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FROM AXIAL TO PEDESTRIAN PATH-CENTRE LINE

The case of 3D Pedestrian Network in Hong Kong, Central

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ABSTRACT

In urban areas where road network and pedestrian network are intimately linked yet wildly different, axial lines and road centre line geometries are often used as strategic pedestrian networks to evaluate accessibility, pedestrian flow potential against empirical pedestrian volume counts. However, pedestrian networks in multi-level urban environments are usually separated from the road network. In Hong Kong, the pedestrian network combines both steep topographies as for the road network and separation from the road network due to extensive publicly accessible multi-level outdoor and indoor pedestrian network.

Taking multi-level urban environment of Central area in Hong Kong, probably one of the most complex urban area in the world as a case study, we examine the correlation coefficient between spatial configuration and pedestrian volume. The study mainly focuses on comparison between three kinds of network data generalisation models: axial line map, segment map derived from axial map, and pedestrian path centre-line map, the link/node standard. Results show that pedestrian network segment and path centre-line representations can capture built environment features better than axial generalisation. A 3D indoor-outdoor centre-line map is also constructed to represent the intricate multi-level pedestrian network. The results suggest that only a floor by floor version of the Indoor-outdoor model would provide an adequate measure of potential pedestrian flow through multi-level urban environments. It is also showed that Angular properties of central area have the strongest effect on pedestrian route choice in the study area. A calibration of 50% - 50% Angular - Euclidean hybrid metric gives a stable result in terms of interpreting pedestrian movement potential.

KEYWORDS

Axial line; path-centre line map; 3D pedestrian network; Spatial Design Network Analysis; Hong Kong

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1. INTRODUCTION

Space Syntax and its axial representation. Over the past decades, it is well received in the space syntax community that both pedestrian and vehicle flows are significantly correlated to spatial configuration variables (Hillier, et al., 1987; Hillier, et al., 1993). Axial map has been tested in a number of European cities with high accuracy. However, on one hand, this method had less empirical evidence in cities with higher density. On the other hand, the subjective construction process and the lack of geometric or metric considerations of axial representation have been constant criticisms of this research program (Jiang & Claramunt, 2002; Batty, 2004, Ratti, 2004). For example, Jiang and Claramunt (2002) attempted to integrate space syntax into GIS and proposed to use nodes of a graph representation of an urban structure. They have also proposed a 'named-street approach' (Jiang & Claramunt, 2004) which used street name as the principle of generalisation. Porta et al. (2006) introduced an MCA approach, which is based on direct representation in a primal street graph and works with a Euclidean metric. They claimed that the primal approach is suitable for making the best use of huge information resources.

Combining Angular and Euclidean metrics. In the case of four London city areas, it has been shown that Angular distance based measures can explain 52% to 72% of pedestrian movement volume variance (Hillier & Iida, 2005) although with an unexplained range of variable radius (number of segment). Ratti (2004) took the map of Manhattan as an example, pointed out that topological metric which captures directness is blind to Euclidean distance and to regular geometry. This was already made apparent in (Hillier, 1999a) where analysis with an Euclidean representation/analysis was used instead of an axial/topological analysis in a toy model of regular grid. Turner (2007) compared Angular and Euclidean distance measures, demonstrated that both measures correlate well with vehicle volume. He therefore suggested to combine Angular and Euclidean metrics to better capture the structure of an urban street network. More recently, a study in Brisbane examining walking route choice data of 178 pedestrians, reported that pedestrians tend to minimise both the directional change and path length if they can (Shatu, et al., 2019). It was showed in Zhang, et al. (2015) that a large proportion of shortest path ranges are also least angular path ranges. This a confounding issue neither acknowledged by pedestrian route choice in transport studies nor by the space syntax literature.

Application of Multi-variable model in 3D environments. Despite the success on 2D environments, conventional space syntax method has shown poor association with movement in dense multilevel urban areas (Chang & Penn, 1998). Therefore, numerous previous studies enhanced axial line analysis in a multileveled environment by using urban design parameters to weight the results. For example, in the empirical study of London, Chang & Penn (1998) developed a multi-variable model for better predicting pedestrian movements by plugging in additional variables, such as grade separation, attractors and generators, depth of primary routes. In the same article Chang & Penn suggested that a path centre line/link representation of pedestrian path might be more suitable. Law & Zhao (2009) tested additional factors in a hyper dense urban environment of Central HK. It was suggested that morphological differences and elevation differences were concluded to have strong combinatorial impacts on pedestrian movement distribution. Zhang et al (2012) investigated the impact of major entrances, level variation, and vertical transitions on pedestrian movement in two multi-level complexes. They concluded that vertical transition is the most influential factor. Song et al. (2013)'s study in Shanghai emphasized the importance of the types of and topological distances to vertical transitions. The above-mentioned studies extended space syntax models to multileveled environments by combining additional urban design factors with traditional axial analysis. However, in practice, it is difficult to use the same additional design parameters in different cases, let alone the 3D modelling limitations of mapping axial map in multi-level spaces.

Recent research has highlighted the importance of developing 3D spatial assessment tools. For example, Hölscher et al. (2006; 2012) used an additional axial line for each connection between two floors and manually connected the additional axis to the corresponding lines in the upper and lower floors. Lu & Ye (2017) investigated people's wayfinding performance in a multilevel shopping mall in Hong Kong. They proposed a GIS-based 3D visibility graph analysis which can deal with 3D environments. An empirical study by Zhang & Chiaradia (2019) proposed that it is unrealistic to study extensive multileveled environments by only considering the outdoor pedestrian network which is why an indoor-outdoor 3D pedestrian network has been tested in Central, Hong Kong.

In our study, we compare the influences of traditional space syntax axial map, segmental map (Hillier & Iida, 2005), and the 2D outdoor only GIS standard path-centreline map (Turner, 2007) on pedestrian movement distribution in a hyper dense urban area. Following Zhang & Chiaradia (2019)'s approach, a 3D indoor-outdoor map is examined to strengthen the argument of modelling detailed 3D pedestrian networks. The main contributions of this paper are in twofolds. First, path-centre line representation is extended to dense 3D environments to provide a higher resolution tool for aiding urban design in complex multi-level environment. Second, a hybrid metric which combines Angular and Euclidean metrics has been tested to compare with other metrics.

The remainder of this paper is structured as follows. Section 2 introduces the study area, datasets, and methods. Section 3 reports in detail the experiments and results, illustrating the fact that a 3D indoor-outdoor map using path-centre line representation is superior to forecast pedestrian flow. Finally, section 4 draws some conclusions and describes ongoing studies.

2. DATASETS AND METHODS

2.1 The Study Area

With over 7.4 million people and built-up land area covering just about 24%, Hong Kong has the highest population density and has transformed into one of the most intense and dense cities in the world. As one of the oldest districts of Hong Kong, the history of Central can be traced back to 1842 since the occupation of Britain. The elevated walkway network of Central area has been developed piecemeal by the Hong Kong Government and various developers since 1970s. Over the past decades, it has spread out in CBD districts horizontally and vertically, playing an important role in connecting mixed urban land use. Therefore, it is important to map a multi-level spatial network to comprehend the complexities that pedestrian movement portrays in Central, Hong Kong (Figure 1). The study area is defined as the 600-meter radius straight line buffer area from entrances/exits of three MTR stations – Central station and Hong Kong station.

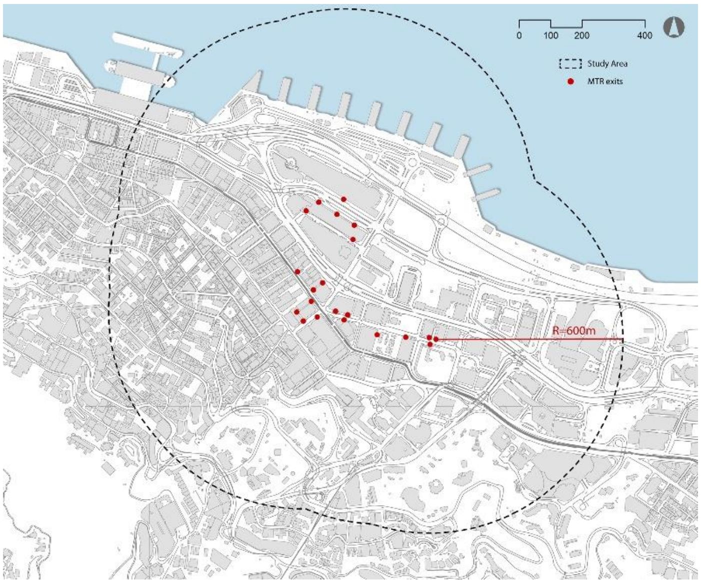
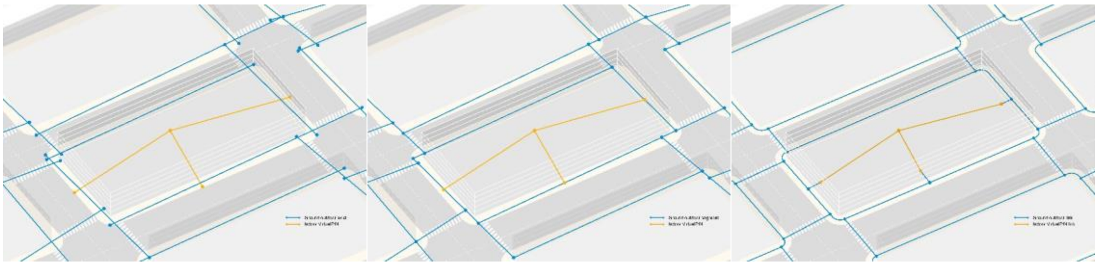


Figure 1 Map of Central area in Hong Kong

2.2 Representations

Concerning the unique spatial characteristics of Central area, a high resolution multi-level spatial model was employed. As suggested by Chang (2000), upper floor skywalk system is represented as an individual axial line system, being connected with ground level using vertical transition spaces. The first space syntax representation applied in this study is called axial map, which is defined as the "longest and fewest" straight lines (Hillier & Hanson, 1984) that can be drawn through a spatial configuration (Figure 2-a). Axial map deemed to be a cognitive representation based on lines of sight (Hillier, 1999b; Penn, 2003) . From an axial map, it is possible to build the second representation, a "segment map", which breaks each axial line at its intersections, allowing for a higher resolution of analysis for street segments (Figure 2-b). The third representation is a standardized transport/GIS link-node linear referencing standard, which defines links as the connection between two adjacent junctions, or between a junction and a dead end (Figure 2-c). We used a system of virtual pedestrian indoor links (Virtual PIN, orange lines in Figure 2-a to c) to maintain a certain level of continuity within the indoor and outdoor pedestrian realms for outdoor only network, i.e. if pedestrian realm switches from outdoor to indoor, virtual PIN links create an imagined route of pedestrians through the indoor realm (Sun, et al., 2018).



(a) (b) (c)

Figure 2 a comparison of different representations: (a) Axial map (outdoor only), space-syntax approach; (b) Segmental map (outdoor only), space-syntax approach; (c) Path-centre line map (outdoor only), sDNA approach

Detailed indoor floor by floor pedestrian pathways of all buildings within the research study area connected to the over ground and underground systems were mapped and merged into the outdoor network to provide a real 3D indoor-outdoor network. Figure 3-a shows the 3D indoor - outdoor network around IFC mall as an example. Actual floor heights are used with vertical transition as lift, escalator and stairways. Figure 3-b illustrates how the analyst radius works in a 3D network.

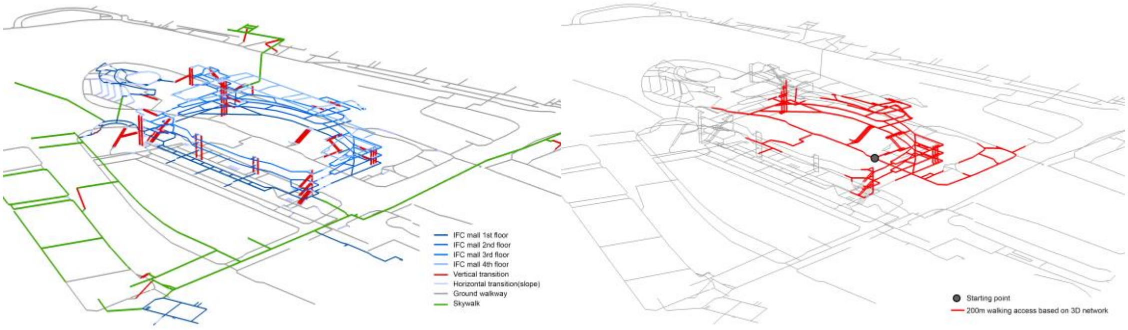


Figure 3 (a) 3D indoor-outdoor network of IFC mall; (b) illustration of 3D network analyst radius

2.3Data Collection

To reduce the edge effect of the configurational analysis, pedestrian volume data was gathered using ‘Cordon Count’ method of observation (Chang & Penn, 1998) within 300 metre buffer areas from MTR exits. The observers recorded for 30 minutes of observation at each location, distributed over 6 different periods for one weekday: 8-10am, 10-12am, 12noon-2pm, 3-5pm, 5-7pm, and 7-9pm, 17,307 People were counted on 33 street links. A massive difference exists between average flows for individual cordon counts in the study area, with a minimum of 12 people per hour and the maximum number of 4,832p/h. Figure 4 shows the average flow rates for all observed cordon counts in the study area. The cordon counts on the upper floor have more pedestrian movement than those on ground floor axials.

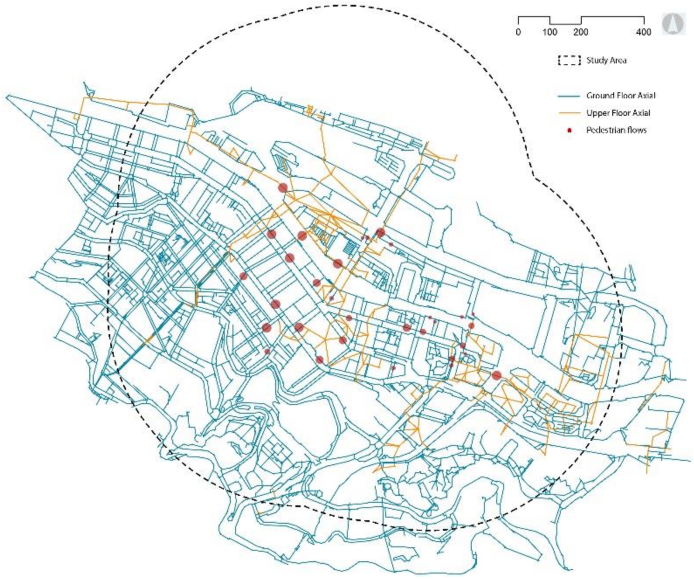


Figure 4 High resolution axial mapping and average daily pedestran moverment of Central Hong Kong

2.4 Centrality variables

Two metrics of network centrality: Closeness centrality (Bavelas, 1950; Freeman, 1977) measures the mean distance from a node to other nodes using the shortest path, capturing the relative ease of reaching destinations. Betweenness centrality (Shimbel, 1953) measures the overlap of shortest paths between all nodes in the system, relating to a network's through-movement potential. In space syntax software, closeness centrality is termed as 'integration' or 'mean depth', and betweenness centrality is called 'choice' (Hillier & Hanson, 1984).

Axial and Segmental maps *are transferred into Depthmap for processing.* According to the Travel Characteristics Survey 2011 (Transport Department, 2014), over 75% of Hong Kong residents walked 5 minutes (200 to 400 metre) or less from their trip origin to access a mechanised transport mode, and from the mode to their trip destination. Therefore, Choice and Integration for axial map at local Radii from R3 to R10, Choice and Mean Depth for segmental map at every 100 metre radii in the range from 200 to 800 metre walking distance thresholds are computed.

Path-centre line maps are computed by the sDNA freeware toolbox for ArcGIS and QGIS (Chiaradia, et al., 2014) . sDNA can be used to analyse complex 3D built environment morphology encoded through linear spatial generalisation of road/path-centre line in order to compute betweenness and closeness metrics for each link in 2D and/or 3D. sDNA can deploy different metrics such as Angular (most direct path), Euclidean (shortest path), topological (least turn path) or a novel 'Hybrid' metric (both shortest and most direct).

'Closeness as mean shortest path' for link x is formalised in Equation 1

$$\mathrm{Farness}(x) = \frac{\sum_{y \in Rx} d\ (x,y) W(y) P(y)}{\sum_{y \in Rx}\ W(y) P(y)} \quad (1)$$

Where **Rx** is the set of all links**, d(x, y)** is the most direct or shortest route between x and y. **W(y)** is the weight of each link y, and **P(y)** is the proportion of y falling within the radius.

'Betweenness as flow potential' in sDNA assumes uniqueness of shortest paths and is defined in Equation 2:

$$\mathrm{Betweenness}(x) = \sum_{y \in N} \sum_{z \in Ry} W(y,z) OD(y,z,x) \quad (2)$$

where **N** is the set of links defined as origins, **Ry** is the set of links defined as destinations, and W(y,z) is the weighting of a trip from y to z. **OD(y, z, x)** is defined in Equation 3:

$$\mathrm{OD}(y,z,x) = \begin{cases} 1, \mathrm{ifxisontheshortestpathfromytoz} \\ \frac{1}{2}, \mathrm{if} x = y \neq z \\ \frac{1}{2}, \mathrm{if} x = z \neq y \\ \frac{1}{3}, \mathrm{if} x = y = z \\ 0, \mathrm{otherwise} \end{cases} \quad (3)$$

The hybrid distance metric is defined in Equation (4):

$$\mathrm{distanceforlink} = a \times \mathrm{ang} + (1\text{-}a) \times \mathrm{euc}$$

$$\mathrm{distancefornode} = a \times \mathrm{ang} \quad (4)$$

Cooper et al. (2018) noted that for Angular-Euclidean hybrid metric, 0.25 <=a <=0.5 gave good results. In this study, we adopted a default half Angular – half Euclidean hybrid metric in sDNA, i.e. a=0.5.

3. RESULTS

3.1 Centrality analysis of outdoor only networks

Figure 5 shows the integration and choice analysis of axial maps in the study area. The red and orange lines represent the spatial most integrated areas in terms of the fewest number of turns. SOHO (South of Hollywood Street) area was captured as the most integrated area. SOHO is an old district which was activated with the implementation of Central-Mid-Levels escalator in 1993. The escalator system runs along Cochrane street and Shelly Street, connects all East-West oriented roads in the Central area, including Queen’s Road, Stanley Street, Hollywood Road, Caine Road, etc., generates an area with small urban blocks and high connectivity.

Figure 5. Closeness (Integratin at Radius 8) and betweenness (Choice at Radius 7) of axial map in Central area, warmer lines are closer to other lines and more central.

Comparing Figure 5 and Figure 6, closeness shows consistency between the two representations, although the most integrated centre of SOHO is strengthened in the segmental analysis. In terms of betweenness results, the main roads such as Des Voeux Road, Chater Road, and Queen’s Road show the highest “through-movement” potentials in axial map, whereas secondary roads such as Wellington Street, Peel Street, Aberdeen Street in SOHO area are highlighted in segmental map.

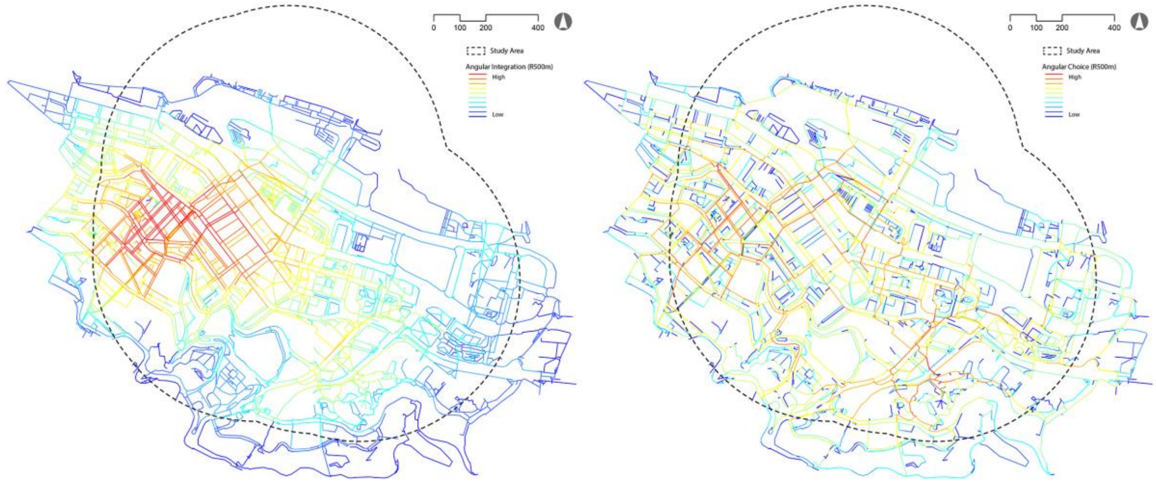


Figure 6. Closeness (Angular Integration) and betweenness of segmenal (Angular Choice at 500 meter radius) map in Central area, warmer lines are closer to other lines and more central.

Figure 7 shows the closeness and betweenness patterns of outdoor only path-centre line map. As can be seen in the figure, spaces close to MTR stations are highlighted in red colours by closeness measure. To our surprise, the betweenness result of path-centre line map shows a similar pattern as integration (a closeness indicator) result of segmental map, while closeness doesn't.

Figure 7. Closeness (Mean Angular Distance at 500 meter radius) and Betweenness (Angualr Betweenness at 500 meter radius) of outdoor only path-centre line map.

3.2 Centrality analysis of indoor-outdoor path-centre line network

Centrality distribution of 3D indoor-outdoor map (Figure 8) is quite different from outdoor only network. On one hand, apart from the SOHO cluster which is still prevalent, there are new multi-level clusters such as IFC mall and Pacific Place that are showing as closeness centres. On the other hand, the footbridge system is clearly highlighted in betweenness analysis, showing a high continuity between Central elevated walkway system and surrounding multi-level publicly accessible spaces.

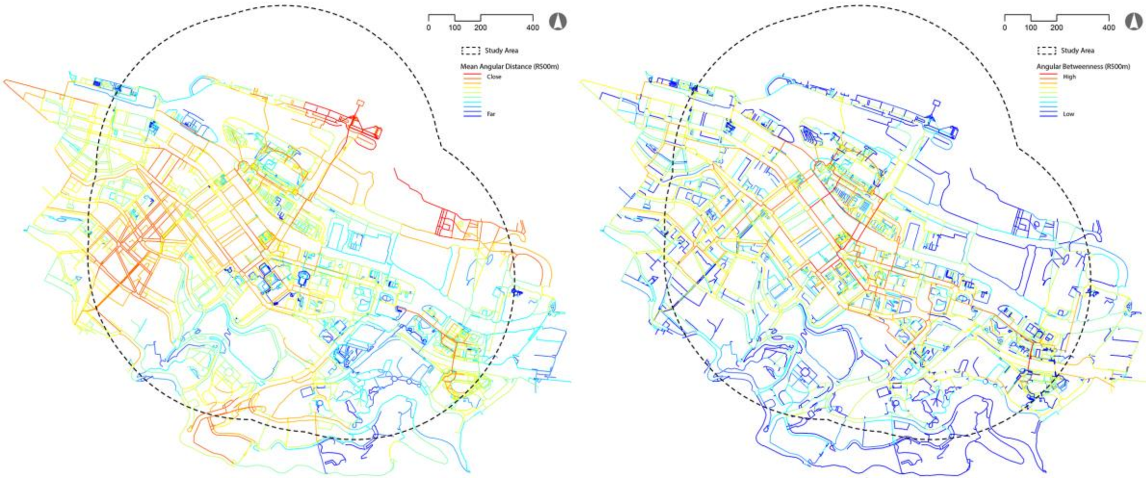


Figure 8. Closeness (Mean Angular Distance at 500 meter radius) and Betweenness (Angualr Betweenness at 500 meter radius) of 3D indoor-outdoor path-centre line map.

3.3 Correlation Analysis between pedestrian movement and centrality measures

To test the relationship between spatial configurations at different radii (3, 4… to 8 for axial map, 200, 300… to 800 for segmental and path-centre line maps) and observed average daily pedestrian movement, a bivariate correlation was adopted for all the models previously described. The pattern of R-square correlation values between pedestrian movement and centrality measures is shown in Table 1. Axial analysis shows moderate predictability, with maximum correlation value 0.38. There is a significant improvement when segmental map and least Angular analysis is adopted (R square = 0.56). Path-centre line map shows a slightly better correlation with pedestrian movement flows than segmental map, with R square value being 0.57. It is notable that the best correlation is achieved by Angular closeness (at the radius of 500 metre) in 3D indoor-outdoor path-centre line map, with an R square of 0.72. The significant improvement of R-square value suggests that pedestrian movement pattern is significantly affected by the indoor pedestrian paths.

Table 1. R-square correlations between Ln pedestrian movement and Ln betweenness and Ln Closeness measures from Axial map, segmental map, 2D outdoor path-centre line map, and 3D detailed path-centre line map (radii between 200 to 800 metre). Best correlations of each profile are marked *. Numbers in round brackets indicate the best radius.

		Space Syntax Software (Depthmap)		Spatial Design Network Analysis (sDNA)	
		Axial map	Axial Segment map	Road/Path-centre line map Outdoor only	Road/Path-centre line map Indoor-outdoor
Topological	Closeness	**0.38 (R8)***	NA	0.25(R800)	0.47(R500)
	Betweenness	0.35 (R7)	NA	0.18(R500)	0.26(R600)
Euclidean	Closeness	NA	**0.08**(R500)	0.15 (R700)	0.20 (R700)
	Betweenness	NA	**0.20**(R500)	0.28(R500)	**0.51(R500)**
Angular	Closeness	NA	**0.56(R500)***	**0.57(R600)***	**0.72(R500)***
	Betweenness	NA	0.31(R600)	0.25(R600)	**0.49(R500)**
Hybrid (Euclidean & Angular)	Closeness	NA	NA	**0.47(R500)**	**0.68(R500)**
	Betweenness	NA	NA	0.26(R600)	**0.52(R500)**

We notice that for all three representations (Axial-segmental, outdoor path-centre line, indoor-outdoor path-centre line), the best correlations are all obtained by Angular closeness measures, with hybrid measures being the second best. It is surprising that betweenness measures, commonly used as an indicator of “through-movement”, displays much lower correlation coefficients with pedestrian movement than closeness measures, with the peak R square 0.52 for detailed indoor-outdoor representation. We speculate that it is due to the substantial proportion of “to-movement” trips on weekdays in CBD area - commuter trips in the morning peak period (8 to 10 am) and evening peak period (5 to 7 pm), and from the continuous flow of tourists in and out of the MTR for the rest of the day. It has been known that route selection is a competition between the least angle route and the closest route to the destination from the origin (Dalton, 2003). Zhang et al. (2015) showed that different configurations will have a different mix of angular shortest that are also euclidean shortest path. In Central area in close proximity to many MTR exits, in a 3D non-grid like area with small block sizes and a lot of complex vertical circulation and at time maze like floor plans, it is understandable that least angle distance may wins the competition. While this is beyond the scope of this paper this is to be further scrutinised. For example, in what way the shortest angular path ranges are related to shortest Euclidean path as a configuration signature given that sDNA Euclidean betweenness is rather high. Also, a wider area pedestrian survey and analysis showed that by factoring in distance to the MTR entry/exit, Hybrid betweenness outperformed Angular closeness (Zhang & Chiaradia, 2019) which is more conform to betweenness being considered as theoretical flow.

As scatter plot in Figure 9-a shows, points in red are those have the most deviation from the results of two representations. Figure 9-b shows the location of these 4 gates, all of them are located at the upper footbridge level. This demonstrates that it is inaccurate to only consider the outdoor pedestrian network to study the pattern of accessibility in multi-level urban environments.

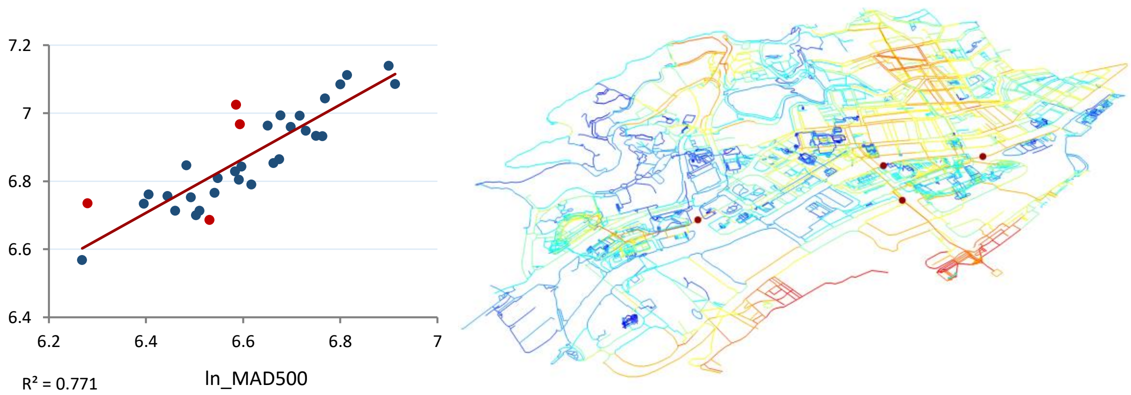


Figure 9. the most deviation gates between Ln Closeness MAD500 of outdoor only map and indoor-outdoor map: a. Scatter plot diagram; b. Angular Closess of 3D indoor-outdoor map.

4. CONCLUSIONS

4.1 Conclusions

Related empirical studies have investigated the relationship between the movement of people and the space syntax's configurational values based on axial and segment representation of spatial configuration. However, this paper shows the limitations to apply this type of representation to dense 3D environments which was somehow anticipated in Chang and Penn (1998) but never tested. In this study, we explore to what extent the variance in pedestrian movement in multi-level urban environments can be accounted for by spatial configurational variables. Using multi-level urban environment of Central area in Hong Kong as a case study, we examine the correlation coefficient between spatial configuration and pedestrian volume. The study mainly focuses on comparison between three kinds of pedestrian network representation data models, which are axial line map, segment map, and pedestrian path-centre line map.

Correlation analyses confirmed a significant relationship between centrality measures and pedestrian movement volume. There correlations are between configurational measures of axial map and pedestrian movement (R-square of 0.38). The segment derived from axial map and path-centre line representations show that there is a significant correlation between Angular closeness and daily pedestrian movement volume, with R-square value of 0.56 and 0.57 respectively. Furthermore, we construct a floor by floor 3D indoor-outdoor path-centre line map that achieve a 0.78 R-square with angular closeness.

This study differs from previous research mainly on pedestrian behaviour for two reasons. Firstly, a floor by floor multi-level model using path-centre line representation show that it improve the performance of measuring accessibility and flow potential. sDNA supports 3D network analysis, computing x, y, z axes equally. With increasing development of urban rail oriented development that involve mixed use complex multi-level built and natural environment, a more precise 3D pedestrian network representation data model would provide an assessment at a higher resolution for multi-level urban environments. Secondly, although further analyses are required to test the hybrid betweenness a purely Angular metric and purely Euclidean metric, a calibration of 50% - 50% Angular - Euclidean hybrid metric gives a stable result in terms of interpreting pedestrian movement potential.

4.2 Suggestions for Further Research

A limitation of the study is the methodology used for manual pedestrian counting. The current study examined only weekday pedestrian volume. An essential extension of this study is to compare with the weekend pedestrian volume counts that would provide additional evidence to test the claims of this study. It would also be helpful to use modern counting techniques including video recordings, Wi-Fi sensors, to produce more accurate data for future research. Further investigation is also needed on the overlapping relationship between shortest angular path and shortest Euclidean path in complex 3D built environment. Known variables, such as distance to transit, have also been omitted as the focus were on comparing pedestrian network representation that are meant to be like for like.

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