FROM EXTERIOR TO INTERIOR:
Mapping Pedestrian Movement in Station Complex Buildings

Shan-shan, Wu¹; Yu, Zhuang²; Yun-xi³, Bai; Yan-ni, Pei⁴

ABSTRACT
Pedestrian movement in the built environment has attracted research foci from both urban planning and transportation. Characteristics of built environment, such as urban forms, road network system, and building layout, can affect people’s movement in different space. Thus, the quality of the space becomes measurable through evaluating people’s movement for design/planning purpose. Nowadays, the built environment is becoming more complex, in which the exterior and interior space are integrated to form a multilevel network. Studying the pedestrian movement in those areas can deepen the understanding toward the mechanism of people’s route choice, and provide useful insights for both spatial design and urban planning. The objective of this study is to construct a model which can map the pedestrian flow in the station complex buildings. The space syntax and SNA (Social network analysis) methodologies are adopted to investigate people’s movement in the built environment with integrated exterior and interior space. The station complex buildings of Tuen Mum station, Hong Kong is selected as case study. The network that connecting the station and surrounding function areas (within walkable distance) is consists of road system, bridges, and interior passageways. The indexes that evaluating the network characteristics, such as integration in space syntax and centralities in SNA will be calculated and compared. The modelling results will be validated by the on-site survey. The accomplished model can be used as a practical tool in designing complex space at metro station catchment area.

KEYWORDS
pedestrian movement, station complex building, space syntax, social network analysis

1. INTRODUCTION
Walking is important for retaining the vitality of the city, since walking behaviour is closely related to many urban functions, such as retails, parks and green space. Also, walking can reduce car

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use in the short-distance trips, and increase sustainability. As a result, how to improve walkability has been a critical issue in Transportation oriented development (TOD) (Duncan, Aldstadt, Whalen, & Melly, 2011; Ewing, Handy, Ewing, & Handy, 2009; Frank et al., 2007; Manaug & El-geneidy, 2011).

Pedestrian movement study is one crucial attempt in investigating the mechanism of walking and walking behaviour. Previous studies have developed two kinds of explorative methodologies. The first kind is the network-based models. The most famous one is space syntax (Hillier, n.d.), which constructs the street network based on urban spatial configuration. The methodology was widely adopted in evaluating the relationship between built environment and pedestrian movement (Foltz & Piombini, 2007; Lerman, Rofè, & Omer, 2014). Similar methods such as GIS network analysis (Ozbil, 2017) and social network analysis (Chen & Chang, 2015) discussed network indicators extensively (Porta, Crucitti, & Latora, 2006a; Sheikh, Zadeh, & Rajabi, 2013; Zhong et al., 2014). The second kind is the agent-based simulation model. Those models started from the microscopic behavioural issues of the individuals, such as speed, direction and visions (Antonini, Bierlaire, & Weber, 2006; Robin, Antonini, Bierlaire, & Cruz, 2009). Thus, pedestrians’ moving choice were determined by both destination and physical movement, which is obtained from behavioural experiments (Seyfried, Steffen, Klingsch, & Maik Boltes, 2005). The attraction of the built environment was important in the modelling process as well. For example, Wang, Lo, Liu, & Kuang, 2014 modelled the attraction of different kinds of retail stores in the shopping centres. The result of the simulation fitted the real situation of the case study area.

Despite the wide application of both methodologies, they still have disadvantages in some respects. The network-based models are useful in analysing cases without surveying. Many previous studies surveyed the pedestrian volume in different cities and nations for correlation analysis (Zhuang & Yao, 2016). Those results prove that the network-based models, especially space syntax were universally applicable. However, space syntax does not consider the influence of urban functions. Existing studies had to evaluate urban functions, such as retail by statistical analysis with the spatial integration distribution. As a result, space syntax can be hardly used for predicting the location of different function of space in the design process. The agent-based models are sensitive to both built environment and human behaviour. Once the model is established, future scenarios can be predicted based on the current situation. The disadvantage of agent-based models is the case-specific characteristics, and the accuracy of the models are largely depended on the survey data. Therefore, those models have limited use in newly built area.

Nowadays, cities are becoming more complex than ever. The walking systems are not restricted at the street level. Lifted and underground walking systems can be found in many metropolitans. Further, those walk ways are integrated with other urban functions to increase the spatial attractions to the pedestrians. This study aimed at establishing a novel network-based methodology – namely WMDA-model to estimate the pedestrian movement in the complex building, with respect to the influence of retail function in the built environment. The proposed model had the potential of investigating current situation, as well as predicting future possibilities. The study looked back upon
the basic algorithm of space syntax, and combined the measures of space syntax and social network analysis. Then, the results of our model and space syntax were compared with the pedestrian volume in the study area to show the improvement of our model.

The study was organized as follow. The second section first discussed the structure of space syntax and WMDA-model. Then, the background of the selected case and data resource were introduced in detail. The third section presented the results of the analysis. Implications and limitations were also discussed in this section. The fourth section summarized the conclusion of the study.

2. DATASETS AND METHODS

This study developed a new methodology based on space syntax and social network analysis. The study first looked back upon basic concepts and algorithms of space syntax, and compared them with the basic ideas of social network analysis. Then, a new index for mapping the pedestrian movement in the complex building was derived from the two methods.

2.1 Methodology discription

![Diagram of datasets and methods](image)

*Figure 1:* Comparison of space syntax, social network analysis and WMDA-model (A) Network analysis with space syntax based on Porta, Crucitti, & Latora (2006b)’s study; (B) Network analysis with social network analysis; (C) Edge-weighted network with social network analysis; (D) Weighted network analysis with WMDA-model.
In network related studies, street network is usually abstracted as a graph $G(s, t)$, in which $s$ is the node set and $t$ is the edge set. As shown in Figure 1(A), $s$ in space syntax is the axes of the streets and $t$ is the connection of the axes. The network under space syntax concept is non-weighted, and its accessibility is evaluated by mean depth. Mean depth, or the integration of the map, measures how close a node is to all the other nodes (Teklenburg & Timmermans, 1993). The equation of mean depth can be written as:

$$MD_i = \frac{\sum_{j=1}^{n} d_{ij}}{n-1}$$  \hspace{1cm} (1)

Where $MD_i$ is the mean depth of node $i$, $d_{ij}$ is the shortest depth between node $i$ and node $j$, and $n$ is the number of nodes on the graph.

Figure 1 (B) shows the non-weighted case of social network analysis. Although some previous studies use similar network construction as space syntax (Porta et al., 2006b), most of geographical and transportation related studies define intersections of the streets as $s$ and parcels of streets as $t$ (Sheikh et al., 2013). The concept in social network analysis which closest to $MD$ is closeness centrality ($CC$):

$$CC_i = \frac{1}{\sum_{j=1}^{n} d_{ij}}$$  \hspace{1cm} (2)

Thus, the relationship between $MD$ and $CC$ (under the same network construction) is:

$$MD_i = \frac{1}{CC_i \times (n-1)}$$  \hspace{1cm} (3)

Notably, the social network analysis has the possibility to turn a non-weighted network into weighted form. For example, in Figure 1 (C), different weights are assigned to all the edges in $t$. Thus, we can estimate the weighted closeness centrality ($CC'$) as follow:

$$CC'_i = \frac{1}{\sum_{j=1}^{n} d'_{ij}}$$  \hspace{1cm} (4)

Where $d'_{ij}$ is the weighted shortest depth between node $i$ and node $j$.

Based on equation (3) and equation (4), mean depth ($MD$) has the potential to be transformed into weighted mean depth. The problem lies in the identification of “weight”. Here we developed a Weighted Mean Depth Analysis Model (WMDA-model) which take into the consideration of functional influence. The concept of impedance is defined and utilized in our methodology. Impedance is a complex-valued generalization of resistance, and has been widely used in electrical and mechanical studies. Some of the transportation related studies had also adopted the concept of impedance. For example, Liu & Zhu (2004) identified three major kinds of travel impedance: distance, time, and cost. Those measures was used to measure accessibility in GIS. Iacono, Krizek, & Elgeneidy (2010) considered impedance as a combined effect of cost and willingness of travel. They calibrated the non-motorized travel impedance in the gravity model for different kinds of travel objectives. Those impedance related studies mostly based on the gravity model and utility-based
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models, and treat impedance as a similar concept to “attractiveness” (Nassir, Hickman, Malekzadeh, & Irannezha, 2016; Ryu, Chen, & Choi, 2017).

In our study, we defined impedance ($Ia$) as the influence (or attractiveness) of the urban function on the pedestrians on the streets. We supposed $Ia$ is a normalized parameter ($Ia \in (0, 1]$). If there are no attractive functions alongside the street, then $Ia$ of the street equals to 1. One of the most attractive functions to pedestrians are retails. Many previous studies had been studying relationship between the attractiveness of retails and pedestrian travel (Clifton, Singleton, Muhs, & Schneider, 2016; Trasberg, Cheshire, & Longley, 2018). To facilitate the research question, we assumed retails as the only function that influence pedestrians, and the value of $Ia$ is arbitrarily given as 0.5 (if the function alongside the street is retails). Otherwise, $Ia$ equals to 1.

In fact, $Ia$ is the node weight of the network, as shown in Figure 1 (D) (node-weighted network). In order to apply equation (4), the node weight should be transformed into edge weight. Kong, Yin, Nakagoshi, & Zong (2010) defined the edge weight as the multiply effect of the node weights that connects in a similar situation. This study adopted this definition, and the weight vector for the edge set $t$ is:

$$w_{ij} = Ia_i * Ia_j, \quad i, j \in s, \text{ and } i \neq j$$

(5)

According to equation (5), there are three possible weights of the edge set $t$: $w_{ij}$ equals to 1, when the two axes are not besides the retail facilities; $w_{ij}$ equals 0.5, if one axis is besides retail facilities and the other is not; $w_{ij}$ equals 0.25, if the two axes are besides the retail facilities. The weight system suggests that the connection of two retail streets is more attractive to pedestrians than two other streets, which well meets the situation of the reality. Thus, the weighted mean depth ($WD'$) of the graph $G$ can be estimated as follow:

$$MD'_i = \frac{1}{CC_i * n - 1}$$

(6)

Figure 2: An ideal network
The new methodology was tested in an ideal network to show the difference with space syntax. Figure 2 is the axial map of the ideal network which contains two level of walkways: the street level walkways and the lifted walkways. Some of the pedestrian streets on the street level are besides the retail stores, and the lifted walkways are all besides retail facilities.

Figure 3 shows the comparison of $MD$ of space syntax and $MD'$ of WMDA-model. If the influence of the retails is not considered (Figure 3, left), the center of the grid is more accessible than the other place. However, the lifted walkways are the least accessible area. If the influence of retails is considered (Figure 3, right), the most accessible areas shift to the streets along retails on the street level, and the accessibility of the lifted walkways is improved as well. The least accessible axis shift to the periphery of the network.

By comparing mean depth and weighted mean depth, we found that the weighted mean depth is more sensitive to the retail function alongside the streets. The results coincided with the common sense that retail facilities can attract people and stimulate pedestrians. In the next step, we will use one case – Tuen Mun of Hong Kong to study the two models, and the number of pedestrians will be used to validate the model.

### 2.2 Case description and data source

Hong Kong is a metropolitan famous for its complex urban feature. The city center such central has been investigated extensively (Jonathan Solomon, 2012), while the new towns are less mentioned in previous study. This study chooses Tuen Mun as an example to validate the WMDA-model. Tuen Mun is the first generation of new towns in Hong Kong, which has a population of 480,500. Lying in the town center of Tuen Mun, Tuen Mun MTR station has complex feature that connect numbers of buildings and create a walking-oriented environment (Figure 4). The connection includes street level walkways and station concourse level walkways (lifted). The street level walkways are mainly sidewalks (Figure 5, left), and it connects the new districts of larger blocks and old districts of smaller

Data resource:
http://gia.info.gov.hk/general/201803/29/P2018032900402_280988_1_1522296427431.pdf
blocks. The older districts are the marketplace of town people. The station concourse level walkways are the indoor walkways (Figure 5, right) inside a number of commercial buildings. As shown in Figure 4, the station concourse level walkways are all surrounded by retail stores, while the street level walkways are partly at retail areas. Also, the goods being sold are different in street level retail area and station concourse level retail areas. The former is cheap and the latter is median price to luxury.

Figure 4: Case study area (Tuen Mun MTR station)

Figure 5: Walkways within the case study area
The data of the study included the street level plans and station concourse level plan. The street level plan was obtained from Openstreetmap, which contains information of building outlines, street outlines and transportation routes. The majority of the station concourse level plan was obtained from the official website of the shopping malls occupying the building. Only one plan at station concourse level was obtained from site survey. The plans on different levels are adjusted to ensure the continuity of the walking system.

3. RESULTS

The network analysis of the case study includes four steps (Figure 6). 1, AutoCad is used to draw the axis of the streets and walkways. The axes are numbered as the node set \( s \). The links of the nodes (edge set \( t \)) and the impedance of the axes (\( I_a \)) are organized in excel. 2, Edge set \( t \) and \( I_a \) are input into Matlab for network analysis. Both mean depth (\( MD \)) and weighted mean depth (\( MDw \)) are estimated for comparison. 3, The results are imported into Arcgis to show the difference of \( MD \) and...
In order to compare the two measures correctly, we normalized the results according to Teklenburg & Timmermans (1993) and Vieira (2012):

\[
n_{MD} = \frac{MD - MD_{\min}}{MD_{\max} - MD_{\min}}
\]

\[
n_{MDw} = \frac{MD_w - MD_{w\min}}{MD_{w\max} - MD_{w\min}}
\]

Where \(n_{MD}\) is the normalized mean depth, and \(n_{MDw}\) is the normalized weighted mean depth. The normalized mean depth and normalized weighted mean depth is compared in this step. 4. The results are also compared to number of pedestrians in the study area. Since counting pedestrians may involve tremendous effort, we use an alternative way to show the distribution of pedestrians. Photos are taken at critical locations. The geographical positions of the photos are extracted by Locaspace Viewer and the number of pedestrians in the photos are counted.

Figure 7: Comparison of normalized mean depth and normalized weighted mean depth
Figure 7 shows the results of estimated mean depth and weighted mean depth (in normalized form). When the retail facilities are not considered (Figure 7, right), the most accessible area located at the center of the street level and station concourse level. The accessibility dropped as the distance to center increased. This phenomenon was found in both street level and station concourse level axes. In all, the change of MD is gradual, and the least accessible areas only appears at the tail of the station concourse level axes. When the retail facilities are considered (Figure 7, left), the accessibility of the street level axes were reduced respective to their locations. The accessibility of the center area reduced slightly, but the places which lies at the periphery of the network reduced dramatically to very low level. However, the axes located at the market area are still highly accessible comparing to the other place. The accessibility of the station concourse level axes increased a lot. The area with smallest MDw are larger than MD, and almost all the station concourse level axes have small MDw, indicating high accessibility.

![Figure 8: Pedestrian distributions in the study area](image)

Figure 8 shows the pedestrian distribution in the study area. Photos were taken at 22 places on the street and 31 places in the indoor walkways. The color of the point describes the level of pedestrian volume. On the street level, the points with high value (green dots) concentrated in the blue oval area, which was close to the market. This oval zone is also an important connection of marketplace and indoor retail stores. The points with low value (red points) located at the periphery of the study area. On the station concourse level, the points with higher value located at the two blue oval zones of the map, and the red points appeared at the tails.
Table 1: Statistical analysis of normalized mean depth (n_MD) and pedestrian flow

<table>
<thead>
<tr>
<th>Model</th>
<th>R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
<th>R Square Change</th>
<th>F Change</th>
<th>df1</th>
<th>df2</th>
<th>Sig. F Change</th>
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<td>.022</td>
<td>4.347/80</td>
<td>0.056</td>
<td>1.667</td>
<td>1</td>
<td>28</td>
<td>.207</td>
</tr>
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</table>

a. Predictors: (Constant), MD

ANOVA*

<table>
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<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
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</thead>
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<td>1.667</td>
<td>.207</td>
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<td></td>
<td>Residual</td>
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<td></td>
<td>Total</td>
<td>29</td>
<td>560.800</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Dependent Variable: PedestrianNo
b. Predictors: (Constant), MD

Table 2: Statistical analysis of normalized weighted mean depth (n_MDw) and pedestrian flow

<table>
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<tr>
<th>Model</th>
<th>R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
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<th>F Change</th>
<th>df1</th>
<th>df2</th>
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<td>.234</td>
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<td>14.911</td>
<td>1</td>
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<td>.001</td>
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a. Predictors: (Constant), MD_w

ANOVA*

<table>
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<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
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<td>29</td>
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</table>

a. Dependent Variable: PedestrianNo
b. Predictors: (Constant), MD_w

Based on the limited data from photos, linear regressions were conducted in IBM SPSS Statistics (Ver. 25) to study the relationship between pedestrian flow and (weighted) mean depth, as shown in Table 1 and table 2. The R square of normalized mean depth (n_MD) and pedestrian flow (0.056) are very low, and the n_MD is not significantly in predicting pedestrian number (Sig. = 0.207). The R square of normalized weighted mean depth (n_MDw) and pedestrian flow (0.347) are comparatively higher than n_MD, and the significance value of n_MDw is 0.001, which indicates a high predictive power of n_MDw in pedestrian flow. Although the results are not yet confident since the lack of complete data, it has partially proved that the proposed WMDA-model has made remarkable progress in mapping pedestrian in complex built environment.

Nevertheless, the algorithm of space syntax used in this study is only part of the space syntax theory. The state-of-the-art theory has been developed extensively during the last decades, which may have the potential to solve similar problem. In our study, the major focus is to establish a novel methodology for mapping of the pedestrians from exterior to interior. As a result, we put less effort on detailed analysis and interpretation of space syntax results. As a matter of fact, our model has shown the potential of illustrate how complex built environment shape pedestrians’ walking behaviour, estimate pedestrian distributions in small urban districts with various retail facilities, and even predict retail performance before investment.

The study also yields some limitations. First of all, the impedances of the axes were arbitrarily given. Secondly, the data of pedestrian number were not sufficient for evaluating the correlation between weighted mean depth and pedestrian volume. In the future, the pedestrian number will be counted at all the critical axes of the study area to validate the model. The data can also be used to
calibrate the appropriate value of impedance. Further, the study has only considered the influence of retail facilities, without taking into concern of all the other functions of the urban area. As a result, the future study will consider the influence of other urban functions on pedestrian movement.

4. CONCLUSIONS

Since the built environment is more complex than ever, modelling pedestrian movement in complex buildings becomes an urgent task for the designers, transportation engineer and other stakeholders. This study proposed a novel WMDA-model to map the pedestrian movement in complex buildings, with respect to the retail functions alongside the walking system. Based on the basic algorithm of space syntax and social network analysis, our model introduced a hypothetical impedance concept to the original axis. Thus, we were able to calculate the weight of the edges (the ease of movement between two axes). The analysis of the ideal street network showed the difference results of our model and space syntax.

Our model was further validated by the case study of Tuen Mun. The walking system of Tuen Mun includes street level walkways and station concourse level walkways. The result showed that the distribution of weighted mean depth is much closer to the distribution of pedestrian volumes estimated by photos. As a result, our model successfully linked urban function with networks by introducing the impedance concept, and has the potential of predicting pedestrian distribution during the design process.

However, our study is not yet sufficient in impedance calibration and statistical validation with necessary pedestrian numbers. In the future, we will put more effort to overcome the two limitations. Also, other urban functions will be considered in the modelling to complement the current model.

REFERENCES


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