Elaboration Model for Mapping Architectural Space

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Abstract
The key objective of this study is to develop an experimental computational method for mapping architectural space, and further validate the method using several case studies. The result will offer possibilities for quantitative design analysis, particularly on spatial quality influenced by architectural elements. Our proposed method for this computation consists of two phases: determination of L-shaped enclosed spaces and axial lines to establish an enclosed space relative to a circulation space, and determination of subdivided enclosed spaces using territorial lines. The concept underlying this method is that architectural space is composed of subdivided enclosed spaces each of which has distinct physical properties influenced by different elements. Therefore, it is possible to develop mapping for the further qualitative evaluation of architectural space.

Keywords: spatial mapping; enclosed space; architectural space

1. Introduction
The study focuses on architectural spaces resulting from the arrangement of architectural elements. There are two main approaches to architectural spatial modeling: One considers the space we experience as a product of our movement and perception, and the other regards a space as an entity resulting from the arrangement of its boundary elements. A space is the void between physical boundaries where its existence is independent of the user’s presence. On the basis of this principle, authors further regard architectural space as a fixed entity because its basic property is that it can be modeled and measured similar to other physical objects.

For this purpose, authors have developed a method for modeling the subdivided enclosed space of an architectural plan. Our method is derived from the following approaches: authors first evaluate previous methods of computing architectural spaces, investigate the relationships between the space, circulation path, and elements of architectural design, and then develop new rules of application on the basis of our findings.

2. Related Work
The concept concerning classification of enclosed space dates back to 1977 when M.D. Gross built a model to measure the level of spatial intensity based on the number of solid boundaries (Gross, 1977). According to his study, an enclosed space is classified by adjacent walls; its numerical scale depends on the number of adjacent walls. An enclosed space can be defined by the following simple procedure: first, draw extension lines from the walls, and then construct perpendicular lines at the wall endpoints. The result creates many enclosed spaces of different sizes. A numeric scale is then assigned to each enclosed space on the basis of the number of solid boundaries it has (Fig.1.). To visualize the concept, it is represented as gray-scale intensities on the floor plan (Fig.2.).

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The highest level of enclosed space is defined as the point at which all sides of a particular space are surrounded by solid boundaries.

This concept describes the relative intensity of the connection between a space and its boundary. However, this model has a few limitations:

1. The model determined enclosed space by non-passable architectural elements. Other passable architectural elements such as windows or doors were determined to have enclosure value zero.

2. There is no attribute such as opaqueness and transparency to categorize physical boundaries, which can influence the intensity level of the enclosed space.

3. Since the model works on extension lines from the boundary, the center area where there are no walls is considered zero on the scale, and therefore has the lowest level of enclosure.

Koile (2001) proposed territoriality as a model for determining an enclosed space in which each region is defined by its enclosure territory. Basically, the region is formed by the overlapping of territorial lines within the space. The architectural space, according to this method, is a juxtaposition of territory, circulation, and use-space models, where the use-space model is an attribute model assigned by the architect (Fig.3.).

Through this approach, it is possible to generate an analytical model of an architectural space in which each region represents a space influenced by architectural elements.

In addition, Koile's model represents the concept of dividing the space into subsets of enclosed spaces using perpendicular lines projecting from the edges of each element. This model can accommodate non-passable solid elements such as walls that form space and other passable elements such as doors that form circulation paths and spaces.

Another approach for determining enclosure was defined by Sora Key (Key, 2008). In this study, the degree of enclosure is inversely proportional to the distance between the observation point and the solid boundary (Fig.4.). Regardless of the type of architectural boundary, the degree of enclosure is computed using the following formula:

\[ E_p = \sum \frac{1}{d_i} \]  

where \( E \) = total degree of enclosure at \( p \); 
\( d \) = distance from \( p \) to each solid boundary \( i \).

This study presents a model for the quantitative measurement of architectural spaces on the basis of the distance to its boundary elements.

3. Architectural space and experience in the space

An architectural space is experienced not just by its boundaries. The variability in the interior (enclosed space) and exterior (enclosure) comprise the essence of architecture (Arabacioglu, 2010). Several architects (Alexander, 1977; Rasmussen, 1959; Lawson, 2001; Bentley, 1985) and psychologists (Shah and Miyake, 2005; Stimson et al., 1997; Tversky, 1998, 2003) have found that experiences in the same space can vary with changes in the architectural design elements such as colors and transparency.

Another aspect of an architectural space is that architects always compose a space according to the boundaries and inter-relationships between the architectural elements and the desired or planned activities. Here, the space qualities are designed even before any real experiences have occurred. March and Steadman (1971) used a network graph to denote the topological relationships between rooms, i.e., which room gives access to another, and which room is adjacent to another. Pénas (2001) suggested that the matrix relationship of activities should be constructed to model the adjacency of spaces. Such basic mathematical models of spatial configuration of architectural spaces were under rigorous research before the era of computation began.

Nevertheless, the computational model for mapping and measuring the architectural quality of enclosed spaces is still in its inception stage.

In modeling a building genotype for spatial network
analysis, Hillier and Hanson (1984) used the center point of an enclosed space as a reference point for the analysis. The studies conducted by Gewirtzmann (2003) and Pinsly et al. (2007) have shown a quantitative model for spatial quality evaluation using a single viewpoint for the object of measurement. Authors suggest that in a unit of interior space called a bounded area, there exist enclosed spaces that have different levels of architectural space quality.

As previously noted by Koile, this layout configuration of enclosed spaces is influenced by the property of the boundary elements.

In this study, authors have developed an elaboration model for computing architectural space quality by developing a map of subdivided enclosed spaces. Authors generate the subdivided enclosed space by analyzing two main factors: bounded area and circulation path.

4. Computational Method

4.1 Arbitrariness of Enclosed Space

The subdivided enclosed space is approximated by the following procedures:

1. Determination of L-shaped enclosed spaces
2. Determination of axial lines
3. Determination of circulation paths
4. Determination of subdivided enclosed spaces

The above procedures indicate that the expected result of our space model represents the interrelationship of the territory influenced by boundary elements and the circulation space.

In addition, these procedures show the hierarchical structure of a subdivided enclosed space as generated by juxtaposition of the territorial lines of boundary elements.

The framework to determine subdivided enclosed spaces is illustrated in Fig.5.

In the context of the architectural plan, we determine each unit analysis as a single interior space. For the model, authors reduce complexity by defining the architectural space unit in the experiment as rectangular. The output of the process is divided into a region of enclosed spaces defined by their territorial parameters that are determined as follows:

1. Bounded area: This is the unit for analysis where enclosed spaces are to be defined. It consists of opaque boundaries (walls), openings (windows or doors), and other architectural objects of attraction if any.
2. Path: It is a connector of the bounded areas. A circulation space is formed by circulation gates such as a door using rules by which the path is to be defined.

The enclosed spaces are established on the basis of the kind of relationship between the path and bounded areas.

According to the territory space hypothesis, a single interior space contains enclosed spaces confined by the territories of boundaries and paths. Authors suggest that the layout of subdivided enclosed spaces is a result of the relationship between the territorial and circulation spaces. Therefore, the computational process is divided into two phases:

a. First phase:
   1. Establish L-shaped enclosed spaces by detecting and computing the co-linearity of boundaries.
   2. Determine horizontal and vertical axial lines to establish a circulation path.
   3. Determine extension lines from each edge of the boundary elements perpendicular to each axial line.

b. Second phase:
   1. Determine the subdivided enclosed space by extending the area of the L-shaped enclosed space determined in the first phase to the nearest territorial...
boundaries.

2. Establish the center point of each rectangular subdivided enclosed space.

The final result of the computational process is the configuration of subdivided enclosed spaces as illustrated in Fig.6.

The detailed rules of computation as demonstrated in Fig.6, are explained below:

1. Determine the existence of the L-shaped enclosed space using the co-linearity test between two polygons (Fig.7.). The test is performed using determinant operation by extracting the maximum and minimum points of each polygon:

\[
\begin{vmatrix}
X_i & Y_i & 1 \\
X_j & Y_j & 1 \\
X_k & Y_k & 1
\end{vmatrix} = 0
\]  

(2)

If the determinant equals zero, then two polygons are linear; otherwise, they are not linear.

If two polygons are not linear, then the area must be determined by establishing the center point of each polygon.

Procedure:
Input: Two curves
Output: Create a center point of each curve and draw extension lines perpendicular to each other
Condition:
If two curves are co-linear, the program is stopped.

2. Establish horizontal and vertical axial lines of the enclosure. The axial line is used to provide a connection between any circulation gate and the boundary for a territorial area of openings and objects of attraction. Authors used the center point of the bounded area to establish horizontal and vertical axial lines. If the area of the boundary is in the following form

then the coordinates of the center point are

\[
C_x = \frac{1}{6A} \sum_{i=0}^{n-1} (x_iy_{i+1} - x_{i+1}y_i)(x_j + x_{j+1})
\]

(4)

Procedure:
Input: Polygons
Output: Create the center points of the polygons and vertical and horizontal extension lines from each boundary line.

3. Establish territorial lines using openings (window) and axial lines mentioned in the second rule. An additional rule is applied if any architectural objects of attraction such as a fireplace have a distinctive territorial region. Figs.8. and 9. illustrate the procedure:

Procedure:
Input: Boundary line of an opening (window, door)
Output: Extension line perpendicular to the axial line

Fig.8. Simple Procedure to Draw a Perpendicular Line to an Axial Line from a Point

Area (A) = \[
\frac{1}{2} |AB||PC| = \frac{1}{2} \sum_{i=0}^{n-1} (x_iy_{i+1} - x_{i+1}y_i)
\]

\[
|PC| = \frac{2A}{|AB|} = \sqrt{(P_x - C_x) + (P_y - C_y)}
\]

Fig.9. (a) First Point Perpendicular to Axial Line; (b) Second Point Perpendicular to Axial Line

4. Establish the center point of each region to represent an enclosed space.

4.2 Rules of Circulation Path

The computation of a subdivided enclosed space is conducted under the rules of the circulation path. Here, the path-space relationship is defined as the connection between bounded areas and circulation paths. These rules represent the model of circulation space in an arbitrary interior plan as a part of the procedures to
approximate spatial configuration (see 4.1)

In architecture, a circulation path is the connection in which people traverse from one node to another (Lynch, 1960). In a narrower sense, a circulation path is the connection between a circulation gate (door) and the space within the enclosure. There are two models of the relationship between the paths and space (Ching, 2002, pp. 278): terminate in space and pass through space.

1. Terminate in space.
   If a room has only one door, then the circulation path is terminated inside the room. The model of the subdivided enclosed space by the circulation path is then the result of the relationship between the enclosed space and circulation area.
   The rules to subdivide the enclosed space are as follows:
   - Define L-shaped enclosed spaces by the center point of each boundary
   - Evaluate the remaining space with respect to the circulation gate and center point
   - Define the axial line along the center point and perpendicular to the path direction
   - Make parallel lines from the gate to the axial line

Table 1. Subdivided Enclosed Space Having a Path that Terminates in the Space

a. Linear path
   The circulation path is defined as linear if two gates are connected by a straight line. The rules to determine the subdivided enclosed space are the same as the previous ones.

Table 2. Subdivided Enclosed Space Having a Linear Path Passsing Through Space

   - Define L-shaped enclosed spaces by the center point of each boundary
   - Evaluate remaining space with respect to the circulation gate and center point
   - Define the minimum convex area
   - Subdivide the area by its center point
   - Define axial lines along the center point and perpendicular to the path direction
   - Define parallel lines from each gate to the axial line

   Following these rules, authors establish the configuration of the enclosed space while creating a circulation space that terminates in the center of the interior space.

2. Pass through space
   If there are more than one circulation gates in a room, the relationship between the paths and space is known as pass through space. Authors developed two models: cut axially and cut obliquely. In both models, the circulation paths may have linear or non-linear positions.

   - Define L-shaped enclosed spaces by the center point of each boundary
   - Evaluate the remaining space with respect to the circulation gate and center point
   - Define the minimum convex area
   - Subdivide the area by its center point
   - Define axial lines along the center point and perpendicular to the path direction
   - Define parallel lines from each gate to the axial line

   Basically, these rules are extensions of the first set of rules. If paths have no eccentricity, i.e., the centers of two gates and the center of the room share the same axial line, then the enclosed space it creates is more regular.

b. Angular path
   The path is defined as angular if two gates are connected by an angular line. In this situation, authors hypothesize that the center point is a significant factor to determine subdivided enclosed spaces and circulation spaces. By considering this, when two paths encounter a space, their connection must pass through a center point or an axial line as defined by the previous rules.

   The rules for subdividing the enclosed space are as follows:
   - Define L-shaped enclosed spaces by the center point of each boundary
   - Evaluate remaining space with respect to the circulation gate and center point
   - Define the minimum convex area
   - Subdivide the area by its center point
   - Define axial lines along the center point and perpendicular to the path direction
   - Define parallel lines from each gate to the axial line

In the two rules and three conditions mentioned above, the hierarchy of subdivided enclosed space can be derived from the composition of boundaries or enclosures (Gross, 1977). However, in this paper, authors apply the rules for subdivided enclosed spaces to map layout or configure an enclosed space by its boundary and circulation path.
4.3 Experiment and Case Study

Authors developed rules using script programming in Grasshopper. The input is CAD polygon. For the experiment, authors used the architectural plans of the Kaufmann House (Falling Water house) by Frank Lloyd Wright and the Rachofsky House by Richard Meier (Fig.10).

Grasshopper is a Rhino3D plug-in and graph-based object oriented program. It is used to analyze and generate forms from parameters and interconnected procedures. Using the input polygon from CAD, authors extracted the polygon's lines and vertices to be evaluated using our procedures.

Fig.11. shows a screenshot of Grasshopper as an example of our procedure to determine the intersection point of an L-shaped enclosed space.

Procedure:
- Obtain line 1 \((X_{1a}, Y_{1a}), (X_{1b}, Y_{1b})\)
- Obtain line 2 \((X_{2a}, Y_{2a}), (X_{2b}, Y_{2b})\)
- Evaluate co-linearity using cross product
- If non-linear, define midpoint 1 and midpoint 2
- Obtain joint point
- Evaluate X of each midpoint with X of joint point to obtain X of extension point
- If X midpoint of line = X joint then stop
- If X midpoint of line != X joint then X extension point = X midpoint
- Evaluate Y of each midpoint with Y of joint point to obtain Y of extension point
- If Y midpoint of line = Y joint then stop
- If Y midpoint of line != Y joint then Y extension point = Y midpoint

An example of the result of the procedure is illustrated in Fig.12:

Figs.13. and 14. illustrate the results of subdivided enclosed spaces in different interior layouts. Magenta lines indicate the area of the L-shaped enclosed space,
green lines indicate axial lines, cyan lines indicate circulation lines, and yellow lines indicate territory lines by a window.

The experiments on simple architectural plans were conducted to validate the computational method of subdivided enclosed spaces based on paths and architectural elements. Using two primary factors: the bounding area and path typology, authors can develop subdivided enclosed spaces that maintain their integrity relative to the boundary elements.

Our experiments combine the theories of relationships between paths and spaces and those between territorial spaces and architectural elements. The final result displayed a configuration of subdivided enclosed spaces with a degree of complexity parallel to the configuration of architectural elements on the enclosure.

This computational method for determining subdivided enclosed spaces reveals the possibility of measuring spatial quality at each subdivided enclosed space. At this point, authors suggest that the quality of an architectural space can be measured by computing variables of measurements at the level of subdivided enclosed space.

5. Summary and Discussion
Authors have presented a methodology for mapping an architectural space by generating subdivided enclosed spaces. The procedures follow the below-mentioned rules applied to polygons of the architectural plan: determination of L-shaped enclosed spaces, establishment of axial lines, determination of circulation space, and determination of subdivided enclosed space.

Generating a subdivided enclosed space provides a visual cue to help designers or users develop more accurate spatial configurations. Based on this model, in our future studies, authors will further develop the computation of architectural space quality using four basic parameters: visual openness, linkage, attractor, and accessibility. The result on index of each parameter provides an analytical cue to quantify the quality of an architectural space in each area of the subdivided enclosed space.

Authors propose that this computational design analysis will improve our understanding of organizing architectural space by a quantitative approach rather than a qualitative or subjective approach.

As a method to compute enclosed spaces, the proposed model has limitations that will be the focus of our future investigation. They include the following:

1. The bounded area is considered as an open plan, and rules are applied only to orthogonal plans. Consequently, all the enclosed spaces produced are rectangular.

Authors are aware that our model works by analyzing pre-built architectural space as a tool to provide cues to the designer for spatial configuration. This model also works under a predetermined examined area called a bounded area. Authors used the bounded area in our approach to structure the entire architectural plan. However, as architectural plans are as flexible as the mind of the designer, authors need to consider non-orthogonal plans and additional building elements as factors that affect our rules to generate the subdivided enclosed space.

2. The measurement applies to the center point of the subdivided enclosed space.

Authors use the center point of the subdivided enclosed space as a reference point of the area. The computational resource that we used to measure quality is linear with a number of measurement points. In this regard, authors advise that the center point is a well-defined point to represent the subdivided enclosed space.
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