for London underground tube station data and London Lightrail data. The data is divided into 16 categories as listed in the image below including: Entry/Exit – total, early, am peak, inter peak, pm peak, evening, Saturday, Sunday and total annual entry + exit station pedestrian frequency.



Figure H. 2008 London Underground exit and entry dataset (Transport for London)

The data we use to correlate to space syntax network indicators is the 2008 total annual weekday entry and exit figure as shown in figure I.



Figure L. Segment angular integration with street network only

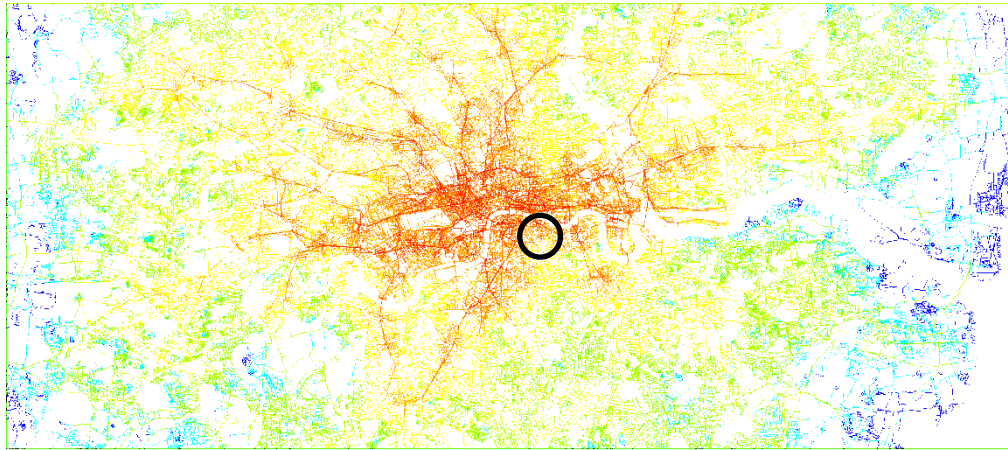


Figure M. Segment angular integration of the bi-modal network

There are strong similarities between the two network models, particularly in central London, which is highlighted as the most spatially integrated area of the city. However, there are also significant differences between the two models:

- The street network shows a higher convexity in Central London with radial corridors leading from the centre to the periphery and additional orbital routes between these corridors. The bi-modal model, by contrast, exposes a higher linearity along the radial routes and fewer orbital links between them.
- The bi-modal model reveals the segregation of South London from the Underground network and the locational difference between town centres with and without an Underground station, which reflects differences in property prices.
- The bi-modal network is also able to show new centres, such as Canary Wharf, which are segregated from the street network, but well-connected in terms of the Underground network

3.4 Quantitative findings

In the quantitative analysis, three scenarios described in figure N are studied. For each scenario, we compare the performance of the street-only model with the bi-modal model in relation to the empirical data on station usage (total annual weekday entry and exit).

- Scenario A compares the two networks through angular segment analysis with the constraint of up to 10,000 metres metric radius.
- Scenario B uses an angular segment analysis with the constraint of up to 10,000 metres in street segments and 25,000 metres in the tube segments
- Scenario C uses a travel time segment analysis where each tube segment is 2.5 times faster than the street segment with a constraint of up to 10,000 metres in street segments and 25,000 metres in the tube segments. *

As a proof of concept, rather than an exact measurement of time the relative difference between the two networks were assumed. Future research should examine exact measurement of travel time in the different tube lines, taking into account average waiting time, average frequency of services, comfort and financial costs through a generalized costs assumption.

Scenario	Network	Depth parameter	Depth calculation	Constraints	OD attraction weighting
A1	street	angular distance	angular	10,000 metres by street	none
A2	Street + tube	angular distance	angular	10,000 metres by street 25,000 metres by tube	none
B1	street	angular distance	angular	10,000 metres by street	none
B2	Street + Tube	angular distance	angular	10,000 metres by street 25,000 metres by tube	none
C1	Street	travel time	travel time	10,000 metres by street	none
C2	Street + Tube	travel time	travel time	10,000 metres by street 25,000 metres by tube	none

Figure N. scenarios to be tested

An ordinary least square regression analysis between the integration measures of the two spatial models and the empirical data for total annual weekday entry and exit were carried out. Concerns of spatial dependency in OLS models leading to biased estimation would be addressed in future studies. Some key statistics were extracted from these scatter grams as shown in figure O.

Scenario	T Ratio	F Ratio	R-square	R-square adjusted	Prob > F
A1	11.8	139.1462	0.360346	0.357756	<0.0001
A2	15.67	245.4813	0.498458	0.496428	<0.0001
B1	10.57	111.823	0.31638	0.308851	<0.0001
B2	15.84	250.8316	0.503848	0.50184	<0.0001
C1	11.87	140.9542	0.363327	0.360749	<0.0001
C2	13.79	190.1184	0.434936	0.432648	<0.0001

Figure O. Scenario statistics

The statistical analysis reveals the following relationships:

- There is significant positive correlation between Underground station usage with integration measures for all the scenarios. This suggests that the station that is closer to all spaces within the network has higher movement potential than stations that are further away from all spaces within the network.

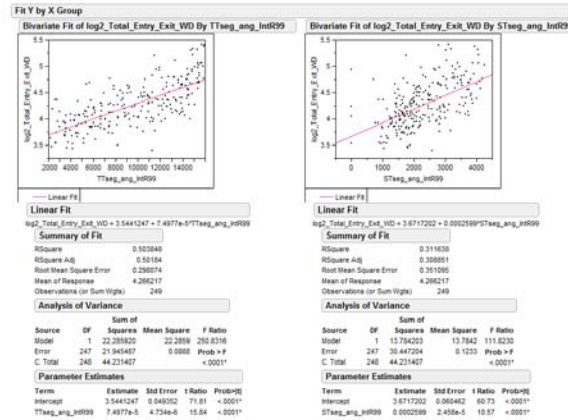


Figure P. A log-normal Scattergram comparison between London bi-modal network with entry/exit pedestrian movement data on the left and London Street network with entry/exit pedestrian movement data on the right

- There is a considerably higher correlation and higher T-values across the different scenarios with the bi-modal network than with the traditional street network. This suggests that combining the street network and the Underground network into a multi-modal network provides a better description of urban activity around transport nodes than the street-only network, both in segment angular analysis and time step analysis.
- The bi-modal segment angular closeness analysis (scenario B) performs marginally better than the bi-modal segment time step closeness analysis (scenario C). The finding is inconclusive as there is a close relationship between the geometric continuity of the network and the geographic speed of the network. The lower angularity between stations along the same line is representing the insensitivity to time between any two stations along the same line. A more complete travel time closeness centrality would need to be examined for future research in comparing the differences of the two.

3.5 Comparative study

To better validate the research approach, an initial comparative analysis was established between the integrated spatial model presented in this paper and the multiple component approach presented in previous research (Chiaradia, 2005) where each movement network were identified as components in relating with entry/exit pedestrian movement data using an ordinary least square multi-variate regression analysis. Four scenarios were compared namely scenario B2 from the previous section and scenario D1, D2 and D3. Summary charts for the four scenarios are presented below.

Scenario	Network	Depth parameter	Constraints	OD attraction weighting
B2	Street + tube	angular distance	10,000 metres by street 25,000 metres by tube	none
D1	tube	Topological step	Topological model with no constraint	none
D2	local analysis + tube	Topological+ angular distance	1,200 metres by street Topological model with no constraint	none
D3	local analysis + global analysis	angular distance	1,200 metres by street 10,000 metres by street	none

Figure Q. scenarios to be tested

Scenario D1 illustrates Tube entry/exit pedestrian movement compared with the topological closeness centrality of the Tube network. Scenario D2 is the first multi-variate regression model where local integration 1,200 metre is combined with the topological closeness centrality of the Tube network. Scenario D3 is the second multi-variate regression model where a street only local integration 1,200 metre is combined with a street only global integration of 10,000 metre. The local integration measure used in scenario D2 and D3 is segment angular closeness with the constraint up to 1,200 metres. This measure is used for two reasons. The first reason is previous research suggest the measure to closely corresponds to active landuse (Chiaradia, Schwander, Honeysett, 2008), pedestrian movement distribution and population density. Second reason is Integration 1,200 metres achieved consistently a higher correlation coefficient then Integration 2,000 meters under a sensitivity tests in similar scenarios. The global integration measure used in scenario D3 corresponds to scenario B2 which is segment angular closeness with constraint up to 10,000 metres. An OLS regression analysis between the integration measures of the four scenarios and the empirical data for total annual weekday entry and exit was carried out. Some key statistics were extracted from these scatter grams as shown in figure R.

Scenario	T Ratio	F Ratio	R-square	R-square adjusted	Prob > F
B2	15.84	250.8316	0.503848	0.50184	<0.0001
D1	-13.22	174.8048	0.414421	0.41205	<0.0001
D2	IntR1200: 4.91 Tube closeness: -7.58	107.6314	0.46682	0.46234	<0.0001
D3	IntR1200: 3.46 IntR10000: 4.40	78.8678	0.39001	0.38512	<0.0001

Figure R. statistical measures

The statistical analysis reveals the following relationships:

- Initial statistical results suggest the integrated bi-modal as presented in the previous chapter correlates better to entry/exit pedestrian movement than the multiple component approach
- Multiple component approach is valuable as it allows for a better understanding from the influence of each variable.

3.6 London Underground network – initial network analysis

As part of the future step in better understanding the development of the London underground network, an initial comparative network analysis was established between the 1908 London tube network, constructed from the first unified London underground tube map from Underground Electric Railway Company and 2010 tube network as constructed in section 3.1. Descriptive statistics of common network analysis attributes of nodes were studied including closeness centrality and degree/connectivity of a node.

		London Underground 2010	London Underground 1908
Nodes/Edges		347/788	136/163
Degree	Average	4.54	2.41
	Std Deviation	1.95	0.97
Closeness Centrality	Average	17.93	9.87
	Std Deviation	6.22	2.09

Figure S. statistical measures comparing the London Underground network of 1908 and 2010

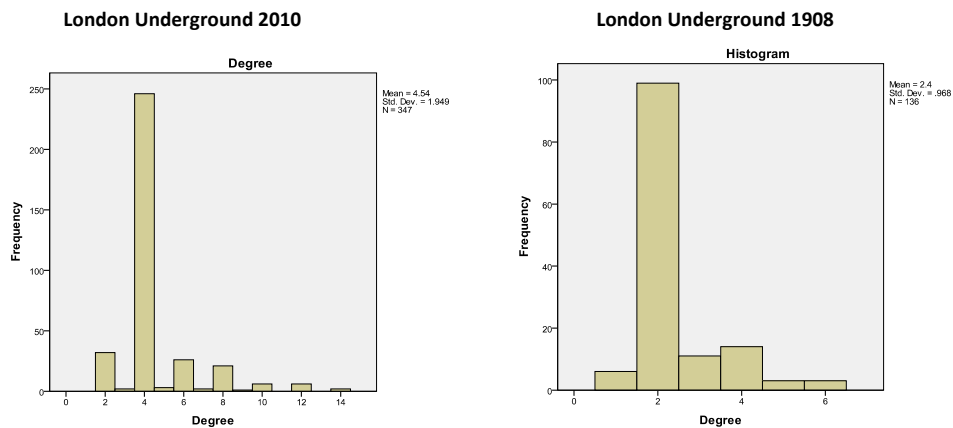


Figure S. Descriptive statistics comparing the London Underground network of 1908 and 2010

Ranking in closeness centrality 1908

- Baker Street
- Oxford Circus
- Regents Park
- Piccadilly Circus
- Tottenham Court Road
- Portland Road
- Edgware Road
- Gower Street
- Kings Cross
- Bond Street

Ranking in closeness centrality 2010

- Green Park
- Westminster
- Bond Street
- Victoria
- Oxford Circus
- Hyde Park Corner
- Waterloo
- Baker Street
- St. James's Park
- Bank

Figure T. Closeness centrality ranking between London underground in 1908 and 2010

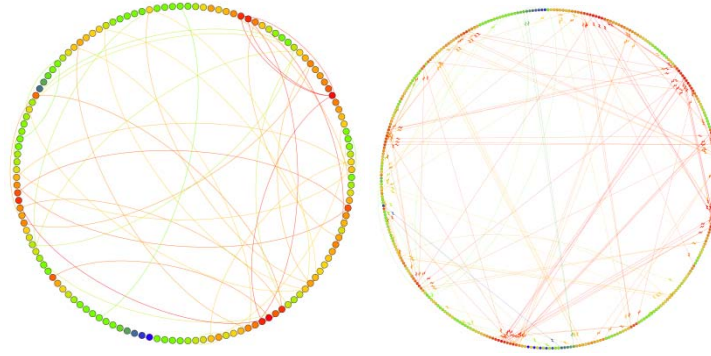


Figure U. Circular graphs of London tube network in 1908 on the left and London tube network in 2010 on the right.

The comparative analysis reveals the following relationships:

- The most common degree distribution for the tube networks were expectedly 4 considering most stations are connected by two other stations. (2 in-degree and 2 out-degree) The main differences between the two periods were the greater variance in degree distribution for the 2010 period illustrated by its differences in standard deviation.
- Node to edge ratio expectedly was much higher in 2010 (1:2.16) as compared to 1908 (1:1.19) which is also reflected in the higher average and variance of both closeness centrality and degree centrality when comparing the two.
- Similarities but also greater variance in ranking of the stations between the two time periods. Consistently, the station with the highest closeness centrality remains to be in the centre of London geographically. This suggests there is some form of spatial preferential construction of new edges to selective nodes in the geographical centre of the city which could be attributed to the demand of transport in the central employment area.

The results suggest the need for further examination in the evolution of public transport network growth.

4. DISCUSSIONS AND FUTURE RESEARCH DIRECTIONS

As a result of the study, two research directions had been identified. The first research direction is to expand upon the simplified bi-modal network of London into a multi-modal network model including the bus network and the National Rail network and to better understand the process in how these networks emerged overtime. An initial national railway network model of Southeast England was constructed with the condition that all stations with direct linkage to London and within a sixty kilometer radius away from Waterloo Station were included in the analysis. Similar to the London underground network, a topological model was constructed where each station is connected topologically through a direct link.

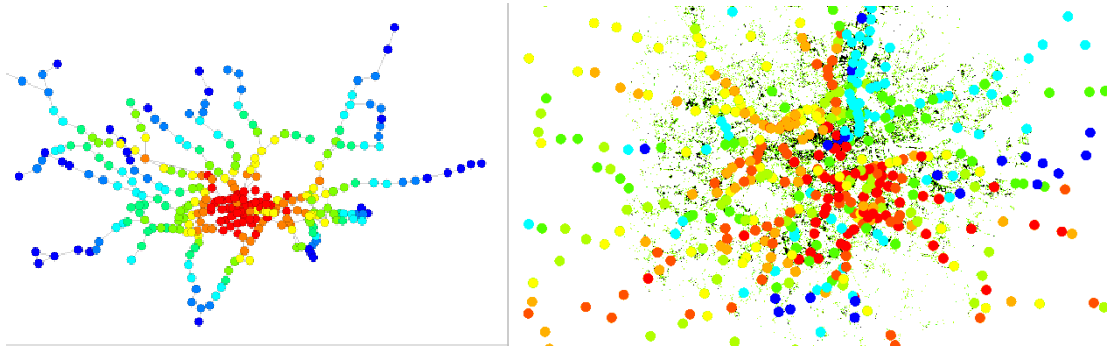


Figure V. Topological closeness of tube network on left and topological closeness of the national railway network weighted by frequency on the right

Figure V illustrates the closeness centrality of the tube stations on the left and the frequency weighted closeness centrality of the National railway network stations within London on the right. Future research would examine the network properties between the two networks and the inclusion of the national railway network with the street network and underground network.

The second research direction is to employ its methodology in urban economic models and testing traditional urban economic assumptions such as urban rent theory. (Alonso, 1964) Despite theoretical reasoning and empirical evidence, there are limited applications of space syntax theory in urban and regional economic models.

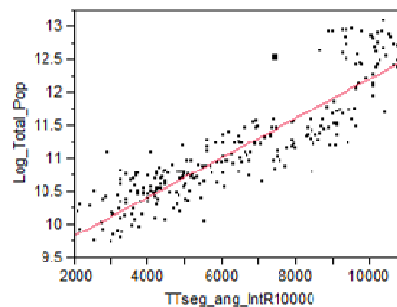


Figure W. A log-normal Scattergram between the sum of population and employment within 1,000 metres against London bi-modal network integration measure

Figure W illustrates the relationship between the bi-model integration measures with the sum of population and employment within 1,000 metres of each station.

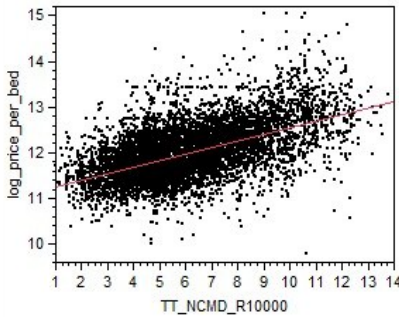


Figure X. A log-normal Scattergram between the transaction price of London in 2011 against London's bi-modal network integration measure

Figure X illustrates the relationship between the bi-modal integration measures and a sample of transaction houses prices in London. (Zoopla, 2011) More thorough spatial data analysis and the inclusion of multiple variables are needed to account for biases in estimation and spatial dependence of the data. (Anselin, 1988)

The positive relationship between densities, transaction price and spatial integration suggests hypothetically a positive feedback process where an accessible location demands higher density and higher land value and higher density and higher land value location demands higher accessibility. A thorough study on London's multi-modal network, its land utilization, its real estate value, its density and the decision making process overtime would be an important research direction in understanding the city and its emergence.

CONCLUSION - TOWARDS A MULTIPLE NETWORK CENTRALITY

This study has shown the need of an integrated network model in space syntax analysis and proposed a preliminary approach to develop this. The integrated network model has been assessed qualitatively and quantitatively to verify its value. The qualitative analysis shows that the bi-modal network displays stronger integration values expected in multi-modal transport hubs such as Canary Wharf and London town centres along underground corridors. The quantitative analysis shows that the bi-modal network consistently performs better in accounting for underground entry/exit pedestrian movement data than street-only network. Preliminary results from the comparative study between the integrated spatial model and the multiple component approach suggest better performance from the integrated spatial model. As a result, a more complex multi-modal network including the national railway network and bus network would be built for the next stage of the research.

The emergence of contemporary metropolis is clearly a product of both historic conditions and technological progress in new modes of transportation and communication such as motorways, airports, railways and the internet. Therefore, there is a need for space syntax research to take these different modes of transportation and communication networks into account and to develop a better understanding on how the geometry and geography of multiple networks influence society and economy. Recent development in Space Syntax research, such as the use of road centre line models (Turner, 2007), origins and destinations attraction weighting and place syntax analysis (Marcus, 2000) are pushing the agenda for stronger integration between configurational analysis and geographical analysis. This paper supports this agenda by suggesting an integrated modeling approach in space syntax analysis with the hope to encourage the space syntax community for further researches towards geometric network analysis of multiple networks.

REFERENCES

- Anselin, L. (1988) *Spatial Econometrics: Methods and Models*. Dordrecht: Kluwer Academic Publishers.
- Banister, D. and Penn, A. and Hillier, B. and Xu, J. (1999) Configurational modelling of urban movement networks. *Environment and Planning B*, 25 (1), 59 - 84.
- Batty, M. (2004), "A New Theory of Space Syntax", Working Paper 75, CASA, UCL, London
- Castells, M. (1996), *The Rise of the Network Society, The Information Age: Economy, Society and Culture Vol. I*. Cambridge, MA; Oxford, UK: Blackwell.
- Chiaradia, A. (2007) EMERGENT ROUTE CHOICE BEHAVIOUR, MOTORWAY AND TRUNK ROAD NETWORK: the Nantes conurbation, 6th international space syntax symposium
- Chiaradia, A. and Moreau, E. and Raford, R. (2005) Configurational Exploration of Public Transport Movement Networks: A Case Study, The London Underground, 5th International Space Syntax Symposium
- Chiaradia, A., Schwander, C., Honeysett, D. (2010) Thematic Seminar – Accessibility. Profiling land use location with Space Syntax in In: Koch, D and Marcus, L and Steen, J, (eds.) (Proceedings) 7th International Space Syntax Symposium.: Royal Institute of Technology (KTH), Stockholm, Sweden.
- Chiaradia, A and Hillier, B and Barnes, Y and Schwander, C (2009) Residential property value patterns in London: space syntax spatial analysis. In: Koch, D and Marcus, L and Steen, J, (eds.) (Proceedings) 7th International Space Syntax Symposium. : Royal Institute of Technology (KTH), Stockholm, Sweden.
- Hillier, B., Turner, A., Yang, T., Park, H. (2010) Metric and Topo-Geometric Properties of Urban Street networks. Some convergences, divergences and new results. *Journal of Space Syntax*. Vol.1, Issue 2, Pg.258-279.
- Hillier, B. and Iida, S. (2005) Network and psychological effects in urban movement. In: Cohn, A.G. and Mark, D.M., (eds.) *Proceedings of Spatial Information Theory: International Conference, COSIT 2005, Ellicottsville, N.Y., U.S.A., September 14-18, 2005*. (pp. pp. 475-490). Springer-Verlag: Berlin, Germany.
- Hillier, B. and Hanson, J. (1984) *The Social Logic of Space*, Cambridge University Press: Cambridge.
- Jiang, B and Jia, T (2011) Exploring Human Mobility Patterns Based on Location Information of US Flights Department of Technology and Built Environment, Division of Geomatics University of Gävle, SE-801 76 Gävle, Sweden
- Jiang, B., Claramunt, B. and Batty, B. (1999) Geometric accessibility and geographic information: extending desktop GIS to space syntax. *Computers, Environment and Urban Systems*, 23, 127-146.
- Jiang, B., Claramunt, C., (2000) An integration of space syntax into GIS: New perspectives for urban morphology. *Transactions in GIS* 6, 295{307}
- Kwan, M.P. (1998) Space-time and integral measures of individual accessibility: A comparative analysis using a point-based framework. *Geographical Analysis* 30:191–216
- Legeby, A. & Marcus, L. (2011) Does the Urban structure of Swedish Cities inhibit the sharing of public space. *Built Environment*. Vol.37 No.2

Marcus, L.(2000) Architectural knowledge and urban form: The functional performance of architecturalurbanity. Ph.D. thesis, KTH School of Architecture, Stockholm, Sweden.

Marcus, L. (2008). "Spatial capital – an outline of an analytical theory of urban form", in *New Urbanism and Beyond*. Ed. Tigran H. New York: Rizzoli.

Miller, H. J. (2000) Geographic representation in spatial analysis. *Journal of Geographical Systems* 2, 55{60.

Miller, H.J. (1999) Measuring space-time accessibility benefits within transportation networks: Basic theory and computational methods. *Geographical Analysis* 31:187–212

Ortiz, C. , Hillier, B.(2005) In search of patterns of Land-use in Mexico City using Logistic regression at the plot level. 6th International Space Syntax Symposium

Rasmussen, S.E. (1934 first edition, 1982 revised edition) *London, the Unique City*. The MIT Press; Revised edition (May 18, 1982)

Sabidussi, G., (1966) The centrality index of a graph *Psychometrika*, 31, p. 581-603.

Schwander, C. (2007) *NETWORK ANALYSIS APPLIED: the railway network in South East England*, 6th International Space Syntax Symposium

Turner, A. (2007) From axial to road-centre lines: a new representation for space syntax and a new model of route choice for transport network analysis. *Environment and Planning B: Planning and Design* 34:539–555

Vaughan, L. (2005) The relationship between physical segregation and social marginalization in the urban environment. *World Architecture*, No.185, pp. 88-96.

Zoopla (2011) Transaction house price. Available at: www.zoopla.co.uk (Accessed: 10 October 2011)