INDOOR SPATIAL ANALYSIS USING SPACE SYNTAX

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ABSTRACT:

Accessibility typically has been applied to urban or transportation problems two dimensionally. However, in large complex buildings as shopping centers or hospitals, inter-spatial accessibility among compartments has to be taken into account such as in building layouts or evacuation planning. This study expands space syntax theory, one of accessibility-related methodologies used for computing connectivity in urban or architectural spaces, into 3D indoor spaces. Although space syntax is basically a topology-based theory that does not consider general costs such as distance or time, this study suggests modification that incorporates different types of impedances in moving between places including distances, turns and transfers between floors. The proposed method is applied to a 3D campus building model in computing and displaying the accessibility to exit doors or cohesive accessibility among similar functions.

1. INTRODUCTION

Accessibility is generally used notion that measures the relative nearness or easiness of movement from one place to another mostly in the network of streets or transportation routes. However, as large scale complex buildings or underground spaces are increasingly built and today's life patterns demand use of such complex spaces, analytical means such as accessibility is required for better spatial plans or guidance purposes for people. Moreover, such technologies as location-based services, or LBS, which have been applied to car navigation or personal guidance systems are now getting attention as technologies also applicable to indoor spaces. In order to apply network analysis techniques to indoor spaces, we need to reestablish proper definition of accessibility. It's because, not like street networks, most indoor spaces are located three dimensionally in buildings or underground structures.

On the other hand, space syntax is the technique that has been used to derive the connectivity of urban or architectural spaces (Hillier 1996, Penn *et al*. 1998). The theory has primarily been applied in the research areas that seek to find the movement of human beings among architectural spaces or pedestrian paths and it has helped to compute the connectivity of the network of built environment (Hillier and Hanson 1984). However, space syntax generally concerns geometric connectivity of locations and places based on their spatial links only and does not include costs of moving between places. But in order to capture the easiness or difficulty of movement in indoor space levels, we need to consider not only structure of spaces but also costs or impedance taken in movement from one place to another such as physical distances, turns and transfers between floors.

Existing spatial analyses such as measure of accessibility are frequently performed using 2D GIS packages. Apart from lack of research efforts, the difficulty of spatial analyses targeting 3D models lie in the structural limitations that current 3D models inherently have. Most 3D modeling techniques have been developed focusing on the visualization of buildings or terrains to increase the feelings of reality of features. They mostly need not or do not have topological structures that are required in spatial analyses in 2D GIS. That is, objects in typical 3D models are not segmented using spatial units (i.e. points, lines and polygons) and relationships between them are not defined thereof, which make it difficult to perform spatial analyses or queries in 3D models.

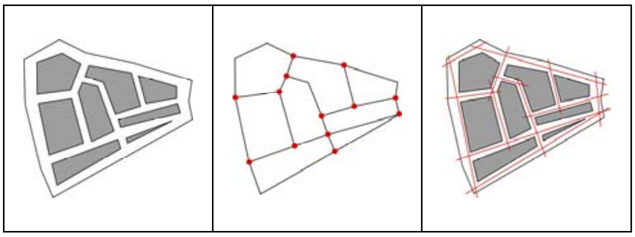
In this paper, we develop an accessibility measure that can generally be applied to not only 3D building levels but all kinds of levels including urban streets networks. We first examine space syntax theory and then derive a more generalized version of accessibility measure based on both existing space syntax principle and the costs terms which are widely used in traditional accessibility research. In order to apply the proposed method to 3D models, we modify existing 3D modeling procedure such that they can have topological structures and attributes of spatial objects by integrating them with 2D GIS layers. Finally, we illustrate the use of the proposed measure comparatively with space syntax using a campus building.

2. SYNTAX-BASED ACCESSIBILITY

Human movement is frequently described in an abstracted form using its topology. Topological description allows researchers to focus on the structural relationship among units of movement while disregarding the details of phenomena. For example, pedestrian movement can be described using network of simple lines without considering the details such as sizes of forms, number of people and speed of movement. Such network configuration is also referred to as graph, which is a way to represent a network by a set of vertices and a set of edges that connects pairs of vertices.

However configuring spaces in space syntax is different from that of street network. In space syntax, when converting the continuous space into a connected set of discrete units, it uses the concept of convex space partitioning or simply axial mapping. The procedure to generate the convex map involves taking a given spatial structure and partitioning it into a set of "fewest and fattest" convex spaces (Hillier and Hanson, 1984, pp.97-98). The procedure for generating the convex maps is iterative, starting with the identification of the fattest of the convex spaces and then progressively identifying the next largest one until the entire area is subdivided into a set of convex spaces. Then, the axial map can be drawn on this convex map by laying down the longest strait lines that passes through theses convex spaces (Figure 1-b). On the other hand, traditional way of abstracting street network follows different procedure. It generally uses center lines of streets. Whenever two center lines intersect each other, an intersection is created (Figure 1-c). When representing the configured lines as a graph, space syntax represents each line by a node and each intersection as an edge, while in traditional method, the situation is vice versa, that is, an intersection becomes a node and a line connecting two nodes becomes an edge.

The resulting axial lines in the axial map can be regarded as the fewest number of visual paths in the existing space where each intersection plays as a turn of sight, which becomes a depth as described previously. Thus, in space syntax, only the number of turns along a path rather than actual journey length is counted. The cost such as distance or travel time along an edge is not regarded as significant factor in space syntax. Therefore, the concept of the depth should not be interpreted as the accessibility of a space; rather it is closer to the connectivity. Although accessibility is often used interchangeably with connectivity, network analysis literature conventionally refers to it as an index that measures relative nearness of a place to another while considering connectivity the linked characteristics in the network between places. Accessibility mostly incorporate the concept of costs such as distance and time required to move between places. Some literature (Jiang *et al*. 1999) uses the term of geometric accessibility to refer to depth-based connectivity of spaces.



a. Real street network   b. Traditional network   c. Axial map

Figure 1. Comparing the network representation of street

Tradition network model is defined using its graph *G(V, E)* where *V* is the set of nodes defining places $\{v_i \mid i = 1, 2, \ldots, n\}$ and *E* is the set of edges or links connecting them $\{v_i, v_j \mid e_{ij}, i,j = 1, 2, \ldots, n\}$, where e_{ij} is defined as:

$$e_{ij} = \begin{cases} 1, \text{ if } v_i v_j \in E \\ 0, \text{ Otherwise.} \end{cases} \quad (1)$$

If we focus on the connectivity of each edge disregarding the physical distance d_{ij} associated with it, the connectivity of an edge can be taken as having the unit distance e_{ij} = 1 or 0. Here, one step connectivity C_{ij} is defined as the number of edges to which node *i* is directly connected as:

$$C_{ij} = \sum_j e_{ij} \quad (2)$$

Here, we define higher-order connectivity widely used in graph theory briefly. Instead of the direct connection between the nodes, we can count the number of paths traversed from any node *i* to any other node *j*, which is defined as S_{ij}. This index measures the depth of a node to other nodes and this structural measure is in fact the basis of *the depth* in the space syntax theory. The depth S_{ij}^z where *z* is the depth of node *j* from *i* can be computed as follows:

Let $S_{ij}^1 = e_{ij}$, then,

$$S_{ij}^z = \begin{cases} 1, \text{ if } \sum_k S_{ik}^{z-1} e_{jk} > 0 \; (k \neq i, k \neq j) \text{ and } \sum_t^{z-1} S_{ij}^t = 0 \\ 0, \text{otherwise.} \end{cases} \quad (3)$$

Then we can define the overall depth of *j* from *i* as S_{ij} = z if S_{ij}^z = 1. As we used the reciprocal of the depth for more intuitive interpretation in space syntax, the overall structural connectivity can now be given as:

$$A_i = \sum_j S_{ij}^{-1} \quad (4)$$

In this paper we will combine this depth-based connectivity and the accessibility traditionally used in network analyses. By combining, we mean to apply the depths being increased as axial lines get transferred to the next ones to the concept of penalty or impedances taken during the movement. These costs including distance or time weights are incorporated into the computation of accessibility.

Usually accessibility balance the benefit of having places to visit *j* with the costs of moving to those places from a location *i*. In general, the accessibility in traditional urban land use modeling is based on a gravitational equation and defined as:

$$A_i = K \sum_j P_j d_{ij}^{-\alpha} \quad (5)$$

where P_j is the population at *j*, *K* is the gravitational constant and α is a friction parameter. This equation is the central to the definition of inter-urban competition models and related travel demand models (Stewart and Warntz 1958, Wilson *et al.* 1981). Usually accessibility is discussed and computed targeting spatial interaction in urban scale. At finer scale as the network of small building blocks or indoor spaces, we can think the attraction factor as P_j is small enough to be ignored. Then eq. (6) can be rewritten as:

$$A_i = \sum_j A_{ij} = \sum_j f(d_{ij}) = \sum_j d_{ij}^{-\alpha} \quad (6)$$

The friction or the distance-decay parameter, α, means that the strength of spatial relationships diminishes more than just proportionally to the distance between features as introduced in spatial interaction literature (Fortherinham and O'Kelly 1989).

That is, α determines how fast the relationship diminishes when distance increases.

Here, we compare the accessibility Eq. (7) with the computation of integration value of space syntax using an example. We put α=1 for simplicity purpose in Eq. (7). Figure 2 shows a street network that is laid on grids of 1×1 size. If we follow space syntax procedure, the node 1 and the node 3 have the same total depth value, that is 14 (1×2 + 2×3 + 3×2), while the accessibility of these nodes is computed as 2.25 and 3.33 respectively. The computed values for all nodes are listed in Table 1. In the list, we can see that nodes (1, 3, 7, 8), (2, 5) and (4, 6) happen to have the same values by space syntax, while distance-based accessibility have higher values as distances to nodes from *i* being closer and node *i* having more connected nodes.

By considering the depth-based accessibility and gravitational distance term along with costs taken in movements, accessibility of node *i* to all other nodes can be defined as:

$$A_i = \sum_k^{D_i} w_k^{-1}\left(\sum_j^{M_k} d_{ij}^{-1}\right) \tag{7}$$

where D_i : the maximum number of depths from node *i*
M_k : the number of nodes *j* at depth *k*
d_{ij} : distance between *i* and *j*
w_k : weight at depth *k*

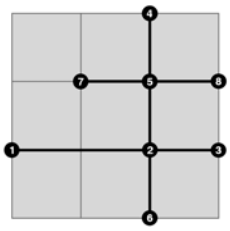


Figure 2. Street network
(each cell is 1×1 dist.)

node #	ND_i^{-1}	$A_i=\sum d_i^{-1}$
1	0.50	2.25
2	0.78	5.00
3	0.50	3.33
4	0.64	3.42
5	0.78	5.33
6	0.64	3.33
7	0.50	3.42
8	0.50	3.42

Table 1. Comparing space syntax and accessibility

Here we introduce weight value w_k that increases as the depth get deepened, which can be thought of as some kind of 'the depth penalty'. Then the reverse of this depth-weight is multiplied with the computed accessibility at each depth. However, assigning the same weight to all the paths if they are at the depth may be impractical in real situations. In space syntax, all kinds of turns or visual transitions are considered to have depths. But in reality, spatial transitions may become more diverse according to the situations one may face with than having depths based on turns. For instance, turns may have different angles or they may be considered different as they are left or right. There may be bigger transition such as movement between floors via either stairs or elevators. Therefore, we need to apply such 'impedances' differently to different kinds of 'depths'. Here we can modify eq. (8) as:

$$A_i = \sum_j^{N_i}\left(d_{ij}^{-1} + \sum_j^{M_k} e_r\right)^{-1} \tag{8}$$

where R_j : the number of costs during the journey *i-j*
e_r : the impedance

Here the set of impedances $E\{ e_r \mid r=1, 2, \ldots, n\}$ can be though of as any costs except for the distances of edges themselves, which a person can face during the movement from *i* to *j*. They can include turns or stairs and can be broken into $E\{ E_L, E_R, E_S, \ldots\}$, where E_L, E_R, E_S ,… are left turns, right turns, stairs,…etc.

The path from *i* to *j* should be the optimal one where d_{ij} and all sorts of impedances are taken into account. This situation is illustrated in Figure 3. There are three possible paths from A to B if we remove the case where the destination is visited more than once. If we assume all turns have same impedance values, since $d_1=d_2<d_3$, path '3' is removed in the beginning from the candidates. If we compare the rest two paths, although $d_1=d_2$, the number of turns in path '2' is bigger than that of path '1' ($\Sigma e_{(2)} > \Sigma e_{(1)}$). Therefore, path '1' becomes the optimal path.

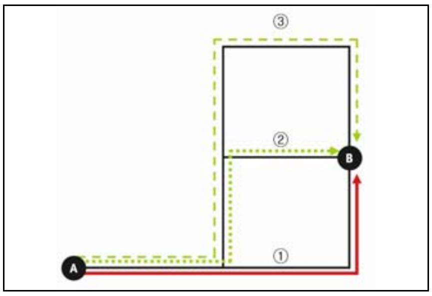


Figure 3. The optimal path from A to B

In order to generate the optimal paths, we used the popular shortest path algorithm by Dijkstra (1959). Dijkstra's algorithm is composed of two key operations; the node selection operation and the distance update operation. We refer to the operation of selecting a minimum temporary distance label as a node selection operation. We also refer to the operation of checking whether the current labels for nodes *i* and *j* satisfy the condition $d(j) > d(i) + c_{ij}$ and, if so, then setting $d(j) = d(i) + c_{ij}$ as a distance update operation (Ahuja *et al.* 1993). In the distance update operation, normal Dijkstra's algorithm defines c_{ij} term as the edge cost of edge *i-j* such as distance or travel time. Here, we included d_{ij} plus impedances Σe_{ij} in c_{ij} as follows:

$$c_{ij} = d_{ij} + \sum e_{ij} \tag{9}$$

3. APPLICATION AND TEST

3.1 Data Construction

To illustrate the way the proposed measure is computed, we chose a campus building that is considered proper for the test in terms of size and complexity. The building includes 7 exits and different types of rooms such as class rooms, professor offices, student lounges and a conference hall.

The indoor spaces in a 3D model are composed of polygons representing rooms, hallways and other compartments. Usually, the relationship between them is not defined while it is clearly defined in most GIS maps through topology. To apply the proposed method in a 3D building, we need to construct a data model representing spaces and their relationship. We use a network model composed of links and nodes. We represent each

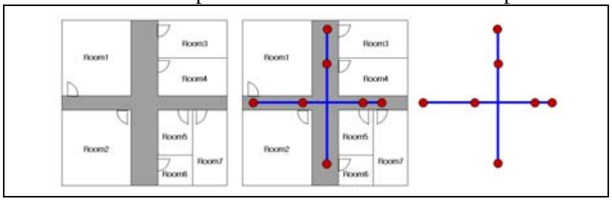


Figure 4. Constructing a network

room a node locating them near the doors because we consider movement begins and ends at the room doors or exits.

Then we build links connecting the nodes along the center lines of hallways. Also, floors are connected via stair links. This way, the whole building is mapped to a network structure. Figure 4 shows how the network is created. It shows nodes at the doors and links between them.

3.2 Room-to-Exits Accessibility

One is usually more sensitive to the access to exits or entrances than to other rooms. Also, taking the emergency situations into account, the accessibility to exits takes priority to other rooms. The test building has 7 exits in total, 5 on the first floor and 2 on the second. They are bound to different directions from which one can choose according to the destinations outside. However, we assumed that one prefers the nearest entrance from one's location. We applied the proposed measure Eq. (9) to computing the accessibilities of individual rooms to all exits. As for the impedances taken in the paths, we included turns and floor transfers either by stairs or elevators. Since we focus on introducing the computing process of the proposed method, we assumed some values that we presume reasonable for the impedances. We assigned 20m, 30m for stairs, 3m for elevators and turns respectively.

Figure 5 shows the evaluation of the accessibility to the exits from each room in 5 strengths. The rooms near the first or second floor where exits are located received higher values than higher floors while those near the exit locations having higher accessibilities than those in distant from the exits.

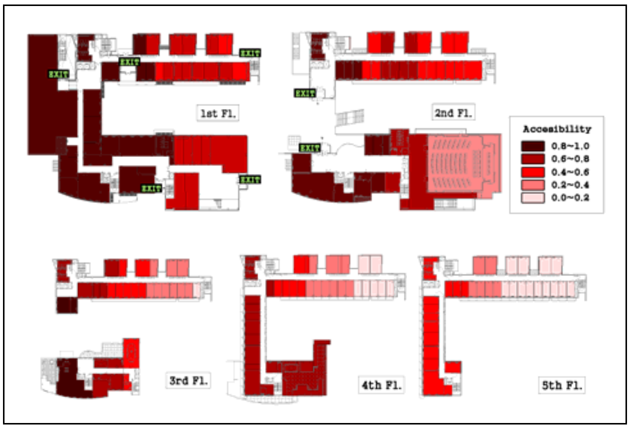


Figure 5. Room-to-exits accessibility

3.3 Spatial Cluster Analysis

While the accessibility of a space to or from others helps evaluating spatial locations individually, we can also consider their spatial configuration in collective manner. In such buildings as hospitals, campus, or office buildings, spaces are planned in such way their similar functions are located closely. We can also apply the proposed method to measuring the 'clusteredness' of spaces that share the similar characteristics. By computing the accessibilities, as for the target rooms repeatedly, we can quantify 'topological' closeness of the related spaces.

Figure 6 shows the department spaces in the test building such as lecture rooms, administrative rooms and professor rooms. We chose two distinct cases for the test; department A and B. The spaces of department A are closely located on the 3rd floor, whereas the rooms of department B are scattered on different floors (1st, 4th and 6th floors).

Figure 7 shows the computed values of accessibility of the spaces of these two departments expressed in 5 gradual color schemes. As a consequence, department A rooms have higher accessibilities than those of department B.

4. CONCLUDING REMARKS

Space syntax theory has been used to compute the connectivity of street or pedestrian network segments. Related empirical studies have investigated the relationship between the movement of people and the space syntax's integration value and found that these two are highly correlated showing highly integrated streets usually tend to attract more people than segregated ones (Hillier *et al.* 1993). However, space syntax has mostly been tested on pedestrian movement at coarser scale. It shows some limitations to apply to small housing blocks or indoor spaces. Space syntax begins by defining space using 'axial lines'. It sees that no matter how long an axial line is all the rooms or spatial segments have the same depth as long as they are on the same axis. However, one can easily guess that walking 50m gives more burden to him or her than to just turning around a corner, which is interpreted to have less connectivity than the former case. In this paper, we viewed that assigning the same depth to the linear space is not applicable to the finer scale cases such as indoor spaces. Instead of giving a depth whenever an angle is changed from the adjacent path, we used the 'impedance' term categorizing it into different types having different strengths. Especially, when it is applied to 3D models, we should incorporate not only turns but floor-to-floor movement by setting some penalties into the computation process of accessibility. With more refinement about these impedances, we view that the proposed measure can be applied to practical situations such as building layout and disaster prevention.

ACKNOWLEDGEMENTS

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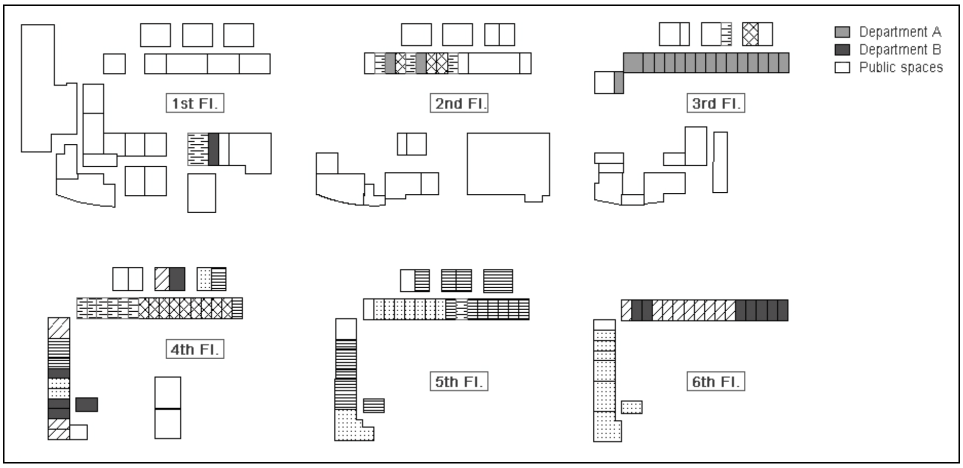

Figure 6. Classification by spatial property(department)

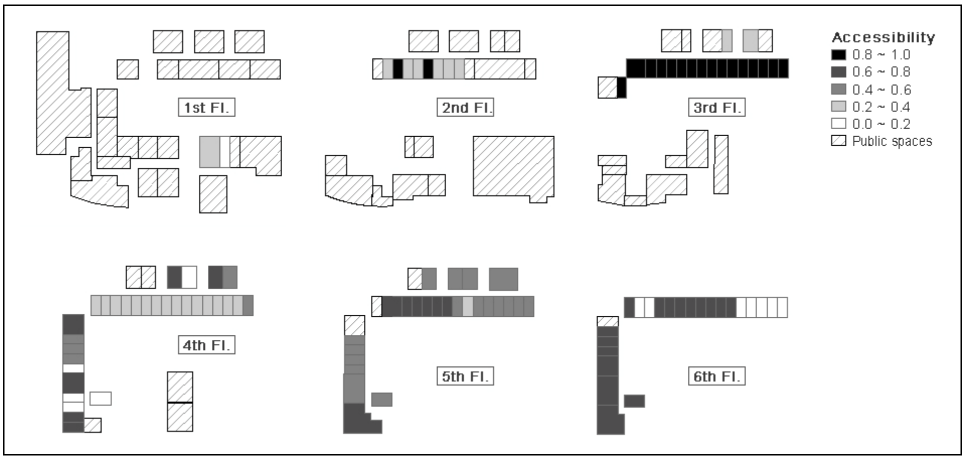

Figure 7. Accessibility of the classified spaces