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The role of street network metrics in shaping distance distributions in a residential neighbourhood

Khair Eddine Demdoum[1, CDFMR], Mohd Yazid Mohd Yunos[2, CDFMR], Norsidah Ujang[3, CDFMR], Nangkula Utaberta[4, CDFMR]

[1,2,3] *Universiti Putra Malaysia*, Department of Landscape Architecture, Faculty of Design and architecture (FRSB), Selangor, Malaysia; [4]*UCSI University,* School of Architecture and Built Environment (SABE), Faculty of Engineering and Built Environment, Malaysia; [1]e-mail: gs49946@student.upm.edu.my (*corresponding author*)

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Abstract. Walkability studies often rely on physical proximity metrics for destination accessibility. However, some recent studies argue that configuration (topological) distance provides a more accurate reflection of the actual distances experienced by individuals. This study therefore aims to test the extent to which an association exists between network-metric proximity to several destinations and two main measures of space syntax – integration and choice – in a dendriform network structure such as Putrajaya city (Malaysia). Using GIS, multiple buffer-service areas were generated around each housing unit (N = 2,392). Interpolation and space syntax analyses were conducted to assess metric and topological distance at local and global levels for each buffer. The statistical analysis showed that distances to commercial areas, transportation and average distances to all destinations were strongly affected by the syntactical properties of the neighbourhood. Moreover, global measures were more powerful in detecting metric-distance changes compared to local measures. Aligned with natural movement theory, these results support the idea that the spatial properties of urban form have a significant impact on distance distributions within residential settings, specifically distances to commercial areas. Therefore, policies that promote mixed-use development, especially in areas with good transportation access, should consider the impact of syntactical accessibility of the network.

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1. Introduction

The urban environment is a complex system that impacts human behaviour and experiences in various ways. One key factor that has received considerable attention in recent years is the role of built environment in promoting or inhibiting physical activity and well-being. In particular, the availability and accessibility of certain destinations such as parks, schools and stores has been shown to impact a range of outcomes related to physical activity, including walking (Tang et al., 2020; Petrunoff et al., 2021). Accessibility to destination is associated with the variety of attractions within walkable distance of a given area, which is usually defined as the relationship between the availability of opportunities in a given location and the supply of transportation services to reach them (De Vos et al., 2023).

The accessibility concept in objective-walkability studies is often operationalised as proximity to destinations (e.g., J. D. Marshall et al., 2009; Frank et al., 2010; Grasser et al., 2017; Habibian & Hosseinzadeh, 2018), which are presumed to function in conjunction with both density and diversity. When high density is combined with high directness or connectivity between the point of origin and destination, it is more probable for the distance to be shorter, which facilitates more walking and reduces car travel (Vargo et al., 2012). Shorter distance to certain destinations, such as commercial centres (Hahm et al., 2017; Neatt et al., 2017; Arranz-López et al., 2019), parks and recreation centres (Koohsari Kaczynski et al., 2013; Hogendorf et al., 2020), schools (Kelly & Fu, 2014; R. Zhang et al., 2017), workplaces (Carlson et al., 2018; Barr et al., 2019) and transport nodes (Tiznado-aitken et al., 2018; Guo & Peeta, 2020) has been proven to encourage more walking activity.

However, conventional measures of proximity have relied on the concept of physical distance metrics, such as metres, yards or miles or of time measures, which are limited in their ability to capture the spatial complexity and connectivity of built environments related to pedestrian movement (Koohsari et al., 2013). Alternatively, recent research has emphasised the use of network topology metrics to measure proximity as a more effective means of predicting accessibility for walking activity (Chiang & Li, 2019). This approach relies on the space syntax hypothesis, which suggests that people tend to perceive and move through urban spaces in terms of geometry and topology, rather than metrics (Hillier & Hanson, 1984). This means that individuals may prefer a route with fewer turns, even if it is the same length as an alternative route with more turns. Therefore, the use of only the shortest distance between two points (metric proximity) is not sufficient to fully capture the spatial configuration of an urban space or how people experience and navigate through it.

The main contrast between space syntax and metric representations lies in the way distance is defined and understood in each approach (Batty, 2022). In space syntax, distance is based on the relationship between streets and their arrangement, while metric representations consider the actual physical distance between locations. Accordingly, previous research found that the association between metric and topological distance within urban network were not always correlated. In particular, Wagner (2008) suggested that networks with a high degree of connectivity, topological and metric distance will be more closely correlated than networks with low connectivity. Therefore, the convergence and divergence between metric and topological distance can be affected by factors such as the type and size of the network and the presence of barriers (Hillier et al., 2007). For example, in some urban structures like an orthogonal grid, the metric distance between two points may be relatively long, but the topological distance may be shorter. Conversely, an irregular or tree-like structure provides short metric but long topological distances (Wagner, 2008). Therefore, optimising physical metrics does not necessarily imply optimising topological metrics, often resulting in a trade-off that needs to be addressed (Lima et al., 2022). Thus, having a clear understanding of the association between metric and topographic distances is essential for conducting rigorous research on the distribution of attractions that may increase walking activites such as parks or commercial areas.

Previous research has provided evidence of the significant influence of topological distance on walking activities, such as reaching parks, open spaces (Koohsari et al., 2013; Chiang & Li, 2019), schools (Cutumisu, 2012; Soltani et al., 2022), commercial areas (Rui & Ban, 2014; Wang et al., 2014; Liu et al., 2016), transit points (Ozbil & Peponis, 2012; Lerman et al., 2014a) and touristic attractions (Mansouri & Ujang, 2017). However, only a few studies have investigated the relationship between metric distance and topological distance to these destinations. Specifically focusing on commercial areas, previous reseach has indicated that the syntactic properties of a network have a great impact on the distribution of commercial land use. For example, Scoppa & Peponis (2015) found that areas with a more integrated and hierarchical street network in Buenos Aires, Argentina, had shorter distances to retail frontages. Similarly, Porta et al. (2009) demonstrated a strong correlation between the integration of the street network and the location and distance distribution of retail and service activities in Bologna, Italy. Similar findings were reported in Barcelona, Spain (Porta et al., 2012) and Wuhan, China (Liu et al., 2016). However, when Porta et al. compared retail locations in Bologna and Barcelona, they discovered that, in Bologna, location strongly correlated with integration and choice, while in Barcelona, choice was slightly more important than integration and straightness due to the different grid structure.

Based on the previous discussion, this study aims to test the extent to which an association exists between network-metric proximity to several destinations and two main measures of space syntax – integration and choice. According to space syntax theory, human movement involves both selecting a destination (known as "to-movement") and choosing the spaces that must be crossed to reach that destination (known as "through-movement"). To account for these two aspects of movement, two syntactic measures are used. The first measure, called "integration" (or closeness), quantifies how close each segment is to all other segments based on different distance definitions. The second measure, called "choice" (or betweenness), quantifies how many shortest paths between every pair of segments a given segment lies on, again based on different distance definitions (Hillier & Iida, 2005; Hillier, 2007). In addition, each of these measures can be applied at different scales or radii. When small radii of five branches or less are used to constrain the calculation, the analysis is used to describe the "local structure" of an area. On the other hand, the "global scale" often describes the calculation on a very large or unconstrained scale of analysis. These two scales are often analysed jointly to describe the "interface" between local and global properties (Hillier & Hanson, 1984). For instance, some street segments are more important for connectivity at the neighbourhood level but are less important for the larger urban context, while other street segments are crucially important for the neighbourhood and have much power when treated as a part of the larger system (Ozbil et al., 2011).

Although we are comparing two closely related measures of proximity, this study can provide valuable insights for researchers seeking to understand the effectiveness of the dendritic urban grid, such as in the case of Putrajaya city, in promoting proximity to walkable attractions. As demonstrated by Wagner (2008), the axial graph implicitly encodes geometric information, influenced by the structural constraints of real cities. Therefore, our hypothesis is that topological distances, based on metrics of integration and choice, exhibit a strong association with metric-network proximity. Furthermore, syntactic measures at different radii can explain the distance distributions to destinations that are supposed to attract pedestrians.

2. Research materials and methods

2.1. Study site and analytical unit

The research was conducted in Putrajaya, Malaysia's new federal government administrative centre located 25 kilometres south of Kuala Lumpur, with a population of 97,185 people in 2020 (https://www.dosm.gov.my). The city provides different built environment characteristics for promoting a healthy lifestyle, with 39.2% of public open spaces relative to 14.4% residential areas. Putrajaya was selected due to its dendritic grid or tree-like structure in the neighbourhood plan (Sharifi, 2019), which is conducive to space syntax analysis (Cutumisu, 2011), Despite the inclusion of cul-de-sacs, footpaths and narrow roads, the tree-like patterns offer semi-private community spaces that may encourage walking activity more than an orthogonal grid (Lima et al., 2022). The study focused on two residential precincts, Precinct 9 and Precinct 11, characterised by high residential density and equitable distribution of facilities within a five- to ten-minute walk (Azmi et al., 2012). The analysis included a total of 2,393 housing units.

The units of analysis were generated by multiplying buffer-service area around each housing unit including semi-detached and high-rise, high-density units. Buffers were drawn on the radiuses of 240, 400, 600 and 1000 m from each unit by utilizing the QNEAT3 extension within QGIS program to produce a layer as below (Fig. 2). The data on road network were sourced from Open Street Map and included pedestrian-only paths, whereas streets that are inaccessible to walkers (i.e., motorways and motorway on- and off-ramps) were omitted prior to the analysis.

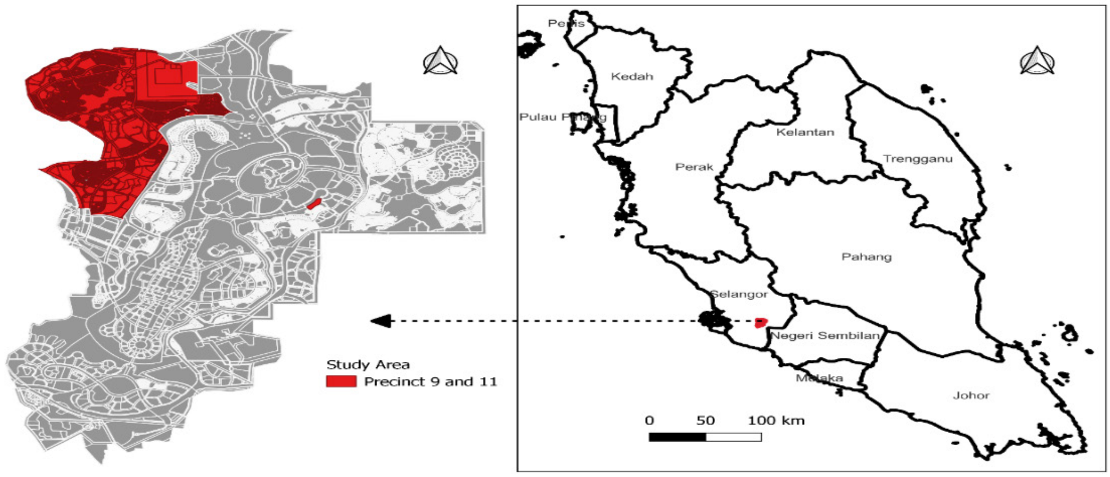

Fig. 1. Location of the study area: Malaysia, Putrajaya and the selected residential precincts
Source: own elaboration based on IPLAN data

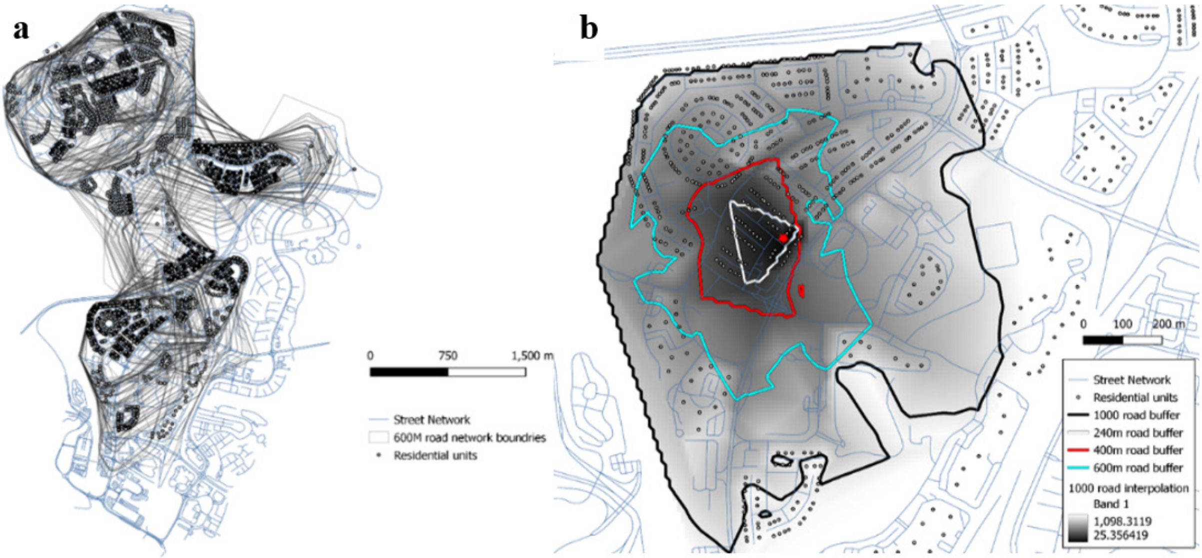

Fig. 2. a) Multi-layered 600-m buffers for 2,392 housing units. b) Example of multi-buffering boundaries at 240 m, 400 m, 600 m, and 1000 m network buffers (Precinct 9)
Source: own elaboration based on Putrajaya's OSM data

2.2. Syntactic measures

The axial map of Putrajaya was generated based on a road map sourced from OpenStreetMap (www.openstreetmap.org), which was then subjected to several cleaning processes. The Space Syntax Toolkit extension within the QGIS program was used to calculate the angular measures of accessibility (integration and choice). To calculate the mean integration and choice values for each buffer, the sum of the values obtained for each street segment was divided by the total surface area of the buffer, enabling a more refined analysis. Angular analysis was performed at different levels (global and local), and different radii (240, 400, 600 and 1000 meters), as shown in the table below.

Table 1. Levels of analysis and unit areas included in this study

Level of analysis	Unit area
Global integration and choice	Entire city network
Local integration and choice	240 m network buffer
	400 m network buffer
	600 m network buffer
	1000 m network buffer

Source: own elaboration

2.2.1. Angular integration

The integration measure used in this study is an indication of how close a street segment is to other segments, which does not reflect the metric distance between the segments; instead, it is a sum of the turns and angles needed to move to the destination based on the assumption that individuals tend to minimise turns during travel. Angular integration was considered in this study using the following equation:

$$D_\theta^{\,-} = \frac{1}{n}\sum_{i=1}^{n} D_\theta(x,i) \qquad (1)$$

Where, D_θ^- is the angular mean depth of a segment, n is the overall segment number, and D_θ is the angle of each turn divided by 90.

2.2.2. Angular choice

The choice measure quantifies the movement that is traversed through each segment on the shortest and simplest way to reach all other segments in the system. A high choice value of a specific street segment translates to high vehicular and pedestrian movement through that segment to reach different destinations. However, for this study, angular choice was measured according to the following equation:

$$B_\theta(x) = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\sigma(i,x,j)}{(n-1)(n-2)/2} \qquad (2)$$

Where i≠x≠j. (i = origins, j = destinations).

2.3. Metric measures

Data on destinations were obtained from the Putrajaya land-use map provided by Malaysia's Department of Town and Country Planning, while data on the street network were obtained from Putrajaya's Open Street Map. Proximity was measured by calculating the metric distance, using the street network, from a housing unit to the closest destination of five types: commercial, schools, services, recreational and transport. The

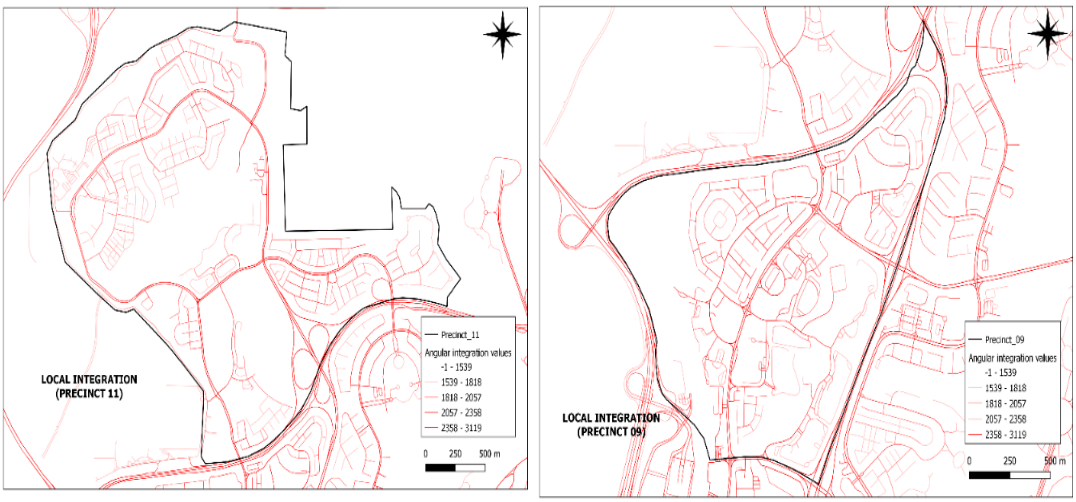

Fig. 3. Local integration analysis for Precinct 9 and 11: main arteries exhibit superior values over secondary and tertiary streets
Source: own elaboration

Qneat3 plugin was first used to convert vectorial maps of destinations into a network distance raster. This was repeated for each destination to understand accessibility grouping. Next, the metric network distance between each residential unit and the nearest destination was computed by converting the network distance raster value to points using sample raster values. This produced maps with residential points weighted according to the distances (Fig. 3).

2.4. Statistical analysis

Non-parametric analysis was employed due to the non-normal distribution of the data (Field et al., 2012). This study utilised the Spearman correlation coefficient to assess the correlation between syntactic accessibility (global/local integration and choice) and metric proximity at the selected scales of analysis (240, 400, 600 and 1000 m). Additionally, a series of multiple linear regressions was conducted to examine the impact of each syntactic metric (integration and choice) on the metric distances at various scales. Four models were created corresponding to each scale of analysis. Scatter plots of predicted values were employed to visualise the impact of syntactic measures on metric distances across the scales. To account for skewness, both exposure and outcome variables in the multiple regression analysis were logged.

3. Research results

3.1. Association between metric and syntactic proximity

According to the correlation table (Table 2), destination accessibility, as measured by network proximity to specific destinations, demonstrated a consistently negative association with global and local measures of configurations, with the exception of parks and recreational destinations, which have a high presence in the study area and thus resulted in less variation in distances and less correlation being detected. Overall, the correlation between distances to specific destinations and syntactic measures was stronger than others. For instance, network distance to commercial destinations showed a consistent negative association with syntactic measures of integration and choice across all scales of analysis (240, 400, 600 and 1000 m), with stronger values for local measures (LI_ $r=-0.363$, -0.360, -0.524, -0.687, LC_ $r=-0.220$, -0.376, -0.596, -0.604, $p<0.01$, respectively) (Table 2). This indicates that an increase in local integration and choice is associated with a shorter distance to commercial destinations, including shops, markets, restaurants, service shops, etc. However, as the scale expands, the correlation coefficient gains more power, which is attributed to the inclusion of more commercial destinations in the analysis.

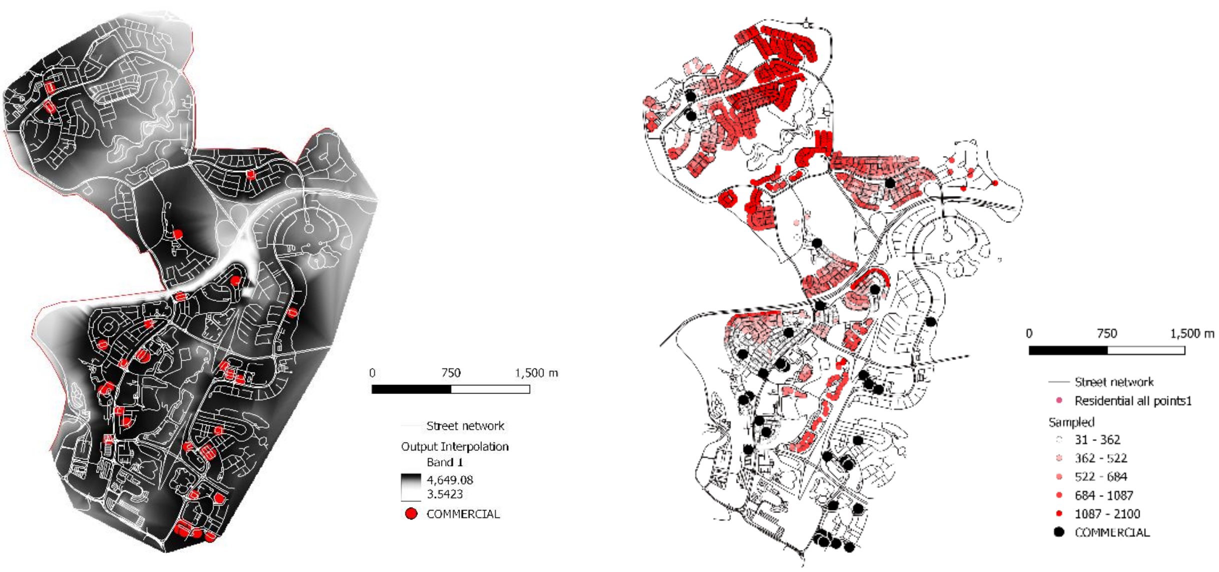

Fig. 4. Converting network distance raster value to point with weighted metric network distance (e.g., commercial distance)
Source: own elaboration based on Putrajaya OSM data

Table 2. The association between syntactic measures and destination accessibility across the scales of analysis

Distances		Scales of analysis			
		240m	400m	600m	1000m
Distance to school	GI	.042*	.045*	.054**	-.085**
	GC	-0.025	-.061**	-.081**	-.049*
	LI	-.070**	-.155**	-.403**	-.314**
	LC	-.129**	-.285**	-.465**	-.326**
Distance to parks and recreation	GI	.065**	.066**	.053*	.090**
	GC	-.067**	-0.001	0.029	.062**
	LI	-.251**	-.144**	.052*	.087**
	LC	-.164**	0.006	.208**	.191**
Distance to commerce	GI	-.289**	-.341**	-.355**	-.535**
	GC	0.039	-.052*	-0.016	-.383**
	LI	-.264**	-.334**	-.524**	-.687**
	LC	-.290**	-.376**	-.596**	-.604**
Distance to community facilities	GI	-.167**	-.177**	-.174**	-.082**
	GC	-.086**	-.152**	-.042*	0.005
	LI	-.363**	-.360**	-.349**	-.272**
	LC	-.220**	-.147**	-.175**	-.143**
Distance to transport	GI	-.602**	-.612**	-.584**	-.502**
	GC	-.346**	-.434**	-.368**	-.463**
	LI	-.060**	-.065**	-.283**	-.281**
	LC	-.116**	-.106**	-.314**	-.303**
Average distance to destinations	GI	-.292**	-.317**	-.312**	-.359**
	GC	-.120**	-.208**	-.124**	-.237**
	LI	-.363**	-.405**	-.550**	-.525**
	LC	-.317**	-.338**	-.485**	-.431**

Correlation is significant at ** p<0.01. * p<0.05, p>0.05 level (2-tailed) (L/GI or C= Local/Global Integration or Choice
(Source: research findings)

The network distance to transportation has a negative correlation with syntactic measures of an area. However, when compared to commercial destinations, global measures have higher correlation values than local measures at all scales (240, 400, 600 and 1000 m) (GI_ r=−.602, −.612, −.584, −.502, GC_ r=−.346, −.434, −.368, −.463, $p<0.01$, respectively) (Table 2). This implies that proximity to bus stops is associated with high configurational properties. Houses close to bus stops are located in more highly integrated areas associated with having more options to move from one point to another.

Average distance to all destinations (commercial, school, community facility, transportation, and park and recreational) was consistently negatively correlated with local and global syntactic measures across all scales of analysis. However, local measures had a more significant association than global measures with integration correlation coefficients of r=−.363, −.405, −.550 and −.525, $p<0.01$, respectively, and local choice of r=−.317, −.338, −.485 and −.431, $p<0.01$, (Table 2). This means that a shorter distance to all destinations is associated with higher integration and choice. In other words, housing units located within a short distance to all five destinations (commercial, school, community facility, transportation, and park and recreational) are in a more highly integrated neighbourhood and have more options to reach these destinations compared to houses with longer average distances. These findings also highlight the importance of local measures in detecting distance changes. Whereas global measures showed weak to moderate correlation coefficients with average distances, local measures produced more powerful results because distances in the neighbourhood fall within walkable intervals (400–800 m).

3.2. The impact of syntactical properties on distance distributions

Regarding the strength and direction of the impact of syntactical properties and certain destinations such as distance to commerce, the regression analysis showed that combined syntactic measures have a consistently increasing impact on distance to commerce across scales, with an adjusted R-squared of 0.282 at the 240 m scale, 0.413 at the 400 m scale, 0.458 at the 600 m scale and 0.512 at the 1000 m scale (Table 3). This corresponds to, for example, 51% of the variation in distances to commerce being explained by syntactic measures at the 1000 m scale. Additionally, this indicates a substantial impact of scale change on this association, which is illustrated in Figure 5.

Global and local integration consistently have a negative impact on the distance to commerce across the scales of 240, 400, 600 and 1000 m, with coefficients of –3.239, –3.879, –2.529 and –4.309 for global integration and –0.100, –0.219, –0.938 and –2.588 for local integration, respectively (Table 3). These findings are supported by the correlation results, highlighting the superior impact of integration measures compared to choice. For instance, an increase of one unit in global integration is associated with a 4.309% decrease in the distance to commercial destinations at the 1000 m scale. On the other hand, choice appears to only predict commerce distance at the local levels (Table 3). The choice measure at the global level might be more suitable for capturing broader patterns or trends in the transportation system, while distance to commerce could be influenced by more localised factors. Despite the minor impact, local choice shows that a variety of street options is related to a reduction in overall distances to all destinations. According to the same concept, this can be attributed to the high movement drawn to the segment with high choice and integration value within a street network. As a result, such integrated streets with high choices attract more mixed destinations, particularly commercial and services (Hillier et al., 1993), resulting in shorter distances to reach these destinations.

Regarding transportation destinations, the combined syntactic measures accounted for 32.3%, 32.7%, 29.2% and 21.7% of the variation in distance to transport across scales of 240, 400, 600 and 1000 m, respectively. This indicates that syntactic measures tend to have a greater impact on transport distance at smaller scales (Table 4). Global integration maintained a negative influence on distance to transport at all scales of analysis with unstandardised coefficients of β=–2.978, –2.789, –2.515 and –2.544, respectively, while local integration reported a smaller impact, particularly at scales 400 and 600 m (β=–0.263, –0.368) (Table 4). This clearly shows the superiority of global integration in explaining distance to transport, which is consistent with the correlation findings. Negative values indicate that less distance to bus stops is related to high integration properties. This means, for instance, that increasing one unit in global integration reduces the distance to bus stops by approximately 3% at a scale of 240 m, from which it can be concluded that houses close to bus stops are in areas characterised by high global integration. However, choice measures showed a similar trend for distance to commerce, as they were only predictors for transport distance at the local levels (Table 3).

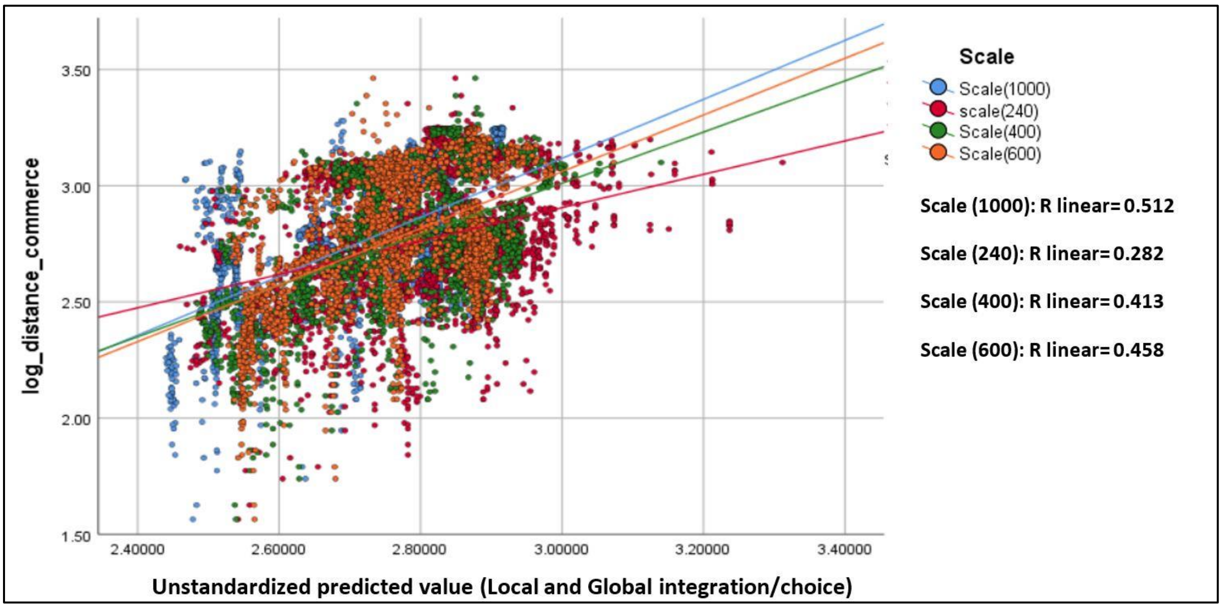

Fig. 5. Impact of syntactic measures on distance to commerce: a grouped scatterplot across multiple scales
Source: own elaboration based on regression results

Table 3. Impact of syntactic measures on distance to commerce: results of multiple linear regression across four scales

		Distance to commerce															
		Model (1) 240 m				Model (2) 400 m				Model (3) 600 m				Model (4) 1000 m			
		Coeff. B	Sta. Coeff.	t Stat	VIF	Coeff. B	Sta. Coeff.	t Stat	VIF	Coeff. B	Sta. Coeff.	t Stat	VIF	Coef. B	Sta. Coeff.	t Stat	VIF
Constant	Constant	**13.012***** (0.432)		30.098		**15.400***** (0.419)		36.761		**11.584***** (0.418)		27.697		**15.817***** (0.594)		26.625	
Syntactic measures	Log_Global integration	**-3.239***** (0.142)	-0.514	-22.811	1.693	**-3.879***** (0.141)	-0.633	-27.446	2.166	**-2.529***** (0.145)	-0.367	-17.463	1.949	**-4.309***** (0.246)	-0.738	-17.495	8.703
	Log_Global choice	**0.282***** (0.015)	0.448	19.308	1.795	**0.321***** (0.016)	0.477	19.708	2.384	**0.316***** (0.018)	0.378	17.561	2.044	**0.637***** (0.038)	0.641	16.733	7.19
	Log_Local Integration	**-0.100***** (0.059)	-0.050	-1.698	2.933	**-0.219***** (0.065)	-0.096	-3.388	3.261	**-0.938***** (0.092)	-0.472	-10.216	9.439	**-2.588***** (0.130)	-1.125	-19.854	9.717
	Log_Local Choice	**-0.310***** (0.028)	-0.326	-11.204	2.819	**-0.412***** (0.028)	-0.405	-14.923	3.005	**-0.109**** (0.044)	-0.114	-2.504	9.180	**0.633***** (0.052)	-0.665	12.291	9.351
Adjusted R^2			0.282 (0.228)				0.413 (0.206)				0.458 (0.198)				0.512 (0.187)		

Standard errors are in parenthesis *** p<0.01, ** p<0.05, * p<0.1
Source: research findings

Table 4. Impact of syntactic measures on distance to transport: results of multiple linear regression across four scales

		Distance to Transport															
		Model (1) 240 m				Model (2) 400 m				Model (3) 600 m				Model (4) 1000 m			
		Coeff. B	Sta. Coeff.	t Stat	VIF	Coeff. B	Sta. Coeff.	t Stat	VIF	Coeff. B	Sta. Coeff.	t Stat	VIF	Coeff. B	Sta. Coeff.	t Stat	VIF
Constant	Constant	**12.566***** (0.338)		37.221		**12.138***** (0.361)		33.653		**11.669***** (0.385)		30.342		**10.750***** (0.602)		17.866	
Syntactic measures	Log_Global integration	**-2.978***** (0.111)	-0.588	-26.864	1.693	**-2.789***** (0.122)	-0.566	-22.922	2.166	**-2.515***** (0.133)	-0.454	-18.889	1.949	**-2.544***** (0.249)	-0.544	-10.199	8.703
	Log_Global choice	**0.040***** (0.011)	0.079	3.509	1.795	0.012* (0.014)	0.021	0.829	2.384	0.010* (0.017)	0.015	0.626	2.044	0.070* (0.039)	0.088	1.806	7.19
	Log_Local Integration	**0.228***** (0.046)	0.144	4.990	2.933	**-0.263***** (0.056)	-0.143	-4.735	3.261	**-0.368***** (0.084)	-0.230	-4.354	9.439	0.334* (0.132)	0.181	2.527	9.717
	Log_Local Choice	**-0.187***** (0.022)	-0.244	-8.646	2.819	**-0.213***** (0.024)	-0.260	-8.955	3.005	0.032* (0.040)	0.041	0.791	9.180	**-0.155***** (0.052)	-0.204	-2.976	9.351
Adjusted R^2			0.323 (0.178)				0.327 (0.117)				0.292 (0.182)				0.217 (0.190)		

Standard errors are in parenthesis *** p<0.01, ** p<0.05, * p<0.1
Source: research findings

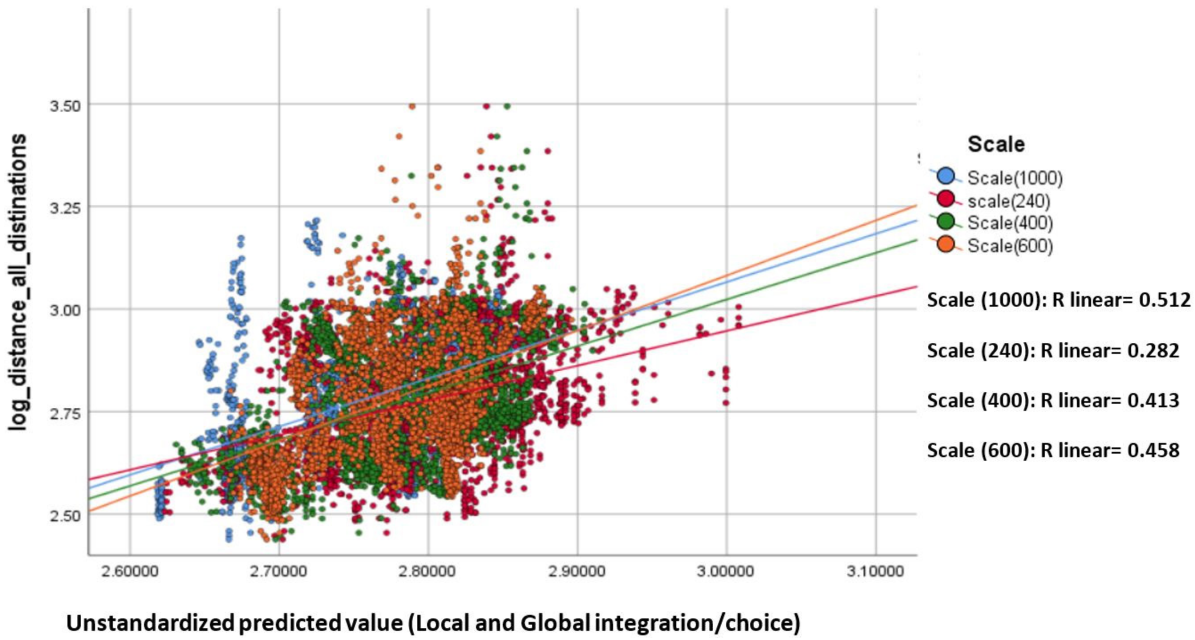

Fig. 6. Impact of syntactic measures on average distance to all destinations: a grouped scatterplot across multiple scales
Source: own elaboration based on regression results

Finally, when considering the average distance to all destinations (including commercial, schools, community facilities, parks and transport), the combined syntactic measures of integration and choice demonstrated an increasing explanatory power with the expansion of scales. They accounted for 19.6%, 24.0%, 32.4% and 34.6% of the variation in average distance to all destinations across scales of 240, 400, 600 and 1000 m, respectively (Table 5). These findings are consistent with the previous correlation analysis. The regression model of average distances to all destinations gained more power as the scales increased, mainly due to the inclusion of more destinations in the analysis (Fig. 6).

Regarding model variables, local integration consistently had a negative impact on the average distance to destinations. The negative impact indicates that increasing syntactic properties is associated with a decrease in the average distance to destinations. Consistently, global integration had the highest negative impact on average distance at scales 240 and 400 m (β=−1.159, −1.105, respectively) (Table 5), while local integration achieved the maximum impact at scales 600 and 1000 m (β=−1.042, −1.822, respectively). This indicates that local integration is more reliable in explaining network distances because the averages in the study area mostly lie between 600 and 1000 m (Table 5). Choice measures, on the other hand, had a mixed impact on average distances, with local choice sustaining a negative influence at all scales, with a maximum value at scale 1000 m (β=−0.703). This means that increasing one unit in local choice is associated with a 0.703% decrease in the average distance to all destinations. Generally speaking, these findings align with the principles of natural movement theory, where the location of attractions is a by-product of movement resulting from the configurational properties of the street network (Hillier, 1996). Consequently, travel distances to these destinations were shorter in areas with well-integrated streets.

4. Discussion

This study aimed to test the association between metric-network proximity and two accessibility measures of space syntax at multiple geographical scales. Using several statistical analyses, the results support the idea that the spatial properties of urban form have a significant impact on distance distributions within residential settings. Specifically, the study found that distances to commercial areas, transportation and average distances to all destinations were affected by the syntactical properties of the neighbourhood. Moreover, global measures were more powerful in detecting metric-distance changes compared to local measures. The findings also suggest that choice measures are less important than integration for predicting the

Table 5. Impact of syntactic measures on distance to all destinations: results of multiple linear regression across four scales

		Distance to commerce															
		Model (1) 240 m				Model (2) 400 m				Model (3) 600 m				Model (4) 1000 m			
		Coef. B	Sta. Coeff.	t Stat	VIF	Coef. B	Sta. Coeff.	t Stat	VIF	Coef. B	Sta. Coeff.	t Stat	VIF	Coef. B	Sta. Coeff.	t Stat	VIF
Constant	Constant	13.012*** (0.432)		30.098		15.400*** (0.419)		36.761		11.584*** (0.418)		27.697		15.817*** (0.594)		26.625	
Syntactic measures	Log_Global integration	-3.239*** (0.142)	-0.514	-22.811	1.693	-3.879*** (0.141)	-0.633	-27.446	2.166	-2.529*** (0.145)	-0.367	-17.463	1.949	-4.309*** (0.246)	-0.738	-17.495	8.703
	Log_Global choice	0.282*** (0.015)	0.448	19.308	1.795	0.321*** (0.016)	0.477	19.708	2.384	0.316*** (0.018)	0.378	17.561	2.044	0.637*** (0.038)	0.641	16.733	7.19
	Log_Local Integration	-0.100*** (0.059)	-0.050	-1.698	2.933	-0.219*** (0.065)	-0.096	-3.388	3.261	-0.938*** (0.092)	-0.472	-10.216	9.439	-2.588*** (0.130)	-1.125	-19.854	9.717
	Log_Local Choice	-0.310*** (0.028)	-0.326	-11.204	2.819	-0.412*** (0.028)	-0.405	-14.923	3.005	-0.109** (0.044)	-0.114	-2.504	9.180	0.633*** (0.052)	-0.665	12.291	9.351
Adjusted R^2			0.282 (0.228)				0.413 (0.206)				0.458 (0.198)				0.512 (0.187)		

Standard errors are in parenthesis *** p<0.01, ** p<0.05, * p<0.1
Source: research findings

distance to destinations. In this sense, syntactic measures were shown to be not only a street-related measure but also a functional measure that can represent several aspects of the built environment, such as the distribution of land uses and distance to destinations. This aligns with the natural movement hypothesis, which states that "attractors", especially commercial land uses, are driven by the configurational aspects of the space layout, as they tend to locate themselves in configurational hotspots to take advantage of movement (Hillier & Hanson, 1984). As a result, the travel distance to certain attractions is shorter between two points in areas with well-integrated streets.

Overall, the findings of this research align with previous empirical studies that have demonstrated a significant impact of street network configurations on the distribution of travel distances to commercial (Kim & Sohn, 2002; Porta et al., 2012; Tsou & Cheng, 2013; Rui & Ban, 2014; Wang et al., 2014; Liu et al., 2016) and transport destinations (Jun et al., 2006; Carpio-Pinedo, 2014; Saari, 2019; Lee et al., 2020). However, while the street network configuration may have a strong influence on commercial distance distribution, it appears to be a less dominant factor in the case of parks and recreational areas in Putrajaya. As mentioned earlier, it is well established that the relationship between topological and metric distances can converge or diverge depending on the type of network grid (Batty, 2022). In more grid-like networks with evenly spaced and interconnected streets, the topological and metric distances tend to align closely, meaning that traveling a certain distance along the network corresponds to a similar metric distance. However, in irregular or fragmented network grids such as Putrajaya, the topological and metric distances can diverge. This means that shorter topological distances on the network may not necessarily correspond to shorter metric distances. This divergence can impact the association between street network configurations and distances to specific destinations like parks and recreational areas. In the case of such destinations, they may not be primarily attracted to the flow or movement created by high syntactical properties of the street network. Consequently, the location of these attractions could be found in close metric distances but in less integrated areas.

Putrajaya is a non-gridded city characterised by a dendritic hierarchy of urban streets where there are a few main arteries that connect different parts of the city (Fig. 7). These arteries are surrounded by a network of smaller streets, resulting in a limited number of possible routes between any two points at the micro-scale and the high presence

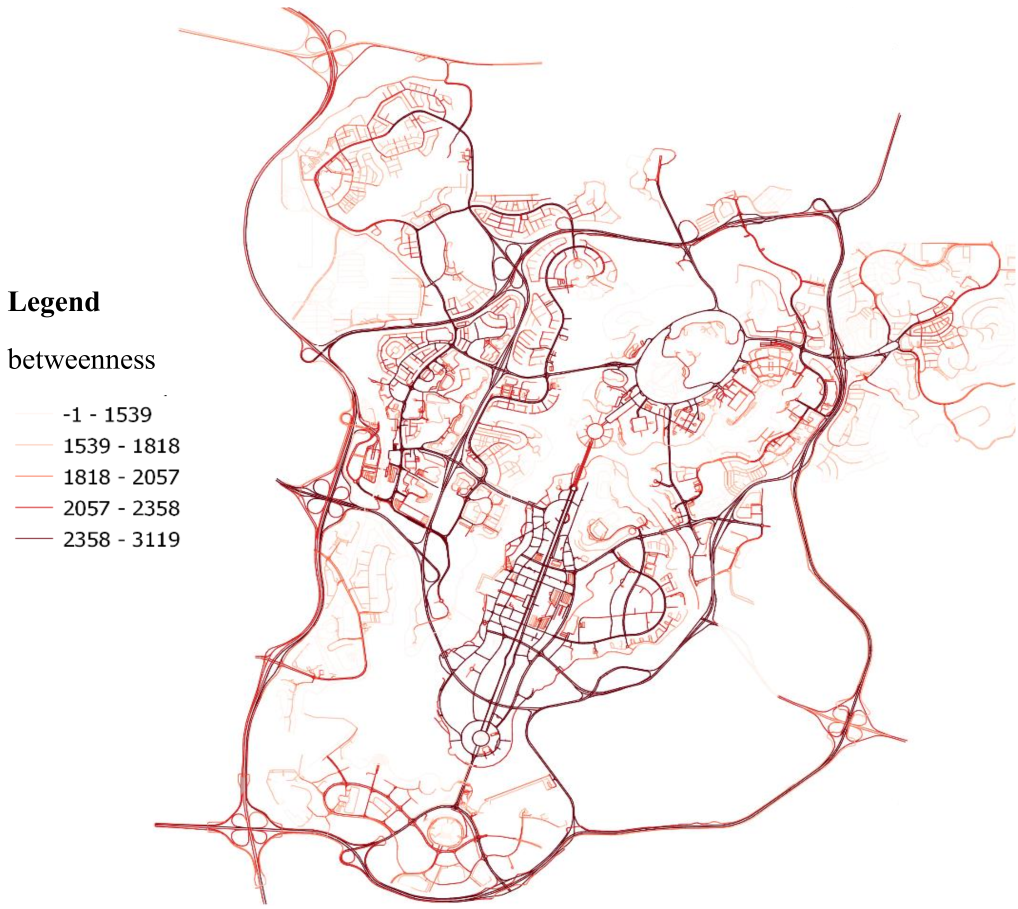

Fig. 7. The global integration of Putrajaya shows its hierarchical street network, where main arteries serve as vital connections linking different parts of the city
Source: own elaboration based on space syntax analysis

of cul-de-sacs. Some research has suggested that networks with a high degree of connectivity (e.g., gridded pattern) exhibit a stronger correlation between topological and metric distance compared to networks with low connectivity (e.g., dendritic pattern) (Wagner, 2008; Feng & Peponis, 2021). To support this point, a separate correlation analysis was conducted between connectivity and syntactic measures at multiple levels. The findings presented in Table 2.1 demonstrate a weak association of global syntactic measures in comparison to the local ones, particularly at the small scales of 240, 400 and 600 m. This weak association can be attributed to the influence of the overall syntactic properties of the system on the studied areas. Putrajaya's residential neighbourhoods are characterised as being located in relatively unintegrated areas compared to the city's core precincts (e.g., precincts 2 and 3). Therefore, the global integration values do not necessarily imply the conventional connectivity measures (intersection density, street density, block size).

The key findings suggest insightful implications for academic and professional communities. First, the application of a syntactical approach can provide an accurate characterisation of the spatial accessibility of the built environment in terms of pedestrian movement, making syntactical measures a valuable surrogate for network-based distances. While the most commonly used measure of proximity – distance to destination – calculates physical network or zonal distance to amenities, it fails to capture the topological dimension of the network and the pedestrian experience. This limitation hinders the prediction of behaviour in translating research results on the role of the street network in walking activity into practice. In contrast, syntactical measures offer improved predictions of pedestrian movement in relation to distance, emphasising their usefulness in understanding and promoting walkability.

The findings suggested that proximity to commercial destinations such as shops, markets and restaurants is associated with higher local integration

Table 6. Association between syntactic measures and design constructs across the scales of analysis

Scale	Intersection density				Street density				Block size			
	GI	GC	LI	LC	GI	GC	LI	LC	GI	GC	LI	LC
240m	.065**	.184**	.510**	.427**	.108**	.221**	.354**	.265**	-.149**	-.199**	-.178**	-.272**
400m	.195**	.150**	.575**	.462**	.246**	.175**	.334**	.109**	-.043*	-.234**	-.135**	-.324**
600m	.311**	.148**	.685**	.631**	.316**	.160**	.330**	.154**	-.089**	-.155**	-.307**	-.464**
1000m	.496**	.336**	.807**	.769**	.503**	.345**	.647**	.522**	-.104**	-.027	-.533**	-.753**

**Correlation is significant at the 0.01 level (2-tailed)

Source: research findings

and choice. Therefore, policies that prioritise the development of mixed-use neighbourhoods with easy access to a variety of destinations may consider spatial accessibility by focusing on the syntactical properties of targeted areas, which provide a cost-effective, evidence-based approach for planning interventions that reinforce movement and provide more walkable and integrated neighbourhoods.

- Design neighbourhoods with well-integrated street networks. As mentioned above, well-integrated street networks can improve destination accessibility. This can be done by designing neighbourhoods with a mix of different street types, such as cul-de-sacs, dead-ends and through streets. This will help to create a more connected street network that is easier for people to navigate.
- Locate commercial land uses in configurational hotspots. As mentioned above, commercial land uses tend to locate themselves in configurational hotspots. This means that these land uses are more likely to be found in areas with well-integrated street networks. By locating commercial land uses in these areas, we can make it easier for people to access them.

One limitation of the conducted study must be mentioned: data on syntactic measures are particularly sensitive to any boundary changes (Turner, 2007). The cartography of the spatial layout obtained from the Open Street Map (OSM) may have an influence on the results of this study. Although several network correction and trimming processes were carried out, the final street map may contain some "noise" because the line segments are artefacts of the way the street map was digitised. Future studies may consider expanding the system's boundaries to 3–5 kilometres to better handle edge effects on analysis (Berhie, 2016).

5. Conclusion

This study examined the relationship between metric-network proximity and space syntax measures of accessibility in residential areas. The findings revealed that the spatial properties of urban form significantly influence the distribution of distances within neighbourhoods. Distances to commercial areas, transportation and overall destinations were affected by the syntactical properties of the neighbourhood. Global measures demonstrated more sensitivity to metric-distance changes compared to local measures. The study also highlighted the importance of integration over choice measures in predicting distances to destinations. Syntactical measures were found to be not only street-related but also functional, capturing aspects like land-use distribution and distance to amenities. These findings aligned with the natural movement hypothesis, emphasising the influence of configurational aspects on the location choices of commercial land uses. However, in the case of parks and recreational areas in Putrajaya, street network configurations had a less dominant impact, suggesting a divergence between topological and metric distances. The study recommended designing well-integrated street networks, locating commercial land uses in configurational hotspots and planning for future growth with accessibility in mind. By using syntactical measures as surrogates for network-based distances, researchers and practitioners can enhance spatial accessibility and promote walkability in urban environments. Overall, this research contributes valuable insights into the relationship between urban form, spatial accessibility and pedestrian movement, offering implications for academic and professional communities.

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