VREDNOTENJE NOTRANJIH POTI, IZRAČUNANIH Z MODELI NAVIGACIJSKIH OMREŽIJ V ZAPRTIH PROSTORIH IN MERAMI PROSTORSKE SINTAKSE

EVALUATION OF INDOOR PATHS BASED ON INDOOR NAVIGATION NETWORK MODELS AND SPACE SYNTAX MEASURES

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IZVLEČEK

Notranja navigacijska omrežja (modeli) so bistven način za karakterizacijo dejanskih navigacijskih vzorcev pešcev. Da bi našli najprimernejšo pot skozi notranja navigacijska omrežja, se obstoječe študije tradicionalno osredotočajo predvsem na zmanjšanje dolžine in spremembo smeri. Žal pogosto ne najdejo poti, saj upoštevajo le prostorsko strukturo zgradbe. Mere prostorske sintakse podajajo interakcijo med konfiguracijo prostora prostorskim razmišljanjem pešca, ki temelji na vidljivosti. V tej študiji smo mere prilagodili za oceno notranjih poti. V praktičnem preizkusu smo zbirali dejanske navigacijske vzorce pešcev in jih na to primerjali z notranjimi potmi prek statistične primerjave glede na mere prostorske sintakse. Za najprimernejše navigacijsko omrežje se je pokazalo t.i. Universal Circulation Network, ki temelji na vidljivosti. Mere prostorske sintakse kažejo, da so navigacijska omrežja, ki temeljijo na središčnici, primernejša, če se upošteva vloga prostorske konfiguracije. Zato se je kot najprimernejše izkazalo navigacijsko omrežje Middle Point Relation Structure Segment Entrance.

ABSTRACT

Indoor navigation networks (models) are an essential way to characterize the navigation patterns of pedestrians. To find the most suitable path existing studies concentrate mostly on the minimization of length and turns. However, they alone may fall short to support one in wayfinding as they only consider the spatial structure of a building. Space syntax measures can reveal the interaction among spatial configurations and visibility-based spatial reasoning of pedestrians. In this paper, our original contribution is to adapt them to evaluate indoor paths. To demonstrate our approach, we first conducted a user experiment to collect the navigation patterns. Then, these navigation patterns were compared with the indoor paths through statistical comparison with respect to space syntax measures. Also, all door-from-door paths were compared by traditional and space syntax measures. The findings of the experimental study show that the visibility-based UCN is the more suitable navigation network by traditional measures. However, space syntax measures suggest that centerline-based navigation networks are more suitable. Considering traditional and space syntax measures together, the centerline-based MPRSSE is found to be the more suitable navigation network to assist one in the wayfinding process for our experimental study.

KLJUČNE BESEDE

navigacija v zaprtih prostorih, model navigacijskega omrežja, iskanje poti, notranje poti, sintaksa prostora, analiza grafa vidljivosti

KEY WORDS

indoor navigation, navigation network, wayfinding, indoor path, space syntax, isovist, visibility graph analysis

1 INTRODUCTION

The usage of outdoor navigation systems has grown rapidly over a decade (Vanclooster et al., 2019). In the case of an outdoor environment, Global Navigation Satellite Systems (GNSS) pave the way for the implementation of navigation, providing sufficiently high accuracy and precision in positioning. Also, outdoor environments surrounded by street networks make it easier to establish a navigation network and implement routing algorithms (Rüetschi and Timpf, 2005). However, indoor environments are often much more complex (fragmented, less visible, and enclosed) (Fellner, Huang, and Gartner, 2017; Giudice, Walton, and Worboys, 2010) and wayfinding can be challenging for many people (Arthur and Passini, 1992).

Due to the current methods for indoor positioning have reached a certain stage of accuracy and precision, indoor navigation finds a place for itself in applications such as customer tracking and guidance in shopping malls, facility management, building evacuation, terror scenarios, and wheelchair navigation (Choi and Lee, 2009; Gunduz, Isikdag, and Basaraner, 2016; Kwan and Lee, 2005; Park, Goldberg, and Hammond, 2020).

Indoor navigation networks serve as a basis for realizing indoor navigation (Karas et al., 2006; Lee and Kwan, 2005; Park et al., 2020) as they enable to conceptualize indoor spaces and characterize actual navigation patterns of pedestrians to a certain extent (Kneidl, Borrmann, and Hartmann, 2012; Pang et al., 2020; Park et al., 2020). Due to the lack of pre-defined paths within an indoor environment, the movement patterns of a pedestrian can vary much more in indoor spaces and the wide range of movement hampers the establishment of a comprehensive navigation network to support wayfinding for level (floor) and non-level paths (e.g., stairs, elevators, ramps, etc.) in line with human spatial cognition (Lin and Lin, 2018; Rüetschi and Timpf, 2005). Considering the lack of pre-defined paths, the chance of disorientation is rather high in an indoor environment (De Cock et al., 2020). Therefore, the indoor paths that are conveyed to the end-users should be cognitively reasonable to retain convenience and orientation.

From the aspect of path-planning, studies on indoor navigation mainly adopted routing algorithms such as Dijkstra (Dijkstra, 1959) which is commonly used for outdoor navigation studies to detect the shortest path distance between a pair of origin-destination nodes. Vanclooster et al. (2019) stated most existing navigation systems focus on minimizing path length, but ideal routes are not always the shortest, and users of these systems do not always prefer them. They also stated that minimizing turns is crucial to providing less challenging route instructions as typically route directions are generated at turns so it can lead to cognitive load. Since a turn made on a path can lead to increased wayfinding time and disorientation, minimizing the turns is an important factor in the route guidance context (Park et al., 2020; Vanclooster et al., 2019) along with distance minimization. Vanclooster et al. (2014a) also stated pedestrians value the form and complexity of a route as much as its total length. Park et al. (2020) stated more criteria should be involved in comparison to evaluate navigation networks to support indoor navigation. A path derived from navigation networks should be cognitively reasonable so that the cognitive load induced on the user could be minimized. Therefore, evaluating the indoor paths alone by traditional measures (length of a path and the number of turns made along a path) may fall short. These paths can overlook the visual perception of pedestrians in the spatial configuration of buildings. De Cock et al. (2020) stated that the architectural properties of a building have a significant influence on the spatial reasoning of pedestrians. The interaction among them can be revealed with space syntax, which is a set of methods to analyze the relationship between spatial layouts and human behaviors (De Cock et al., 2020; Van Nes and Yamu, 2021). Furthermore, Vanclooster et al. (2014a) provided some measures from space syntax theory (i.e., integration, choice, and the number of visible decision points) that contribute to defining the risk of getting lost in a building. However, they have not included these measures to evaluate their proposed algorithm in their study and stated they can be used in future studies. To the best of our knowledge, a study that compares indoor paths with actual navigation patterns of pedestrians through space syntax measures has not been reported yet.

Given these research gaps, this paper aims to: (1) refine the most commonly used navigation networks in a way that better matches with navigation patterns of pedestrians, (2) include the cognitive aspects in the evaluation of the indoor paths through the use of space syntax measures, (3) provide a comparison of indoor paths and actual navigation patterns of pedestrians through space syntax measures in addition to traditional measures.

In this study, the five most commonly used navigation networks which are Medial Axis Transform (MAT), Conformal Constrained Delaunay Triangulation (CCDT), Grid, Middle Point Relation Structure Segment Entrance (MPRSSE), and Universal Circulation Network (UCN) (Lee, 1982; Lee et al., 2010; Lewandowicz, Lisowski, and Flisek, 2019; Park et al., 2020; Li, Claramunt, and Ray, 2010) are utilized each with slight refinements to better reflect actual navigation patterns of the pedestrian. Space syntax measures that reflect the visual perception of pedestrians and spatial configuration of buildings are then assigned to the indoor paths. Since pedestrians are the main user of indoor navigation networks (models), the actual navigation patterns of users are compared with the indoor paths via a user experiment. Thus, the wayfinding results (i.e., computed indoor paths) are quantified not only by traditional measures but also by considering visual access and spatial configuration via the space syntax measures.

The remainder of the paper is organized as follows. The next section describes the background and key concepts of indoor navigation networks and space syntax theory with related works. Section 3 describes the methodology conducted in this study. Section 4 provides a case study and presents the experimental results. Section 5 provides a discussion and the last section concludes the main findings and presents future works.

2 RELATED WORK

2.1 Indoor navigation networks and wayfinding

For decades, graphs have served as models for the mental representation of an environment (Franz, Mallot, and Wiener, 2005). Such graphs can briefly express indoor spaces as nodes and edges to explain their interrelations. A navigation model is a specific type of data structure that facilitates the execution of path planning algorithms. Two distinct types of navigation models can be identified, which are network-based navigation models and grid-based navigation models, which respectively correspond to vector and raster representation. Commonly, network-based navigation models (i.e., navigation networks) are considered more efficient as they enable faster processing which is vital for the implementation of indoor navigation (Yan and Zlatanova, 2022).

Vanclooster et al. (2016) classified the navigation networks that evolved from topological connectivity graphs into three main categories as corridor derivation, cell decomposition, and visibility partitioning.

The corridor derivation category mainly emphasizes corridors, where most of the movement takes place. In this category, the centerline of a corridor is obtained through MAT methods (Lee, 1982; Lee, 2004; Taneja et al., 2011) or the Constrained Delaunay Triangulation (CDT). In the related studies, CDT-based methods are commonly used to form navigation networks (Lin and Lin, 2018; Mortari et al., 2014; Teo and Cho, 2016). CDT is improved by densifying the vertices along the boundary of a given geometry in the CCDT algorithm (Park et al., 2020).

In the cell decomposition category, indoor space is divided into numerous cells and each cell is represented by a node, and the nodes are connected based on the adjacency aspect of the cells. The grid-based model is one of the cell decomposition models. In grid-based models, each grid cell is expressed by its centroid and the adjacent centroids are connected to form the navigation network and the cells which intersect with the built-in features are eliminated. It is adopted by several studies (Li et al., 2010; Park et al., 2020; Wang et al., 2014; Xu et al., 2017; Xu et al., 2018). The MPRSSE is another navigation network that belongs to the cell decomposition category first used by Lewandowicz et al. (2019). The navigation network uses the centroids of the CDT to construct Voronoi tessellation from these centroids. Then, the Voronoi kernels are connected to each other to form the network edges based on the Poincaré Duality. Lewandowicz et al. (2019) concluded that the MPRSSE navigation network decreases fragments in the corridor centerline while retaining efficiency. Park et al. (2020) used the MPRSSEM navigation network to compare it with the common navigation networks according to the traditional measure. They concluded that MPRSSEM is the most suitable navigation network for minimizing turns made along the route although UCN does not differ significantly from MPRSSEM. A path planning algorithm which adapts the famous concept of the Travelling Sales Person problem to indoor spaces is proposed by Yan et al. (2021). Voronoi tessellation is employed as the basis for deriving the navigation network based on Poincaré Duality for their proposed path planning algorithm. Yan et al. (2022a) also proposed a navigation network based on space subdivisions using Voronoi diagrams. They integrated QR code locations into indoor space to derive their navigation network. Another use of Voronoi tessellation (based on Poincaré Duality) to derive a navigation network is proposed by Yan et al. (2022b). In their study, service area analysis is adapted to indoor spaces, which is a common GIS analysis used mainly in street networks for outdoor spaces. They concluded the proposed method is able to accurately determine the accessible areas, assisting individuals in choosing and reaching the optimal location.

The last category defined by Vanclooster et al. (2016) is visibility partitioning emerged from the concept of visibility graph (Turner et al., 2001). In visibility partitioning navigation networks, edges are formed by connecting the nodes using the shortest lines based on their inter-visibility (Pang et al., 2020; Yang and Worboys, 2015). In the case of non-direct visibility, concave corners of the corridor structures are used as intermediate nodes to partition visibility to ensure connectivity within the visibility graph (Vanclooster et al., 2016). Stoffel, Lorenz, and Ohlbach (2007) introduced a partitioning algorithm by using concave vertices of corridor space to divide indoor space into sub-convex spaces. They named door openings as “boundary nodes”, concave vertices as “reflex nodes” and in the case of non-direct visibility between boundary nodes, the line from the boundary node is connected to the centroid of the line segment between reflex nodes. Yuan and Schneider (2010) presented another visibility partitioning method. They used concave vertices to break the shortest straight lines into segments to retain the shortest distance as much as possible in the case of non-direct visibility between door openings. Although the end-users of the navigation networks are mostly pedestrians, wheel-chaired pedestrians, and robots, hence they all have a width, this factor is ignored in the navigation networks such as those introduced by Liu and Zlatanova (2011) and Yuan and Schneider (2010). As a result, users are forced to follow a path that is too close to built-in features such as walls and columns. Lee et al. (2010) proposed a navigation network based on visibility partitioning named UCN that utilizes buffer zones to shift door nodes to the inner buffer of corridor space to overcome the problem of walking too closely to built-in features. They used the navigation network to compute the walking distances of pedestrians in a building. Park et al. (2020) also utilized the same navigation network to compare it with commonly used navigation networks according to the traditional measures. They concluded that the UCN navigation network generates shorter walking distances.

2.2 Space syntax and wayfinding

Evaluating indoor paths solely by distance traveled and turns made along a path gives a coarse solution. This can cause overlooking of the visual perception of pedestrians and the architectural properties of an indoor environment, which have a significant impact on how pedestrians perceive indoor space (Mahdzar and Safari, 2014). Studies have shown that the legibility of a spatial configuration (i.e., how easily navigable a space is) depends on the differentiation of appearance, visual access, and layout complexity of a building (Mahdzar and Safari, 2014; Montello, 2014; De Cock et al., 2020). The overall properties of a spatial configuration can be quantified via isovists and visibility graph analysis (VGA) (Montello, 2014), which are commonly used methods in space syntax theory.

Several studies have investigated the relationship between space syntax and wayfinding in indoor spaces. Peponis, Zimring, and Choi (1990) investigated the relationship between global VGA measure integration with wayfinding performance in a hospital. They found that the higher the integration value is, the higher the people spent time in those spaces. Choi (1999) made an effort to explain the relationship between museum visits and space syntax measures by tracking people in a museum. He found that integration is the best measure to explain museum visits. Haq and Girotto (2003) conducted a wayfinding experiment in two complex hospital buildings to evaluate the relationship between overall layout complexity and intelligibility (which is the correlation coefficient between connectivity and integration). They found that intelligibility is a good predictor to evaluate success in a wayfinding task. Haq and Zimring (2003) investigated the relationship between people’s topological knowledge of a space and space syntax measures. They concluded that as people get to know the space better, their movement can be predicted via a global measure such as integration. Li and Klippel (2012) used interconnection density, axial analysis, and VGA. They found that spending time in a space correlates with the integration value. They also observed that low visibility had a significant effect on the wayfinding performance of participants so it can be concluded that visual access is an important factor to evaluate wayfinding performance.

All the mentioned studies made a significant effort to explain the relation between space syntax and wayfinding behavior within indoor spaces. However, they focus on relations between space and random walking patterns within space, they do not strict participants to follow pre-defined routes such as indoor paths that are computed from navigation networks. Hölscher, Brösamle, and Vrachliotis (2012) made an effort to explain the navigation patterns of novice and expert users within space by using connectivity, visual step depth, and integration measures along the trajectories participants walked. They found that novice users tend to walk higher connected and more integrated paths, whereas since expert users generally know the exact location of space, they tend to move more directly to the destination resulting in less connected and integrated paths.

3 METHODOLOGY

3.1 An overview of the methodology

The evaluation of indoor paths requires the generation of navigation networks. For this purpose, a GIS environment is used, which enables the processing of vector spatial data. The five most common navigation networks, which are MAT (Lee, 1982), CCDT (Park et al., 2020), Grid (Li et al., 2010), MPRSSE (Lewandowicz et al., 2019), and UCN (Lee et al., 2010), are utilized with slight refinements to better express actual navigation patterns of the pedestrians. A common way to evaluate indoor paths is to compare the length of a path. In this context, Dijkstra's shortest path algorithm is employed (Dijkstra, 1959). Vanclooster et al. (2019) and Park et al. (2020) suggested the number of turns made along the paths should also be considered when evaluating wayfinding results (i.e., indoor paths) as turns induce cognitive load in users. Therefore, the number of turns is computed with "node-coordinate based turn calculation algorithm" (Vanclooster et al., 2014b). These discrete measures are converted to raster surfaces. A user experiment is also conducted to obtain actual navigation patterns. Then, the mean values of the computed space syntax measures along the paths are assigned to the indoor paths and collected navigation patterns of the pedestrians. Next, the collected navigation patterns and indoor paths that are computed from navigation networks are compared with respect to the space syntax measures to evaluate indoor paths. Statistical analyses are then performed to check whether the space syntax measures differ significantly among navigation networks for all door-from-door paths. Figure 1 illustrates the outline of the methodology.

The details of the methodology are provided in the sub-sections. Subsection 3.2 describes the data preprocessing steps. The generation of indoor navigation networks and the computation of indoor paths are given in Subsection 3.3 and Subsection 3.4, respectively. Then, space syntax analysis is described in Subsection 3.5. The process of capturing actual navigational patterns is explained in Subsection 3.6. In Subsection 3.7, the comparison of the actual navigation patterns with indoor paths by related measures is described. Finally, the statistical methods for the comparison of all door-from-door paths are given in Subsection 3.8.

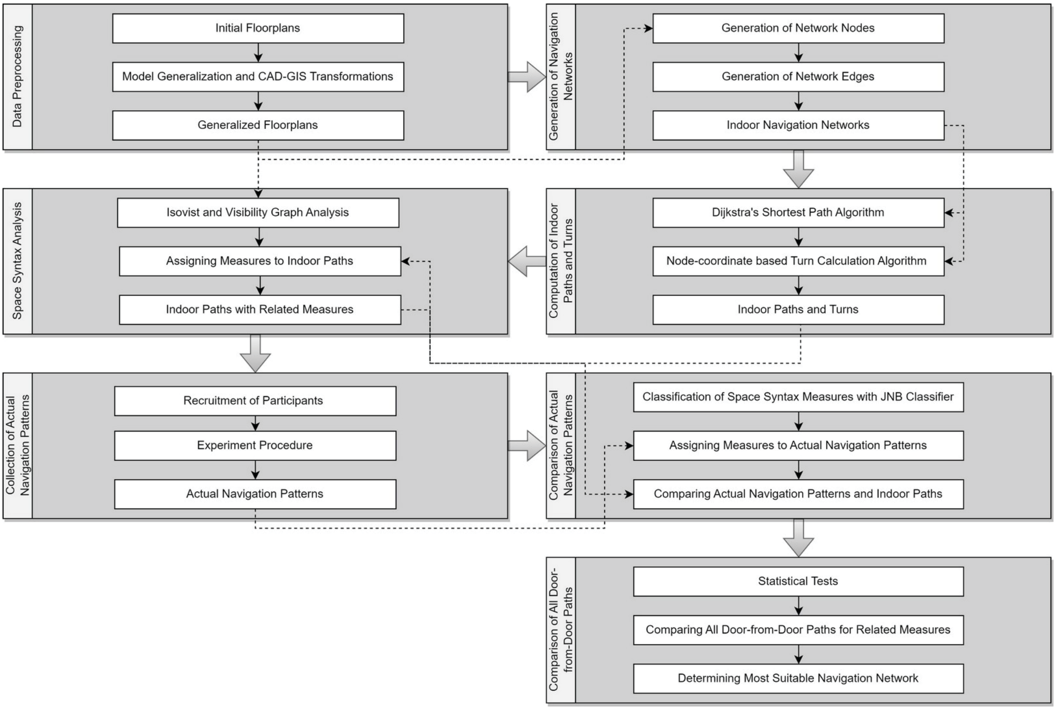

Figure 1: The overall methodology of the study

3.2 Data preprocessing

An indoor spatial dataset that represents indoor space is needed to create indoor navigation networks. Typically, floorplans can be considered primitive indoor maps (Chen and Clarke, 2020). They contain necessary geometric information related to the structure of the buildings to extract indoor topology and thus construct indoor navigation networks (Yang and Worboys, 2015). However, floorplans usually contain layers that are unnecessary for the generation of indoor navigation networks and hence need to be eliminated (i.e., text, measures, materials, notations, axis). In this study, for the simplification of the floorplans, the model generalization approach is utilized. The semantic selection and semantic grouping operations are adopted to preprocess data in a CAD environment. Semantic selection is utilized by keeping built-in structures such as walls, columns, doors, and stairs, and they are grouped semantically for a clear transformation of the CAD floorplans into a GIS environment. The final form of indoor spaces (rooms and corridors), walls, columns and doors are formed via various GIS tools. An example of the model generalization process for the case study buildings is illustrated in Figure 2.

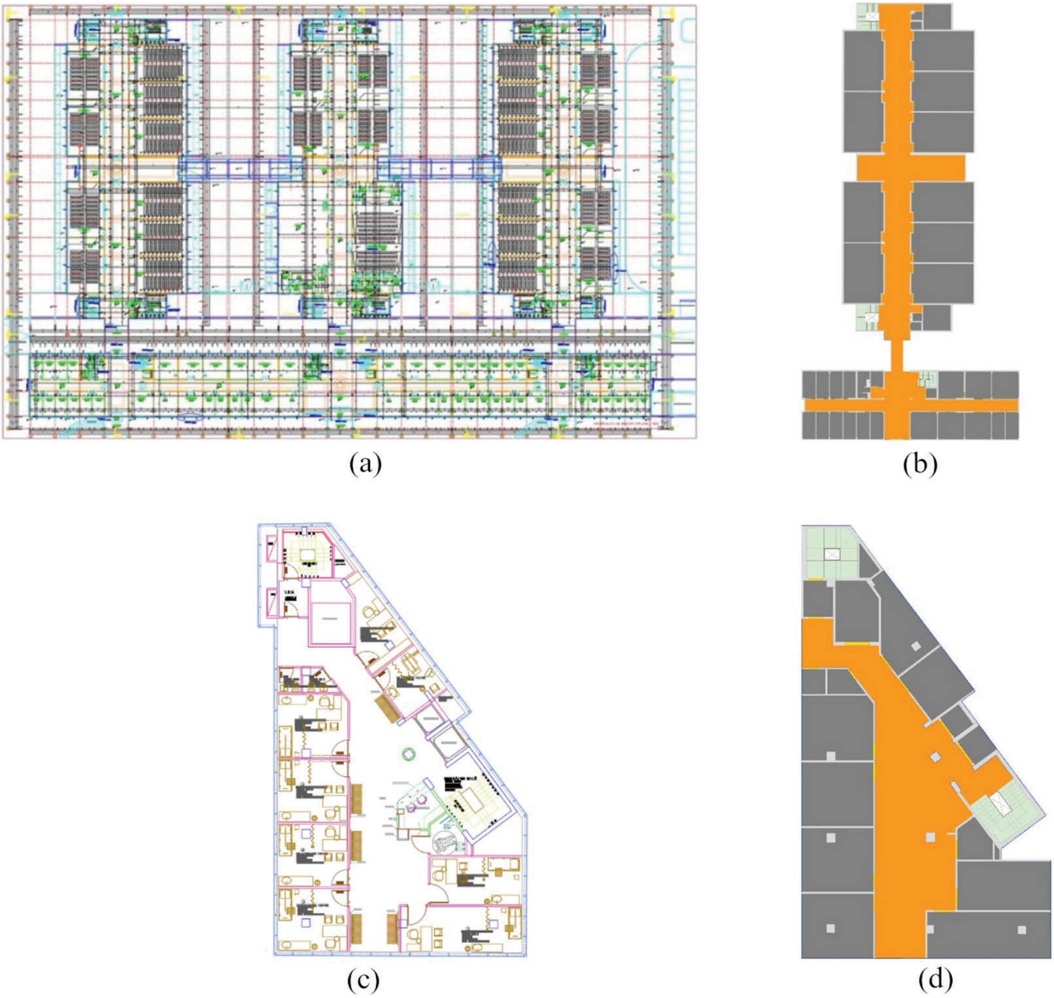

Figure 2: Model generalization process for case study buildings: (a), (b): university, (c), (d): hospital

3.3 Generation of the indoor navigation networks

Since indoor paths are derived from indoor navigation networks, their generation plays a significant role in realizing indoor navigation. The generalized floorplans are used to create corresponding navigation networks. An overall flowchart of the methodology to generate navigation networks is illustrated in Figure 3.

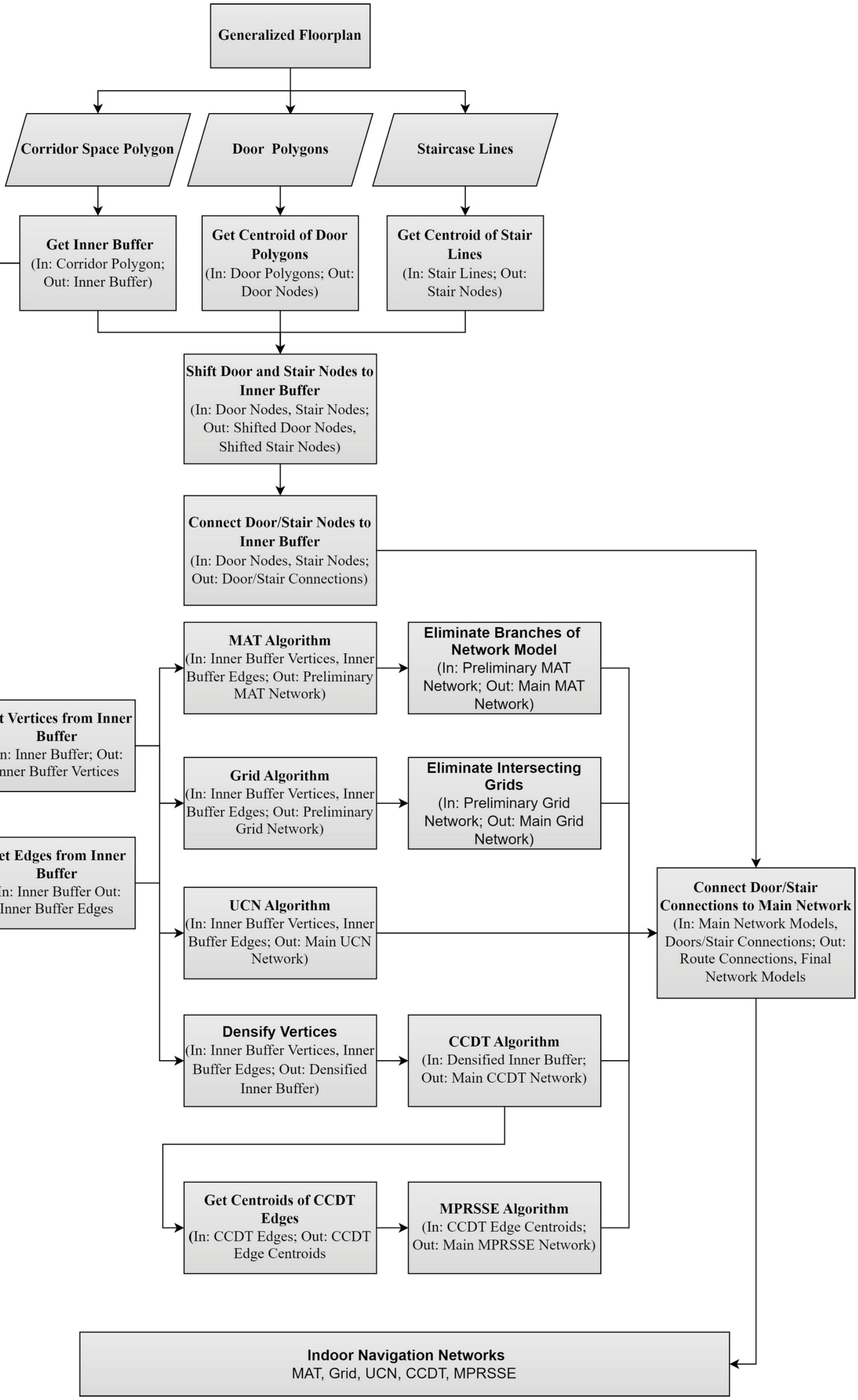

Figure 3: Overall methodology to generate indoor navigation networks

Commonly used navigation networks, especially those that adopt door-to-door approaches in the literature have the problem of network edges being too close to built-in features such as walls, columns, and stairs. To overcome this problem, Lee et al. (2010) proposed a method of shifting door centroids and start/end centroids of the stairs to an inner buffered space from built-in features, using half of the shoulder width of the average human shoulder as the minimum inner buffer distance. Additionally, people tend to start and end their locomotion process perpendicular to the door and start/end centroids of the stairs (in this study, referred to as "door/stair connection") (Vanclooster et al., 2014b). Considering these, an approach is proposed by shifting door centroids and start/end centroids to an inner buffer of the corridor. The buffer size is decided as 0.25 m by both observing the pedestrian's behaviors for the test buildings and considering half of the shoulder width (McDowell et al., 2009) to retain comfort and to match human spatial cognition. Exceptionally, considering the restricted visibility of the door opening area that connects the doors in recesses of the walls to a corridor, which does not affect pedestrian way-finding decisions, the network edges in this area are eliminated. To achieve this, the wall corner vertices corresponding to the doors of the inner buffer are eliminated and the relevant recesses are removed. An example of the shifted door and stair nodes and the inner buffer of corridor space is illustrated for the case study buildings in Figure 4.

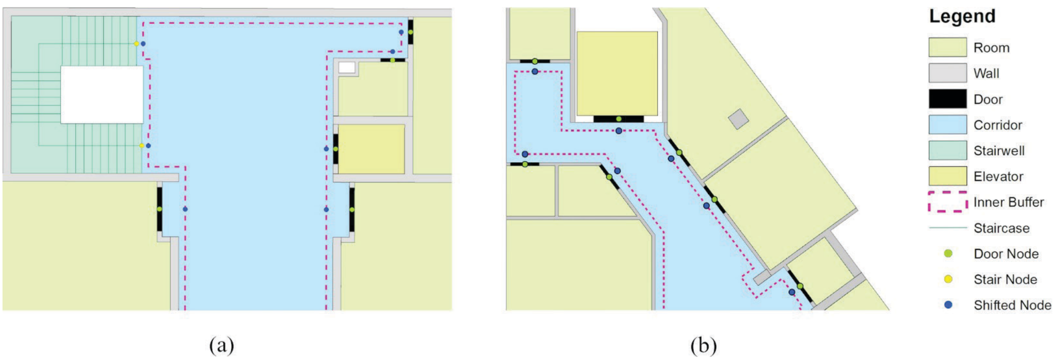

Figure 4: Shifted Door/Stair nodes and inner buffer polygons for case study buildings (a) university (b) hospital

3.3.1 MAT navigation network

MAT algorithm is originally proposed by Lee (1982). The algorithm extracts the medial axis by drawing centerlines having the same distance from the given geometry's edges. In this study, Lee (1982)'s algorithm is adopted with slight differences. For the proposed approach, first, door/stair connection segments are generated between the doors/stairs and the inner buffer of the corridor. Second, the medial axis of the inner buffer is created using the MAT algorithm. Third, to create the main network, the branches of the medial axis are eliminated considering the Voronoi diagram segments that do not intersect with the boundary of the inner buffer. Then, route connection segments are created by linking the endpoints of the door/stair connection segments to the nearest points on the main network. Finally, the MAT network is created by linking the route connection segments and door/stair connection segments to the main network. An example of the proposed approach for the MAT navigation network is illustrated for the case study buildings in Figure 5.

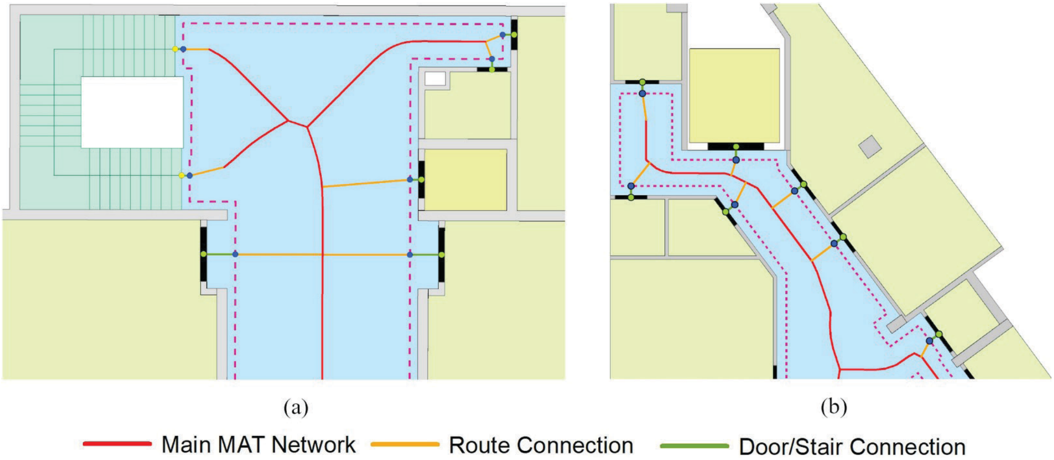

Figure 5: MAT navigation network: (a) university, (b) hospital

3.3.2 CCDT navigation network

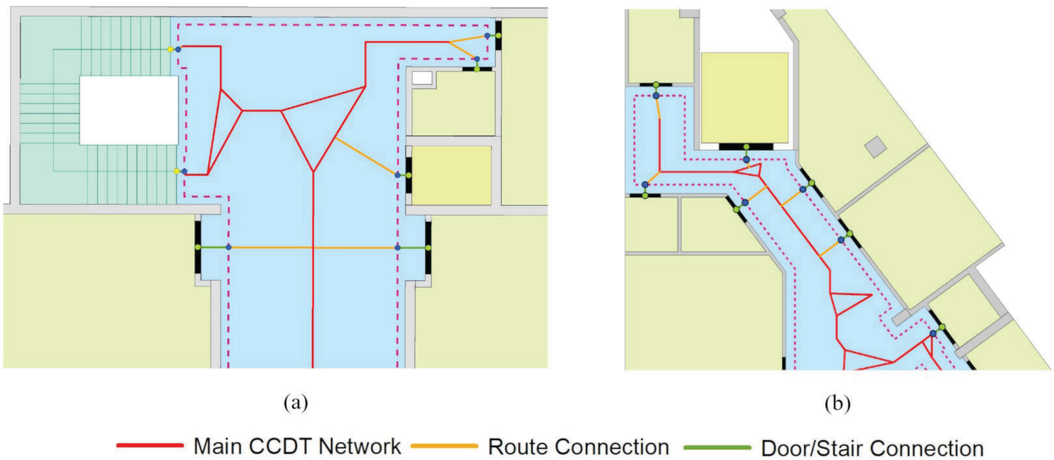

Figure 6: CCDT navigation network: (a) university, (b) hospital

CDT connects the centroids of triangle edges that compose Delaunay triangles. Thus, it calculates the centerline of the geometry (approximates the medial axis). The problem is that CDT can produce inadequate edges, especially in long and narrow corridors (Park et al., 2020), besides it can also lead to undesired spikes which hinder the centerline (Haunert and Sester, 2008). Hence, the CCDT algorithm is proposed by Park et al. (2020) to overcome inadequate edges by densifying the vertices along the boundary of a corridor polygon. The algorithm densifies the vertices along a given geometry's edges and uses the vertices of built-in features (i.e., walls, doors, stairs, and columns) to construct constrained Delaunay triangles. The centroids of Delaunay triangles are then used to construct network edges. In this study, Park et al. (2020)'s algorithm is utilized with slight differences. For the proposed approach, first, door/stair connection segments are generated. Second, the new vertices along the boundary of the inner buffer are linearly interpolated to retain conformal characteristics of the Delaunay triangulation that the centerline relies on. Third, CDT is generated based on the final state of the inner buffer, taking walls and columns as constrained edges. Fourth, the centroids of non-constrained edges of CDT are derived and the main CCDT network is formed by connecting them. Finally, the CCDT network is created by linking the route connection segments and door/stair connection segments to the main network. An example of the proposed approach for the CCDT navigation network is illustrated for the case study buildings in Figure 6.

3.3.3 Grid navigation network

Grid-based navigation network creation algorithm proposed by Li et al. (2010) forms their network by putting a grid in the extent of indoor space, thus the indoor space is divided into a set of cells. Each cell in the grid is expressed by its centroid and the adjacent centroids are connected to form the navigation network, and the cells which intersect with the built-in features such as walls, columns, and doors are eliminated to ensure that there is no network edge across built-in features. The size of the grid (i.e., resolution) determines the sensitivity of the modeling of movement and the efficiency of the algorithm. In this study, Li et al. (2010)'s algorithm is adopted with slight differences. For the proposed approach, first, door/stair connection segments are generated. Second, the square grids are created within the inner buffer. For this purpose, the grid resolution is set to 0.5 m. In this way, a grid cell represents the shoulder width of an average-sized human, thus forming a more realistic navigation network (McDowell et al., 2009). Third, the directional routes from each grid centroid are formed by the queen's case. Fourth, the intersecting grids with wall boundaries are eliminated, and thereby the main network is generated. Finally, the grid network is created by linking the door/stair connection segments to the main network. An example of the proposed approach for the grid navigation network is illustrated for the case study buildings in Figure 7.

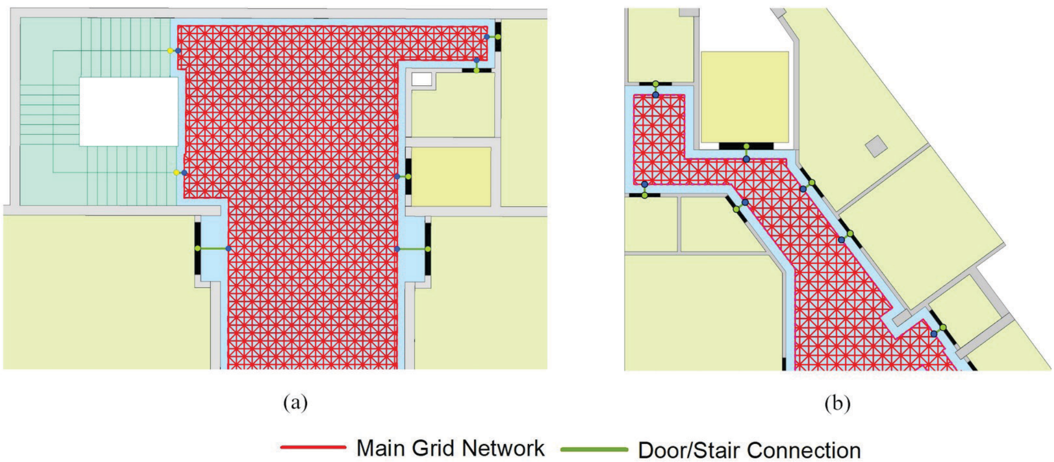

Figure 7: Grid navigation network: (a) university, (b) hospital

3.3.4 MPRSSE navigation network

The MPRSSE algorithm is proposed by Lewandowicz et al. (2019). The algorithm uses the centroids of the CDT edges or the CCDT edges as Voronoi kernels and forms Voronoi polygons from these centroids. The Voronoi polygons are then used to decompose indoor space into neighboring cells. Based on the adjacency of Voronoi polygons, the Voronoi kernels are connected to form corridor paths for all neighboring Voronoi polygons. To form entrance-corridor connections, the MPRSSE navigation network connects the centroid of the corresponding door to the nearest Voronoi kernel. In this study, Lewandowicz et al. (2019)'s algorithm is adopted with slight differences. For the proposed approach, first, door/stair connection segments are generated. Second, the main network is created through the Voronoi polygons obtained from the centroids of CDT edges. Third, the centroids in the Voronoi neighborhood are connected. Finally, the MPRSSE network is created by linking the route connection segments and door/stair connection segments to the main network. An example of the proposed approach for the MPRSSE navigation network is illustrated for the case study buildings in Figure 8.

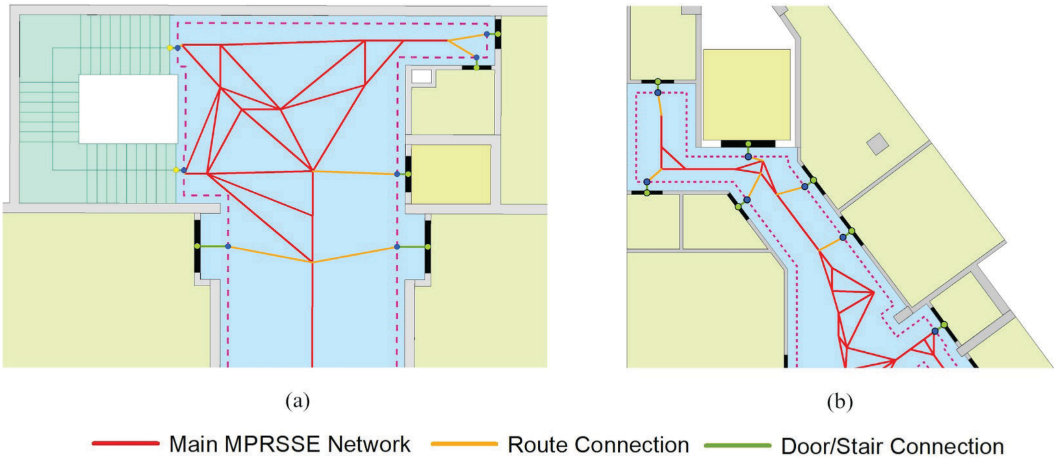

Figure 8: MPRSSE navigation network: (a) university, (b) hospital

3.3.5 UCN navigation network

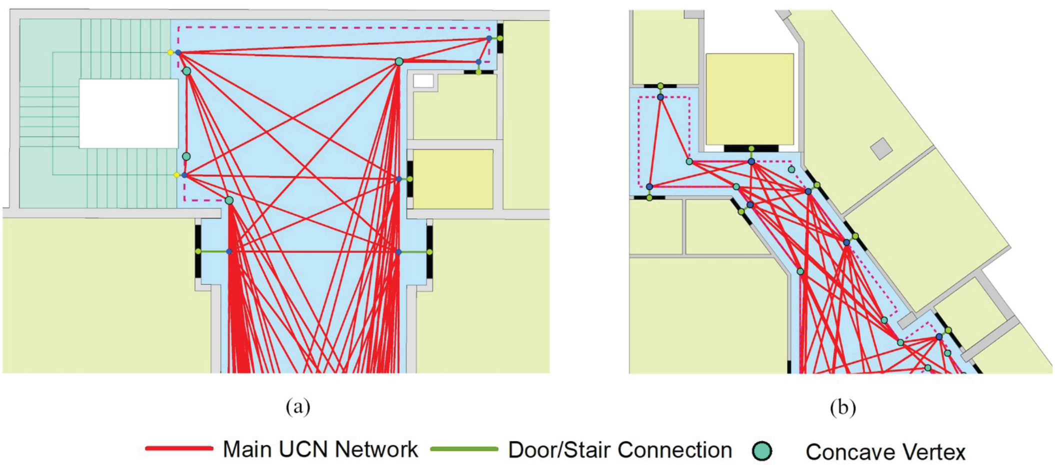

Figure 9: UCN navigation network: (a) university, (b) hospital

The UCN algorithm utilizes buffer zones to shift door/stair nodes to an inner buffer of corridor space and the algorithm forms the network edges based on the inter-visibility of the shifted nodes (Lee et al., 2010). In the case of non-direct visibility, the algorithm uses concave vertices of the inner buffer to generate network edges. In this study, Lee et al. (2010)'s algorithm is used with slight differences. For the proposed approach, first, door/stair connection segments are generated. Second, the endpoints of the door/stair connection segments are connected if they had inter-visibility. Finally, in the case of non-direct visibility, the concave vertices of the inner buffer of the corridor are used as intermediate nodes to create the visibility lines. An example of the proposed approach for the UCN navigation network is illustrated for the case study buildings in Figure 9.

3.3.6 Computation of indoor paths and turns

Dijkstra's shortest path algorithm (Dijkstra, 1959) is utilized on the five navigation networks to compute all possible door-from-door paths and their distances. For the turns, the "node-coordinate based turn calculation algorithm" is utilized (Vanclooster et al., 2014b). The algorithm considers a change of direction as a turn only if the angle exceeds a given threshold (the commonly used threshold value is 45°, which is also used in this study).

3.4 Space Syntax analysis

The legibility of a spatial configuration depends on the differentiation of appearance, visual access, and layout complexity of a building. The isovists and VGA, which are commonly used methods in space syntax theory, can quantify the overall properties of a spatial configuration.

An isovist is defined as a polygon that reflects the visible area from a vantage point from the visual perception of human cognition (Benedikt, 1979). The vantage point of an isovist represents a human observer hence they can be referred to as cognitive measurements of the visual perception of a pedestrian (Hölscher and Brösamle, 2007). Isovists focus on architectural layouts (Turner et al., 2001), thus isovists can be generated on floorplans to evaluate visual access from an observation point. Therefore, isovist measures are usually referred to as local measures (De Cock et al., 2020). To associate the related local isovist measures along a continuous path (e.g., to express how the user experiences space through movement), a set of isovists at regular intervals can be generated. This kind of isovist is referred to as the Minkowski model, and can potentially be used to evaluate indoor paths (Benedikt, 1979; Al-Sayed et al., 2014).

VGA is a commonly used analysis in space syntax theory, originally emerged from the concept of isovists (Turner et al., 2001). Representing spatial space in a similar manner to axial lines (Hillier and Hanson, 1984), but in a more granular way by putting a grid to the extent of the spatial unit. The grid size defines the precision of the analysis, thus allowing modeling of the spatial relationships and space occupancy based on the resolution. The VGA measures such as mean visual depth and integration (normalized mean visual depth) can be used to evaluate a place's centrality in a spatial configuration as it accounts for all other places in the spatial configuration.

In this study, five local isovist measures (area, perimeter, occlusivity, vista length, and average radial) and five VGA measures as semi-global and global measures (overt control, covert control, choice, mean visual depth (MVD), and integration) are computed for corridor space (McElhinney, 2020) to evaluate visual access and the characteristics of spatial configuration. An overview of the local, semi-global and global measures is given in Table 1 and Table 2, respectively. In Table 1, L is radial length, E is edge lengths between the ends of radials, n is the total number of radial samples and k is the sample number in a 360° cycle (McElhinney, 2020). In addition to these measures, through vision (Turner, 2007) is computed. The measure is defined as for each cell in the grid, the number of times a cell is crossed by the inter-visibility lines drawn between the centroid of grid cells. Thus, the places that are most probable to be traveled can be identified (Koutsolampros et al., 2019).

Table 1: Equations and short descriptions of local isovist measures (Benedikt, 1979)

Local Measures	Equation	Description
Area	$A_v = \frac{\pi}{n}\sum_{i=1}^{n} L_i^2$	The area of the isovist generated from a vantage point.
Perimeter	$P_v = \frac{k}{n}\sum_{i=1}^{n} E_i$	The sum of the length of edges of an isovist.
Occlusivity	$O_v = \frac{k}{nP_v}\sum_{i=1}^{n}\left\lvert E_{i\_occ}^2 \cdot L_i \right\rvert$	The proportion of the isovist edges that do not intersect with physical objects within the environment. It indicates the potential to see a space that cannot previously be seen along with the movement.
Vista Length	$H_v = max\ (H_v, L_i)$	The length of the longest view of an isovist.
Average Radial	$Q_v \quad -\sum L_i$	The mean value of all possible view lengths of an isovist.

In Table 2, n is the total number of isovist samples, Wv is directed visibility (see McElhinney, 2020), B is the number of points belonging to random walking routes falling within isovists, F is the shortest distance from sample location to all other locations in a spatial configuration and G is the least number of visual steps from sample location to all other locations in a spatial configuration.

Table 2: Equations and short descriptions of VGA measures

Category		Equation	Description
Semi-Global	**Overt Control**	$X_v = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{1}{A_i}\right)$	The area of visible space concerning the immediate neighbors. Indicates places where the observer's view is large (McElhinney, 2020).
	Covert Control	$Y_v = \frac{1}{n.Wv}\sum_{i=1}^{n} A_i$	Mean area of visible space within one visual step divided by Directed Visibility (McElhinney, 2020).
	Choice	$Z_v = \frac{1}{n}\sum_{i=1}^{n} B_i$	The average number of times the given location stands on the shortest path between all other spaces (Hillier et al., 1987).
Global	**MVD**	$MVD_v = \frac{1}{n}\sum_{i=1}^{n} G_i$	The average number of visual steps from a sample point to all other locations (Hillier, 1996).
	Integration	$dValue = \frac{2\left\{k.\left[log2\left(\frac{k+2}{3}\right)-1\right]+1\right\}}{(k-1)(k-2)}$ $Ing_v = \frac{dValue.(k-2)}{2(MeanVisualDepth_v - 1)}$	A normalized version of MVD by using d-value, allowing comparison between spatial layouts independent from their size (Hillier and Hanson, 1984). It indicates the centrality of a place in the layout.

Usually, isovist and VGA measures are computed for a set of grid coordinates in the space syntax analysis. To assign these measures to indoor paths, these discrete points should be converted into continuous data. Therefore, these discrete measures are converted to the raster surfaces (in this study, the resolution is utilized as 0.1 m) and the mean value of the raster cells for each measure is assigned to the respective indoor paths. An example of the raster surfaces is illustrated for the case study buildings in Figure 10.

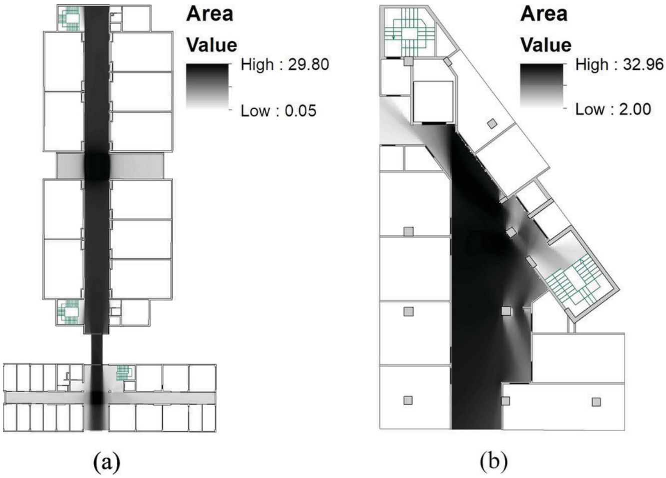

Figure 10: Raster surfaces for area measure: (a) university, (b) hospital

3.5 Collection of the actual navigation patterns

An individual's actual navigation pattern can be defined as their preference to move in a certain area or zone while they locomote in an environment (Jamshidi et al., 2020). A user experiment is conducted to capture the actual navigation patterns of pedestrians and to compare them with indoor paths.

3.5.1 Recruitment of the participants

A self-report questionnaire to collect fundamental information about the participants (i.e., age, gender, degree of education) is conducted. Spatial abilities are important in the wayfinding process (Li and Klippel, 2016). Therefore, participants are asked to complete the Santa Barbara Sense of Direction scale (SBSOD) (Hegarty et al., 2002), to ensure that there is no significant difference between male and female participants. Also, since the familiarity of a pedestrian with a building has an impact on their wayfinding decisions, their degree of familiarity with the related test buildings is considered (see Section 4.2 for details).

3.5.2 Experiment procedure

The experiment procedure is briefly introduced to the participants, and they are accompanied to the main entrance of the related area. At the starting point, the floorplans of the buildings are shown to the participants, and they are asked to find some spaces in the study area. The tasks are chosen as they broadly cover the environment. The participants are not allowed to look further into the floorplan or any kind of map and they are not allowed to ask any questions during the experiment. Each task is assigned by giving semantic information related to indoor spaces (e.g., office Z-067, the stairs that lead to the 1st floor, kitchen, class DZ-132, class DZ-135, WC, etc.).

The participants are invited to the experiment one by one, and the tasks are assigned to the participants step by step; after they reach a goal, the following task is assigned to them and their walking patterns are collected (Hölscher and Brösamle, 2007; Hölscher et al., 2012; Li and Klippel, 2016) and then regenerated in the GIS environment for further analysis.

3.6 Comparison of the actual navigation patterns

To determine substantial isovist and VGA measures for human spatial cognition and link them with navigation patterns of pedestrians; first, Jenks Natural Breaks (JNB) classification is used to classify isovist and VGA measures into three ordinal categories, i.e., "low", "mid" and "high". Next, to compare them with the actual navigation patterns of pedestrians, the mean values of the space syntax measures are assigned to the actual navigation patterns of the pedestrians. After that, the paths are categorized by their values. In this way, the preferences of pedestrians for related isovist and VGA measures are determined. Finally, the mean differences between the actual navigation patterns and indoor paths are evaluated to determine the closest navigation network to the actual navigation patterns for the related routes.

3.7 Comparison of all door-from-door paths

All door-from-door indoor paths are evaluated to compare navigation networks against each other by traditional measures as well as isovist and VGA measures with statistical tests. One way-ANOVA test is performed to check whether the mean of traditional measures differs significantly among the navigation networks (i.e., indoor paths for each navigation network). If ANOVA results are significant ($p < .05$), the Tukey HSD or Games-Howell post-hoc tests are implemented based on the assumption of homogeneity of variance for the data.

Concerning isovist and VGA measures, first, a dimension reduction via factor analysis is executed on the interrelated measures (De Cock et al., 2020). Then, these measures are evaluated statistically as applied to the traditional measures. If they fail to fulfil the assumption of normality of one way-ANOVA test, non-parametric Kruskal-Wallis H test can be implemented. If the Kruskal-Wallis H test is significant ($p < .05$), pairwise Mann-Whitney U tests (with Bonferroni correction) can be implemented as post-hoc tests. Finally, the most suitable navigation network for traditional and space syntax measures is determined.

4 EXPERIMENTS AND CASE STUDY

4.1 Dataset and materials

It is acknowledged within the literature that there exist some distinctions between outdoor and indoor environments with regards to navigation and wayfinding (Yan, Zlatanova, and Diakité, 2021). The configuration of indoor spaces (e.g. corridors) differs from the linear layout commonly observed in outdoor environments (Diakité and Zlatanova, 2018). Hence, they vary much more than outdoor spaces (Fellner, Huang, and Gartner, 2017) which results in the lack of a comprehensive network model (Park et al., 2020). Furthermore, along with the spatial configuration, the function of an environment (e.g., educational, healthcare, airport, mall) plays a significant role in wayfinding tasks (Devlin, 2014).

Considering the aforementioned aspects, to understand how navigation networks respond to different forms of corridors (e.g., cross junction and complex combined junction), two distinct buildings with different functions, one designed for educational purposes (i.e., university) and the other for healthcare (i.e., hospital), were utilized for the experimental study. The basement floor of a university building was chosen as the first test area (Figure 11a). For the first building, the indoor spaces (e.g., rooms) have a common form. They vary in size, but the typical shape is a rectangle with each surrounded by walls and columns, with different-sized door apertures. The second building is a hospital (Figure 11b). The first floor was utilized as the test area because it contains an L-shaped and combined-shaped complex corridor structure. The corridor space has two square-shaped columns and two rectangular columns along with a sub-corridor that leads to staircases. They tend to cause inaccurate and non-linear paths according to the structural shape of the sub-corridor. Both buildings were chosen as they contain at least a sub-corridor to evaluate indoor paths.

Generalized floorplans of the two buildings (see Section 3.2) were utilized as the indoor spatial dataset which is commonly used in the literature to derive indoor navigation networks. For the navigation networks, the generalized floorplans were used as input data and all operations were performed with ArcPy and ArcGIS tools, additionally, for the MAT navigation network, the medial axis was created through the "centerline" Python library (https://github.com/fitodic/centerline). In addition, for the space syntax analysis, isovist and VGA measures were computed through open-source software Isovist_App (McElhinney, 2020) and depthmapX (Varoudis, 2012).

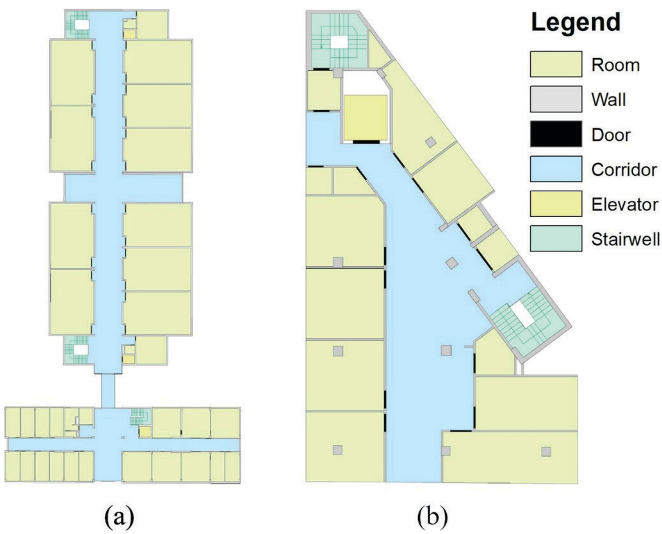

Figure 11: Generalized floorplans used in the study: (a) university, (b) hospital

4.2 Results of collecting the actual navigation patterns

We conducted a user experiment to capture the actual navigation patterns of pedestrians and to compare them with indoor paths. A total of 30 individuals (13 female and 17 male) aged 19 to 31 (M = 22.63 SD = 2.47) voluntarily participated in the experiment. All the participants provided a written consent form, and they were informed that they could retreat any time from the experiment. Since there was no significant difference between the wayfinding ability of the male and female participants in accordance with SBSOD test, ($t(28) = 1.947$, $p = .062$), all participants were treated as equals. For the university building, most of the participants were students or staff, however, four participants had no prior or minor knowledge of the test area. For the hospital, all of the participants were unfamiliar with the building. The impact of familiarity on the results is discussed in the discussion section. In this study, the participants were asked to find six spaces sequentially in the test areas. After the experiment, the actual navigation patterns were regenerated in the GIS environment (see section 3.5.2). The resulting navigation pattern for a task is given in Figure 12.

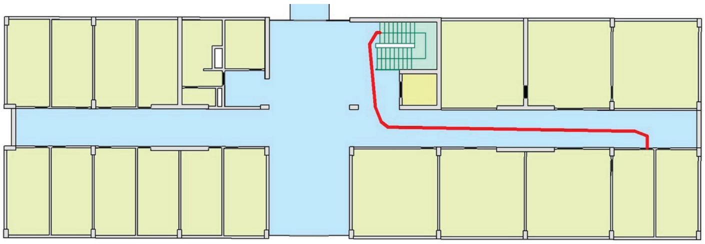

Figure 12: An example of an actual navigation pattern in the GIS environment

4.3 Results of the comparison for the actual navigation patterns

The results of assigning actual navigation patterns (averaged across participants) to the related classes are given in Table 3. For the university, results show that participants prefer to walk on routes that have a "medium" level of isovist measures and overt control that quantifies visual access within the building. Participants tend to prefer "high" choice, and "medium" level of integration, which quantify a place's centrality (betweenness and closeness centrality) in the spatial configuration of a building. For the hospital, results show that participants again prefer to walk on routes that have a "medium" level of isovist measures and overt control whereas they tend to walk routes with "high" choice and integration.

Table 3: Class labels for isovist and VGA measures derived from actual navigation patterns of pedestrians for the university and the hospital

Measure	University		Hospital	
	Value	Class	Value	Class
Area	14.111	Medium	23.743	Medium
Occlusivity	0.425	Medium	0.403	Medium
Overt Control	6.839	Medium	6.010	Medium
Choice	0.400	High	0.357	High
Integration	21.069	Medium	36.401	High

The results for mean differences in isovist and VGA measures between the actual navigation patterns and the navigation networks are given in Table 4. For the university, in terms of isovist measures, the navigation network closest to the actual navigation patterns is the MPRSSE navigation network followed by CCDT, MAT, Grid and UCN in decreasing order. In terms of VGA measures, the MPRSSE navigation network is the closest followed by CCDT, MAT, Grid and UCN, except for overt control, where MPRSSE and CCDT switch the orders with a slight difference. For the hospital, with respect to isovist measures, the CCDT navigation network is the closest to the actual navigation patterns, followed by MAT, MPRSSE, Grid and UCN in decreasing order. Concerning VGA measures, for integration, the MAT navigation network is closer to the actual navigation patterns, followed by CCDT, MPRSSE, UCN and Grid in decreasing order. Concerning overt control, CCDT is the closest navigation network followed by MAT, UCN, Grid and MPRSSE.

Table 4: Mean differences of actual navigation patterns and navigation networks for the six tasks

Measure	Movement Model	University		Hospital	
		Mean Value	Mean Difference	Mean Value	Mean Difference
Area	Actual	14.111		23.743	
	MAT	14.719	-0.608	23.331	0.412
	CCDT	14.359	-0.248	23.344	0.399
	Grid	13.048	1.063	22.786	0.957
	MPRSSE	14.155	-0.044	23.090	0.653
	UCN	12.938	1.173	22.744	0.999
Occlusivity	Actual	0.425		0.403	
	MAT	0.421	0.004	0.413	-0.010
	CCDT	0.426	-0.001	0.413	-0.010
	Grid	0.446	-0.021	0.429	-0.026
	MPRSSE	0.424	0.001	0.426	-0.023
	UCN	0.451	-0.026	0.435	-0.032
Overt Control	Actual	6.839		6.010	
	MAT	6.967	-0.128	5.810	0.200
	CCDT	6.848	-0.009	5.812	0.198
	Grid	6.194	0.645	5.728	0.282
	MPRSSE	6.795	0.044	5.723	0.287
	UCN	6.128	0.711	5.763	0.247
Choice	Actual	0.400		0.357	
	MAT	0.403	-0.003	0.350	0.007
	CCDT	0.402	-0.002	0.350	0.007
	Grid	0.394	0.006	0.351	0.006
	MPRSSE	0.401	-0.001	0.349	0.008
	UCN	0.393	0.007	0.354	0.003
Integration	Actual	21.069		36.401	
	MAT	22.283	-1.214	34.712	1.689
	CCDT	21.733	-0.664	34.586	1.815
	Grid	18.749	2.320	32.585	3.816
	MPRSSE	20.988	0.081	33.225	3.176
	UCN	18.628	2.441	32.788	3.613

4.3 Results of the comparison for all door-from-door paths for traditional measures

The descriptive statistics for traditional measures and the one way-ANOVA results for traditional measures are given in Table 5 and Table 6, respectively.

Table 5: Descriptive statistics for traditional measures

Navigation network	University				Hospital			
	Distance (m)		Turn		Distance(m)		Turn	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
MAT	52.428	30.678	4.32	1.806	11.635	5.072	4.26	1.664
CCDT	52.874	30.872	4.40	2.263	11.419	5.018	4.52	2.443
Grid	48.148	30.187	10.30	7.318	9.743	4.699	7.08	4.603
MPRSSE	50.673	29.995	2.85	0.958	10.969	4.932	2.89	1.676
UCN	46.948	29.659	2.18	0.709	9.331	4.514	1.41	0.830

Table 6: Results of one way-ANOVA test for traditional measures

ANOVA	University		Hospital	
	Distance	Turn	Distance	Turn
df (between groups)	4	4	4	4
df (within groups)	6625	3110.890	675	315.629
F-value	9.804	993.838	6.095	153.306
p-value	$p < .001$	$p < .001$	$p < .001$	$p < .001$

Since ANOVA results were significant ($p < .05$) for both buildings, Tukey-HSD and Games-Howell post-hoc tests were executed for the traditional measures, respectively (see Table 7).

Table 7: Results of post-hoc test for traditional measures (*p < .05, **p <.01, ***p < .001. MD = Mean Difference)

Navigation network		University		Hospital	
		Distance(MD)	Turn(MD)	Distance(MD)	Turn(MD)
MAT	**CCDT**				
	Grid	4.280**	-5.98***	1.892*	-2.82***
	MPRSSE		1.47***		1.37***
	UCN	5.480***	2.14***	2.304**	2.85***
CCDT	**MAT**				
	Grid	4.726**	-5.90***	1.676*	-2.56***
	MPRSSE		1.55***		1.63***
	UCN	5.926***	2.22***	2.088**	3.11***
Grid	**MAT**	-4.280**	5.98***	-1.892*	2.82***
	CCDT	-4.726**	5.90***	-1.676*	2.56***
	MPRSSE		7.45***		4.19***
	UCN		8.12***		5.67***
MPRSSE	**MAT**		-1.47***		-1.37***
	CCDT		-1.55***		-1.63***
	Grid		-7.45***		-4.19***
	UCN	3.725*	0.67***	1.638*	1.48***
UCN	**MAT**	-5.480***	-2.14***	-2.304**	-2.85***
	CCDT	-5.926***	-2.22***	-2.088**	-3.11***
	Grid		-8.12***		-5.67***
	MPRSSE	-3.725*	-0.67***	-1.638*	-1.48***

Note: MD values are shown if the p-value is significant (p < .05).

For indoor path distances, MD implies the amount of difference between the mean values of the navigation networks in meters. For example, for the university, the average distance obtained from the MAT navigation network is 5.48 m longer than the UCN navigation network (shorter is better). For turns, MD implies the difference in the average number of turns between the navigation networks (lower is better). Regarding the average distances, the greatest of the significant differences occurred between UCN and CCDT for the university while between UCN and MAT for the hospital. The lowest significant difference was between UCN and MPRSSE for both the university and the hospital (see Table 7). For the hospital, the UCN navigation network yields shorter distances followed by Grid, MPRSSE, MAT and CCDT, while for the hospital MAT and CCDT switch the orders with a slight difference. Regarding the average turns, the highest significant difference occurred between UCN and Grid for both the university and the hospital. The lowest significant difference was between UCN and MPRSSE for the university and MAT and MPRSSE for the hospital (see Table 7). Since the average differences between the remaining models were insignificant, they were considered equivalent for both measures. For both buildings, the UCN navigation network yields a lower number of turns followed by MPRSSE, MAT, CCDT and Grid.

4.4 Results of the comparison for all door-from-door paths for space syntax measures

Table 8: Descriptive statistics for isovist and VGA measures

Measure	Navigation network	University		Hospital	
		Mean	SD	Mean	SD
Area	**MAT**	16.114	3.418	23.088	4.930
	CCDT	16.072	3.490	23.046	4.919
	Grid	15.013	3.556	22.321	5.142
	MPRSSE	15.439	3.579	22.722	4.684
	UCN	15.150	3.617	22.564	5.115
Overt Control	**MAT**	6.785	0.857	5.781	0.689
	CCDT	6.759	0.857	5.751	0.727
	Grid	6.346	0.802	5.515	0.732
	MPRSSE	6.496	0.751	5.687	0.725
	UCN	6.372	0.794	5.564	0.733
Integration	**MAT**	23.947	4.801	33.775	8.271
	CCDT	23.883	4.807	33.384	8.682
	Grid	21.815	4.858	32.172	8.687
	MPRSSE	22.490	4.835	32.498	8.475
	UCN	21.923	4.946	32.355	8.843

Note: Only one measure from each category (local, semi-global, global) is given in the table.

The descriptive statistics of all door-from-door indoor paths for isovist and VGA measures are given in Table 8. Since the distribution of the space syntax measures rejected the assumption of normality of one way-ANOVA test, the Kruskal-Wallis H test was used. The resulting significance values of the Kruskal-Wallis H test and the following pairwise Mann-Whitney U tests (with Bonferroni correction) on average ranks between navigation networks for isovist and VGA measures are summarized in Table 9 and Table

10. For the university, the average ranks of all measures differed significantly among groups. For factor A (area, perimeter, vista length and average radial), factor B (overt control and covert control), factor C (through vision and choice) and integration, the MAT navigation network yields higher average ranks, followed by CCDT, MPRSSE, UCN and Grid navigation networks. For occlusivity, the Grid navigation network yields a higher average rank, followed by UCN, CCDT, MPRSSE and MAT (see Table 9). For the hospital, the measures that differed significantly were solely factor B and factor C. The MAT navigation network yields a higher average rank, followed by CCDT, MPRSSE, UCN and Grid (see Table 10).

Table 9: Results for Kruskal-Wallis H test and pairwise Mann-Whitney U tests (with Bonferroni correction) for isovist and VGA measures for the university (p < .05)

Measure	p-value (KW)	Model	University				
			MAT	**CCDT**	**Grid**	**MPRSSE**	**UCN**
Factor A	p < .001	**MAT**			-1218.112	-596.108	-914.569
		CCDT			-1184.587	-562.582	-881.044
		Grid	1218.112	1184.587		-622.005	-303.543
		MPRSSE	596.108	562.582	622.005		-318.462
		UCN	914.569	881.044	303.543	318.462	
Occlusivity	p < .001	**MAT**			-669.400		-622.925
		CCDT			-516.556		-470.081
		Grid	669.400	516.556		-656.450	
		MPRSSE			656.450		-609.976
		UCN	622.925	470.081		609.976	
Factor B	p < .001	**MAT**			-1027.278	-617.446	-907.795
		CCDT			-988.235	-578.403	-868.752
		Grid	1027.278	988.235		-409.832	
		MPRSSE	617.446	578.403	409.832		-290.349
		UCN	907.795	868.752		290.349	
Factor C	p < .001	**MAT**			-1504.581	-423.391	-1443.031
		CCDT			-1444.170	-362.980	-1382.620
		Grid	1504.581	1444.17		-1081.189	
		MPRSSE	423.391	362.980	1081.189		-1019.64
		UCN	1443.031	1382.620		1019.640	
Integration	p < .001	**MAT**			-1224.845	-820.451	-1129.006
		CCDT			-1212.270	-807.876	-1116.431
		Grid	1224.845	1212.270		-404.394	
		MPRSSE	820.451	807.876	404.394		-308.555
		UCN	1129.006	1116.431		308.555	

Factor A: Factor of interrelated measures, i.e., Area, Perimeter, Vista Length, Average Radial
Factor B: Factor of interrelated measures, i.e., Overt Control, Covert Control
Factor C: Factor of interrelated measures, i.e., Choice, Through Vision
Note 1: The measures are given in the table if the Kruskal-Wallis H test is significant (*p* < .05)
Note 2: Null columns mean that there is no significant difference for the Mann-Whitney U test

Table 10: Results for Kruskal-Wallis H test and pairwise Mann-Whitney U tests (with Bonferroni correction) for isovist and VGA measures for the hospital ($p < .05$)

Measure	p-value (KW)	Model	Hospital				
			MAT	CCDT	Grid	MPRSSE	UCN
Factor B	0.013	**MAT**			-69.963		
		CCDT					
		Grid	69.963				
		MPRSSE					
		UCN					
Factor C	p < .001	**MAT**			-132.886		-109.923
		CCDT			-108.143		-85.180
		Grid	132.886	108.143		-74.445	
		MPRSSE			74.445		
		UCN	109.923	85.180			

Factor B: Factor of interrelated measures, i.e., Overt Control, Covert Control
Factor C: Factor of interrelated measures, i.e., Choice, Through Vision
Note 1: The measures are given in the table if the Kruskal-Wallis H test is significant ($p < .05$)
Note 2: Null columns mean that there is no significant difference for the Mann-Whitney U test

5 DISCUSSION

5.1 Comparison of the actual navigation patterns

Some noteworthy remarks can be drawn from the comparison of actual navigation patterns and navigation networks. A priori outcome that can be inferred is that participants tend to prefer isovist measures, i.e., those pertaining to visual access, to be in the medium category since low or high visual access can induce cognitive load in users. For example, low occlusivity, i.e., the potential to see a space that cannot previously be seen along with the movement, can lead to uncertainty to decide where to head whereas high occlusivity can lead to a higher amount of information to be processed, thus demanding a higher cognitive load. Another outcome that can be drawn is that since people tend to walk routes that belong to high choice and through vision categories (Factor C), these measures can be used to forecast where human's movement flow may occur; therefore, it can come in handy when planning a path with navigation networks or when designing a building based on the occupancy. From the perspective of VGA measures, i.e., those related to the centrality of a place in a building, the university belongs to the medium category of integration whereas the hospital belongs to the high category of integration (see Table 3). The possible reason for this may be the individual's familiarity with the building (Hölscher et al., 2012). For the university, most of the participants have been in the building before whereas none of the participants has ever visited the hospital before. Another factor may be the shape of the corridor spaces of buildings. Since the hospital has a more complex corridor structure and some less visible areas than the university, it can be stated that people prefer walking through higher integrated spaces (higher integration indicates the centrality of a place) which complies with the prior studies in the literature (Haq and Girotto, 2003; Haq and Zimring, 2003; Li and Klippel, 2012).

Since isovist measures are a representation of human cognition from a vantage point, isovist measures are crucial to reflect human cognition when traveling along a path. Therefore, assessing the closeness between actual walking patterns and indoor paths by space syntax measures should be considered when evaluating the navigation networks (i.e., computed indoor paths), which has not been reported yet. In this study, the MPRSSE, CCDT and MAT navigation networks come closer to the actual navigation patterns in terms of space syntax measures, i.e., isovist and VGA measures except choice measure for the hospital where UCN is closer (see Table 4). Although they differ slightly, MPRSSE, CCDT and MAT navigation networks, being a kind of centerline approximation models, can be useful to reflect human perception when navigating indoors. Besides, for our experimental study, the building configuration does not significantly affects the results in terms of the comparison of the actual navigation patterns. Although we only compared them by six routes for both test buildings, the routes containing non-level paths such as stairs, elevators and ramps could also be employed to assess a complete coverage within the building. Also, the participants mostly are in the 20-30 age period and have similar levels of education. These factors can also influence the results as shown by De Cock et al. (2020).

5.2 Comparison of all door-from-door paths

The results of traditional measures suggest that the UCN model is the most suitable for length and turn minimization (see Table 7). It is expectable since the UCN model mostly consists of shortest paths or slightly broken shortest paths between a node pair. In most of the previous studies, the visibility-based navigation networks were found the most suitable model; however, it is arguable because that is the case if people know the exact location of the destination. Moreover, in our case, although most of the participants knew the exact location of some destinations, they first tended to walk towards the centerline until they saw the destination. This indicates that visual access parameters may play a role and should be considered when evaluating navigation networks.

From the perspective of isovist and VGA measures, one striking result is that the leading navigation network for traditional measures, which is UCN, falls behind the other navigation networks for space syntax measures (see Table 9 and Table 10). On the other hand, two centerline approximation navigation networks, i.e., CCDT and MAT outperform others.

According to both traditional measures as well as isovist and VGA measures, the MPRSSE navigation network can be deemed the most feasible navigation network for indoor navigation as it stands between mid to top for concerned measures (See Table 4 and Tables 7-10). This may stem from the additional paths that come from the adjacency of Voronoi polygons, thus it both approximates the centerline and the break lines of visibility to some extent. However, it should be noted that we are aware of the preference level of participants for related space syntax measures for only six given tasks (given via the user experiment). Here, in this section, we have checked whether the related measures differ significantly for all indoor paths (for each navigation network). Therefore, we can only interpret the results in a general sense. Besides, for our experimental study, the building configuration does not significantly affects the results in terms of the comparison of the all door-from-door paths. Further research is needed to determine whether preferences for space syntax measures change with task variation (i.e., other indoor paths via the collection of navigation patterns).

6 CONCLUSION AND FUTURE WORK

Indoor navigation networks are a significant way to implement indoor navigation since they conceptualize indoor space, model the interrelations of structural components, and try to express the actual navigation patterns of pedestrians. Due to the lack of clear movement patterns in an indoor environment, there is an ongoing debate to establish an indoor navigation network that is in line with human cognition to support the wayfinding process. However, existing studies mostly focus on length and turn minimization to evaluate navigation networks. In this study, to address the related gap, we utilized also space syntax measures to evaluate the five most commonly used navigation networks (MAT, CCDT, Grid, MPRSSE, and UCN) each with slight refinements, followed by a user experiment to assess the closeness between actual navigation patterns and the navigation networks as well as to determine user preferences for related space syntax measures.

The findings of the experimental study show that according to the traditional measures, a visibility-based navigation network (UCN) is the most suitable. However, the user experiment suggests that the centerline approximation navigation networks (MAT, CCDT and MPRSSE) are better to reflect the visual perception of pedestrians and the preference for the centrality of a place according to the space syntax measures. When all measures are concerned, it can be concluded that the MPRSSE navigation network is the most feasible for indoor navigation for our test buildings. However, it should be noted that none of the examined navigation networks step forward for all the tested measures. Nevertheless, the MPRSSE model covers most of the aspects of our experimental study.

For future studies, the variety of the user characteristics (age, gender, level of education), the participant's degree of familiarity with the building, and the buildings with different configurations/functions (e.g., airports, shopping malls, metro stations, etc.) should be considered when evaluating indoor paths. In addition, the routes containing non-level paths can be investigated to assess complete coverage within a building.

Despite the availability of various algorithms and studies, establishing an indoor navigation network that fully supports one's wayfinding process remains challenging and the debate to determine the most proper navigation network seems to continue to grow.

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