The Generation of Inclined Roofs for Buildings using Polygon Shift Method

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Abstract

This study is the extended research on the development of polygon shift method for generation of 3D view map of buildings. After successfully generated a 3D view map of buildings with flat roofs, using the same method, 3D view map of buildings with inclined roof was also successfully implemented which is represented in this paper.

Prior to generation of inclined roofs using polygon shift method, the new concept of pseudo-polygon, extended pseudo-polygon, including the concept of of Roof Plane, Roof Plane Depth, Roof Plane Slope Shift Direction Vector, Roof Plane Slope Shift Direction Angle which are the additional part of the method was introduced and developed for the generation of the digital elevation model (DEM) of a specific regular shaped polygon (rectangular, triangular and trapezoidal shape) using the polygon shift method.

After implementing the polygon shift method with the generated digital elevation model (DEM) of inclined roof base plan, the 3D view of inclined roofs is generated.

1. Introduction

The generation of inclined roof for buildings is the next challengeable step of the application of polygon shift method for the generation of 3D view map of buildings. Previously, this method was successfully applied to generate a 3D view of buildings with flat roofs, especially for the area of very tall building with many stories or skyscrapers in many developed countries like Japan, Hong Kong or United States. But, in the real world, there are not only buildings with flat roofs, but also many buildings or houses with inclined roofs. Therefore the study on the generation of inclined roofs for buildings using polygon shift method is needed.

There is a vast variety of 3D modeling techniques for visualisation of urban areas that have been developed over the last decade. They were developed within various disciplines using different theories and methodologies. The difference and complexity of all these techniques depend on data input, processing methods, theoretical assumptions and solving problem methods.

Several researchers have developed methodologies for 3D urban model using particularly 3D data capture to construct 3D structures in urban areas. Raper and Kelk (1991) and Tsai (1993) proposed Delaunay Tetrahedral Tesselation (DTT) for 3D GIS. But they proposed only the concept but could not implement the algorithm. Chen, Ikeda, Yamakita, and Nasu (1994) have developed the three-dimensional modeling of GIS based on DTT. Chen, Doihara and Nasu (1995) have developed another methodology which is the introduction of a 3D spatial research, based on the octree decomposition and the DTT dividing algorithms, that provide efficient modeling and fast analysis for raster/ vector-based 3D data. Haala, Brenner and Statter (1998) have combined height data and existing ground plans of buildings and multi-spectral images in an integrated system for the generation of 3D urban models. Shi and Shibasaki (1998) have developed a practical system for automated 3D city model reconstruction from stereo urban scenes. Ozawa, Notomi and Zen (1998) have developed techniques for modeling of city scenes which is based on Extended EPI (Epipolar Plane Image) concept. Klaus, Brenner and Fritsch (1998) have introduced a methodology for 3D object reconstruction using a high-resolution hybrid measurement system. The reconstruction of textured urban 3D model by fusing ground-based laser range image and video image was developed in the research by Zhao and Shibasaki (1998). This is a method of combining a ground-based laser finder and CCD camera for the

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purpose of reconstructing textured 3D urban objects. The application of 3D photo-models using hybrid block adjustment with assumptions on the object shape was applied to the visualization of buildings by Dorffner and Forkert (1998). Labe and Gulch (1998) have developed a robust technique for estimating parameters of 3D buildings primitives.

In the summary of existing techniques, Chen has developed several algorithms for the implementation of 3D GIS (Chen et al., 1994, 1995, 1997, 1998). Other researchers have also developed several techniques to generate for 3D buildings, 3D city model (e.g. Gruen, 1998, Brenner 1998, Shi 1998) and 3D GIS (Tempfli, 1998). These methodologies are based on complicated mathematical calculations in vector model. Therefore, in this study, the basic logical operations were applied to the raster data of inclined roofs base plan. The key point of this research is the development of the concept of extended pseudo-polygon which is a new concept to generate the digital elevation model (DEM) for a roof using polygon shift method, and finally the 3D view of inclined roofs with a pyramidal look-like shapes.

2. Geometry of a Roof in Polygon Shift Method

The development of the data structure for a roof of a building to be generated by the polygon shift method, several components which are discussed in this section include:

2.1 Roof in Polygon Shift Method

In polygon shift method, a roof R of a building is considered to be a combination of one or several roof planes $\mathbf{r}_i$ which are connected to each other as components of roof R (Figure1).

$$R = \{r_1 \cup r_2 \cup ... \cup r_n\} \quad \text{where } n \geq 1$$

n is the total number of roof planes combined into the roof.

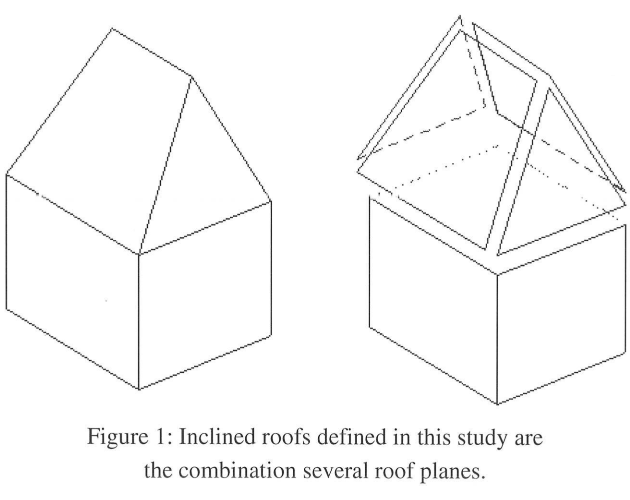


Figure 1: Inclined roofs defined in this study are the combination several roof planes.

2.2 Roof Plane

A roof plane $\mathbf{r}_i$ is a polygon of specific geometric shape that are all kinds of triangles and regular quadrangle (rectangle, parallelogram, trapezoid) (Figure 2). Irregular quadrangles are not considered in this study.

$$\mathbf{r}_i = \{ \text{triangle, quadrangle} \}$$

A plane roof $\mathbf{r}_i$ is identified by an identification number. A roof plane $\mathbf{r}_i$ is given with nodes $\mathbf{p}_k$ and sides $\mathbf{s}_k$ in clockwise, where **k** is the number of nodes and sides:

$$\mathbf{r}_i = \{p_k\}, \mathbf{r}_i = \{S_k\}$$

Each node $\mathbf{p}_k$ has coordinates of $\{x_k, y_k\}$, where $k \in n$

$$\mathbf{p}_k = \{x_k, y_k\}$$

Each side $\mathbf{S}_k$ is given by a pair of two nodes: p_k and P_{k+1}, where $k \in n$

$$\mathbf{S}_k = \{p_k, P_{k+1}\}$$

Since the roof plane shapes are selected to be triangles and quadrangles, the number of nodes and sides in each roof plane is limited only for 3 nodes and 3 sides (for the case of triangular shape) or 4 nodes and 4 sides (for the case of quadrilateral shapes) (Figure 6).

$$\mathbf{r}_i = \{p_1, ..., p_n\}, \mathbf{r}_i = \{S_1, ..., S_n\}, \text{ where } 3 \leq n \leq 4$$

The sides of a roof plane is also called also boundary. A roof plane boundary can be divided into lower boundary **LB** and upper boundary **UB**. The lower boundary **LB** is the boundary at the lowest elevation from which the slope starts, and the upper boundary is the boundary at the highest elevation which the slope ends.

Upper and lower boundary of a roof plane can be a straight line or a point (Figure 4). Two adjacent roof planes can have common lower and upper boundaries (Figure 5).

2.3 Roof Height

Roof height **h** is the vertical distance from the roof basement to roof ridge (Figure 3).

2.4 Roof Plane Slope Shift Direction Vector

Roof Plane Slope Direction vector $\mathbf{S}_d$ is the vector which has its starting point on the roof plane boundary and has the direction to a roof plane side (Figure 7). This vector has the direction towards to the ridge of the roof plane or the roof top. Therefore, this vector indentifies the direction of the roof plane slope. This vector also identify the shift direction to generate the roof plane digital elevation model.

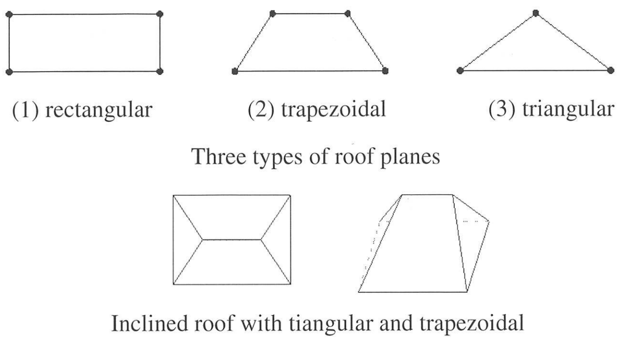


Figure 2: Roof planes types with their examples

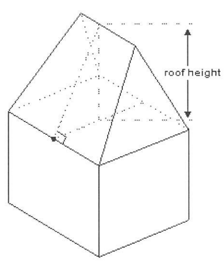


Figure 3: Roof height

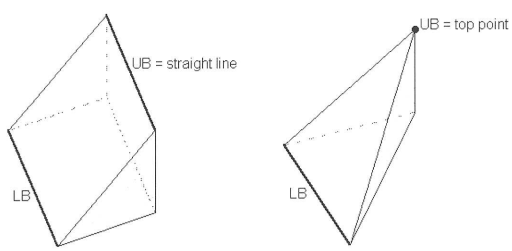
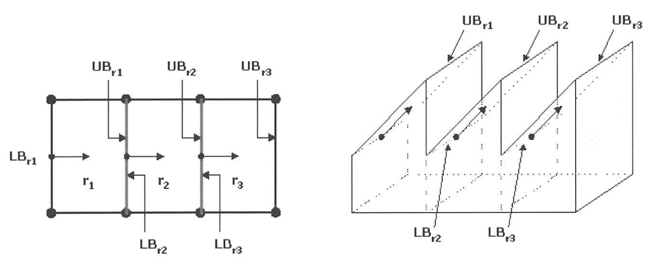
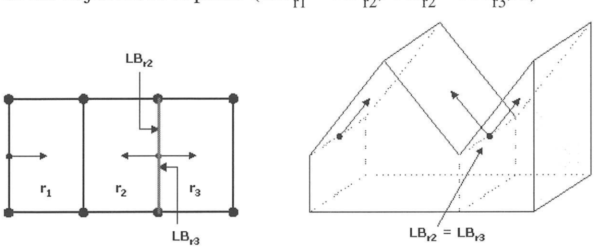


Figure 4: Example of lower and upper boundary in roof plane



(a) The lower boundary of one roof plane can be the upper boundary of the adjacent roof plane ($UB_{r1} = LB_{r2}$, $UB_{r2} = LB_{r3}$,...)



(b) Two adjacent roof planes can have common lower and upper boundary ($UB_{r2} = LB_{r3}$)

Figure 5: Characteristics of lower and upper boundary in roof planes

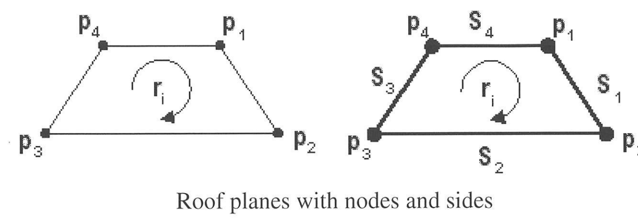


Figure 6: Definition of nodes and sides

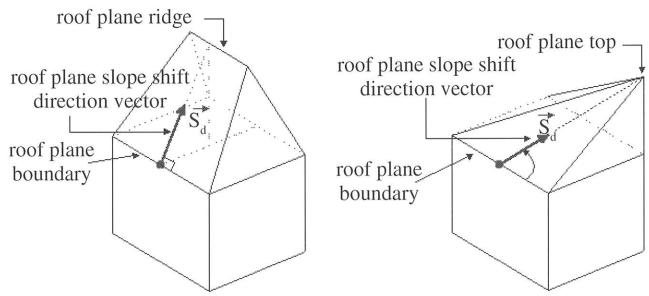


Figure 7: Definition of a roof plane slope shift direction vector

2.5 Roof Plane Slope Shift Direction Angle

Roof Plane Slope Shift Direction Angle β on a roof plane $\mathbf{r}_i$ of roof R is the angle which forms by Roof Plane Slope Direction vector S_d and roof plane lower boundary **LB** (Figure 8 (a))

In most case, for ordinary inclined roof, roof plane slope direction angle is considered to be 90°. For only some special cases, this angle can varies from 0° to 90° (Figure 8(b)).

The Roof Plane Slope Direction Angle is an important roof plane component for the generation of DEM for roof plane as well as for inclined roof, because it identifies the slope direction of the roof plane.

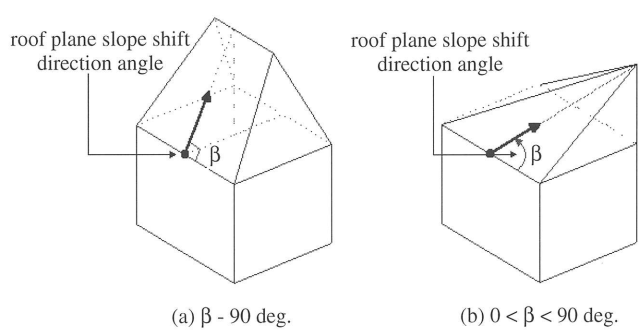


Figure 8: Definition of a roof plane slope shift direction angle

2.6 Roof Plane Depth

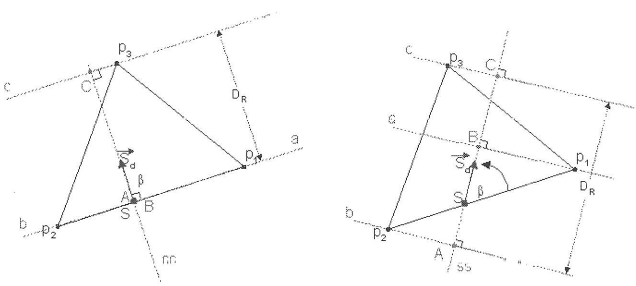
Roof plane depth D_R of roof plane $\mathbf{r}_i$ is the maximum distance between the lines projected through each roof plane node which perpendicular to the projected line along the slope shift direction vector S_d.

Given a roof plane $\mathbf{r}_i$ with n nodes which n = 3, 4 and a slope shift direction vector S_d starting from lower boundary p_1p_2 at point S with the slope shift direction angle β. (Figure 9 (a))

$$R_i = \{p_1, p_2, p_3\}$$

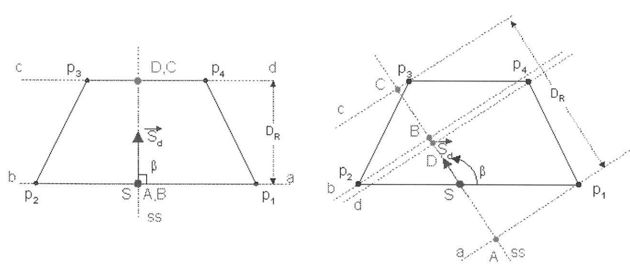
Let project a line ss along the point S and slope shift direction vector S_d. The projected line ss is parallel to the vector S_d :

$$S \xrightarrow{project} ss, \quad ss \,//\, \vec{S}_d$$



D_R = max (AB, BC, AC) D_R = max (AB,BC,AC)

(a) Depth of roof plane of triangular shape



D_R = max (AB,BC,AC,BD) D_R = max (AB,BC,AC,AD,CD,BD)

(b) Depth of roof plane of quadrangular shape

Figure 9: Definition of roof plane depth

Let project another lines a, b and c through nodes p_1, p_2 and p_3 and perpendicular ss respectively:

$$p_1 \xrightarrow{project} a, \quad a \perp ss$$

$$p_2 \xrightarrow{project} b, \quad b \perp ss$$

$$p_3 \xrightarrow{project} c, \quad c \perp ss$$

We can see that, lines a,b and c is perpendicular to line ss and intersected at point A, B and C respectively:

$$a \cap ss \rightarrow A$$
$$b \cap ss \rightarrow B$$
$$c \cap ss \rightarrow C$$

which create a line AC with three segments AB, AC and BC. Find the maximum length of these segments which is the roof plane depth D_R of $\mathbf{r}_i$:

$$D_R = \max\ (AB, BC, AC)$$

The roof plane depth identifies the highest elevation value of the roof plane, which is used in the generation of DEM for the roof plane that will be discussed in the next section.

3. Roof Planes Digital Elevation Model

The digital elevation model (DEM) of the roof plane in polygon shift method is to be considered as the stripes of elevation value which increase along the direction of the slope shift direction vector and perpendicular to this vector.

Roof planes digital elevation model can be generated using the roof planes components described above in previous sections which are: roof plane slope shift direction vector, roof plane slope shift direction angle and roof plane depth.

Firstly, the roof has to be subdivided into roof planes, then assign the slope shift direction vector and angle to each roof plane. Next, perform the polygon shift to each roof plane to generate its digital elevation model. Finally, re-combine all the resulted roof planes of digital elevation model into it original position to get the final digital elevation model of roof.

When the digital elevation model of the roof is generated, the 3D view of inclined roof can be generated easily using the polygon shift method.

Table 1 shows the process of the generation of digital elevation model of a roof with additional step of the generation of the 3D view of the inclined roof.

Table 2 shows the sub-routine of the digital elevation model generation for a roof plane.

4. Application of Polygon Shift Method to the Generation of Inclined Roofs of Buildings

According to the Tables 1 and 2 in previous section, the generation of inclined roof of buildings can be represented by the following steps:

1. Subdivide the roof into N roof planes.
2. Input the geometric data of each roof i^{th} plane.
3. Generate the digital elevation model for each roof i^{th} plane using polygon shift method.
4. Repeat step 2 until the digital elevation model of all roof planes were generated.

Table 1: The process of the digital elevation model generation of a roof

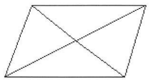
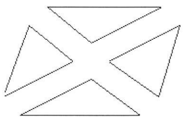
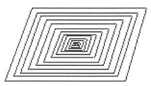
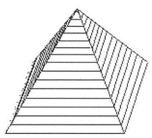
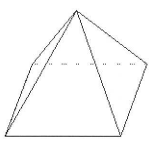
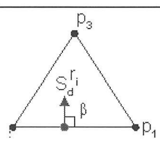
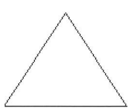
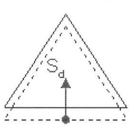
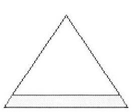
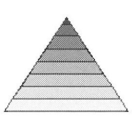
Figures	Description
1 	A roof which is composed by triangular roof planes
2 	Subdivide the roof into roof planes and generate the digital elevation model for each roof plane.
3 	Subdivide the roof into roof planes and generate the digital elevation model for each roof plane. Finally re-combine the each roof plane digital elevation model to its original position. The result is the digital elevation model of a roof.
4 	Apply the polygon shift method to the digital elevation model of the roof to generate 3D view of inclined roof.
5 	Apply the color shading effect to the inclined roof to make it more realistic.

Table 2: The sub-routine of the digital elevation model generation of a roof plane

Figures	Description
1 	roof plane with its geometric structure
2 	roof plane in initial step
3 	shift the roof plane to the slope shift direction
4 	after shifting for one step along the direction of the slope shift direction S_d, the first elevation value is made
5 	after completing **n**-steps of shifting which **n** = $\mathbf{D_R}$, all value of digital elevation model are generated

5. The result of the process will be digital elevation model of the entire roof.

4.1. Generation of Roof Plane Digital Elevation Model

The generation of roof plane digital elevation model using polygon shift method is the key point of this study which is the basic step, prior to generate 3D view of inclined roof of building using polygon shift method.

The method demonstrated in Table 2 can be used successfully for the case of a roof plane that has lower boundary longer or equal to the upper boundary (Figure 4).

$$LB \geq UB$$

But when we apply this method to a roof plane which has lower boundary shorter than upper boundary, the digital elevation model is not properly generated as already defined in section 3 (Figure10).

$$LB < UB$$

Therefore, to overcome this problem, the pseudo-polygons for these roof planes should be introduced.

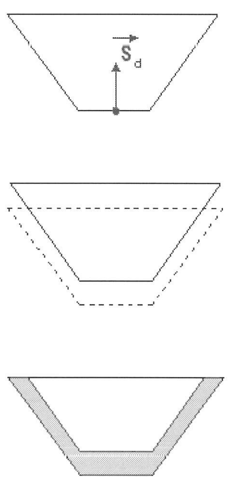
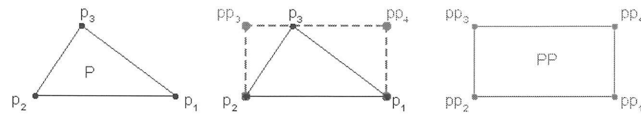


Figure 10: The method discussed in Table 2 cannot work properly for the case when the lower boundary is shorter than the upper boundary

4.1.1 Pseudo-polygon of a polygon

The introduction of the pseudo-polygon for a roof plane allows the generation of DEM for any roof plane shapes defined in section 2.2 become easily, because the pseudo-polygon of each roof plane will be a polygon of rectangular shape which is the most simple roof plane shape and the DEM can be generated within the frame of this pseudo-polygon. Figure 11 shows an example of pseudo-polygon convertion from a roof plane which has triangular shape.



(a) polygon with original shape

(b) modifying original polygon to pseudo-polygon

(c) pseudo-polygon PP of original polygon P

Figure 11: Polygon P and its pseudo-polygon PP

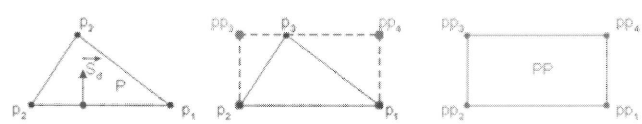
The conversion of a polygon to a pseudo-polygon can be done by a simple modification of geometric shape of the original polygon.

In our example, the roof plane P of triangular shape is converting to rectangular shape PP just by tracing a line from a node p_1 to intersect with another line traced from node p_3 that form a right angle and a new node pp_4 . Similarly, for the another two nodes p_2 and p_3, after intersection it will create another right angle and new node pp_3 (Figure 11 (b)). Finally, the newly formed polygon pp_1, pp_2, pp_3, pp_4 is the pseudo-polygon PP to the original polygon P with nodes p_1, p_2, p_3 (Figure 11 (c)).

In the case of roof plane has the shape of rectangle, the pseudo-polygon for this roof plane will be the same as its original polygon.

Once the pseudo-polygon is created, the DEM of the roof plane can be generated within the frame of the pseudo-polygon can be performed by following algorithm:

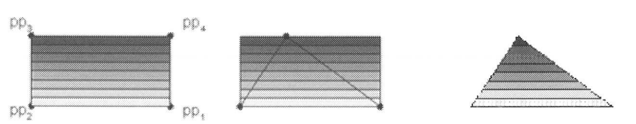
1. Input roof plane with its geometric data.
2. Define the slope shift direction vector and angle.
3. Perform the pseudo-polygon conversion.
4. Apply the polygon shift method to generate DEM within the pseudo-polygon.
5. Perform the overlapping between the pseudo-polygon with DEM and the original polygon.
6. The result of the overlapping above is the original polygon or roof plane with generated DEM (Figure 12).



(a) original roof plane

(b) pseudo-polygon conversion

(c) pseudo-polygon



(d) pseudo-polygon with DEM

(e) overlap pseudo-polygon with original polygon

(f) roof plan with DEM

Figure 12: DEM generation for a roof plane using pseudo-polygon

Using this algorithm, we can easily generate the DEM for any roof plane type defined in section 2.2, without concerning to the difference between the length of the lower and upper boundary.

The algorithm above is a very simple algorithm to generate DEM of a roof plane. It can be used only for the case when the slope shift direction angle is perpendicular to the lower boundary, i.e. $\beta = 90.0°$.

For the case of roof plane having a slope shift direction angle not equal to 90.0°, i.e. $0.0° \leq \beta \leq 90.0°$. The algorithm which uses the pseudo-polygon can not be applied for the generation of DEM. This algorithm has to be improved by introducing a new additional component to the concept of pseudo-polygon that is the extended pseudo-polygon.

4.1.2 Extended pseudo-polygon of a polygon

The extended pseudo-polygon is the most important key point in the generation of DEM of roof plane. Adding this component into the algorithm defined in previous section, the DEM of roof plane with any slope shift direction angle can be generated easily.

The DEM generation algorithm with the use of the extended pseudo-polygon can be described as below:

After the pseudo-polygon of a roof plane r_i is created as explained in the section 4.1.1, the slope shift direction angle is remained oblique ($\beta \neq 90.0°$) to the lower boundary p_1p_2 (Figure 13 (a)).

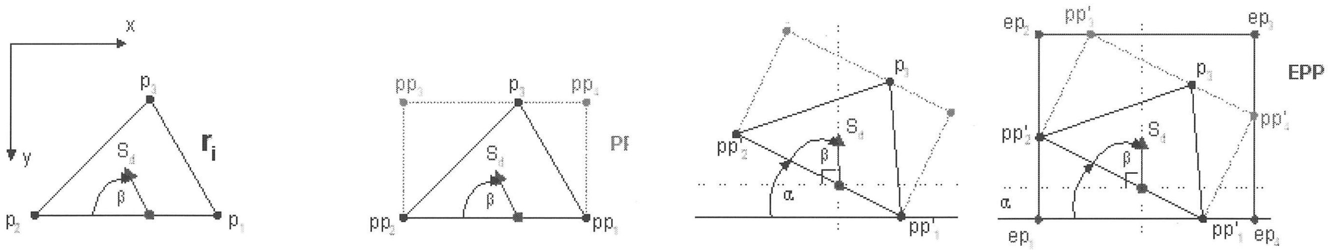
The pseudo-polygon and its original roof plane has to be rotated for an angle α that make the angle β to be perpendicular to the axis-x (Figure 13 (c)).

Convert the pseudo-polygon PP to be another new pseudo-polygon which is called extended pseudo-polygon EPP or "the pseudo-polygon of pseudo-polygon PP" by the same method as done for the original polygon of the roof plane shown in Figure 11 (Figure 13 (d)).

The polygon shift method can be applied to generate the generation of DEM within the frame of the extended pseudo-polygon EPP (Figure 13 (f)).

Overlap the roof plane rotated by α with the DEM generated inside the extended pseudo-polygon to obtain the roof plane with DEM, before rotating it back to its original position bythe angle - α (Figure 13 (g)).

Figure14 shows the flowchart of algorithm for the DEM generation for a roof plane.

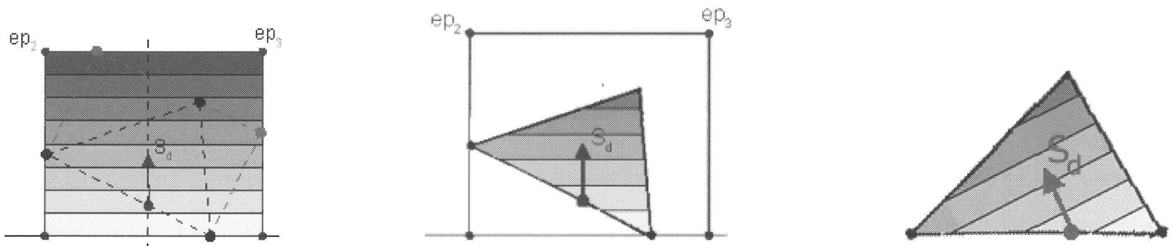


(a) a roof plane with slope shift direction angle and vector, where $0 < \beta < 90$ deg.

(b) creating a pseudo-polygon PP for roof plane ri

(c) perform rotation by $\alpha = 90 - \beta$ to make the vector S_d to be perpendicular with lower boundary.

(d) create extended pseudo-polygon EPP.



(e) apply the polygon shift method to generate DEM within the frame of EPP.

(f) overlap the DEM generated within the EPP with the roof plane.

(g) roof plane with generated DEM in original position

Figure 13: Illustration of the generation of DEM for roof plane using the extended pseudo-polygon

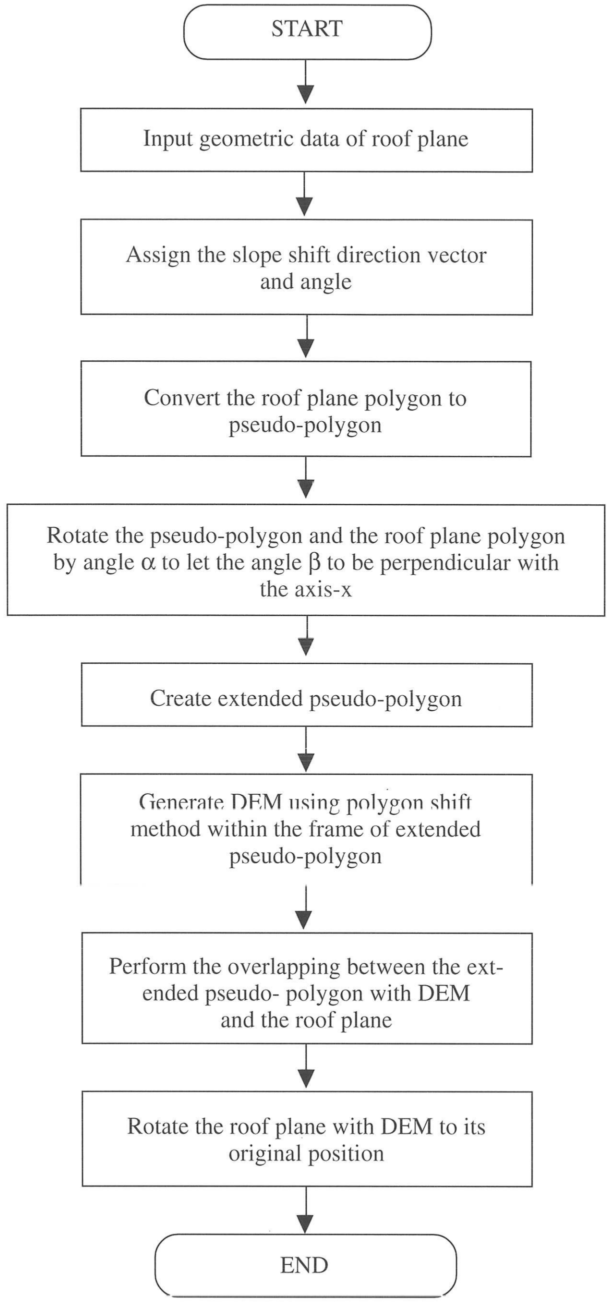


Figure 14: The flowchart of algorithm for the DEM generation for a roof plane

4.2. Three-Dimensional View Generation Algorithm of Inclined Roofs

In section 4.1, the algorithm for the generation of digital elevation model for roof plane was discussed and developed. Applying the developed algorithm, the 3D view of inclined roof can be generated. In this section, the final 3D view generation algorithm of inclined roof using polygon shift method is finalised and demonstrated in the flowchart as shown in Figure 15.

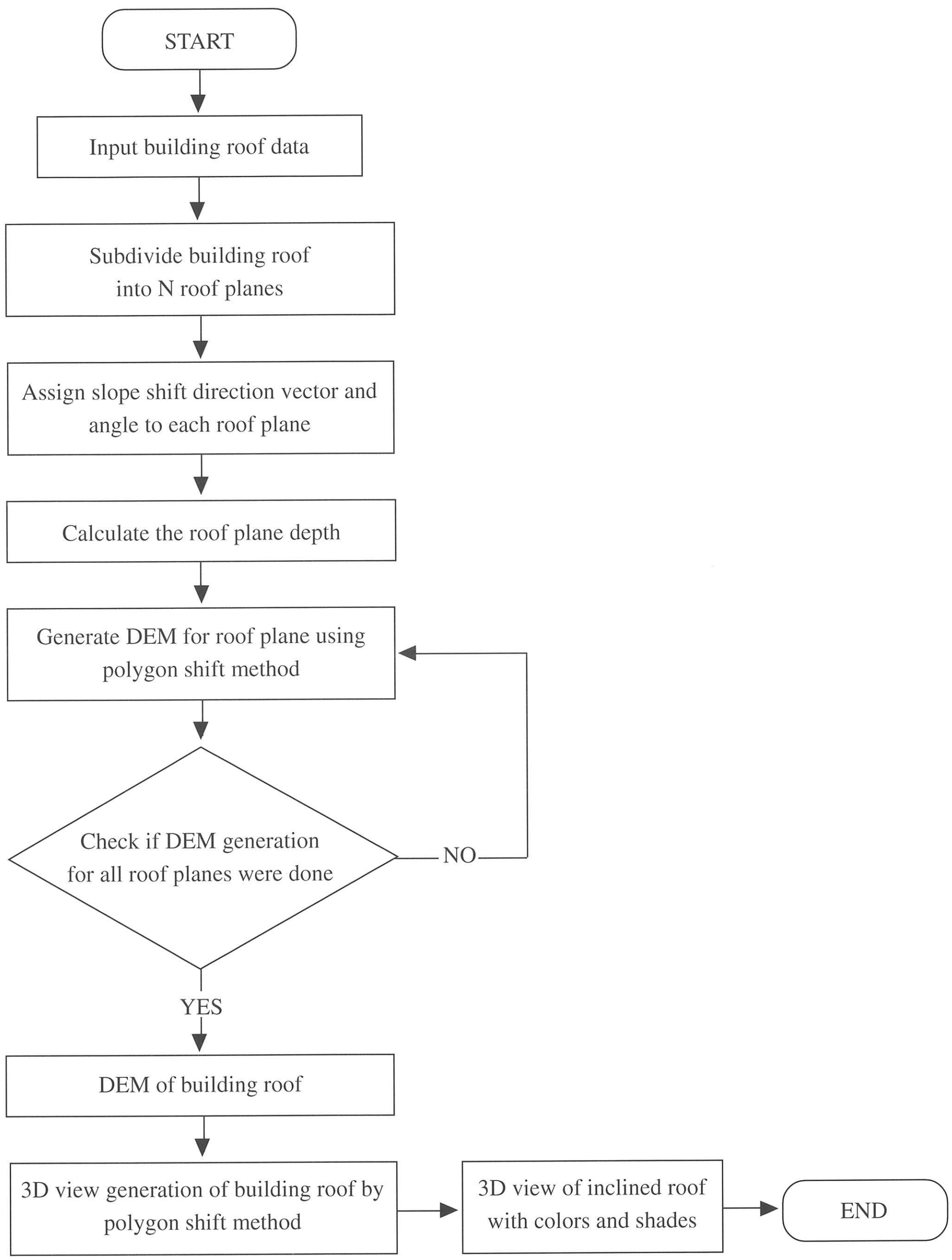


Figure 15: 3D view generation algorithm of inclined roof using polygon shifft method

5. Implementation on Various Examples

In this section, various examples of the 3D view of inclined roofs of buildings with different shapes are illustrated.

Figure 16 shows various examples of inclined roofs types which are different types of pyramidal shapes (Figure 16(a), 16(b), 16(c) and 16(d)). Inclined roof for a building with inner open-air garden is shown in Figure 16(e). The hexagonal shape of inclined roof is shown in Figure 16(f).

Examples of inclined roofs and their digital elevation model generated using polygon shift method by assigning different slope shift angle are shown in Figure 17. Figure 17(a) and 17(c) show the digital elevation model of inclined roofs with the slope shift direction angle of 90° and 45° respectively. Figure 17(b) and 17(d) show the 3D view of inclined roofs with the slope shift direction angle of 90° and 45°, respectively.

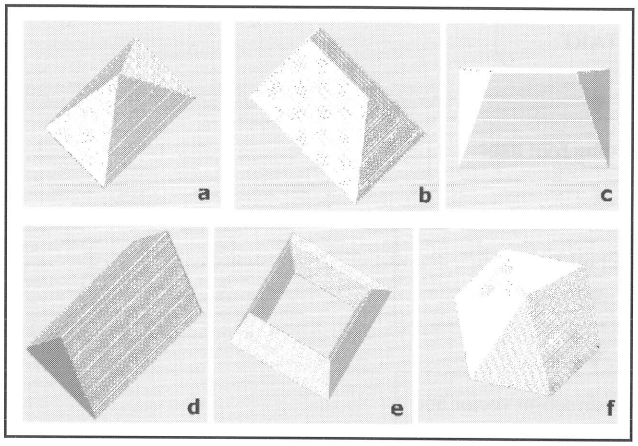


Figure 16: Various examples of 3D view of inclined roofs types generated by polygon shift method.

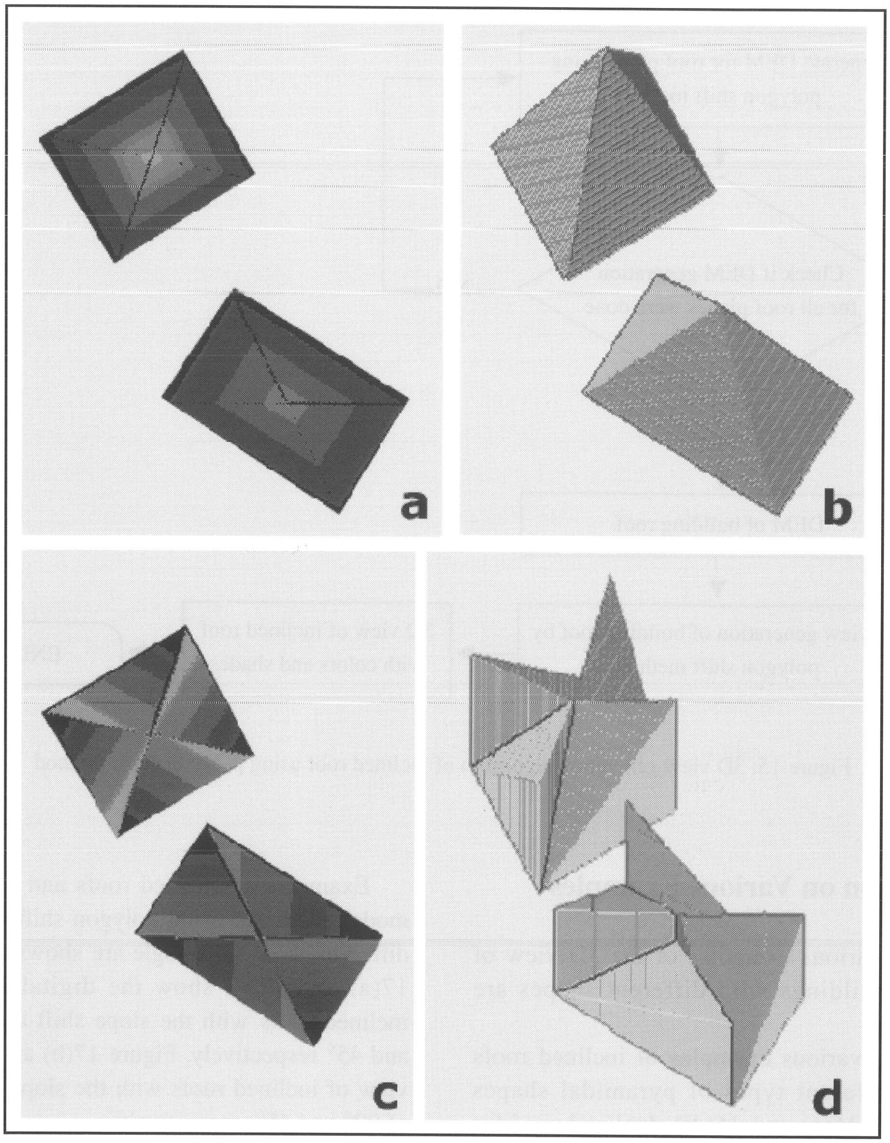


Figure 17: Examples of inclined roofs and their digital elevation model generated using polygon shift method by assigning different slope shift angle.

6. Conclusions

A polygon shift method was developed to generate 3D view map of buildings with flat roofs and now it is extended as a powerful algorithm to generate 3D views of inclined roof for buildings without any complicated data structure and computation. The major advantage of the polygon shift method is its simplicity in the generation of 3D view of inclined roof as compared to the existing algorithms. Its simplicity lies in simple geometrical and logical mechanism of DEM generation of inclined roofs.

The introduction of the concept of Roof Plane, Roof Plane Depth, Roof Plane Slope Shift Direction Vector, Roof Plane Slope Shift Direction Angle, Pseudo-Polygon, Extended Pseudo-Polygon, Roof Plane Digital Elevation Model (DEM) was applied to simplify the geometric, topologic and logical operations required for three-dimensional visualization of inclined roof. It can overcome the weakness of raster data structure with respect to topology.

A new algorithm called the Extended Pseudo-Polygon (EPP) was developed to be the key point in the generation of DEM of roof plane as well as for the entire roof of buildings.

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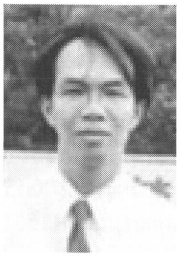

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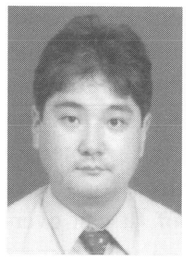

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