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The influence of spatial configuration on pedestrian movement behaviour in commercial streets of low-density cities

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A R T I C L E I N F O

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A B S T R A C T

This research investigates the interplay of spatial arrangement and pedestrian behaviour in Toowoomba City Centre, a low-density city in Australia, using a combination of quantitative and qualitative analysis through Space Syntax. In contrast to high-density and medium-density areas where street connectivity typically drives movement patterns, this study emphasises the significant roles of both syntactical factors and land-use mapping in low-density contexts. The study identifies a correlation between pedestrian activity and land-use mapping and compatibility in low-density areas, advocating for strategic land-use planning within a 150–320-metre radius. It demonstrates that while traditional syntactic metrics are relevant, pedestrian movement in low-density areas is more significantly influenced by land-use diversity and compatibility during daytime hours (1–3 PM). Both syntactical factors and land-use are also crucial for attracting pedestrians during evening and night hours (6–8 PM). These findings highlight the importance of place-making strategies to foster vibrant, pedestrian-friendly environments.

1. Introduction

Central business centres of cities have evolved beyond being mere shopping destinations into multifaceted spaces that attract pedestrians to tourist attractions [1], recreational areas [2], and hubs for public transportation [3]. The dynamics of urban spaces have evolved significantly in recent years, particularly in low-density cities where sprawling streetscapes and commercial areas define the urban experience. When the city centre is designed with appropriate land-use conditions and incorporates initiatives to improve pedestrian facilities, it can support sustainable modes of transportation and even positively influence pedestrians' choice of travel mode [4]. Low-density urban areas often lack pedestrian-friendly mixed land-use, leading to increased travel distances and a reliance on cars. The separation of residential, commercial, and industrial areas contributes to a car-dependent lifestyle, as residents must travel substantial distances for work, shopping, and leisure activities. Furthermore, there is a correlation between pedestrians' rate of walking activity and cities' densities [48,49].

Literature in the domain of pedestrians' behavioural pattern and walking pattern through urban layouts includes studies by Stea [5], Lee et al. [6], Portugali [7], Kim and Penn [8], Heft [9], Olazabal and Pascual [10], Eldiasty et al. [11], and Bruns and Chamberlain [12]. Extensive research in the field of urban behaviour highlights significant connections between behavioural occurrences in urban spaces, movement patterns, and the overall sense of pedestrians' environmental satisfaction [13,14–18]. This has led to the development of quantitative theories and methodologies aimed at comprehending and modelling the intricate relationship between spatial configurations and social behaviours [19]. Human walking behaviour within urban layouts can be predicted utilsing Space Syntax techniques specifically for mixed-use urban areas such as city centres with diverse population densities. A spatial configuration analysis reveals a significant correlation between this pattern in a physical setting, and a spatial configuration analysis [24,25].

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Extensive research has primarily focussed on movement patterns and individuals' behaviour through the application of Space Syntax [34,35], as well as individuals' spatial perception [36,41], in high-density city centres such as Kuala Lumpur, Shanghai, Barcelona, Beijing, and Tehran [27–33]. Cities with a moderate population density, such as Oporto, Brisbane, and Melbourne, have also been subject to comprehensive research efforts. These studies predominantly focus on all aspects of the socio-spatial experience within moderate-density cities, namely movement patterns, individuals' behaviour, and spatial perception [20,42–47]. Previous studies have noted the challenges faced by low-density cities, such as long commute times, car dependency, and a lack of mixed land-use and connectivity [26]. The lack of connectivity between different land uses further exacerbates these issues, resulting in less vibrant pedestrian environments [93]. Although studies on pedestrian behaviour in low-density cities are relatively sparse compared to those in high-density areas, some research highlights the importance of spatial configuration and land-use compatibility in shaping pedestrian movement. For example, Gunn et al. [94] demonstrated that strategic placement of amenities and improved connectivity can enhance walkability even in lower-density environments. This underscores the need for purposeful place-making strategies based on compatible land-use to foster vibrant, pedestrian-friendly environments. Additionally, Ewing and Cervero [95] found that low-density development patterns can negatively impact walkability and public health outcomes, with the lack of mixed land-use and connectivity contributing to less vibrant pedestrian spaces [96]. Understanding the specific dynamics of pedestrian movement in low-density cities is crucial for urban planners and policymakers. For instance, Koohsari et al. [93] used space syntax to characterize the built environment and its impact on walkability, providing insights into how urban design can influence pedestrian behaviour in low-density settings.

Despite advancements in understanding pedestrian movement in denser environments, there is a significant research gap in low-density cities regarding pedestrian dynamics and spatial configuration. The literature often does not provide a holistic approach that combines real-time data with spatial metrics, leaving a gap in comprehensively understanding how various factors influence pedestrian behaviour in low-density city contexts. Only a handful of studies, such as those by Atakara and Allahmoradi [50] and Şahin [51], have addressed aspects like connectivity and accessibility, primarily through mathematical analysis of the urban environment, rather than comparing these results with real-time observations and monitoring. These efforts primarily focus on network analysis and lack a comprehensive approach to investigating pedestrian movement patterns and preferences in low-density areas.

To address this research gap, this study aims to deepen the understanding of pedestrian movement patterns within low-density urban environments, going beyond focusing solely on the morphological aspects of the environment. Understanding the specific dynamics of pedestrian movement in low-density cities is crucial for urban planners and policymakers. Gaining insights into how pedestrians interact with urban spaces in these environments can help formulate strategies to create more vibrant and walkable areas. This, in turn, can significantly enhance the livability of low-density cities by making them more attractive to pedestrians. The main aim of this study is to provide a comprehensive understanding of pedestrian movement patterns in low-density urban environments. This involves investigating street connectivity and integration metrics while simultaneously analysing land-use patterns. The study compares actual pedestrian behaviour with these metrics and maps to assess how various factors influence pedestrian movement patterns in the city centres of low-density cities. Specifically, the research seeks to answer the following key questions:

- How does spatial configuration influence pedestrian behaviour patterns in the city centre of lower-density cities?
- How does the combination of spatial configurations and land-use most effectively enhance pedestrian movement and urban vibrancy in low-density city centres?

2. Theoretical framework

2.1. Wayfindng in urban space

Wayfinding involves navigating from an origin to a destination using paths and routes, guided by visual information [52,53]. Key elements influencing wayfinding behaviour include visual access, distinctiveness, layout arrangement, and signage [54]. Visual access refers to the ability to see various parts of a place from different viewpoints. Distinctiveness relates to how well different areas of an environment are differentiated, aiding in memory and navigation. A well-arranged layout simplifies wayfinding, while complex layouts can be confusing [54].

2.2. Behavioural patterns in urban layouts

Environmental psychology explores the complex relationship between humans and their surroundings. Unlike approaches that view the environment and individuals as separate entities, this field emphasises their interconnected nature [55]. It asserts that to fully understand environmental issues, one must investigate how people interact with their environments. This interplay influences observable behaviours, which are shaped by physical factors such as noise levels, environmental conditions, and the characteristics of enclosed spaces [56]. Spatial integration and differentiation are crucial in facilitating interactions and shaping behaviours in public spaces [57,59]. For instance, a case study by Askarizad and Safari in Rasht, Iran, illustrates how spatial configuration influences behavioural patterns in urban spaces. Their research focused on the pedestrian zone of Rasht Municipality Square, revealing that areas with higher spatial integration and differentiation facilitated more diverse social behaviours, demonstrating the practical application of environmental psychology principles in urban design [20]. In addition to this study, another detailed investigation by Askarizad and He in the city centre of Rasht explored the perception of spatial legibility and its association with human mobility patterns. They found that the spatial configuration of the historical districts significantly impacted pedestrian movement and social interactions. High legibility areas, characterised by clear visual access and distinct landmarks, encouraged more pedestrian activity and social engagement [37]. This study highlighted the importance of spatial design in enhancing urban livability and social dynamics, showing that well-integrated and legible urban spaces can foster vibrant pedestrian environments and facilitate social interactions [62].

2.3. Space Syntax and pedestrian movement

Space Syntax is a mathematical approach used to analyse how spatial arrangements influence social, cognitive, and experiential aspects of urban layouts [57]. It represents environments as graphs, where spatial features are transformed into nodes and links, allowing analysis of the impact of layout on pedestrian movement [22,58]. This method helps urban planners understand the relationship between spatial configurations and human behaviour, providing insights into the social implications of design choices [60]. In Space Syntax, an environment's layout is converted into a graph, where each line represents a node, and intersections between lines form links. Researchers have discovered significant correlations between specific graph indicators and both vehicular movement rates and pedestrian behaviour [61,62]. The "configuration of space" in Space Syntax involves transforming continuous spaces into networks of interconnected areas, enabling the identification of behaviour patterns and the assignment of cultural or symbolic significance to different space parts [63]. A key application of Space Syntax is examining spatial configuration to understand how people behave in unfamiliar environments [64]. This method challenges the simplistic division between "space-as-form" and "society-as-content," suggesting that social structures and spatial configurations are inherently linked [65,66]. Space Syntax reveals how spatial conditions correspond to human behaviour, offering valuable insights for urban design and planning. The present study employs Space Syntax to investigate pedestrian behaviour using a mixed-method approach. Table 1 provides an overview of relevant studies utilizing Space Syntax to explore pedestrian movement in various city centres. These studies, employing tools like field observation, GIS, GPS tracking, and surveys, highlight key findings such as the impact of mixed land-uses on movement behaviour, the need for improvements in pedestrian networks, and the influence of digital navigation on the pedestrian experience. Results emphasize factors like low slopes and high integration values in enhancing accessibility. While Space Syntax has been extensively used in high- and moderate-density cities, its application to low-density urban areas remains limited. This study aims to address this gap by applying Space Syntax to understand pedestrian movement patterns in low-density city centres.

3. Method and methodology

This study employed a mixed-methods approach, combining both quantitative and qualitative techniques to analyse the urban environment of Toowoomba City Centre. The methodologies integrated Space Syntax analysis, field observations, and ArcGIS mapping to provide a comprehensive understanding of pedestrian movement patterns and spatial arrangements. Space syntax serves as a methodology employed to analyse urban environments [66]. In addition to the Space Syntax method, field observations played a crucial role in strengthening the research implementation. Pedestrians' movement behaviour patterns heavily rely on visibility and spatial arrangements within urban settings [68]. The research methodology was augmented by the ArcGIS software, ensuring alignment with Space Syntax analysis and on-site observations. By integrating Space Syntax results and aligning them with individuals' movement behaviour in the field, the study delved into the intrinsic potential of spatial arrangements and topology, with the goal of enhancing physical activities for pedestrians. Fig. 1 illustrates the methodological framework, highlighting how these techniques were used in conjunction to assess the interplay between spatial configuration and pedestrian behaviour.

3.1. Field observation of individuals' movement behaviour within Toowoomba city Centre

Field observations encompass a range of techniques designed to study the flows of movement and individuals' movement patterns within urban settings [70]. To discern the behavioural patterns of individuals and attain a comprehensive understanding of activities in the city centre of Toowoomba, three distinct observation techniques focused on pedestrians were employed: Gate counts, people following, and GPS tracking. All observations were conducted during two specific time periods—between 1 PM and 3 PM (considered a busy period due to lunchtime activity and early afternoon shopping) and between 6 PM and 8 PM (capturing evening activity). These timeframes were chosen to ensure a representative sample of pedestrian behaviour, as they coincide with peak activity periods. The observations were conducted under stable weather conditions. This contrast between the afternoon and night observations allows researchers to examine how pedestrian behaviour might differ between daytime and nighttime conditions, providing insights into how lighting and other environmental factors influence movement patterns. Additionally, the observations were carried out on both weekdays and weekends to capture differences in pedestrian density under varying circumstances.

Table 1
A summary of research using Space Syntax as an integrated approach within City centres.

Study	Methods	Effective variables	Location	Density	Key findings
Mansouri and Ujang [27]	Field observation: *(Observation tool)*	Connectivity	Kuala Lumpur, Malaysia	High density	The varied place uses, and street activities enhance city centre walkability.
Jabbari *et al* [42]	GIS: *(Technology-based tool)*	Connectivity/ Network	Oporto, Portugal	High density	Pedestrian network issues highlight the need for urban planning improvements.
Vaez *et al* [43]	GPS tracking and voice recording: *(Technology-based tools)*	Wayfinding	Brisbane, Australia	Moderate density	Diverse digital navigation options are needed to enhance the pedestrian experience.
Şahin [51]	GIS: *(Technology based tool)*	Accessibility	Çankırı City, Turkey	Moderate density	Streets with low slopes and high integration values are the most accessible.
Fan *et al.* [28]	GIS: *(Technology based tool)*	Accessibility	Shanghai, China	High density	Traffic stations and people flow significantly influence hotel distribution.
Rismanchian and Bell [29]	ArcGIS: *(Technology-based tool)*	Regeneration	Tehran, Iran	High density	The study demonstrated that an evidence-based approach can identify essential spatial patterns, offering a cost-effective foundation for creating a pedestrian-friendly street network to alleviate spatial isolation in deprived areas.
Shatu *et al.* [45]	Survey, ArcGIS and virtual street audit tool: *(Observation, Participatory and technology-based tools)*	Route choice behaviour	Brisbane, Australia	Moderate density	Pedestrians prefer routes with minimal directional changes.
Fang *et al* [30]	Photographed and recorded: *(Observation tool)*	Pedestrian density/ Remodelling	Shanghai, China	High density	Factors influencing commercial pedestrian density are identified.
Atakara and Allahmoradi [50]	GIS: *(Technology-based tool)*	Network	Famagusta, Cyprus	Moderate density	Specific findings related to syntactic analysis and the city's growth process are examined.
Nourian *et al.* [31]	SNA: *(Technology-based tool)*	Accessibility	Lisbon, Portugal	High density	Model utility validated with crowd-sensed human mobility data for assessing urban mobility plans.
Wang [32]	GIS: *(Technology-based tool)*	Designing /Redesigning:	Beijing, China	High density	Century-long analysis of old Beijing's street network highlights enduring grid-like structure.
Gath-Morad *et al* [41]	GPS tracking and survey: *(Technology-based and participatory tool)*	Environmental factors/ Perceptions/ Urban design	Tel Aviv, Israel	High density	Factors influencing route choice in leisure walks emphasise the complexity of walking environments.
Zhang *et al* [33]	Fieldwork observation: *(Observation tool)*	Network	Hangzhou, China	High density	The importance of pedestrian permeability in Chinese urban contexts and the impact of car dependency on walkability are emphasised.

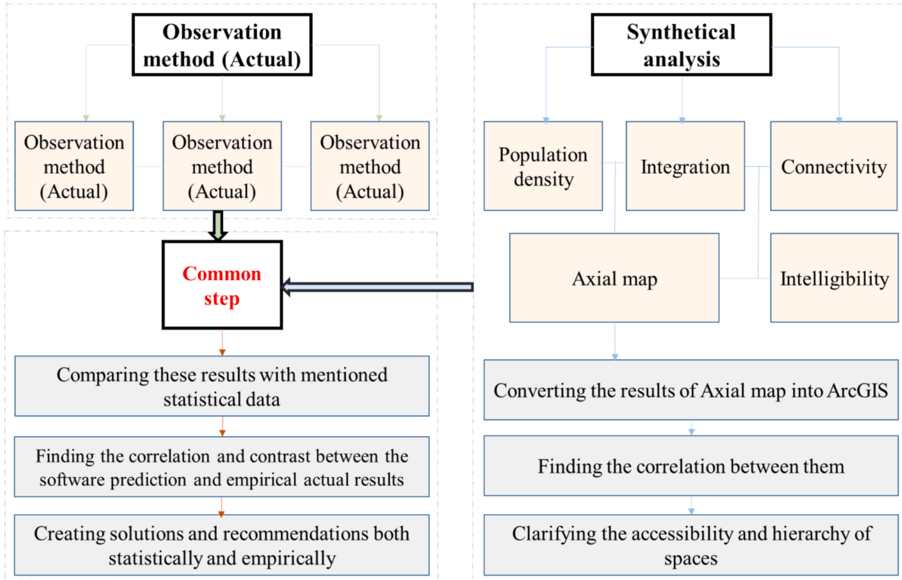


Fig. 1. A detailed breakdown of the research process, including data collection, analysis, and spatial techniques.

3.1.1. People tracing and GPS tracking for investigating individuals' movement behaviour within Toowoomba city Centre

Observing movement flows from a specific focal point is a critical technique known as people tracing, applicable in both urban layouts and architectural spaces. To maintain objectivity in interpreting movement behaviours, observers randomly selected individuals at the start of their journey from a predefined starting point and tracked their routes. This technique is particularly advantageous for comparing movement behaviours from specific points within a layout [70]. A hybrid approach was employed to capture intricate details of pedestrian movement, combining empirical people-following techniques with GPS tracking technology using the Relive app on smartphones. The investigator discreetly followed pedestrians from the primary entrances of the Grand Central Shopping Centre, specifically gates 2 and 5. Gates 2 and 5 were selected for their high pedestrian activity and strategic importance within the commercial layout. As shown in Fig. 2, these gates were strategically chosen for tracking pedestrian flows in and around the shopping centres. A total of 400 individuals were tracked—50 from each gate during different times, including weekday afternoons and weekend evenings—while activating real-time GPS tracking to prevent any potential alteration in behaviour due to awareness of being tracked. Handheld GPS data loggers provided detailed information on locations visited, duration of stay, and walking distances, aiding in identifying areas prone to congestion [71]. This combination of People tracing and GPS Tracking allowed for comprehensive data collection on pedestrian patterns from the selected gates, ensuring accurate movement tracking. In the sample selection process, only adults were considered, specifically excluding children to focus on the movement behaviours of the adult population. Both men and women were included, ensuring a balanced representation of adult pedestrians. This approach allows for a more accurate analysis of pedestrian dynamics, as adults typically exhibit distinct movement patterns compared to children. This method ensured natural and authentic behaviour by keeping participants unaware of the tracking, thereby enhancing the reliability and accuracy of the results and offering a genuine representation of everyday pedestrian movements within Toowoomba City Centre.

3.1.2. Gate counting for investigating individuals' movement behaviour within Toowoomba city Centre

Gate counting represents a technique for assessing the pedestrians' density in an urban layout. This method allows investigators to catch a significant volume of data, which can be visually depicted or subjected to statistical analysis. To understand how pedestrian movement patterns, align with spatial configurations, the gate Counting data—which captures the density of pedestrian activity—was correlated with several key Space Syntax variables, including:

- **Integration**: Refers to the degree to which a space is connected to all other spaces in the system. Higher integration values indicate spaces that are more accessible and likely to attract greater pedestrian movement [58]

Fig. 2. Study area gates: Overview and detailed view. (A). Gates (entrances) studied around the shopping centre; (B). Zoomed-in view of selected gates.

- **Connectivity**: Refers to the number of immediate connections a space has with its neighboring spaces. Spaces with higher connectivity are often more accessible and experience higher pedestrian flows [58]
- **Intelligibility**: Measures how well the connectivity of individual spaces correlates with their overall integration into the layout. High intelligibility suggests that spaces are easy to navigate and understand, encouraging pedestrian movement [63].

When conducting these observations, specific locations across the study area are chosen deliberately. Observers position themselves strategically at the periphery of each gate to optimise their field of vision, tallying individuals crossing an imaginary line connecting different parts of the urban environment. As a result, this approach is recognised as a quantitative observational method. The selected gates encompass areas of varying usage, including well-utilised, moderately-utilised, and underutilised spaces within and around the study area boundaries [35]. For the field observations aimed at assessing the congruence between the simulated software model and reality, a total of 10 gates were chosen (Fig. 3A). Gate observations were conducted to provide a comprehensive understanding of pedestrian behaviour. Fig. 3B shows axial map analysis based on the spatial integration achieved from the Space Syntax method.

3.2. Space Syntax analyses in urban environment

The Space Syntax analysis utilises a spatial configuration approach to quantify the connections between the built environment and social behaviours, seeking to unveil the relationships between individuals' movement behaviours and the spatial arrangements within a given space [58,65]. At the heart of this theoretical framework is the exploration of how spatial arrangements influence the movement behaviour of pedestrians, with Space Syntax suggesting a connection between the built environment and social life [58]. Numerous studies consistently indicate a significant correlation between spatial configuration and behavioural patterns within the population [72]. According to the foundational principles of Space Syntax, space configuration is shaped through the direct interplay between space and individuals, resulting in the humanisation of the constructed space or the built environment [22,66]. Several research endeavours focused on urban design have affirmed the effectiveness of this approach for urban research [38–40,67,73–77].

3.3. Merging Space Syntax with land-use mapping through the ArcGIS for predicting individuals' movement behaviour within Toowoomba city Centre

The attributes of Space Syntax significantly influence the dynamics of natural movement [69]. Serving as the backbone of movement structure, spatial configuration features have the potential to entice individuals to linger in space and reap its advantages. In densely populated areas with distinct spatial configuration characteristics, functions tailored to answer the needs of a large population tend to aggregate, resulting in overcrowding, termed Movement Economy. Congestion in movement patterns affects the functionality of nearby features and often increases the value of neighbouring properties. Several studies have established a notable connection between spatial configuration, movement congestion, the nature and types of functions, and the value associated with adjacent properties [58,77–82].

The examination of spatial data has led to sophisticated approaches for analysing spatial patterns and processes. Despite the progress in geographic information systems (GIS), there is a crucial necessity to integrate them with innovative analytics and modelling techniques to enhance their effectiveness as robust tools in urban planning analysis. Analytical applications within GIS cover a broad spectrum, ranging from studying environmental phenomena to analysing regional and urban systems. Integrating the Space Syntax analytical tool into GIS provides substantial advantages, expanding the capabilities of urban morphological analysis within the GIS environment. Conversely, GIS delivers suitable spatial analysis and visualisation tools for exploring urban morphology. A network that intentionally fosters communication among its compatible uses can influence social interactions and behavioural patterns. Thus, paying careful attention to land-uses conducive to pedestrian activities is considered essential for improving the behavioural patterns of citizens. The process began with axial map analyses using Space Syntax, which generated key metrics such as Integration, Connectivity, and Intelligibility. These results were exported and brought into ArcGIS, where they were overlaid with land-use data from the study area, including the 320-meter radius around the Grand Central Shopping Centre. Land-use categories (e.g., residential, commercial, recreational) were then analyzed in ArcGIS to assess their relationship with pedestrian flow patterns. Using ArcGIS's spatial analysis tools, areas with mismatched land-use patterns that did not support pedestrian activity were identified. To compare pedestrian movement with spatial configuration metrics, pedestrian density data collected through gate counts and GPS tracking were analyzed against land-use categories and the syntactical results from Space Syntax. This comparison provided insights into how well-connected spaces facilitated pedestrian movement versus areas where land-use and spatial configuration hindered accessibility. By visualizing these spatial relationships within ArcGIS, the study was able to demonstrate how land-use compatibility and spatial integration influence pedestrian movement across different parts of Toowoomba's city centre during both weekdays and weekends.

3.4. The city of Toowoomba as a case study

In the Toowoomba's Central Business District (CBD), factors such as

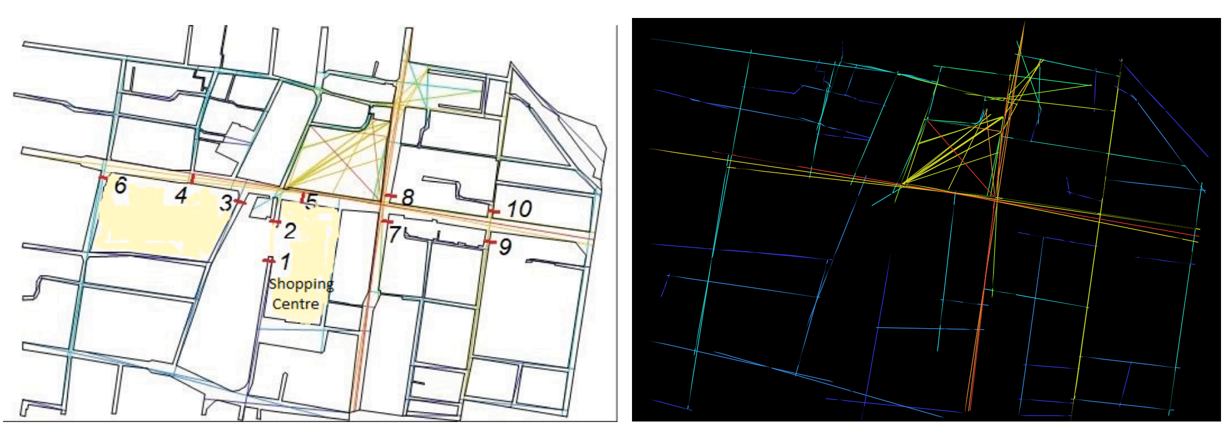


Fig. 3. **(A).** Specified gates for population density estimation in the studied area; **(B).** Axial map Analysis using spatial integration from the Space Syntax technique.

street connectivity and land-use distribution significantly influence pedestrian movement. The city's walkability is often limited by its low-density layout, which reduces the overall pedestrian experience. Weak urban arrangements in the CBD may reduce the appeal of walking streets and negatively impact livability [21]. Accessibility, particularly street connectivity and the location of spaces, plays an important role in how pedestrians interact with public areas [20]. Furthermore, Toowoomba has been as a case study as it has relatively low population density compared to larger Australian cities. Its urban layout is characterized by sprawling residential areas and lower-rise developments. Unlike high-density metropolitan areas, Toowoomba lacks significant vertical development in its CBD, contributing to its overall low-density classification. The city covers a large geographic area with a dispersed population, which is typical of low-density urban environments [23]. The spatial arrangement within the commercial streets of a low-population city named Toowoomba will be analysed and human movement behaviour will be monitored. Toowoomba is a city in the Toowoomba Region of Darling Downs, Queensland, Australia. To explore the mentioned issues, a 1-kilometer radius around the Grand Central Shopping Centre, including parts of Margaret and Ruthven Streets, has been selected as the study area, as shown in Fig. 4. This invetigation contributes to a broader understanding of how targeted urban design strategies can make walking streets more attractive in low-density urban environments.

4. Results

4.1. Pedestrian movement patterns

The analysis of pedestrian behavior, based on people-following using GPS tracking technology, reveals distinct patterns between weekday and weekend afternoons (1–3 PM) and evenings (6–8 PM) at gates 2 and 5 near the Grand Central Shopping Centre in Toowoomba. The data shows distinct pedestrian behavior patterns between weekday and weekend afternoons (1–3 PM), at gates 2 and 5 (Fig. 2B) near Grand Central Shopping Centre in Toowoomba (Table 2). On weekdays, pedestrians tend to travel shorter distances and spend less time walking compared to weekends. From gate 2, the average distance traveled on weekday afternoons is 198 m, with an average travel time of 6.6 min. In contrast, weekend afternoons see longer journeys, with an average distance of 321 m and travel time of 7.8 min. Similarly, from gate 5, weekday afternoon travel averages 150 m and 5.4 min, while weekend afternoons

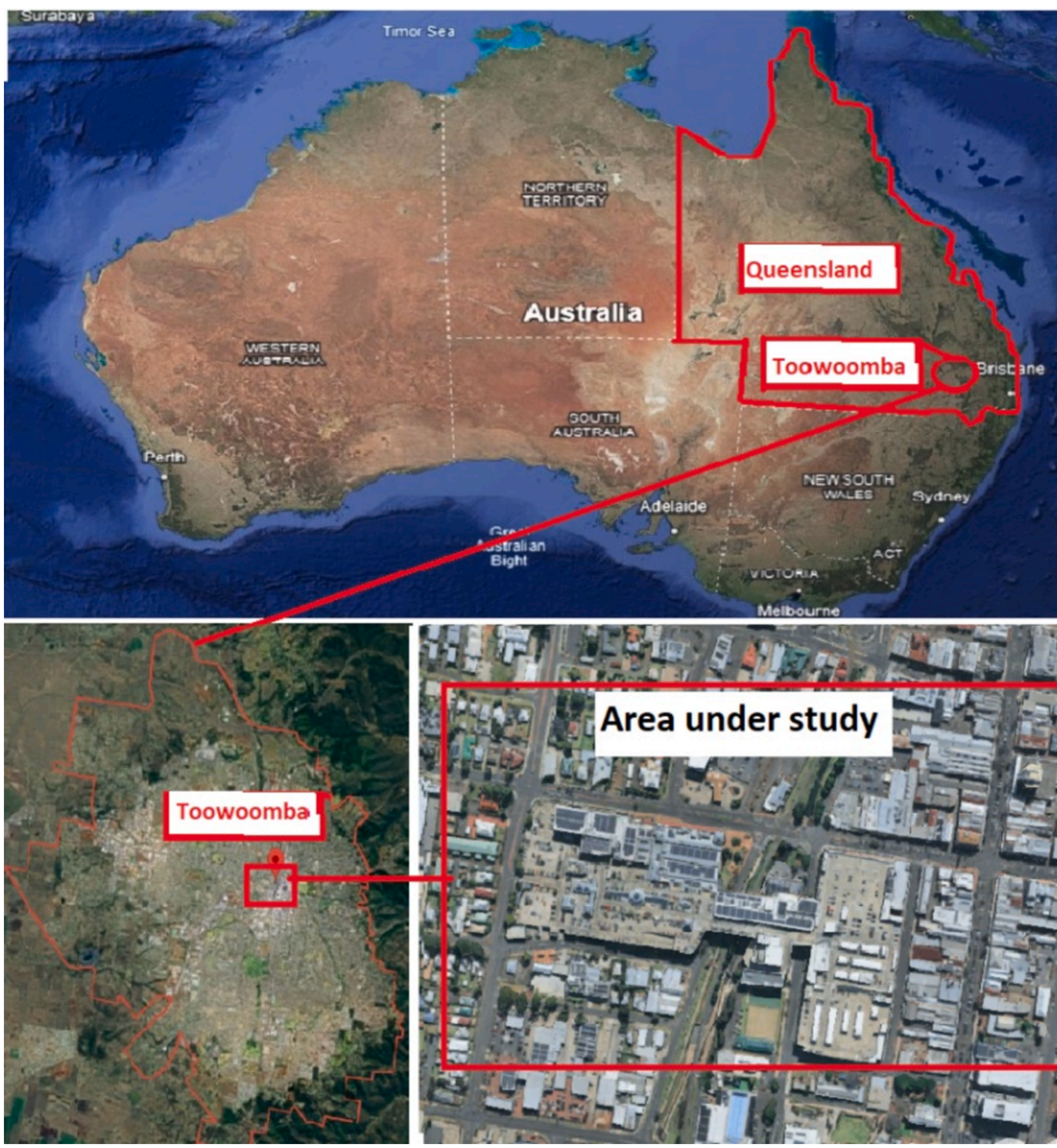


Fig. 4. Location of the Grand Central Shopping Centre within Toowoomba City Centre.

Table 2
Tracking pedestrian movement patterns across two main entrances of Central Shopping Centre.

Gate	Day Type	Time Period	Average Distance (m)	Highest Distance (m)	Average Travel Time (min)	Highest Travel Time (min)
Gate 2	Weekday	Afternoon	198 m	780 m	6.6 min	11.1 min
Gate 2	Weekday	Evening	155 m	650 m	4.8 min	9 min
Gate 2	Weekend	Afternoon	321 m	890 m	7.8 min	12 min
Gate 2	Weekend	Evening	181 m	620 m	5.4 min	9.6 min
Gate 5	Weekday	Afternoon	150 m	680 m	5.4 min	8.4 min
Gate 5	Weekday	Evening	124 m	580 m	4.2 min	6.6 min
Gate 5	Weekend	Afternoon	231 m	710 m	6 min	9.6 min
Gate 5	Weekend	Evening	225 m	700 m	6 min	10.8 min

show increased activity with average distances of 231 m and travel times of 6 min (Table 2).

During weekday evenings (6–8 PM), there is a noticeable decrease in both distances traveled and time spent walking compared to afternoons. From gate 2, the average distance traveled drops to 155 m, with an average travel time of 4.8 min. Gate 5 shows an even more pronounced reduction, with average distances of 124 m and travel times of 4.2 min. Conversely, during weekend evenings, the average distance traveled from gate 2 is 181 m with a travel time of 5.4 min, and from gate 5, it is 225 m with a travel time of 6 min. These observations suggest that pedestrian behavior varies significantly across different times of the day and week (Table 2).

As shown in Table 2, the analysis indicates that strategically locating places that align with pedestrian preferences within short distances significantly influences pedestrian choices. However, it is noteworthy that within a 320-meter radius of the shopping centre, there are places that are incompatible with pedestrian needs, as depicted in Fig. 5. Consequently, the livability and attractiveness of the city centre, along with the encouragement of active transportation, may face challenges when incompatible land uses are present within close proximity to the shopping centre.

4.2. Gate counting and syntactical analysis

Unravelling Toowoomba City Centre dynamics focused on understanding pedestrian behaviour, particularly during the lively 1 to 3 pm slot on weekdays and weekends, as well as during the 6 to 8 PM slot on both weekdays and weekends. Employing detailed map analyses and on-site observations, ten entry points were strategically selected based on integration and mapping insights (Fig. 3A). Table 3 provides a detailed comparison of pedestrian density and spatial configurations at various entry points in Toowoomba City Centre. During weekday afternoons, gates 2, 4, and 5, particularly near Grand Central entrances, experienced the highest foot traffic. Notably, gate 2, despite not being the most integrated or connected, recorded the highest pedestrian flow with 84 pedestrians and an integration value of 4.2. This indicates that compatible land-use during this time attracts more pedestrians. In contrast, gate 5, which boasts the highest integration and connectivity values (6.4 and 230, respectively), observed a relatively lower flow of 76 pedestrians. On weekend afternoons, gate 5 saw a substantial increase, reaching 33 pedestrians, while gate 2 had 39 pedestrians. These results suggest that despite gate 2′s lower integration value compared to gate 5, it still draws significant foot traffic in the afternoon, likely due to leisure activities and shopping.

Fig. 5. Bus Station Layout at Grand Central Shopping Centre.

During weekday evenings from 6 to 8 PM, pedestrian traffic was generally lower across all gates compared to other times. Gate 7 recorded the highest count with 18 pedestrians, despite a lower integration value of 5.2. Gate 5 followed with 12 pedestrians, maintaining its importance even as overall traffic diminished. In contrast, gate 2 had only 2 pedestrians, indicating a distinct shift in pedestrian preferences towards more integrated and connected pathways during the evening. This suggests that pedestrians prioritise these pathways, alongside areas with more compatible land-use for nighttime activities. In the weekend evenings, gate 5 continued to show a high flow with 28 pedestrians, aligning with its high integration and connectivity scores. Gates 7 and 8 also recorded relatively high flows of 11 and 13 pedestrians, respectively, alongside relatively high integration rates. Meanwhile, gate 2 maintained a relatively low pedestrian count, suggesting that both weekday and weekend evenings see pedestrian traffic influenced by the integration and connectivity of pathways, as well as the suitability of land-use for evening activities. These trends underscore the importance of considering both spatial integration and the compatibility of land-use in urban planning, particularly to accommodate different times of the day and week.

4.3. Analysis of Toowoomba city Centre via Space Syntax

Nuanced spatial characteristics within the city centre were revealed by the exploration. Notably, the entrances to the Grand Central Shopping Centre played a pivotal role in shaping pedestrian movement. Gate 2, located near the bus station, emerged as a central hub with a moderate integration value of 4.2 and a connectivity score of 120. However, it is important to note that other gates within Toowoomba City Centre exhibited even higher integration and connectivity metrics, such as gates 5 (integration 6.4, connectivity 230), 6 (integration 4.5, connectivity 148), 7 (integration 5.2, connectivity 194), 8 (integration 5.2, connectivity 194), 9 (integration 5.3, connectivity 133), and 10 (integration 4.8, connectivity 129) (Table 3). This revelation adds complexity to the understanding of spatial dynamics, suggesting that pedestrian movement is influenced by a combination of factors beyond mere integration and connectivity metrics (Table 3) and (Fig. 6).

Nuanced spatial characteristics within the city centre were revealed by the exploration. Notably, a pivotal role in shaping pedestrian movement was played by the entrances to the Grand Central Shopping Centre. Gate 2, situated near the bus station, emerged as a central hub with relatively moderate integration (4.2) and connectivity (120). However, it is crucial to recognise that even higher connectivity and integration were demonstrated by certain other gates within Toowoomba City Centre, such as gates 5, 6, 7, 8, 9, and 10 (Fig. 6). This intriguing revelation adds complexity to the understanding of spatial dynamics, suggesting that the intricate interplay of factors influences pedestrian movement in ways that go beyond conventional expectations

Table 3
A comparison of observations at gates and the syntactical factors in Toowoomba City Centre.

Gate Reference Number	Total population density at gates (Weekday: 1–3 PM)	Total population density at gates (Weekend: 1–3 PM)	Total population density at gates (Weekday: 6–8 PM)	Total population density at gates (Weekend: 6–8 PM)	Integration HH	Connectivity
1	14	8	1	1	2.6	45
2	84	39	2	4	4.2	120
3	0	3	0	1	4.3	110
4	16	4	0	6	5.6	205
5	76	33	12	28	6.4	230
6	2	0	1	2	4.5	148
7	5	8	18	11	5.2	194
8	4	9	3	13	5.2	194
9	10	7	1	9	5.3	133
10	1	0	0	4	4.8	129

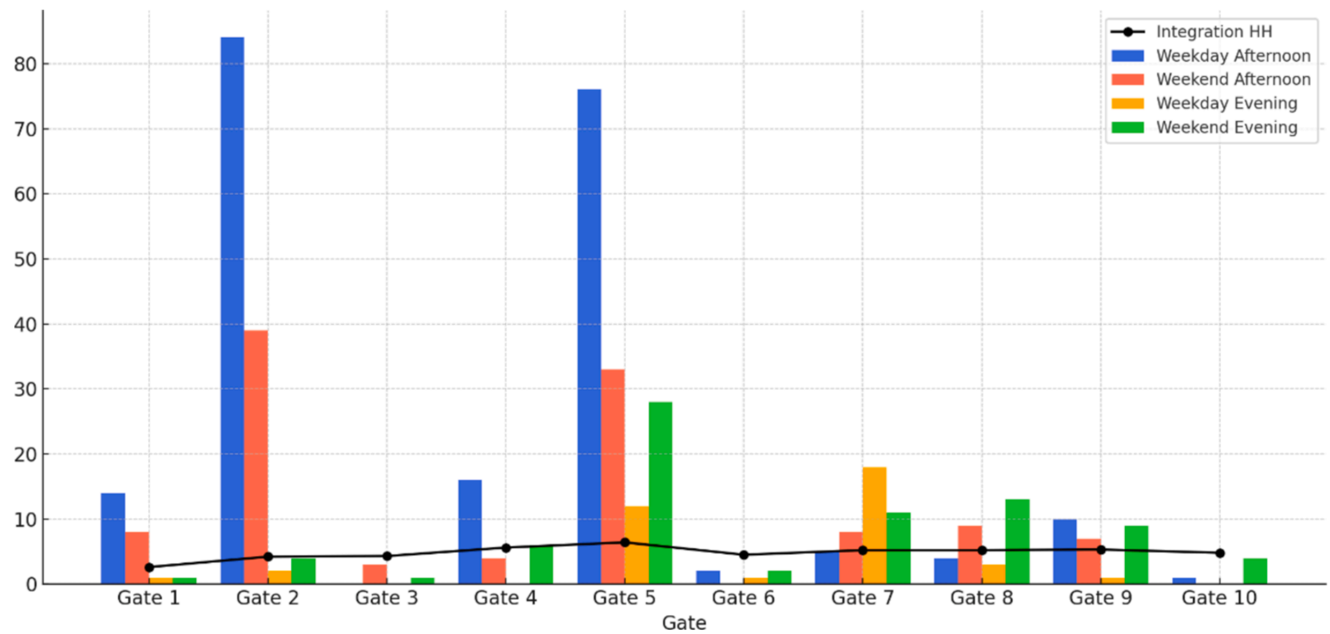


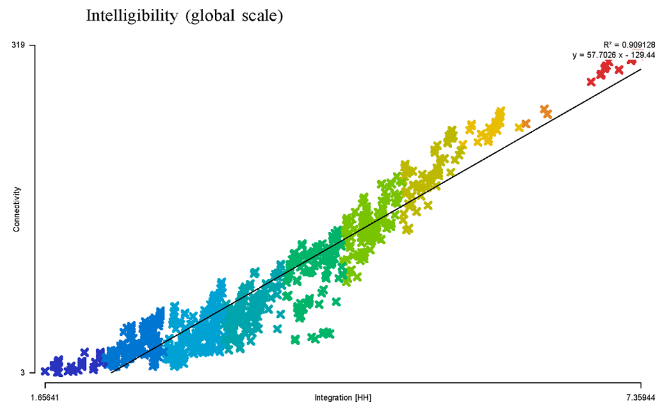
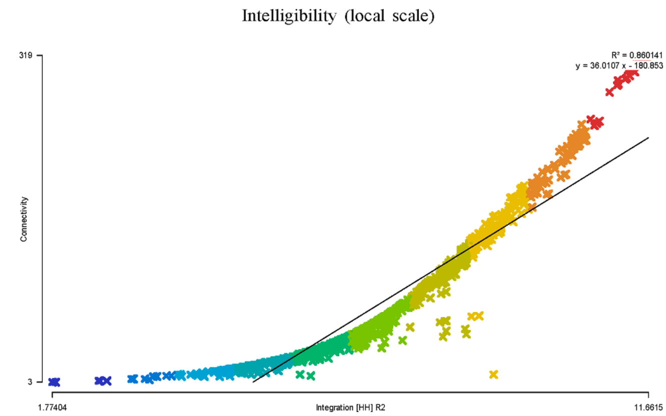
Fig. 6. Comparative values of total pedestrian density and integration HH by gate and time.

based solely on integration and connectivity metrics. Furthermore, a modest pedestrian flow was still attracted by gate 1, despite having relatively lower integration and connectivity. The integration and connectivity values suggest a gateway that is accessible but may not be a primary focal point.

Gate 5, which has the highest integration value of 6.4 and a connectivity score of 230, recorded pedestrian densities of 76 during weekdays (1–3 PM), 33 during weekends (1–3 PM), 28 during weekdays (6–8 PM), and 12 during weekends (6–8 PM). Despite its high integration and connectivity metrics, the pedestrian counts are lower than might be expected, especially during weekend hours. gate 4, with an integration value of 5.6 and a connectivity score of 205, showed pedestrian densities of 16 during weekdays (1–3 PM), 4 during weekends (1–3 PM), 6 during weekdays (6–8 PM), and 17 during weekends (6–8 PM). While gate 4′s metrics suggest strong potential for pedestrian movement, the actual counts during all observed times are lower than anticipated, indicating a discrepancy between its metrics and pedestrian use. Gate 3, with an integration value of 4.3 and a connectivity score of 110, recorded very low pedestrian flow: 1 pedestrian during both weekday periods (1–3 PM and 6–8 PM), with zero pedestrian flow during weekends. This lack of activity, despite reasonable integration and connectivity metrics, highlights a significant divergence from expected usage (Table 3) and (Fig. 6). A significant incongruity between anticipated and observed pedestrian flows, notably during weekends, is exposed by the data. Diminished pedestrian activity in major gates, specifically gates 5, 6, 7, 8, 9, and 10, is uncovered by gate observations, contrary to predictions forecasting heightened foot traffic on weekends. This unanticipated trend necessitates a deeper investigation into the variables shaping pedestrian behaviour during weekends, prompting an in-depth examination of the distinctive attributes associated with each of these gates. A comprehensive analysis of these reasons will be delved into in a subsequent section relating to land-use mapping.

The syntactic intelligibility of a given area refers to the extent of correlation between the integration and connectivity values associated with each line within that space. The term ’intelligibility’ is employed as a stronger correlation implies a greater capacity to deduce and comprehend the global positioning of a space [66]. Table 4 presents the correlation between intelligibility, a measure based on the relationship between integration (the accessibility of a space within the overall system) and connectivity (the number of direct connections to adjacent spaces), in the context of Toowoomba City Centre. Intelligibility reflects how easily a pedestrian can navigate through the city, where higher values indicate a more understandable and well-connected layout. This analysis helps to assess how spatial configurations impact overall accessibility and navigation within the city but does not include direct measurements of pedestrian movement. A robust local intelligibility level of 0.8 is indicated by the findings, suggesting a strong correlation between local connections and the observable global position of spaces within Toowoomba City Centre. Moreover, the city’s overall coherence is highlighted by the global intelligibility level of 0.9, emphasising a

Table 4
Intelligibility Analysis in Toowoomba City Centre.

Intelligibility (global scale)	Intelligibility (local scale)
	

high degree of consistency between local and global integration (Table 4).

4.4. Combining syntactical results with pedestrians' friendly compatible land-use through ArcGIS

This approach sheds light on the dynamics of pedestrian activity around the Grand Central Shopping Centre. Despite being a major attractor of the city's population, our analysis reveals a nuanced picture. The land-use mapping and on-site observations indicate that while the shopping centre draws significant foot traffic, the compatibility of place-making with pedestrian needs varies across its different sections. Notably, the south side of the shopping centre, designated as Number 3 in our analysis, presents challenges in terms of compatibility with pedestrian preferences. This is particularly evident during weekdays, weekends, and especially after work hours. The presence of institutions such as the Council, Administrative Building, and Automobile Repair place contributes to an environment that may not align with the desires of pedestrians in this area (Fig. 7). Similarly, the north side of the shopping centre (Number 2) reveals several incompatible establishments for pedestrians, including a petrol station, legal offices, and orthodontic clinics. This suggests potential barriers to pedestrian movement and engagement in these areas (Fig. 7).

Contrastingly, our findings highlight that the right side of the Grand Central Shopping Centre features more compatible land-use. Commercial, recreational, and cultural complexes are prevalent, offering a pedestrian-friendly environment that aligns with the preferences of the city's residents. This insight into the distribution of compatible and incompatible uses within the shopping centre area is crucial for urban planning and the creation of pedestrian-friendly spaces in the city.

5. Discussion

Through examining actual observations in the Toowoomba City Centre at specific locations, it becomes apparent that in a smaller city centre, characteristic of low-density urban environments, land-use mapping plays a notably crucial role in people–place making compared to the emphasis on street network connectivity during the day. Furthermore, street connectivity, coupled with compatible land-use mapping, can play a crucial role at nighttime. During the afternoon or daytime on both weekdays and weekends, gate 2, which has a relatively low integration value of 4.2, attracts the highest number of pedestrians (84 on weekdays and 39 on weekends). In contrast, gate 5, with a higher integration value of 6.4, attracts the second-highest pedestrian flow (76 on weekdays and 33 on weekends). This disparity highlights that factors beyond street integration metrics, such as the suitability of surrounding land-uses, play a key role in shaping pedestrian patterns in lower-density settings.

The dynamics shift in the evening and nighttime. On weekend evenings, gate 5, which maintains its status as the most connected area with

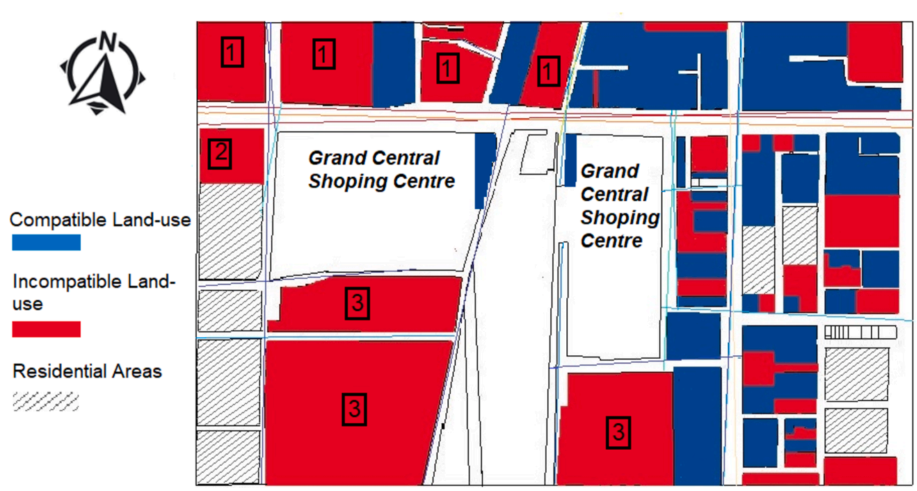


Fig. 7. Combining synthetical analysis with compatible land-use into ArcGIS for the designated area under study.

an integration value of 6.4 and benefits from compatible land-use (as illustrated in Fig. 6, experiences the highest pedestrian flow (28 pedestrians). This shift suggests that at night, pedestrians prefer pathways that combine both strong connectivity and compatible land-uses. Additionally, on weekday evenings, the highest pedestrian flow pertains to gate 7, followed by gate 5, with gate 7 having a relatively high integration value of 5.2 and gate 5 having the highest integration value of 6.4. Both gates are located in areas with compatible land-use. Thus, in low-density contexts, a balance of land-use suitability and street integration is essential for influencing pedestrian choices, particularly in the evening and at night. These results indicate that, at night, pedestrians prefer pathways that offer both compatible land-uses and strong integration/connectivity metrics. Therefore, both land-use suitability and street integration are crucial in influencing pedestrian route choices during the evening or night in low-density cities. Data from Table 2 emphasise the vibrancy of environments along well-connected streets near gate 5 (Fig. 8). Overall, in low-density cities, land-use mapping plays a critical role in shaping pedestrian behaviour and enhancing urban appeal, especially during the daytime. Streets with compatible land uses improve livability and draw more pedestrians. At night, the integration of land-use mapping with street connectivity becomes vital for sustaining vibrancy and ensuring safety. Well-lit, accessible routes with strategically placed amenities foster nighttime pedestrian activity. In these areas, land-use mapping often exerts a stronger influence than street connectivity during the day, contributing to inviting and lively urban spaces.

[51,83–86]. Contrastingly, the observations of this study reveal a distinctive pattern, indicating that in low-density cities, the frequency of conflicts between observed pedestrian behaviour and street accessibility is surprisingly higher than expected compatibility. After investigating the reasons behind the apparent lack of utilisation of highly integrated gates, particularly gate 3 which showed negligible pedestrian flow during the investigation, it becomes evident that the incompatibility of land-use mapping based on pedestrian preferences, along with poor lighting during the evening and night, contributes to its underutilisation. Conversely, gate 2, situated beside one of the two main entrances to the shopping centre, exhibits the highest pedestrian flow despite its moderate integration level of 4.2. Upon investigating the discrepancy between software predictions and the observed reality, it becomes apparent that the main bus stop is located around this gate. However, despite being one of the most populated areas, the absence of vibrant street performances, such as theatre and concerts, wide footpaths, diverse and user-friendly furniture, creates an environment marked by confusion and conflict, as depicted in the accompanying Fig. 6.

This observation highlights the impact of additional elements beyond connectivity metrics and compatible land-use mapping, such as cultural and enriching live entertainment offerings, along with the importance of pedestrian-friendly amenities and infrastructure on the vibrancy and user experience of urban spaces. While gate 2 attracts a significant pedestrian flow during the day due to its proximity to the main bus stop, the absence of diverse and lively features contributes to a less dynamic atmosphere.

According to Colman [87], individuals residing in lower-density areas, or perceiving their environment as lower-density, exhibit reduced walking activity compared to those in higher-density areas [87–89]. Rural and remote areas have been reported to experience elevated rates of overweight and obesity [90–92]. In regional cities, this challenge is attributed to factors such as low population density, inadequate urban connectivity, and limited land-use diversity, all contributing to a decline in physical activity and walkability [26]. In support of earlier statements, this research reveals a correlation between the average distance covered by individuals in reaching their destinations and the city's density. Comparative analyses with larger cities like Brisbane emphasise residents of Toowoomba exhibit lower rates of walking. On average, individuals in Toowoomba City Centre traverse approximately 150–320-metre radius from the primary entrance of the shopping centre to their destinations, underscoring the significance of promoting compatible land-use within a 150–320-metre radius. Notably, the study highlights that the presence of a large park within the shopping centre, even at distances of 1.2 km and 900-metre radius, does not effectively attract pedestrian activity. The detrimental effect of distance to a park on pedestrian walking will be apparent when parks are located beyond 400-metre radius of pedestrian density [27]. This suggests that the availability of recreational spaces alone may not suffice; alignment with pedestrian preferences is' equally vital. Contrastingly, Vaez et al. [43] discovered that individuals in the moderately dense city of Brisbane cover distances exceeding 5 km within the city centre to reach their destinations. This disparity in results underscores the divergence in pedestrian movement behaviour across cities with different population densities.

The comparison between syntactical analysis more specifically the spatial and pedestrian-compatible land-use mapping in Toowoomba's low-density city centre, particularly around the Grand Central Shopping Centre, provides insightful observations into pedestrian movement patterns during both weekdays and weekends. The analysis identifies that areas with high integration and connectivity values, such as gate 5, show increased pedestrian movement, particularly when combined with diverse and compatible land-uses, both during the day and at night, as well as on weekdays and weekends. For example, the presence of commercial spaces, public amenities, and recreational zones around well-integrated streets encourages higher foot traffic and longer durations of pedestrian activity. In contrast, areas with lower connectivity and fragmented land-uses, such as gate 2, hinder pedestrian movement, even in central locations. The spatial fragmentation limits accessibility, and

Fig. 8. (A). Pedestrian flow dynamics between gates in the study area. (A) Flow patterns between the gates of 5 and 8; (B) Pedestrian movement along the gate 5.

incompatible land-use further reduces the vibrancy of these areas, especially during nighttime. This demonstrates the importance of aligning spatial configurations with diverse, pedestrian-friendly land uses to encourage active transportation and livability. Therefore, the combination of well-connected street networks, high integration values, and mixed land-uses—particularly those that serve pedestrian needs—proves to be the most effective in enhancing urban vibrancy and increasing pedestrian movement in low-density city centres like Toowoomba.

Furthermore, the study highlights a higher overall walking rate on weekend, suggesting a potential disparity in the city's pedestrian environment appeal for leisurely walks on weekends. Conversely, a previous investigation in Rasht by Askarizad and Safari [20] found elevated pedestrian flows during weekends, attributing this to the city centre's relatively compatible land-use. Features like pedestrian-only streets, a spacious square, distinctive landmarks, diverse furniture options, and room for street events contribute to a livelier atmosphere, drawing in more pedestrians. However, despite the Toowoomba city centre's interconnected street layout, the prioritisation of place-making doesn't align with pedestrian needs, evident in incompatible land-use identified through ArcGIS mapping. The study emphasises that mere street connectivity is inadequate, highlighting the substantial influence of land-use compatibility on pedestrian choices. This intentional approach to walking underscores the importance of designing city centres to be inherently pedestrian-friendly, moving beyond mere accessibility to actively encourage exploration and engagement with the urban fabric. Place-making strategies in low-density cities should prioritise elements enhancing the pedestrian experience, including well-connected streets and, more importantly, a deeper connection with urban space through compatible land-use. The findings underscore the significance of fostering a pedestrian-friendly environment within low-density city centres to promote active lifestyles and establish a profound connection with urban spaces. Urban planners and policymakers are encouraged to prioritise initiatives enhancing city centre walkability by incorporating proven pedestrian-attracting features such as scenic pathways, sidewalk widths [45,92], distances to green spaces [24,34,42], landmarks [43], street events or gathering points [20,49] and strategically placed amenities. This approach aims to encourage individuals to choose walking as a preferred mode of exploration and transportation. Addressing spatial isolation in deprived areas, it contributes to a vibrant urban environment and attracts pedestrians to take more walks. This study provides critical insights that can significantly inform urban planning and policy, particularly in the context of pedestrian behaviour within low-density urban environments. The following implications are derived from the key findings:

- Land-use mapping within a 320-metre radius

The study highlights the importance of land-use mapping within a 320-metre radius, particularly in densely populated city centre areas. GPS tracking data reveal that this distance significantly influences pedestrian route choices, underscoring the need for urban planners to optimise land-use within this range to boost pedestrian activity and reduce car dependency.

- Daytime focus on land-use over connectivity

During the day, land-use mapping has a greater impact on pedestrian movement than traditional connectivity metrics. Urban planners should prioritise land-uses that support daytime activities to create a more vibrant and accessible environment.

- **Integrating land-use and connectivity in the evening/night:**

Effective integration of land-use mapping and co-street connectivity is essential for attracting pedestrians during the evening and nighttime. Planners should focus on creating well-lit, accessible routes with strategically placed amenities to encourage evening foot traffic.

- **Promoting mixed-use development and enhancing environmental comfort:**

To maximise pedestrian activity, the study advocates for mixed-use development within the 320-metre radius. By providing a variety of accessible amenities—such as green spaces, shops, cafes, and essential services—urban planners can significantly reduce vehicular reliance and support a walkable environment. Simultaneously, enhancing environmental comfort through the incorporation of shade trees, noise barriers, and aesthetically pleasing street furniture is crucial. These features not only improve physical comfort but also make urban spaces more attractive and inviting, fostering greater pedestrian engagement.

- **Implementing place-making strategies**

To emphasise creating engaging, experiential, and culturally vibrant urban spaces. This approach is broader and aims to improve the overall atmosphere and appeal of public spaces through aesthetics, landmarks, and events, which in turn can encourage more pedestrian activity.

- Utilising advanced analytical tools for spatial optimisation

The study recommends the use of advanced analytical tools, such as Space Syntax and Geographic Information Systems (GIS), to assess and optimise the spatial configurations of urban areas. These tools enable urban planners to evaluate the effectiveness of land-use and street connectivity in attracting pedestrian activity during both day and night. Such data-driven approaches are essential for informed decision-making in urban design and planning.

6. Conclusion

In conclusion, this study elucidates the intricate relationship between pedestrian movement patterns and urban design in low-density cities, with a focus on Toowoomba City Centre. Unlike medium and high-density cities where street integration and connectivity metrics often dictate pedestrian flows, our research underscores the pivotal role of land-use mapping in shaping interactions within low-density environments. The findings reveal that land-use compatibility, cultural offerings, and infrastructure significantly influence pedestrian dynamics, particularly during daytime hours. While land-use mapping is more influential during the day, both syntactical metrics and land-use factors are essential in attracting pedestrians during nighttime hours. This highlights the need for urban planners and policymakers to focus on areas with high land-use compatibility and connectivity to enhance urban functionality.

Moreover, the study establishes a correlation between city density and pedestrian activity, advocating for strategic land-use within a 320-metre radius to attract pedestrians. By prioritising place-making strategies that foster exploration and engagement, and avoiding incompatible developments near high pedestrian traffic areas, urban planners can enhance walkability and livability in low-density city centres. Future research should explore these dynamics across different urban contexts and examine temporal variations to further understand pedestrian behaviour in low-density environments. These insights provide a foundation for creating vibrant, pedestrian-friendly urban spaces, contributing to the overall sustainability and appeal of low-density cities.

This research lays the groundwork for future investigations into the intricacies of pedestrians' movemnet pattern within low-density urban areas. While the current study specifically investigated pedestrian movement behaviour and the amount of walking, the broader aim is to enhance pedestrian experiences and community life in a more sustainable and livable manner. Future studies can build upon the findings of this research by:

- Conducting comparative analysis with larger cities:

Future studies can compare low-density cities like Toowoomba with larger cities to explore differences in urban spatial configuration, placemaking strategies, and pedestrian needs across varying scales. Such comparisons will provide valuable insights into the nuanced dynamics that influence pedestrian movement behaviours in different urban contexts.

- Validating findings in different cities and environments:

To enhance the broad applicability of this research, future studies should validate the current findings in different low-density cities and environments. This could involve comparing Toowoomba's pedestrian behaviour patterns with those of other low-density cities in Australia and internationally, and investigating how cultural and climatic differences might influence the relationship between land-use, spatial configuration, and pedestrian behaviour.

- **Examining temporal variations**:

Expanding on the current study by examining how pedestrian behaviour changes across different times of day, climatic conditions, and seasons in more case studies of city centre low-density cities. This could provide insights into designing urban spaces that are attractive and functional throughout the year.

CRediT authorship contribution statement

Elham Mehrinejad Khotbehsara: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Kathirgamalingam Somasundaraswaran:** Supervision, Investigation, Data curation. **Tracy Kolbe-Alexander:** Writing – review & editing, Writing – original draft, Supervision, Data curation. **Rongrong Yu:** Writing – review & editing, Validation, Supervision, Software, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Hegazy IR. Towards sustainable urbanization of coastal cities: The case of Al-Arish City. Egypt, Ain Shams Engineering Journal 2021;12(2):2275–84. https://doi.org/10.1016/j.asej.2021.04.017.
[2] Huang YH, Ouyang Y. Measuring visual attractiveness of urban commercial street using wearable cameras: A case study of Gubei Gold Street in Shanghai. In: International Conference on Human-Computer Interaction. Cham: Springer International Publishing; 2022. p. 403–14. https://doi.org/10.1007/978-3-031-05900-1_28.
[3] Anastasiadou K, Vougias S. "Smart" or "sustainably smart" urban road networks? The Most Important Commercial Street in Thessaloniki as a Case Study, Transport Policy 2019;82:18–25. https://doi.org/10.1016/j.tranpol.2019.07.009.
[4] Zannat KE, Raja DR, Adnan M-S. Pedestrian facilities and perceived pedestrian level of service (PLOS): A case study of Chittagong metropolitan area, Bangladesh. Transport Development and Economics 2019;5(2):9. https://doi.org/10.1007/s40890-019-0078-4.
[5] Stea D. Image and environment: Cognitive mapping and spatial behaviour. Routledge 2017. https://doi.org/10.4324/9780203789155.
[6] Lee JH, Ostwald MJ, Zhou L. Socio-spatial experience in Space syntax research: A PRISMA-compliant review. Buildings 2023;13(3):644. https://doi.org/10.3390/buildings13030644.
[7] Portugali J. The construction of cognitive maps, Springer Science & Business. Media 1996. https://doi.org/10.1007/978-0-585-33485-1.
[8] Kim YO, Penn A. Linking the spatial syntax of cognitive maps to the spatial syntax of the environment. Environ Behav 2004;36(4):483–504. https://doi.org/10.1177/0013916503261384.
[9] Heft H. Environment, cognition, and culture: Reconsidering the cognitive map. J Environ Psychol 2013;33:14–25. https://doi.org/10.1016/j.jenvp.2012.09.002.
[10] Olazabal M, Pascual U. Use of fuzzy cognitive maps to study urban resilience and transformation. Environ Innov Soc Trans 2016;18:18–40. https://doi.org/10.1016/j.eist.2015.06.006.
[11] Eldiasty A, Hegazi YS, El-Khouly T. Using space syntax and TOPSIS to evaluate the conservation of urban heritage sites for possible UNESCO listing: The case study of the historic centre of Rosetta. Egypt, Ain Shams Engineering Journal 2021;12(4):4233–45. https://doi.org/10.1016/j.asej.2021.04.017.
[12] Bruns CR, Chamberlain BC. The influence of landmarks and urban form on cognitive maps using virtual reality. Landsc Urban Plan 2019;189:296–306. https://doi.org/10.1016/j.landurbplan.2019.05.006.
[13] Steg L, Vlek C. Encouraging pro-environmental behaviour: An integrative review and research agenda. J Environ Psychol 2009;29(3):309–17. https://doi.org/10.1016/j.jenvp.2008.10.004.
[14] Abu-Ghazzeh TM. Housing layout, social interaction, and the place of contact in Abu-Nuseir. J Environ Psychol 1999;19(1):41–73. https://doi.org/10.1006/jevp.1998.0106.
[15] Fried M, Gleicher P. Some sources of residential satisfaction in an urban slum. J Am Inst Plann 1961;27(4):305–15. https://doi.org/10.1080/01944366108978363.
[16] P. Calthorpe, The Next American Metropolis, Princeton Architectural Press, New York, 1993. ISBN: 1878271687.
[17] R.W. Marans, W. Rodgers, Toward an understanding of community satisfaction, in: Metropolitan America in Contemporary Perspective, 1975, pp. 299–352. doi: 10.3886/icpsr07986.v1.
[18] Festinger L, Schachter S. Social Pressures in Informal Groups: A Study of Human Factors in Housing, Harper and Row. N Y 1950. https://doi.org/10.2307/3348388.
[19] Lee JH, Ostwald MJ, Lee H. Measuring the spatial and social characteristics of the architectural plans of aged care facilities. Front Archit Res 2017;6(4):431–41. https://doi.org/10.1016/j.foar.2017.09.003.
[20] Askarizad R, Safari H. The influence of social interactions on the behavioral patterns of the people in urban spaces (case study: The pedestrian zone of Rasht Municipality Square, Iran). Cities 2022;101:102687. https://doi.org/10.1016/j.cities.2020.102687.
[21] E. Conticelli, A. Maimaris, G, Papageorgiou et al., Planning and designing walkable cities: a smart approach. Smart planning: Sustainability and mobility in the age of change, (2018) 251-269. .
[22] Karimi K. A configurational approach to analytical urban design: 'Space syntax' methodology. Urban Des Int 2012;17(4):297–318. https://doi.org/10.1057/udi.2012.19.
[23] Toowoomba Region. (2022). Toowoomba Regional Planning Scheme: Available from:Version 28. https://www.tr.qld.gov.au/planning-development.
[24] Koohsari MJ, Karakiewicz JA, Kaczynski AT. Public open space and walking: The role of proximity, perceptual qualities of the surrounding built environment, and street configuration. Environ Behav 2016;45(6):706–36. https://doi.org/10.1177/0013916512440876.
[25] Koohsari MJ, Mavoa S, Villanueva K, et al. Public open space, physical activity, urban design and public health: Concepts, methods and research agenda. Health Place 2015;33:75–82. https://doi.org/10.1016/j.healthplace.2015.02.009.
[26] Dygryn J, Mitas J, Stelzer J. The influence of built environment on walkability using geographic information system. J Hum Kinet 2010;24:93–9. https://doi.org/10.2478/v10078-010-0025-2.
[27] Mansouri M, Ujang N. Space syntax analysis of tourists' movement patterns in the historical district of Kuala Lumpur. Malaysia, Journal of Urbanism: International Research on Placemaking and Urban Sustainability 2017;10(2):163–80. https://doi.org/10.1080/17549175.2016.1213309.
[28] Fan W, Zhang J, Shan B, et al. Evaluating the impact of road network configuration on hotel layout based on big data, GIS and space syntax–evidence from Shanghai. Curr Issue Tour 2023:1–18. https://doi.org/10.1080/13683500.2023.2184680.
[29] Rismanchian O, Bell S. Evidence-based spatial intervention for the regeneration of deteriorating urban areas: A case study from Tehran, Iran. Urban Des Int 2014;19:1–21. https://doi.org/10.1057/udi.2013.6.
[30] Fang K, Wang X, Chen L, et al. Research on the correlation between pedestrian density and street spatial characteristics of commercial blocks in downtown area: A case study on Shanghai Tianzifang. Journal of Asian Architecture and Building Engineering 2019;18(3):233–46. https://doi.org/10.1080/13467581.2019.1627215.
[31] Nourian P, Rezvani S, Valeckaite K, Sariyildiz S. Modelling walking and cycling accessibility and mobility: The effect of network configuration and occupancy on spatial dynamics of active mobility. Smart Sustainable Built Environ 2018;7(1):101–16. https://doi.org/10.1108/sasbe-10-2017-0058.

[32] Wang F, Jiang C, Li W, et al. What changes? What remains? The evolution of the street networks in old Beijing city over one century. J Spat Sci 2018;63(2):203–23. https://doi.org/10.1080/14498596.2018.1479985.
[33] Zhang Y, Guo J, Wu D, et al. Delineating the urban walking environment in modern China: A descriptive assessment of pedestrian permeability around subway stations in central Hangzhou. Journal of Urbanism: International Research on Placemaking and Urban Sustainability 2023:1–23. https://doi.org/10.1080/17549175.2023.2178027.
[34] F. Mohammadi Tahroodi, N. Ujang, Engaging in social interaction: Relationships between the accessibility of path structure and intensity of passive social interaction in urban parks, ArchNet-IJAR: International Journal of Architectural Research 16 (1) (2022) 112–133. doi: 10.1108/arch-04-2021-0100.
[35] Safari H, Moridani F-F, Mahdzar S-S. Influence of geometry on legibility: An explanatory design study of visitors at the Kuala Lumpur City Center. Front Archit Res 2016;5(4):499–507. https://doi.org/10.1016/j.foar.2016.08.001.
[36] Zaleckis K, Doğan HA, Arce NL. Evaluation of the interventions to built heritage: Analysis of selected facades of Kaunas by space syntax and sociological methods. Sustainability 2022;14(8):4784. https://doi.org/10.3390/su14084784.
[37] Askarizad R, He J, Khotbehsara E. The legibility efficacy of historical neighborhoods in creating a cognitive map for citizens. Sustainability 2022;14(15): 9010. https://doi.org/10.3390/su14159010.
[38] Wang L, Han X, He J, et al. Measuring residents' perceptions of city streets to inform better street planning through deep learning and space syntax. ISPRS J Photogramm Remote Sens 2022;190:5–230. https://doi.org/10.1016/j.isprsjprs.2022.06.011.
[39] Rui J. Measuring streetscape perceptions from driveways and sidewalks to inform pedestrian-oriented street renewal in Düsseldorf. Cities 2023;141:104472. https://doi.org/10.1016/j.cities.2023.104472.
[40] Clua Á, Llorca-Bofí J, Psarra S. Urban opportunities and conflicts around street musicians: The relationship between the configuration of public space and outdoor acoustics in Ciutat Vella. Barcelona, Journal of Urban Design 2020;25(5):561–89. https://doi.org/10.1080/13574809.2019.1699398.
[41] Gath-Morad M, Plaut P, Kalay YE. Attract or repel: How street features shape pedestrians' leisure walks in cities. J Urban Des 2023:1–21. https://doi.org/10.1080/13574809.2023.2237468.
[42] Jabbari M, Fonseca F, Ramos R. Combining multi-criteria and space syntax analysis to assess a pedestrian network: The case of Oporto. J Urban Des 2018;23(1):23–41. https://doi.org/10.1080/13574809.2018.1426960.
[43] Vaez S, Burke M, Yu R. Visitors' wayfinding strategies and navigational aids in unfamiliar urban environments. Tour Geogr 2020;22(4–5):832–47. https://doi.org/10.1080/14616688.2019.1696883.
[44] Geng S, Chau HW, Jamei E, et al. Understanding the street layout of Melbourne's Chinatown as an urban heritage precinct in a grid system using space syntax methods and field observation. Sustainability 2022;14(19):12701. https://doi.org/10.3390/su141912701.
[45] Shatu F, Yigitcanlar T, Bunker J. Shortest path distance vs. least directional change: Empirical testing of space syntax and geographic theories concerning pedestrian route choice behavior. J Transp Geogr 2019;74:37–52. https://doi.org/10.1016/j.jtrangeo.2018.11.005.
[46] O. Güngör, E. Harman Aslan, Defining urban design strategies: An analysis of Iskenderun city center's imageability, Open House International 45 (4) (2020) 407–425. doi: 10.1108/ohi-07-2020-0104.
[47] Edwards D, Griffin T. Understanding tourists' spatial behaviour: GPS tracking as an aid to sustainable destination management. J Sustain Tour 2013;21(4):580–95. https://doi.org/10.1080/09669582.2013.776063.
[48] Ewing R, Hamidi S. Compactness versus sprawl: A review of recent evidence from the United States. J Plan Lit 2015;30(4):413–32. https://doi.org/10.1177/0885412215595439.
[49] Næss P. Critical realism, urban planning and urban research. Eur Plan Stud 2015; 23(6):1228–44. https://doi.org/10.1080/09654313.2014.994091.
[50] Atakara C, Allahmoradi M. Investigating the urban spatial growth by using space syntax and GIS—A case study of Famagusta city. ISPRS Int J Geo Inf 2021;10(10): 638. https://doi.org/10.3390/ijgi10100638.
[51] Şahin Körmeçli P. Analysis of walkable street networks by using the space syntax and GIS techniques: A case study of Çankırı City. ISPRS Int J Geo Inf 2023;12(6): 216. https://doi.org/10.3390/ijgi12060216.
[52] Garling T, Book A, Lindberg E. Cognitive mapping of large-scale environments: The interrelationship of action plans, acquisition, and orientation. Environ Behav 1984; 16(1):3–34.
[53] Golledge RG. Place recognition and wayfinding: Making sense of space. Geoforum 1992;23(2):199–214. https://doi.org/10.1016/0016-7185(92)90017-x.
[54] Weisman J. Evaluating architectural legibility: Way-finding in the built environment. Environ Behav 1981;13(2):189–204. https://doi.org/10.1177/0013916581132004.
[55] Billet MI, Baimel A, Sahakari SS, Schaller M, Norenzayan A. Ecospirituality: The psychology of moral concern for nature. J Environ Psychol 2023;87:102001. https://doi.org/10.1016/j.jenvp.2023.102001.
[56] I. Altman, The environment and social behavior: Privacy, personal space, territory, crowding, New York: Brooks/Cole Publishing Co. (1975). ISBN: 0818501685.
[57] B. Hillier, Specifically architectural theory: A partial account of the ascent from building as cultural transmission to architecture as theoretical concretion, Harvard Architectural Review 9 (1993) 8–27. doi: https://discovery.ucl.ac.uk/id/eprint/1027.
[58] Hillier B, Penn A, Hanson J, et al. Natural movement: or, configuration and attraction in urban pedestrian movement. Environ Plann B Plann Des 1993;20(1): 29–66. https://doi.org/10.1068/b200029.
[59] Penn A, Desyllas J, Vaughan L. The space of innovation: interaction and communication in the work environment. Environ Plann B Plann Des 1999;26(2): 193–218. https://doi.org/10.1068/b260193.
[60] Meenar M, Afzalan N, Hajrasouliha A. Analyzing Lynch's city imageability in the digital age. J Plan Educ Res 2022;42(4):611–23. https://doi.org/10.1177/0739456x19844573.
[61] Meenar M, Flamm B, Keenan K. Mapping the emotional experience of travel to understand cycle-transit user behavior. Sustainability 2019;11(17):4743. https://doi.org/10.3390/su11174743.
[62] Askarizad R, He J. Perception of spatial legibility and its association with human mobility patterns: An empirical assessment of the historical districts in Rasht, Iran. Int J Environ Res Public Health 2022;19(22):15258. https://doi.org/10.3390/ijerph192215258.
[63] Bafna S. Space syntax: A brief introduction to its logic and analytical techniques. Environ Behav 2003;35(1):17–29. https://doi.org/10.1177/0013916502238863.
[64] M. Haciomeroglu, R.G. Laycock, A-M. Day, Distributing pedestrians in a virtual environment, in: Proceedings of the International Conference on Cyberworlds, IEEE, School of Computing Sciences, University of East Anglia, Norwich (2007). doi: 10.1109/cw.2007.9.
[65] Karimi K. Space syntax: consolidation and transformation of an urban research field. J Urban Des 2018;23(1):1–4. https://doi.org/10.1080/13574809.2018.1403177.
[66] Hillier B, Hanson J. The Social Logic of Space. Cambridge University Press 1989. https://doi.org/10.1017/CBO9780511597237.
[67] B. Hillier, Space Is the Machine: A Configurational Theory of Architecture, Space Syntax, London (1996). Available at: https://discovery.ucl.ac.uk/id/eprint/3848/1/SpaceIsTheMachine_Part1.pdf.
[68] Sailer K, Penn A. The Performance of Space—Exploring Social and Spatial Phenomena of Interaction Patterns in an Organisation. In: Proceedings of the Architecture and Phenomenology Conference. 2007.
[69] Koohsari MJ, Oka K, Owen N, et al. Natural movement: A space syntax theory linking urban form and function with walking for transport. Health Place 2019;58: 102072. https://doi.org/10.1016/j.healthplace.2019.01.002.
[70] K. Al-Sayed, A. Turner, B. Hillier, et al., Space Syntax Methodology, Bartlett School of Architecture, UCL (2014). Available at: https://www.ucl.ac.uk/bartlett/architecture/research/space-syntax-laboratory/2014-publications.
[71] East D, Osborne P, Kemp S, et al. Combining GPS & survey data improves understanding of visitor behaviour. Tour Manag 2017;61:307–20. https://doi.org/10.1016/j.tourman.2017.02.021.
[72] A. Penn, A. Turner, Space Syntax Based Agent Simulation, in: Springer-Verlag, Berlin (2002), pp. 99–114. Available at: https://discovery.ucl.ac.uk/id/eprint/75.
[73] A. Van Nes, C. Yamu, Space Syntax Applied in Urban Practice, in: Introduction to Space Syntax in Urban Studies, Springer, Berlin (2021), pp. 213–237. doi: 10.1007/978-3-030-59140-3_7.
[74] Garau C, Annunziata A, Yamu C. A walkability assessment tool coupling multi-criteria analysis and space syntax: the case study of Iglesias. Italy, European Planning Studies 2024;32(2):211–33. https://doi.org/10.1080/09654313.2020.1761947.
[75] Batty M. Integrating space syntax with spatial interaction. Urban Inf 2022;1(1):4. https://doi.org/10.1007/s44212-022-00004-2.
[76] Agirbas A. Characteristics of social formations and space syntax application to quantify spatial configurations of urban regeneration in Levent, Istanbul. J Hous Built Environ 2020;35:171–89. https://doi.org/10.1007/s10901-019-09671-1.
[77] Law S. Defining street-based local area and measuring its effect on house price using a hedonic price approach: The case study of Metropolitan London. Cities 2017;60:166–79. https://doi.org/10.1016/j.cities.2016.08.008.
[78] Khotbehsara EM, Askarizad R, Mehrinejad M, Nourmusavi Nasab S, Kathirgamalingam S. The impact of COVID-19 on visitors' wayfinding within healthcare centers. Ain Shams Eng J 2023;14(5):101957.
[79] Alalouch C, Al-Hajri S, Naser A, et al. The impact of space syntax spatial attributes on urban land use in Muscat: Implications for urban sustainability. Sustain Cities Soc 2019;46:101417. https://doi.org/10.1016/j.scs.2019.01.002.
[80] S. Srirangam, S. Gunasagaran, T. Mari, V. Ng, et al., Spatial intelligence: integration of land use to connectivity in the context of eastern urbanism, Archnet-IJAR: International Journal of Architectural Research 17 (1) (2023) 184–202. doi: 10.1108/arch-12-2021-0355.
[81] Jiang B, Claramunt C, Klarqvist B. Integration of space syntax into GIS for modelling urban spaces. Int J Appl Earth Obs Geoinf 2000;2(3–4):161–71. https://doi.org/10.1016/s0303-2434(00)85010-2.
[82] Matthews JW, Turnbull GK. Neighborhood street layout and property value: The interaction of accessibility and land use mix. J Real Estate Financ Econ 2007;35(2): 111–41. https://doi.org/10.1007/s11146-007-9035-9.
[83] Hajrasouliha A, Yin L. The impact of street network connectivity on pedestrian volume. Urban Stud 2015;52(13):2483–97. https://doi.org/10.1177/0042098014544763.

[84] Molaei P, Tang L, Hardie M. Measuring walkability with street connectivity and physical activity: A case study in Iran. WORLD 2021;2(1):49–61. https://doi.org/10.3390/world2010004.
[85] Lee S, Yoo C, Seo KW. Determinant factors of pedestrian volume in different land-use zones: Combining space syntax metrics with GIS-based built-environment measures. Sustainability 2020;12(20):8647. https://doi.org/10.3390/su12208647.
[86] Marshall W-E, Garrick N. Effect of street network design on walking and biking. Transp Res Rec 2010;2198(1):103–15. https://doi.org/10.3141/2198-12.
[87] S. Coleman, Australia state of the environment 2016: built environment. Independent report to the Australian Government Minister for the Environment and Energy. Australian Government Department of the Environment and Energy; 2017. Available at: https://soe.dcceew.gov.au/sites/default/files/2022-05/soe2016-built-launch-20feb.pdf.
[88] Colbran R, Nicol A, Mangan S, et al. Outcomes of the overweight and obese major trauma patient in the rural setting. Injury 2020;54(5):1369–73. https://doi.org/10.1016/j.injury.2023.01.021.
[89] Burke MI, Bonham J. Rethinking oil depletion: what role can cycling really play in dispersed cities? Australian Planner 2010;47(4):272–83. https://doi.org/10.1080/07293682.2010.527291.
[90] Australian Institute of Health and Welfare. Rural and remote health. Available from: https://www.aihw.gov.au/reports/rural-remote-australians/rural-remote-health; 2022.
[91] Powell KE, Martin LM, Chowdhury PP. Places to walk: convenience and regular physical activity. Am J Public Health 2003;93(9):1519–21. https://doi.org/10.2105/ajph.93.9.1519.
[92] Koohsari MJ, Sugiyama T, Sahlqvist S, et al. Neighborhood environmental attributes and adults' sedentary behaviors: review and research agenda. Prev Med 2015;77:141–9. https://doi.org/10.1016/j.ypmed.2015.05.027.
[93] Koohsari MJ, Sugiyama T, Mavoa S, et al. Street network measures and adults' walking for transport: Application of space syntax. Health Place 2016;38:89–95. https://doi.org/10.1016/j.healthplace.2015.12.009.
[94] Gunn LD, Mavoa S, Boulangé C, et al. Designing healthy communities: creating evidence on metrics for built environment features associated with walkable neighbourhood activity centres. Int J Behav Nutr Phys Act 2017;14:1–12. https://doi.org/10.1186/s12966-017-0479-9.
[95] Ewing R, Cervero R. Travel and the built environment: A meta-analysis. J Am Plann Assoc 2010;76(3):265–94. https://doi.org/10.1080/01944361003766766.
[96] Hamidi S, Ewing R, Preuss I, Dodds A. Measuring sprawl and its impacts: An update. J Plan Educ Res 2015;35(1):35–50. https://doi.org/10.1177/0739456X14565247.

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