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Exploration of Isovist Fields to Model 3D Visibility With Building Facade

Dongkuk Chang and Joohee Park
Professor, School of Architecture, Chosun University
Senior Researcher, Center for the Design of Architectural Space Structure(CDASS), Chosun University

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Abstract Visibility of a space have been defined in several different ways: such as the axial line covering a convex space, a convex space defining the fattest shape in a space and an Isovist field formed by a field of vision at a given vantage point. Isovist fields are referred to as a descriptive medium to describe a movement by reviewing and analyzing geometric properties in them. Many descriptive methods for analysis of three-dimensional isovist are applied to analyzing the morphological properties in a 3D space more realistically. Although these models are regarded as a more advanced method for describing spatial properties, they have pros and cons such as complex mathematical calculations and somewhat arbitrary calibration in addition to huge consumption of memory space. These difficulties lead to the development of a three-dimensional visual accessibility model that explores the implication of building shape on the calculation of isovist fields drawn on a 2D plane. We propose a conceptual framework of how to measure the isovist field not as a 3D volume but as a combination of 2D plane on the ground with the 3D building shape of it's facade.

Keywords: Isovist, Visibility, Space Syntax, 3D Building Shape

1. INTRODUCTION

Configuration of a space in an urban area of high density has a direct effect on human's visual recognition. An isovist field at a point may be highly affected by changes in the direction of building arrangement or partial transformation of the shape. The townscape sketch of Gorden and Cullen (1961) (Figure 1) shows the volume and facade of a building which is not shown in an arrangement plan, and the external space of a city formed thereby. However, Gorden's sketch shows a limited partial view to represent the characteristics of a space in an urban area towards a specific visual line from a viewpoint as mentioned by Hillier et. al. (1983).

Gorden's consideration for visible scenes led to an architectural space study designed to quantitatively identify the isovist fields in overall configuration. Benedikt (1976) studied the geometrical characteristics of visible fields observed in all directions from a point in a space to develop a method of quantifying them with the theory of isovist and isovist fields. The methodology of isovist field analysis (IFA) consists of dividing a space to be analyzed into a desired number of continuous grids, forming isovist figures observed from the central point of each grid space and analyzing the geometrical characteristics (area, length, etc.) of the figure to identify overall visibility characteristics.

The representative quantitative indices proposed by Benedikt include areas, circumferences, occlusivity, compactness, variance and skewness. Batty (2001) and Conroy (2001) further studied the indices to connect them with societal characteristics of a space, e.g., special recognition or potential use of a space.

Hillier focused on considering structural patterns of the entire space by means of visual connectivity of the space. The axial map and the convex map applied in space syntax proposed by Hillier, et al., are used to divide a space into formal units based on a given condition to convert them to a mathematical graph for path search. Each unit space is a node to convert the visual relationship between spaces to edges to depict a graph and to calculate indices, e.g., connectivity and integration, by means of a graph algorithm, e.g., the number of connected nodes, depth and shortest distance graph search.

The methods of isovist and space syntax for special analysis are considered to be highly applicable and usable for quantitative analysis but have some problems. One of the problems is that axial lines or convex spaces are rendered to be one node regardless of their size if a special configuration is embodied in a graph. This implies that various visual and spatial attributes included in a space are represented by means of a single index. For example, it is impossible to represent details of characteristics depending on a

Corresponding Author: Joohee Park, Senior Researcher
CDASS, Chosun University, 309 Pilmoondae-ro, Dong-gu, Gwangju, South Korea
Tel :+82 62 230 7851 e-mail: guiness@hanafos.com
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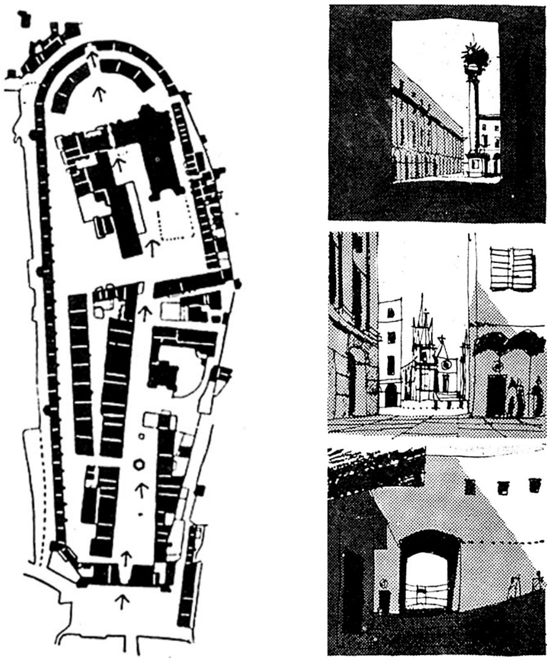

Figure 1. Townscape sketch of G. Cullen

specific position in an isovist field or convex space.

Batty (2001) and Turner et al. (2001) developed the method of Visibility Graph Analysis (VGA) for analyzing visibility in a more detailed area. In a VGA analysis the axial lines, convex spaces and isovist fields are divided into grids. They are in a given size to set them to a basic space for calculating desired indices and then to render visual connectivity between them as a graph to calculate quantitative indices for space syntax, e.g., connectivity, depth, mean depth, integration, etc.

The focus of existing studies about relationship between urban properties and visibilities have been laid on two-dimensional model assuming isovist fields are at a specific point of human eye level(1.4m) whereas real world is full of 3-dimensional objects that form, affect and interrupt human vision. This makes difference this study from conventional visibility model.

One of the problems of conventional studies is that they do not deal with the visual information being formed from façades of three-dimensional buildings in real while the visible range of a view point is being considered from all directions. Because the visual information in high density urban environment with full of high rise buildings is significantly affected by the area, shape and direction of building facades in reality, as shown in Gulen's sketch, this study more concentrates the visual relations of ground and façade. Thus what we propose here are entirely new measurements of three-dimensional visibilities and computational algorithms in two ways according to view point of the 3D model: one be at ground, one be at facades of building.

As shown in Figure 2, the isovist field not considering observer's eye level and the level of each building is narrow and long not to be wide as shown in the left Figure. However, in reality, the observer's vision is significantly different depending on the height of the building at the forefront that interrupts the visibility and the size and height of the buildings behind it. Assuming that the ground plan on the left is in 3D as in the right Figure, and the observer is positioned at X, the observer can see a part of the facade of large high rise buildings, e.g., B and E, located behind the building A. Large and high buildings in a city center can be seen from many locations in the city: when the observer is positioned at ground level, from the inside of another high rise building, or seen from locations nearby or far away.

Previous visibility studies have not considered the effect of building facades on the visibility environment. The fact that large buildings of high visibility act as a landmarks to be a visual characteristic in an urban area and represent the city describes reflection of such 3D visual characteristics. It is the main objective of this study to develop an algorithm for analyzing 3D visual characteristics consisting of the facades of a building along with the ground and combine the method of 3D visualization with the result of analysis.

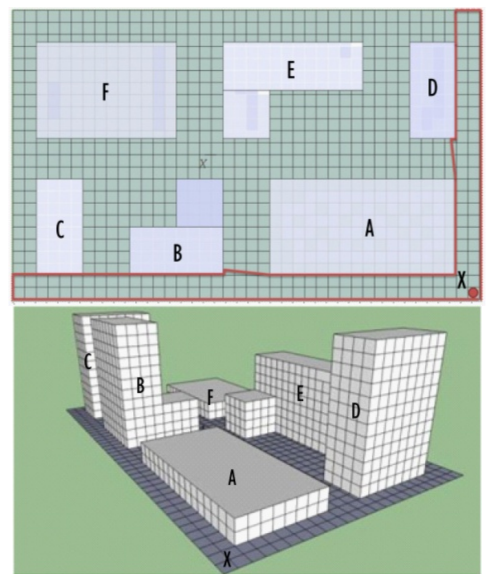

Figure 2. 2D isovist and 3D building model

2. VISIBILITY ANALYSIS IN 3D SPACE

An exemplary study related to isovist in a 3D space is for reflecting the height of a topography in measuring visibility. This covers spaces consisting of the geographical environment, e.g., land, mountains and rivers in an observer's vision for analyzing the isovist field. The 3D topography is rendered to analyze visibility with other grid areas with respect to each grid area, using the digital elevation models (Ratti and Richens, 2004). Since such a method of analysis is usually applied to application programs of GIS and based on the TIN or raster data structure which is the data structure of GIS to derive the isovist field, it is not compatible for an analysis of a construction structured with a complicated building complex and urban spaces comprising geometrical information of 3D figures.

For studying 3D visibility indices, Culagovski et. al(2009) proposed 3D visibility indices based on visual information in which a space at a specific position is associated with other spaces at different positions. They rendered the association between spaces in small units by means of graphs and announced coefficients of closeness centrality, betweenness centrality, degree centrality, clustering coefficient, etc., on the basis of the graphs. This is different from typical 2D analysis in that the 3D matrix is used instead of the 2D matrix for calculation and 3D models are represented for displaying models. This method also does not reflect buildings of an urban area and does not cover isovist fields of building facades as well.

Fisher-Gewirtzman et. al (2005) most actively studied how to evaluate the characteristics of 3D visibility in the field of buildings and urban areas. They proposed a method of analyzing 2D isovist fields from the facades of each floor. Their measure was based on the existing environmental study by Oh and Lee (2002) and Murakawa et al., (1994) who believed that visible spatial openness towards natural scene affects resident's satisfaction. The spatial openness index proposed by Fisher-Gewirtzman et. al is to render the 3D isovist fields in urban areas formed by 3D spaces made by buildings and vantage points by means of the method of analyzing isovist fields.

Their Spatial Openness Index(SOI) is the volume of open space potentially seen from a given point which can be mapped to perimeters or area of 2D isovist by first proposed by Benedickt(1977). Their study was significant in the sense that it not only suggests new 3D measures of visibility but also implemented and made available online. Nevertheless what we point here is that their study was on experiments with limited to the environments of 10x10x4 for vantage points and building blocks, assuming that all buildings are regularly hexahedron shaped. What they eventually measure is the amount of empty space with ambiguous boundary towards formless sky. This was completely different from visibility measurements what we suggest here via amount of visual information being seen or can see environmentally formed concrete object.

Another similar study is the field-oriented spherical metric proposed by Teller (2003) for analyzing open urban spaces surrounded by buildings. The modeling technique developed by Teller maps the changing shapes of a 3D space depending on moving viewpoints, provided that the sky is spherical. This enables changes in volume of a 3D space to be rendered on a 2D plane when the sky is seen from the ground of an open space in an urban area, e.g., a public square.

Kim and Choi (2009) who are Korean researchers added the height information to a drawing comprising steps and the like to calculate the total depth index based on visibility between points, by means of the space syntax calculation technique, on the basis of 3D visibility.

Gwon (2010) developed a method of analyzing visibility of 3D topographies to propose the average of integration indices and the difference of standard deviations on an inclined plane in various shapes with the same external space. He identified the isovist difference among low lands, ridges and valleys in 3D topographies on the basis of contours, with the result, and demonstrated that the actual isovist field at the summit depends on the arrangement of ridges.

Kim and Jeon (2008) proposed theories and indices of moving the point of view as well as sightlines, thus the visibility frequency and effective level visibility for which the previous theory is extended to open 3D spaces. They developed a methodology for calculating the proposed indices by means of the 3D game engine and rendering the result by means of CAD.

3. 3D VISUAL ACCESSIBILITY MODEL

Visions of urban people living in highly dense urban area is strongly affected by scale, height, and shape of buildings, etc that cannot be fully rendered on a 2D plan. As described above, with regards to 3D visibility study, there has not been much study done on visibility projected on the facades of a 3D building. Since buildings in an urban space are closely related with the cognitive and societal environment of the space, it is necessary to study visual relationships between the facades of each building in the space. In this study, the 3D visibility environment constructing urban configuration is classified into the ground and the building facades. We propose a computational method of analyzing 3D visibility on the ground and on the building facades, and then of 3D visualization.

The main purposes of this study are as follows. The first object is to divide a space into the ground and facades in order to propose a new visibility measurement of a 3D space for each of them and to develop an algorithm. Visibility of the ground comprises visibility with the ground, visibility with the facades and the integration visibility thereof. Visibility of the facades comprises visibility with the ground, visibility with other facades and integration visibility thereof. The next step is to standardize the mutual influence of ground visibility in which the influence of facade visibility is reflected and facade visibility in which the influence of ground visibility is reflected.

The second object is to implement those measurements on the computer program of 3DSpacer. It is used to render 3D graphic information of the analysis results on a computer screen. Thus enabling overall visibility of facades and the ground plane of buildings, which make up the urban environment with many buildings visualized from every corner of the area analyzed. The resulting values of each area are visualized using color spectra and the 3D images are projected on a 2D screen to enable observation in all directions, at all degrees, e.g., from the top, the bottom, the left and the right, and at all viewpoints.

The third objective of this research is to analyze a simple 3D model with the 3DSpacer to render all of the proposed indices on a computer screen in 3 dimensions in order to identify compatibility of 3D spaces and visibility indices in terms of the cognitive viewpoint for mutual connectivity thereof.

The 3D visibility analysis tool, the 3DSpacer, was developed in C# under the Windows operating system environment along with the development tool of Microsoft Development Studio 2008. The Microsoft DirectX9 3D library of was used for drawing 3D objects and visualizing them on the screen.

The time and space complexity of computational algorithms on this study of 3D visibility analysis not only depends on the size of ground and the number of buildings and size but also the degrees of details in representation which are affected by the defined size of unit space triangularly shaped. The complexity of drawing 3D model is not really an issue here since we leave 3D graphical image processing such as rendering pipeline to directX3D API which utilize hardware acceleration unit on graphic card mostly installed on personal computer nowadays. Thus time complexities of proposed measurements for 3D visibility are described in detail in each section followed.

While typical isovist calculation based on 2D plans is based on the central point in the area divided into grids (Figure 3), the basic unit which configures an object is a triangle and the vertex of each triangle is the reference point for deciding visibility (Figure 4). That is, the facades and the ground of a site consist of a set of continuous triangles divided into a given size. It is not the central point of a triangle that is judged for visibility, it is the 3 vertices of a triangle. The color inside of the triangle which represents the visual result is blended from the colors of three vertices from it.

This is different from conventional methods of rendering the visual relationship between grid cells in the same color uniformly in the grid, the central point of a grid cell being the reference point The positive aspect of this vertex based coloring method is to avoid rough representation in which a cell-based coloring technique has, while rendering analysis results in soft hues in a basic unit divided in low density for quick calculation.

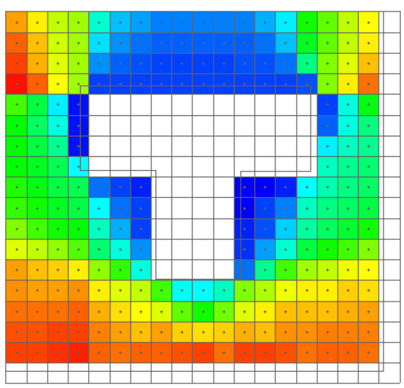

Figure 3. 2D space consisting of grid cells (MoonSpacer)

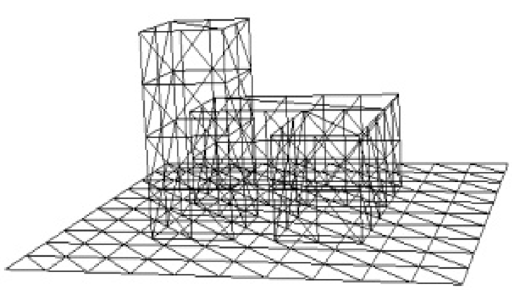

Figure 4. 3D space consisting of a set of triangles (3DSpacer)

(1) 3D Visibilities at Ground Level

In this section, visual relationships of space on all ground level such as land, roads or park become an object of analysis. The visual information of 3D buildings visible from the eye-level on the ground as well as 2D analysis is used on a ground plan and consists of the following four indices. Each index was analyzed using two different samples, in which one of them is a T-shaped model of the same height and the other is an L-shaped model consisting of buildings different in height.

VisibilityGG

First, visibility of different areas on the ground was analyzed on the basis of ground level. Using the method proposed by Betty (2001) in which the visibility index is specified as Z_i for each vertex i consisting of a space and the number of vertices visible at Z_i is n_i, the visibility index Z_i is defined as j Z_j,j=0,1,2…n_i . The pseudo code for finding an isovist field for v_i and v_j is shown below.

```
VisibiltyGG(i,j)
For Each  vi
 For Each  vj=i+1
  If CheckVisibilityGround(vi, vj)
         Add vi  to  Zi,
         Add vj  to  Zj
  End If
 End For
End For
```

```
CheckVisibilityGround(vi, vj)
For Each k
 For Each  Sl,m  on k
  If   IntersectLine(Sl,m,  Si,j)
      Return False
 End For
End For
Return True;
```

Assuming that the figure formed by projecting each building in a space on a plane is referred to as k, the algorithm IntersectLine decides whether each edge $S_{l,m}$ of k crosses the segment $S_{i,j}$ connecting two different points of locations on the ground for all k. If the segment $S_{i,j}$ connecting two points on the ground crosses any one side of the building, the algorithm CheckVisibility has the result of value False. In this case, the time complexity is O(n^2) since inspecting is needed for every vertices with every other vertice for all k.

The algorithm IntersectLine, which identifies crossings between two line segments, finds values of t and s when two lines meet by matching two points P(t) and P(s), on the condition that the equation of two straight lines between two points P_i and P_j, two points P_l and P_m is $P(t)=(1-t)\ P_i+ tP_j$ and $P(s)=(1-s)\ P_l+ sPm$, respectively. In this case, if t and s is not 0 and 1, the two lines do not cross each other. In the process of finding t and s, the denominator is used to identify running in parallel and matching of the lines.

Since the analysis result describes visibility with other points on the ground, there is no significant difference from the typical isovist field analysis. The back area of the T shape (upper part of first two in Figure 5) is hidden by the widest façade of the T-shaped object and it is colored with solid blue which means the lowest visibility value on the whole ground. The greatest visibility index is exhibited at both sides at the front, basically the parts other than the center (lower part of the first two in Figure 5).

This is because both sides are widely viewed concave area of T-shaped object whereas the T-shaped object located right behind of the concave area in the center obstructs the visibility of the front center. Visibility of the narrow bystreet for the L-shaped model is interrupted by the high-rise buildings on both sides therefore the lowest visibility is exhibited at the interior corners and the highest visibility is exhibited in the 4 outer corners on the ground with wide visibility for the ground (last sample in Figure 5).

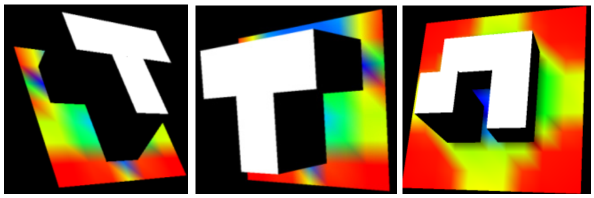

Figure 5. Visibility analysis for the ground : VisibilityGG

VisibilityGB

VisibilityGB is the second visibility index of the ground level and it measures the visual relationship between the ground and buildings. Unless the place where an observer is positioned is widely opened to the horizon, the building facades interrupt the observer's vision along the path between the buildings. At the same time the VisibilityGB forms other types of visual information different from the plane-base visibility. In addition, pedestrians are provided with visual information for determining social behavior by means of high-rise buildings or landmarks standing behind the invisible path.

A typical example is a case of displaying advertisements, the most expensive per hour, in the large buildings just in the heart of Times Square in Manhattan, New York. Other examples are landmarks installed in a large place like parks or on riverbanks, where are easily seen from everywhere near and far. People in urban areas are consciously and subconsciously exposed to visual advertisement signboards and landmarks. Mutual visibility between the ground and buildings is a new concept, reflecting that of buildings standing by pedestrian space on the ground level, beyond the pedestrian space to the 3D space.

The visibility analysis algorithm between the ground and the building facades is shown below.

```
VisibilityGB(i, j)
For Each Vertex vi  in Grounds
 For Each Vertex  vj  in Facade
  If CheckVisibility3D(vi, vj)
   Add  vi  to  Zi
  End For
End For
```

```
IntersectPolygonLine(k, i,j)
p = PlaneLineIntersection(k, i, j)
If (InsidePolygon(k, p))
  Return True
```

```
CheckVisibility3D(vi, vj)
 For Each Building
  For Polygon k in Each Facade
   If   IntersectPolygonLine(Polygon(k), Si,j)
    Return False
   End For
  End For
 Return True
```

Here, $S_{i,j}$ is a line segment from a point on the ground to one point in building facade. Polygon k is a façade of each building. If a segment from one point on the ground to the other point on the facade is made and buildings are positioned between two points of the segment, the two points are not visible each other. Therefore, visibility is decided while comparing all vertices on the ground with all vertices on the facade. The vertex list of geometrical figure of facade is created on the basis of the entire scale and the position information of the building, before it is determined that the collision happens between this polygon and the line segment. The following process is applied to determine the collision between the facade and the line segment connecting a vertex on a facade with a vertex on the ground.

1. Find the normal vector product, using any three points in a figure of a facade.
2. Find an intersection point with an infinite plane of the plane.
3. Decide whether the intersection is located in the finite plane of the building façade. The point is inside the facade if the sum of angles between the intersection p and vectors towards each side of façade polygon is 2π.

As shown in the Figure 6, VisibilityGB has greater values in the visible area of the widest facade of the widest object. For a limited ground as shown in the model, the closer a specific ground area to a building is, the lower the visibility it obtains. The farther ground from the building, the greater visibility it has as the amount of visible façade of the building becomes widened.

For the L-shape model, VisibilityGB with the building on the ground exhibits more realistic results than the T-shape. The ground in strong red is located in the place to meet the corners of two buildings to view both side facades of the buildings. On the contrary, the ground to meet one side of the building is shown in the solid blue of very low visibility.

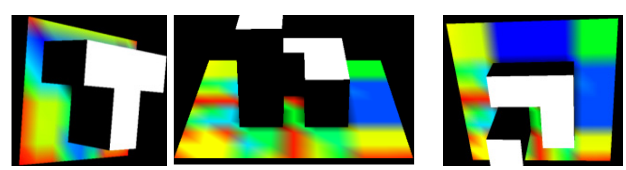

Figure 6. Visibility analysis of ground considering only building facades: VisibilityGB

VisibilityGGB

This is an index for identifying the visibility of building facades along with the ground in total. The analysis results of two samples are shown in Figure 7. The vertices forming a 3D space, regardless of their locations, are added to the set of visible vertices for finding VisibilityGGB. If VisibilityGG and the VisibilityGB have already calculated on the memory, the VisibilityGGB is simply a sum of those two.

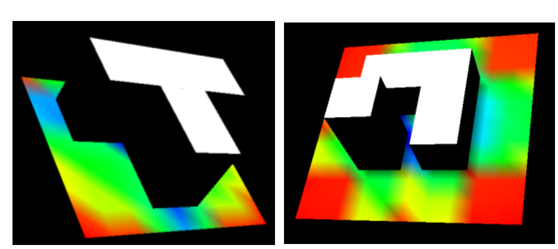

Figure 7. Visibility analysis of the ground, considering both of the ground and building facades: VisibilityGGB

The value of VisibilityGGB is not likely to reflect both VisibilityGG and VisibilityGB equally, even though they form integrated visibility index on ground. The dominant value between two exhibits a prevailing effect when the tendencies of two values conflict with each other. In a highly densely developed urban area with full of large tall buildings, the visibility of facades may be more noticeable than of ground. Therefore the VisibilityGB of facades is more dominant. However, the VisibilityGG is more dominant in desolated areas such as parks, river where there are few buildings around.

VisibilityG3D

VisibilityGGB has the problem of excessively reflecting its visibility of either VisibilityGG or VisibilityGB depending on density of buildings on the ground as described above. To address this problem, the values are normalized before added, both having same range from the minimum 0 to the maximum 100. This finally makes the integrated visibility index of the ground in 3D space. That is, VisibilityG3D is an index to objectively identify visibility of both of the facades and the ground.

Assuming that VisibilityGG and VisibilityGB of the i-th vertex in the set of vertices belonging to the ground is referenced as $Vis(G,G)_i$ and $Vis(G,B)_i$, respectively, the sum of the two $Vis(G,G)_i+Vis(G,B)_i$ is referenced as S_i, VisibilityG3D of Vis(G_i is calculated as follows, on the condition that the minimum and the maximum of S_i with respect to all vertices i on the ground are $Min(S_i)$ and $Max(S_i)$, respectively.

$$Vis(G)_i = \frac{S_i - Min(S_i)}{Max(S_i) - Min(S_i)} \times 100$$

With reference to the results of two sample models(Figure 8), for the T-shape model, it is seen that there is no significant difference from VisibilityGGB but the red area in the corner is slightly extended. For the L shape model, note the visibility of the ground on the side of lower L-shaped building. With reference to both the VisibilityGG and VisibilityGB in this area, it is observed that the distribution of analysis values for VisibilityGGB does not reflect the form of VisibilityGG distribution, and exhibits different color from the distribution form of VisibilityGB. However, Visibility3DG represents the characteristics of two indices both in color and the color distribution form.

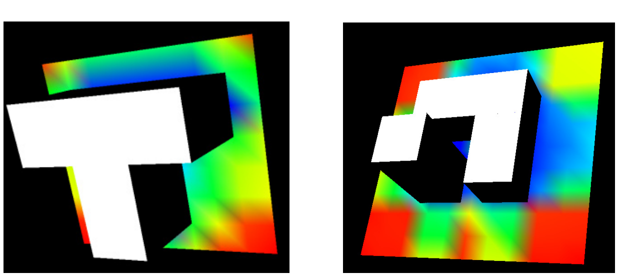

Figure 8. Visibility analysis of the ground normalized for the visibility of the ground and building facades: VisibilityG3D

(2) Visual analysis of building facades

Visual analysis of building facades is performed to identify mutual visibility between building facades and visible connectivity between the facades and the ground. The more the entire building or a specific part thereof, e.g., advertising sign boards or landmarks which have a significant meaning for a place, is exposed to people the stronger the advertising signboards or landmarks represent the characteristics of the place.

It is possible to effectively identify the effect of the 3D shape of a building in the visual environment of the place by analyzing the visibility of building facades.

We are accustomed to the building facades of an apartment building located at the front of a building, which are visible from the inside of the building, e.g., a balcony in modern apartment complexes which are getting more and denser. Exposure of private spaces is common in our daily living, which cannot be addressed by minimum safety regulations for compulsory adequate residential building distances. If we can analyze visibility between building facades to identify mutual visibility of the facades it will aid in designing buildings so that the exposure of private space is minimized. Thus it will greatly contribute to improving the residential environment of in the areas of high building density.

VisibilityBG

VisibilityBG measures the visible relationship between a building facade and the ground. It is possible to quantify the level of exposure of a building façade to the ground as well as the visibility of a building to ground by such index. The quantification of visible significance of a building facade in an urban area enables the landmark feature or view of a building to be objectified.

Visibility is calculated by connecting each vertex located on the building's elevation to all of the divided vertices on the ground one by one to make a segment of the lines. Then it is possible to check whether other objects interrupt the visibility of the segment by means of the crossing decision algorithm between sides and straight lines. The crossing decision algorithm CheckVisibility3D is the same as already described.

VisibilityBG(i, j)

```
For vi in Buildings
 For vj in Grounds
  If CheckVisibility3D(vi, vj)
    Add vi to Zi
  End If
 End For
End For
```

The result of the model analysis shown in Figure 9 is described below. The color in ground is the result of visibility analysis with VisibilityGG. For the T-shaped model, VisibilityBG is high in the concave part whereas low in outer part of the T-shape. The reason is that the former have more visible ground space by inside of T shape whereas the latter is blocked by the visibility to the ground by outer part of T-shape itself. The corners have visibility of 270 degrees to exhibit high value in red in all parts of the building.

For the L-shaped model, it is necessary to pay attention to the facades facing the narrow alley between buildings. This part is rendered in blue, which indicates low visibility for both of VisibilityGG of the ground level and VisibilityBG of the facade. On the other hand, the rectangular corner of the ground which allows the wide ground to be seen is rendered in red which implies high visibility. The corner of the building nearest the corner of the street is rendered in strong red as well thus showing that the corner visible in both directions.

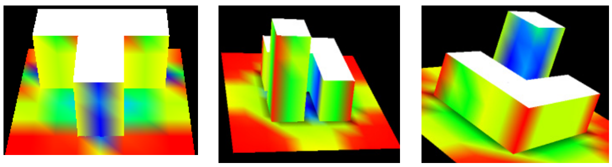

Figure 9. Visibility analysis of the building facade considering visibility with the ground : VisibilityBG

VisibilityBB

Every building in an urban area has an effect on the visual environment around the ground where it is located. Furthermore the building facade itself receives visual information through the windows and balconies. VisibilityBB is an index that measures the visibility in which one building facade is related to another. Sometimes a private area such as a living room may be seen through windows and balconies which could be one of the attributes of a facade. VisibilityBB is used to identify the level of exposure of such a personal space.

VisibilityBB

For $\mathbf{v_i}$ in Building
 For $\mathbf{v_{j=i+1}}$ Buildings
  If CheckVisibility3D(i, j)
   Add $\mathbf{v_i}$ **to** $\mathbf{Z_i}$
   Add $\mathbf{v_j}$ **to** $\mathbf{Z_j}$
  End If
 End For
End For

For the calculation of visibility between building facades, a building façade is divided into triangles where each vertex of them is considered as viewing point of others. The visual relationship with the ground is not considered. Unlike in VisibilityGG which indicates mutual visibility on the ground, visibility analysis at each different position (vertex) in the same façade of a building and therefore on the same plane is not included in the calculation. This is because of the following reason. Since the level of human eyes increases visibility on the ground, the locations of two on the ground plane are considered visible unless there is an obstacle between them. As compared to this, for a building facade, two locations are not visible each other on one facade (plane) unless we freely move on building facades like a Spiderman. It is considered that there is not any object to interrupt general visibility other than small objects negligible for calculating visibility of a large building, e.g., a small structure or sign board installed on the exterior wall of a building.

In the analysis results for the model in Figure 10, the inner façade of the T-shaped building in the same height reflects a mutually visible symmetrical distribution and exhibits a simple distribution. The blue façade is visible from the façade smaller than itself and the red façade is visible from the façade larger than itself. On the other hand, it is necessary to notice the inner side of a high-rise building for the L-shaped model. Since both sides of the L shape is seen from the inner side of L-shaped building, relatively high visibility is exhibited. In this case, since the upper part of the building corner which exhibits significantly high visibility is viewed from both of the inner side of the L shape and the corner of the roof on the outer side of L shape as well, the distribution thereof is rendered in significantly strong red. Two samples in Figure 10 show a distribution of inter-façade visibility (VisibilityBB) for the facades and inter-ground visibility (VisibilityGG) for the ground.

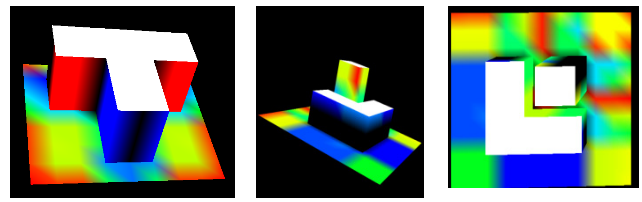

Figure 10. Visibility analysis between building façades: VisibilityBB

VisibilityBGB

VisibilityBGB is an index to identify visibility of nearby building facades and the ground visible from a building façade without consideration of the scale of the building and the ground. This is the sum of VisibilityBG and VisibilityBB at a point for analyzing visibility of a building façade. The algorithm is shown below.

VisibilityBGB

For Each Vertex $\mathbf{v_i}$ in Building
 For All Vertex $\mathbf{v_j}$
   Add $\mathbf{v_i}$ **to** $\mathbf{Z_i}$ if CheckVisibility3D(i, j)
 End For
End For

The vertex v_j compared with vertex vi located at a building façade comprises all of other facades and the ground except itself. If VisibilityBG and VisibilityBB are already calculated, add the two numbers.

Figure 11 shows VisibilityBGB analysis of a façade along with VisibilityGGB of the ground. The distribution of VisibilityBGB for both the T-shaped model and the L-shaped model reflects both indices in terms of colors and distributions as compared to VisibilityBB and VisibilityBG. While the T shaped model exhibits highly different visibility on the boundary between the ground and the façade, the L shaped model consisting of two different buildings exhibits smooth transition at the boundary with the visibility of the ground to the bystreet.

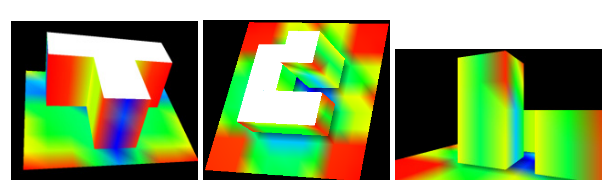

Figure 11. Visibility analysis of building façade, considering both of the ground and the building façade : VisibilityBGB

VisibilityB3D

Unlike VisibilityBGB calculated by considering values of

VisibilityBB and VisibilityBG independently and adding each number, VisibilityB3D is used to implement visibility of a building façade by normalizing visibility of the building façade and the ground to be the same range. The values of VisibilityBG and VisibilityBB range from a minimum 0 to the maximum 100. Assuming that VisibilityBG and VisibilityBB of the i-th vertex among the set of vertices belonging to a building façade are referred to as $Vis(B,G)_i$ and $Vis(B,B)_i$, the sum thereof $Vis(B,G)_i+Vis(B,B)_i$ as S_i and the minimum and the maximum of S_i as $Min(S_i)$ and $Max(S_i)$, respectively, VisibilityG3B $Vis(B)_i$ is calculated as follows.

$$\mathrm{Vis(B)_i} = \frac{\mathrm{S_i} - \mathrm{Min(S_i)}}{\mathrm{Max(S_i)} - \mathrm{Min(S_i)}} \times 100$$

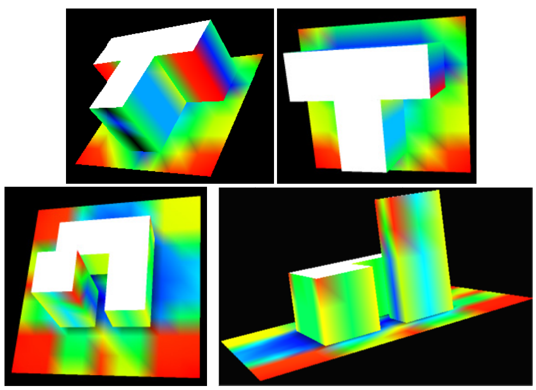

Figure 12. Visibility analysis of a building façade normalized for visibility of the building façade and the ground: VisibilityB3D

This index exhibits well-matched colors and distribution patterns when rendering analysis results along with VisibilityG3D of the ground. This is because VisibilityG3D analyzes the amount of the ground and the façade seen from the ground in the same manner. For the inner side of the T of the T-shaped model, it is thought that the ground contrasts with the façade. The ground of the concave part of building is rendered in medium-level green in which the effect of VisibilityGG with low visibility is cancelled by the effect of VisibilityGB with high visibility. By the way, the upper part of the concave façade of the building highly reflects the wide area of the lower façade of the T shape to exhibit a great value. In the L-shaped model, a more dramatic analysis result of the ground and the façade is shown. While the façade near to the ground in the narrow alley between buildings exhibits minimum visibility, the maximum visibility is exhibited at the corners on floors higher than a specified floor in the same façade.

4. 3D VISIBILITY MEASURNG TOOL: 3DSPACER

3DSpacer is a Windows-based analysis tool for selectively combining and analyzing 3D visibility indices for the ground and facades as described above. It was developed in C# by using the Microsoft's Development Studio 2008. Microsoft DirectX9 3D is used to satisfy the necessity of accessing a dedicated graphic accelerator for fast graphic processing since the CPU is not enough for the complicated 3D graphic calculation. Functions for drawing, rotation and view transform on the 3D-models are implemented using DirectX 3D library.

The structure of the program is classified into 6 steps: input, partition, drawing, analysis, display and storing. These steps are further described below (Figure 13).

(1) Input

This is to input sizes and coordinates of buildings and grounds along with necessary information through Space Input Tools such as unit size, interval, etc to be partitioned. Entering the interval from the beginning to the end of a building constructed on the ground and the interval between buildings results in automatic calculation of the position of the next building, it is possible to correct the locations in detail with the coordinate.

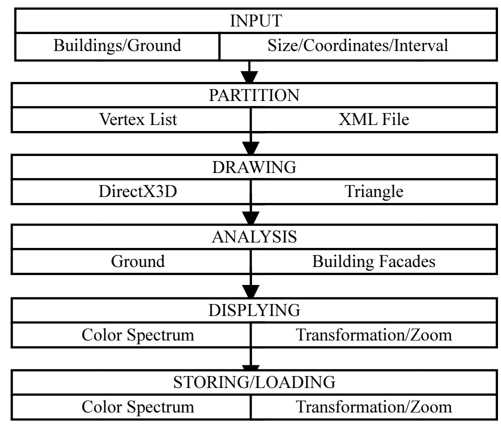

Figure 13. Execution process

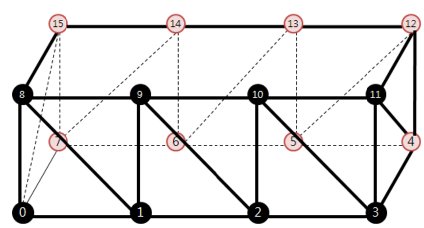

Figure 14. Dividing cells and creating a triangle set

(2) Partitioning

The entered buildings and the ground are partitioned in equal size at the specified intervals to create a vertex set and to create 3D buildings with a set of triangle whose index is the order of vertices. In this case, a triangle is the basic unit for drawing 3D objects and the 3 vertices of the triangle are the reference of visibility. Figure 14 shows a tetrahedron partitioned by 16 vertices. The front of the building is in black and the back thereof is in red. The triangle formed by 3 vertices is one unit cell for forming a 3D object, and the building shown in Figure 14 is represented as a set of vertex indices as shown below.

B = {(0,8,1),(8,1,9),(1,9,2),(9,2,10),(2,10,3),(10,3,11),
(3,11,4),(11,4,12),(4,12,5),(12,5,13),(5,13,6),
(13,6,14),(6,14,7),(14,7,15),(7,15,0),(15,0,8)}

(3) Drawing

A 3D model is represented with a set of vertex. The vertex structure is defined with the flexible vertex format as shown in

Figure 14 and the basis coordinate and color is stored in the array of vertex structure. A polyhedron is defined as a set of triangles through a combination of vertices. The index buffer is used for fast cache processing and avoiding errors resulting from redundancy of vertices. The index buffer stores indices of vertices in order. Perspective projection is employed to represent 3D models on a 2D computer screen to reflect the scale of objects on the screen depending on the distance for a sense of reality.

(4) Analysis

The vertex structure is transformed into two structures for representing the ground and the façade depending on the position of a vertex for analyzing visibility (Figure 15). Each structure comprises attributes of each node required for visibility analysis in addition to the basic position coordinate of the vertex structure. Values of each visibility index described above are normalized and stored as a number between 0 and 100 inclusive for the minimum and the maximum number of visible vertices by the relevant vertex.

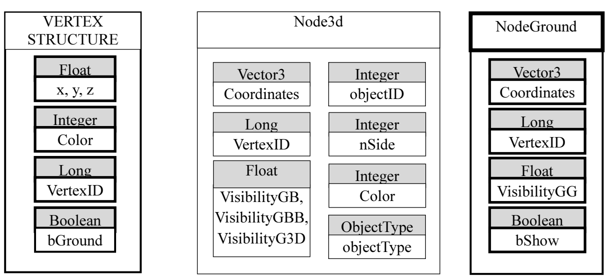

Figure 15. Vertex structure(General, Façade, Ground)

(5) Displaying

The values normalized with the vertex analysis result are mapped into colors between red (RGB(255,0,0)) with the highest value and blue (RGB(0,0,255)) with the lowest value. They are stored in the color member of the vertex buffer structure of DirectX3D. The color inside a triangle is blended from the colors of its 3 vertices.

(6) Storing

A 3D space is divided into the planar ground and vertical building facades, and visibility thereof is calculated by means of visual relationship between vertices partitioned to a triangle. All of the coordinates, the number and analysis results of each vertex are stored in the format of an XML file. The advantage of this type of file format is easy search information using internet browser, which provides great compatibility and extendibility. The list of vertices is stored in the array of vertex comprising the core information such as coordinates, colors for calculating and displaying visibility, and the array of indices comprising the order of drawing triangles.

The XML file stores core information for working with DirectX3D such as information of vertex, index, primitive parameters and other information on VERTEXINFO structure (Figure 16).

(7) User Interface.

A simple standard graphical user interface of windows system consisting of main window with menus and popup windows is used. Main window initially displays nothing until the information of building and ground objects is entered via Input Window or

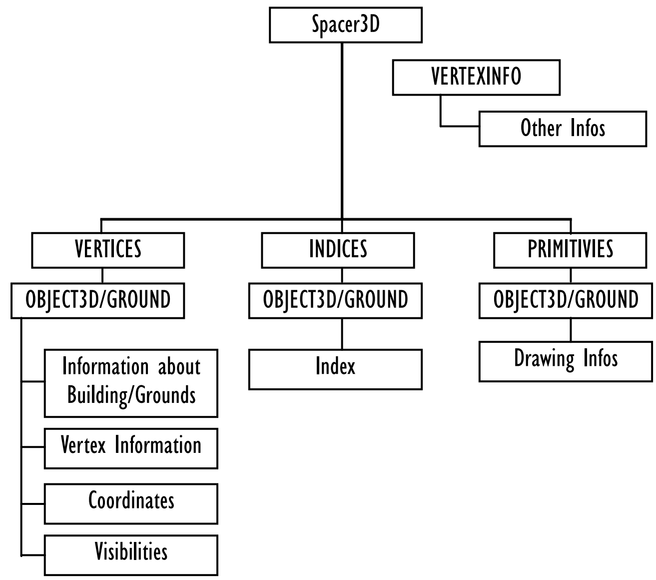

Figure 16. XML data structure

loaded from existing file.

File menu provides functions for creating new space, saving into file and loading existing space files. Selecting [Create 3D Space File] in [File-Creating New] menu showing in figure 17 to open [Creating 3D Space] dialog window. [Creating 3D Space] dialog window is divided into two panes showing in figure 18. One pane on the left accepts the locations and sizes of cubes in 3-dimesional coordinates syst em representing each buildings and ground. When [Input] button is delivered after entering all the 3D coordinate information, another pane on the right displays the information being entered. Left pane consists of several group of input boxes such as [Ground Space], [Size], [Location] for accepting x, y, z coordinates and other input boxes [Gap], [Standard Axis] along with command buttons such as [Modify], [Input] for each cubes that forms each building. Each cubes are entered when [Load], [Save], [Create], [Cancel] command button pressed.

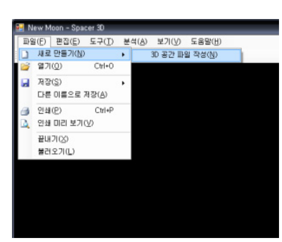

Figure17. Selecting menu on [creating 3D space]

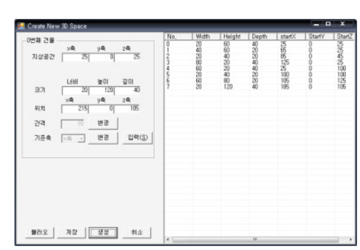

Figure18. Dialog window for [creating space]

After completion of all the input, [Create] button on the bottom of this dialog conveys the command to the application so that it builds necessary information such as vertices, indices, and primitives in defined data structures. This information will be stored into file and loads into memory for main window to draws 3D model as shown in figure 19.

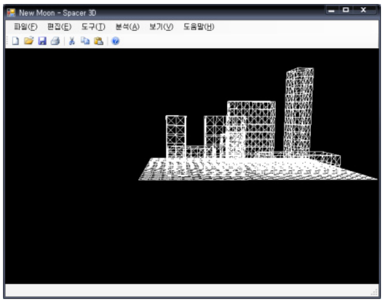

Figure 19. Initial main window after creations of 3D objects

Figure20. Sub menus for [Analysis](upper) and [View](under)

[Analysis] menu is divided into two sub menus [Ground] and [Buildings] that process the analysis commands. [Ground] menu has VisibilityGG, VisibilityGB, VisibilityGGB, VisibilityG3D and [Buildings] menu has VisibilityBB, VisibilityBG, VisibilityBBG, VisibilityB3D those perform visual analysis described in chapter 3 respectively (Figure 20). [View] menu provides three different choice of objects fill mode which are [Solid], [Frame] and [Point] (Figure 20). The initial fill mode is set to [Frame] as shown on Figure 19, and it changes to [Solid] upon user's selection. The final results can be any combinations of two visual analyses. Figure 21 shows the results combination of VisibilityGG and VisibilityBG with [Solid] mode.

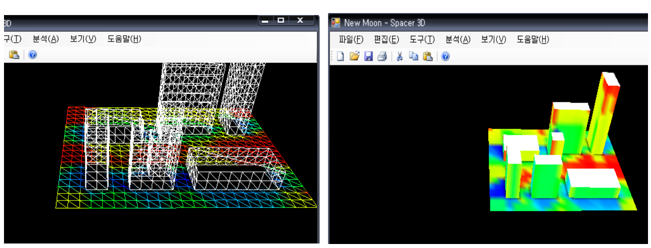

Figure 21. Left – Visual analysis of Ground(VisibilityGG) in frame mode. Right – Analysis combination of ground with buildings(VisibilityGB) and buildings with ground(VisibilityBG) in solid mode.

Main window supports mouse driven user interface for rotating, zooming in and out to navigate at any desired vantage point. Scrolling mouse ball downwards makes zoom out, scrolling upwards makes zoom in. Figure 22 shows the view rotated to left and zoomed in to look into the visibility of alley.

(8) Usefulness of the proposed measurement and its computational tool.

The test shown in previous section consisted of 6 heterogeneous buildings and a ground divided total 1160 vantage points took 60 seconds under the 2.4GHz Intel® Core™2 Quad CPU with 2.0G RAM and NVIDA GetForce 85GT GPU hardware environment while other applications such as Word, IE8, Visual Studio, Excel, etc was running . Thus it proved that a reliable computational speed with satisfactory resolution in a small site roughly divided one level into one column of unit space is achieved as a ever attempted application delivered innovative idea of visual relationships on ground and façade of buildings.

However it is still to go further to prove usefulness of the application in proposed measurement in visual relationships. It is necessary to be given wider publicity for improvement. We will constantly discuss usefulness of the measurements proposed and the computational tool with many experts throughout the world.

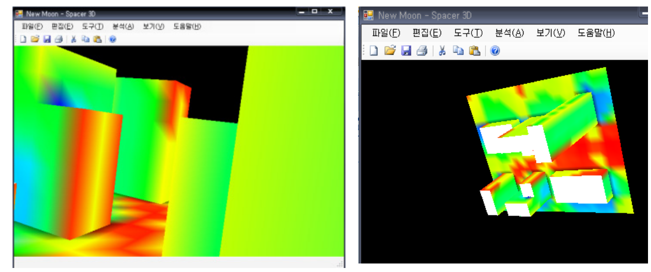

Figure 22. Visual analysis from different view point.

5. CONCLUSION

In this study, we divided a visible object of a 3D space into the ground and facades to propose a method of 3D visibility analysis for representing the analysis result by means of 3D models. We developed 3DSpacer which is an analysis tool for rendering the 3D visibility analysis result on a computer screen.

This method of visibility analysis was designed on the basis of the conventional method of analyzing isovist fields to divide a space into small units and then to determine visibility by means of the crossing decision algorithm between points. The method of dividing triangles was employed which allows 3D representation instead of the method of grid unit division used in analyzing isovist fields.

The 3DSpacer was developed to analyze effectiveness and characteristics of visibility indices for the ground and the facades. It can analyze models in 2 different shapes. The model sample used in this study was the T model, which has been used in other studies, in order to compare our results with those from other studies. 3D visibility was also analyzed for a model arranged in a L shape with 2 buildings of different heights. We proposed the following visibility indices in addition to VisibilityGG which is significant of visibility of the 2D ground presented in previous other studies. That is, they are indices of visibility towards building facades, the sum of visibility for the building facades and the ground, and integration visibility of the building facades and the ground.

Studying the visibility of building facades is the core of this study. The building facades were specified as a major visual element, which has a direct effect on 3D visibility environment in an urban area. A main goal was to quantify 3D visibility of a building façade and then to represent the ground and the building facades by means of visibility.

We analyzed visibility of the ground, which is a basic object for visibility analysis, and visibility of 3D building facades thereon in the same dimension and represented them by means of the color spectrum in the same category in order to easily identify visibility of a 3D urban space. The 3DSpacer is a computer-aided visibility analysis tool of 3D spaces developed for the first time in the world to control 3D graphics and enables extension, reduction, rotation and view transformation, as well, by means of simple mouse click operation.

3DSpacer further facilitates 3D visibility analysis of a space and is highly applicable to 3D analysis of various buildings and spaces in urban areas. Further study is required for compatibility with CAD data and development of devices for entering a variety of 3D shapes for more refined 3D space analysis.

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