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メタデータ	言語: eng 出版者: 公開日: 2017-10-05 キーワード (Ja): キーワード (En): 作成者: メールアドレス: 所属:
URL	http://hdl.handle.net/2297/46727

Automatic Generation of 3D Building Models with Efficient Solar Photovoltaic Generation

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Received: January 05, 2016; Accepted: September 30, 2016

Key words: 3D building model, automatic generation, solar photovoltaic generation, 3D city model

Abstract: To facilitate public involvement for sustainable development, 3D models simulating real or near future cities using 3D Computer Graphics (CG) can be of great use. 3D city models are important in environmentally friendly urban planning that will use solar photovoltaic (PV) generation. However, enormous time and labour has to be consumed to create these 3D models using 3D modelling software such as 3ds Max or SketchUp. In order to automate laborious steps, this paper proposes a Geographic Information System (GIS) and CG integrated system that automatically generates 3D building models based on building polygons or building footprints on digital maps, which show most building polygons' edges meet at right angles (orthogonal polygon). A complicated orthogonal polygon can be partitioned into a set of rectangles. The proposed integrated system partitions orthogonal building polygons into a set of rectangles and places rectangular roofs and box-shaped building bodies onto these rectangles. In this paper, for placing solar panels on a hipped roof, the structure of an ordinary hipped roof that is made up of two triangular roof boards and two trapezoidal ones is clarified. To implement efficient PV generation, this paper proposes to automatically generate 3D building models for buildings topped with double shed roofs with overlaid PV arrays. The sizes and positions, slopes of roof boards and main under roof constructions are made clear by presenting a top view and side view of a double shed roof house. For the applied example of the developed system, this paper presents a simulation of the solar photovoltaic generation change of a city block by performing land readjustment and changing the shape of buildings, ordinarily roofed houses or double shed roofed houses suitable for efficient PV generation. Our simulation reveals that double shed roofed houses have greatly improved solar photovoltaic generation.

1. INTRODUCTION

A 3D city model such as the one shown in *Figure 1* is important in urban planning and gaming industries. Urban planners may then draw maps for sustainable development. 3D city models based on these maps are quite effective in understanding what occurs if this alternative plan is realized. To facilitate public involvement for sustainable development, 3D models

simulating real or near future cities by 3D Computer Graphics (CG) can be of great use. 3D city models are important in environmentally friendly urban planning that will use solar photovoltaic (PV) generation. However, enormous time and labour has to be consumed to create these 3D models, using 3D modelling software such as 3ds Max or SketchUp. For example, when manually modelling a house with roofs by Constructive Solid Geometry (CSG), one must use the following laborious steps:

(1) Generation of primitives of appropriate size, such as box, prism or polyhedron that will form parts of a house, (2) Boolean operations are applied to these primitives to form the shapes of parts of a house, such as making holes in a building body for doors and windows, (3) Rotation of parts of a house, (4) Positioning of parts of a house, and (5) Texture mapping onto these parts.

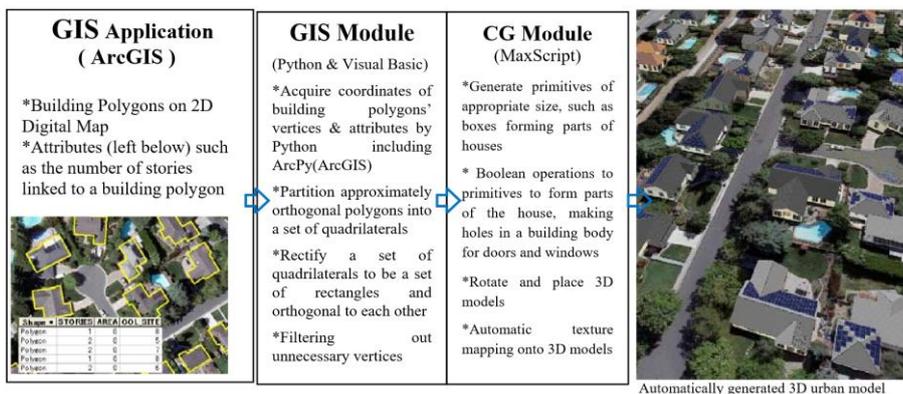


Figure 1. Pipeline of Automatic Generation for 3D Building Models

In order to automate laborious steps, this research proposes a GIS and CG integrated system for automatically generating 3D building models (Sugihara & Kikata, 2012) based on building polygons or building footprints on a digital map, as shown in *Figure 1 Left*, which shows most buildings' polygon edges meet at right angles (orthogonal polygons). A complicated orthogonal polygon can be partitioned into a set of rectangles. The proposed integrated system partitions orthogonal building polygons into a set of rectangles and places rectangular roofs and box-shaped building bodies onto these rectangles. In order to partition an orthogonal polygon, the research also proposes a useful polygon expression (RL expression: an edge's Right & Left turns expression) and a partitioning scheme for deciding from which vertex a dividing line (DL) is drawn (Sugihara, 2009).

Since technicians are drawing building polygons manually with digitizers, depending on aerial photos or satellite imagery as shown in *Figure 1 Left*, not all building polygons are precisely orthogonal. When placing a set of boxes as building bodies for forming the buildings, there may be gaps or overlaps between these boxes if the building polygons are not strictly orthogonal. In the integrated system, the GIS module rectifies the shape of building polygons and creates a set of mutually orthogonal rectangles without any gap or overlap.

In this paper, to place solar panels on the roof for efficient solar photovoltaic (PV) generation, the structure of an ordinary hipped roof that is made up of two triangular roof boards and two trapezoidal ones is clarified. To implement efficient PV generation, this paper proposes to automatically generate 3D building models topped with double shed roofs with overlaid PV arrays. The sizes and positions, slopes of roof boards and main under roof constructions are made clear by designing a top view and side view of a

double shed roofed house. For the applied example of the developed system, this research simulates the solar photovoltaic generation change of a city block by performing land readjustment and changing the shape of buildings, i.e., ordinary roofed houses or double shed roofed houses suitable for efficient PV generation. This simulation reveals that double shed roofed houses have greatly improved solar photovoltaic generation.

2. RELATED WORK

Since 3D urban models are important information infrastructure that can be utilized in several fields, researches on the creation of 3D urban models are in full swing. Various types of technologies, ranging from computer vision, computer graphics, photogrammetry to remote sensing, have been proposed and developed for creating 3D urban models.

Procedural modelling is an effective technique to create 3D models from sets of rules such as L-systems, fractals, and generative modelling language ([Parish & Müller, 2001](#)). [Müller et al. \(2006\)](#) have created an archaeological site of Pompeii and a suburban model of Beverly Hills by using a shape grammar that provides a computational approach to the generation of designs. They import data from a GIS database and try to classify imported mass models as basic shapes in their shape vocabulary. If this is not possible, they use a general extruded footprint together with a general roof obtained by the straight skeleton computation defined by a continuous shrinking process ([Aichholzer et al., 1995](#)). By using the straight skeleton, [Kelly and Wonka \(2011\)](#) present a user interface for the exterior of architectural models to interactively specify procedural extrusions, a sweep plane algorithm which computes a two-manifold architectural surface.

Image-based capturing and rendering techniques, together with procedural modelling approaches, have been developed that allow buildings to be quickly generated and rendered realistically at interactive rates. [Bekins and Aliaga \(2005\)](#) exploit building features taken from real-world capture scenes. Their interactive system subdivides and groups the features into feature regions that can be rearranged to texturize a new model in the style of the original. The redundancy found in architecture is used to derive procedural rules describing the organization of the original building, which can then be used to automate the subdivision and texturing of a new building. This redundancy can also be used to automatically fill occluded and poorly sampled areas of the image set.

[Aliaga, Rosen, and Bekins \(2007\)](#) extend the technique to inverse procedural modelling of buildings and they describe how to use an extracted repertoire of building grammars to facilitate the visualization and modification of architectural structures. They present an interactive system that enables both creating new buildings in the style of others and modifying existing buildings in a quick manner.

[Vanegas, Aliaga, and Beneš \(2010\)](#) interactively reconstruct 3D building models with the grammar for representing changes in building geometry that approximately follow the Manhattan-world (MW) assumption which states there is a predominance of three mutually orthogonal directions in the scene. They say automatic approaches using laser-scans or LIDAR data, combined with aerial imagery or ground-level images, suffer from one or all of low-resolution sampling, robustness and missing surfaces. One way to improve quality or automation is to incorporate assumptions about the buildings such as the MW assumption.

By these interactive modelling systems, 3D building models with plausible detailed façades can be achieved. However, the limitation of these modelling systems is the large amount of user interaction involved ([Jiang, Tan, & Cheong, 2009](#)). When creating 3D urban models for urban planning or facilitating public involvement, 3D urban models should cover a lot of involved citizens' and stakeholders' buildings. This means that it will take enormous time and labour to model a 3D urban model with hundreds of buildings. Thus, a GIS and CG integrated system that automatically generates 3D urban models immediately is proposed, and the generated 3D building models that constitute 3D urban models are approximate geometric 3D building models that citizens and stakeholders can recognize as their future residence or real-world buildings.

[Xiao and Furukawa \(2014\)](#) present a 3D reconstruction and visualization system to automatically produce clean and well-regularized texture-mapped 3D models for large indoor scenes from ground-level photographs and 3D laser points. The key component is a new algorithm called "Inverse CSG" for reconstructing a scene in a Constructive Solid Geometry (CSG) representation consisting of volumetric primitives, which imposes regularization constraints to exploit structural regularities. However, with the lack of ground-truth data preventing them from conducting quantitative reconstruction accuracy evaluations, they have to manually overlay their model with a floor plan image.

This computer vision methodology, together with following the Manhattan-world (MW) assumption ([Vanegas, Aliaga, & Beneš, 2010](#)), uses 3D point clouds from laser-scans, extracting line segments passing through them by the Hough transformation for structural regularities. In the approach presented in this paper, only the position of the vertices of a building polygon is used for structural regularities or rectification, which reduces the heavy burden of dealing with a huge amount of 3D point cloud data.

3. PIPELINE OF AUTOMATIC GENERATION

As shown in *Figure 1*, the proposed automatic building generation system consists of the GIS application (ArcGIS, ESRI Inc.), GIS module and CG module. The source of the 3D urban model is a digital residential map that contains building polygons linked with attribute data shown in *Figure 1*, consisting of the number of storeys, the image code of the roof, wall and the type of roof (gable roof, hipped roof, gambrel roof, mansard roof, temple roof and so forth). The maps are then pre-processed within the GIS module, and the CG module finally generates the 3D urban model. As a GIS module, a Python program including ArcPy (ArcGIS) acquires coordinates of the building polygons' vertices and attributes.

Pre-processing within the GIS module includes the procedures as follows: (1) Filter out any unnecessary vertex whose internal angle is almost 180 degrees, (2) Partition or separate approximately orthogonal polygons into a set of quadrilaterals, (3) Generate inside contours by straight skeleton computation for placing doors, windows, fences and shop façades which are setback from the original building polygon, (4) Rectify a set of quadrilaterals to be a set of rectangles and orthogonal to each other, (5) Export the coordinates of polygons' vertices, the length, width and height of the partitioned rectangle, and attributes of the buildings.

The CG module receives the pre-processed data that the GIS module exports, generating 3D building models. In the GIS module, the system

measures the length and inclination of the edges of the partitioned rectangle. The CG module generates a box of the length and width measured in the GIS module.

In the case of modelling a building with roofs, the CG module follows these steps: (1) Generate primitives of appropriate size, such as boxes, prisms or polyhedra, that will form the various parts of the house, (2) Boolean operations are applied to these primitives to form the shapes of parts of the house, for example, making holes in a building body for doors and windows, making trapezoidal roof boards for a hipped roof or a temple roof, (3) Rotate parts of the house according to the inclination of the partitioned rectangle, (4) Place parts of the house, (5) Map texture onto these parts according to the attribute received, (6) Copy the 2nd floor to form the 3rd floor or more in case of buildings higher than three stories.

The length and width of a box as a house body are decided by the rectangle partitioned or separated from a building polygon in the GIS module. Also, the length of a thin box as a roof board is decided by the rectangle partitioned while the width of a roof board is decided by the slope of the roof given as a parameter. The CG module has been developed using Maxscript that controls 3D CG software (for example, 3ds MAX, Autodesk Inc).

4. 3D BUILDING MODEL FOR EFFICIENT SOLAR PHOTOVOLTAIC (PV) GENERATION

4.1 3D Model of Town Block and the Display of Solar PV Generation Area

Generated power of solar photovoltaic (PV) panels depends on the intensity of the sunlight and the installation condition of the panels such as the panels' azimuth, pitch, surrounding environment, atmospheric temperature, and its location. The data map for the amount of sunshine is made and well maintained by the New Energy and Industrial Technology Development Organization (NEDO) of Japan. In the map, by indicating where the installation of the panels is, the amount of sunshine is then given.

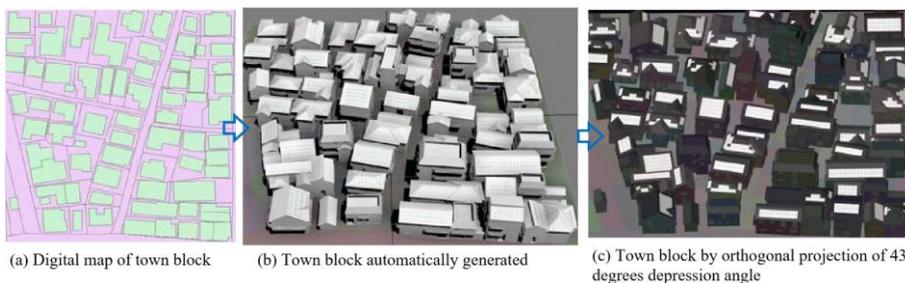


Figure 2. 3D town block model automatically generated and imaged by orthogonal projection

Figure 2 shows the flow of automatic generation from a digital map of a town block to a 3D model of a town block, and an orthogonal projection image with 43 degree depression angle. In the town block model, 3D building models have south and east facing solar panels. The recent research shows putting panels on east-west facing roofs will smooth the supply of power during the day and prevent spikes of power at midday (www.telegraph.co.uk/news/10996273).

Since the solar power generation of panels will be proportional to the panel side perpendicular to the light of the sun, one can know how much solar energy the buildings with panels can create by calculating the area of the perpendicular component of panels by using a projection image such as in *Figure 2 (c)*. Although through the NEDO data map the average quantity of solar radiation of a certain spot is estimated by the positional relationship and the distance from meteorological observation sites, one cannot simulate the shadow of neighbouring terrestrial objects such as buildings or trees.

The sunlight and daylight systems of 3ds Max use the light in a system that follows the geographically correct angle and movement of the sun over the earth at a given location (<http://www.autodesk.com/support/3ds-max/learn-explore/>). When using this system, one chooses location, date, time and compass orientation indicating a user orientation, and shadow studies of proposed and existing structures will be implemented by 3ds Max. In these studies for simulating shadows, 3D models of city blocks are necessary.

Figure 3 shows a digital map of a town block after land readjustment, an automatically generated 3D town block model, 3D building model with double leaned roof and images by orthogonal projection of various degree depression angles. Leaned roof houses can have large roof boards for panels. In a scene, virtual cameras are placed with a certain direction and depression angle at a certain height, and orthogonal projection images can be shot. Panels on roofs are self-illuminated for easy calculation of the area component perpendicular to the sun.

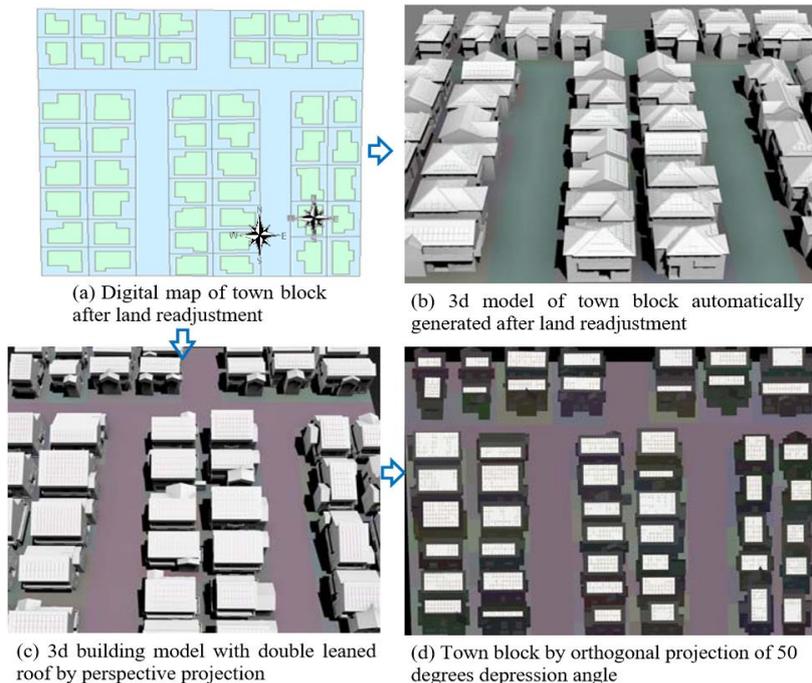


Figure 3. Digital map of town block after land readjustment, 3D town block model, 3D building model with double leaned roof automatically generated, and image by orthogonal projection of various degree depression angles

Since the panels' solar power generation is decided by the panel area of the component perpendicular to the sunshine, we have investigate how the solar power generation varies according to the land rezoning and the shape of the houses by calculating the area of the perpendicular component of panels. *Figure 4* shows ratios of the perpendicular component of the panel

area to the total area before and after land rezoning and the changing of the shape of the houses, i.e., double leaned roof structure or not. This numerical experiment for the virtual city block reveals that the shape of the houses, rather than the land readjustment, has a major impact on the solar power generation.

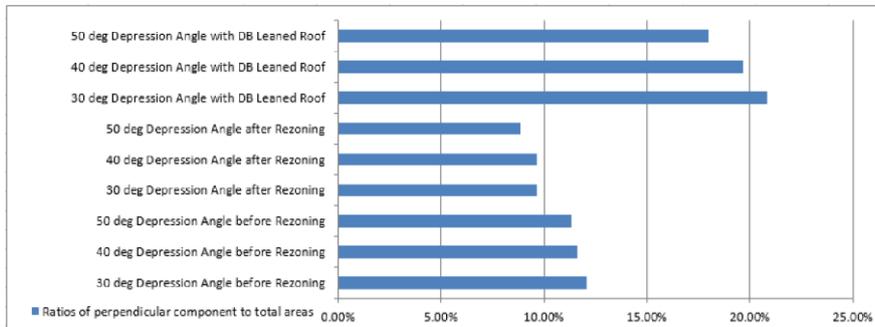
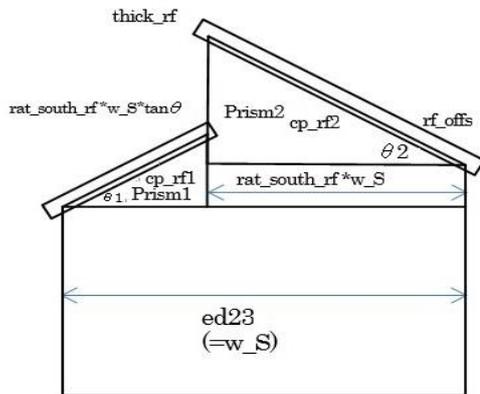


Figure 4. Ratios of perpendicular area component of panels to total area before & after land rezoning, and whether leaned roof structure or not

4.2 Automatic Generation of a 3D Model with Double Leaned Roof

A complicated orthogonal polygon can be partitioned into a set of rectangles. The proposed integrated system partitions orthogonal building polygons into a set of rectangles and places rectangular roofs and box-shaped building bodies on these rectangles, which will be used as a floor plan. A double leaned roof house consists of two leaned roofs. These houses are formed by placing two roof boards, the under roof construction (prism), and a house body, depending on the side view (Figure 5) and top view (Figure 6).

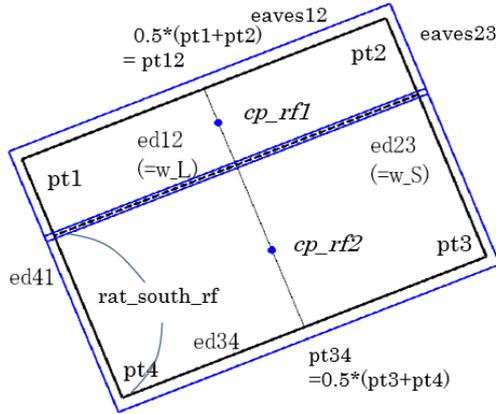


The width of south facing roof board (wid_rfb) is
 $wid_rfb = side23L + eaves23 + rf_offs \times \tan \theta$
 Here, $side23L$ is $side23L = rat_s_rf \times w_S \times \sqrt{1 + \tan^2 \theta}$
 'thick_rf' is the thickness of roof boards. 'eaves23' is the length of eave along $ed23$ direction. θ is the angle of gradient of a roof board.
 'rf_offs' is the offset of a roof board from under roof construction.
 * The height of south facing roof board (hei_rf) is as follows:
 $hei_rf = st_heit - rat_south_rf \times \tan \theta \times w_S - 0.5 \times wid_rfb \times \sin \theta - thick_rf \times \cos \theta + rf_offs \times \cos \theta$
 Here, 'st_heit' is the height of the building body.

Figure 5. Side view for double leaned roof, the position of the control point of two roof boards

The placing of these parts of a building is implemented in the following steps. After measuring the length and the direction of the edges of the partitioned rectangle, the edges are categorized into a long edge (w_L) and a short edge (w_S). The vertices of the rectangle are numbered clockwise with the upper left vertex of a long edge being numbered 'pt1' as shown in *Figure 6*. In a Constructive Solid Geometry (CSG) representation, we use volumetric primitives for the creation of 3D models. Each building part or primitive has its own control point ('cp') and local coordinates that control its position and direction. The position of a 'cp' is different in each primitive. As shown in *Figure 6*, for placing building parts properly, their 'cp' is positioned at the point that divides edge12 and edge23 at an appropriate ratio. For example, a prism is used for the construction under roof boards. The 'cp' of a prism lies in one of the vertices of the base triangle in an upright position when a prism is newly created.

The top of a double leaned roof consists of two roof boards (two thin boxes). Since the 'cp' of a box lies in a center of a base, it is placed on the point that divides the line through pt12 and pt34 at the ratio shown in the ground plan (*Figure 6*). The heights of the 'cp' of two roof boards are shown in the side view of a double leaned roof (*Figure 5*).



$$\text{ratio}_s = 0.5 \times (1.0 - \text{rat_south_rf})$$

$$\frac{0.5 \times (\text{eave23} \times \cos\theta + \text{rf_offs} \times \sin\theta)}{w_S} + \frac{\text{thick_rf} \times \sin\theta}{w_S}$$

$$\text{cp_rf1} = (1.0 - \text{ratio}_s) \times \text{pt12} + \text{ratio}_s \times \text{pt34}$$

$$\text{cp_rf2} = \text{ratio}_s \times \text{pt12} + (1.0 - \text{ratio}_s) \times \text{pt34}$$

* Here, 'rat_south_rf' is the ratio of width of south facing roof to the width of a rectangle. 'thick_rf' is the thickness of roof boards. 'eaves23' is the length of eave along ed23 direction is the angle of gradient of a roof board. 'rf_offs' is the offset of a roof board from under roof construction.

Figure 6. Floor plan for double leaned roof, the position of the control point of two roof boards

To have a larger south facing roof and to get more solar power generation, the ratio of the width of the south facing roof (rat_south_rf) will be increased. The slope of two leaned roofs are given independently so that the system freely creates this type of roof, since the slope of the roof is also an important factor for solar power generation. The width and slope of two leaned roofs will decide the height of the top line of these roofs. If the difference in height between these top lines is greater than a certain length, then the prism (under roof construction) will be in the Boolean operation to

have holes for windows, and windows will be installed between two leaned roofs as shown in *Figure 7*, which is the city block full of double leaned roof houses automatically generated after land readjustment.



Figure 7. 3D building models with double leaned roof automatically generated after land readjustment

4.3 Automatic Generation of a Hip Roofed House with Panels

A hip roof is a type of roof where all sides slope downwards to the walls, usually with a fairly gentle slope (en.wikipedia.org/wiki/hip_roof). Thus it is a house with no gables or other vertical sides to the roof. A square hip roof is shaped like a pyramid. Hip roofs on houses could have two triangular sides and two trapezoidal ones. A hip roof on a rectangular plan has four faces. They are almost always at the same pitch or slope, which makes them symmetrical about the centerlines.

In our system, parameters for hip roof formation are the angle of the roof slope (α) and the ratio of the top ridgeline to the long edge of the rectangle floor plan (r_{hip_top}) as shown in *Figure 8*.

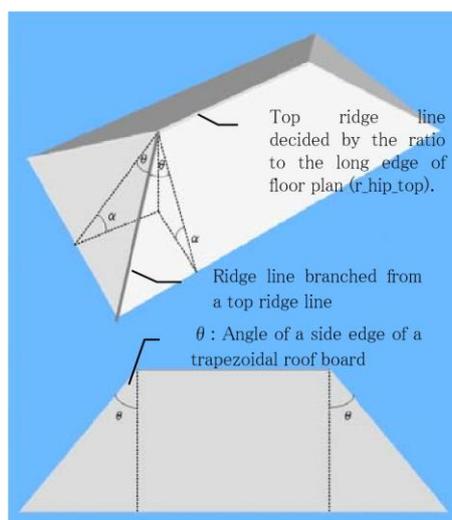


Figure 8. The slope of the roof (α) and angle (θ) of a side edge of a trapezoidal roof board

Since, in most cases, the number of tiles from a branch ridge down to two boundaries (*ed14* and *ed23*) is the same, a branch ridge line will be a bisector

of each corner of a rectangle in a top view. Then, the following relational expression is established.

$$\tan \theta = \frac{0.5 * (1 - r_{hip_{top}}) * w_L}{side23L} = \frac{0.5 * w_S}{side23L} = \frac{0.5 * w_S}{0.5 * w_S / \cos \alpha} = \cos \alpha$$

Here, w_L is a long edge and w_S is a short edge of a rectangle of a ground floor. $side23L$ is the height of the trapezoidal roof board:

$$side23L = 0.5 * w_S * \sqrt{1 + \tan^2 \alpha}$$

Usually,

$$r_{hip_{top}} = \frac{w_L - w_S}{w_L}$$

Then,

$$\tan \theta = \cos \alpha$$

Figure 9 shows the trapezoidal roof board of a hip roof is overlaid by an array of solar panels. Panels are placed, depending on the angle of a bottom corner of a trapezoid.

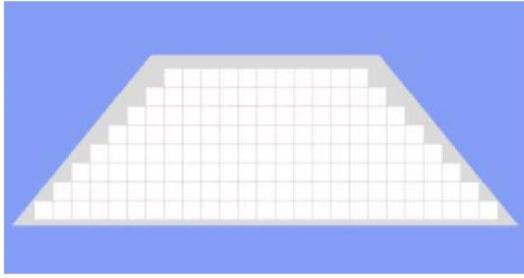


Figure 9. Trapezoidal roof board overlaid by solar panels

5. CONCLUSIONS

To facilitate public involvement for sustainable development, 3D models simulating real or near future cities using 3D CG can be of great use. 3D city models are important in environmentally friendly urban planning that will use solar photovoltaic (PV) generation. However, enormous time and labour has to be consumed to create these 3D models, using 3D modelling software such as 3ds Max or SketchUp. For example, when manually modelling a house with roofs by Constructive Solid Geometry, one must use the following laborious steps: (1) Generation of primitives of appropriate size, such as box, prism or polyhedron that will form parts of a house, (2) Boolean operations are applied to these primitives to form the shapes of parts of a house, such as making holes in a building body for doors and windows, (3) Rotation of parts of a house, (4) Positioning of parts of a house, and (5) Texture mapping onto these parts.

In order to automate these laborious steps, we proposed a GIS and CG integrated system that automatically generates 3D building models, based on building polygons or building footprints on digital maps, which show most buildings' polygon edges meet at right angles (orthogonal polygon). A complicated orthogonal polygon can be partitioned into a set of rectangles. The proposed integrated system partitions orthogonal building polygons into a set of rectangles and places rectangular roofs and box-shaped building bodies onto these rectangles.

In this paper, for placing solar panels on the hipped roof, the structure of an ordinary hipped roof that is made up of two triangular roof boards and two trapezoidal ones has been clarified. To implement efficient PV generation, this paper has proposed to automatically generate 3D building models topped with double shed roofs overlaid by PV arrays. The sizes and positions, slopes of roof boards and main under roof constructions are made clear by designing the top view and side view of a double shed roofed house. For the applied example of the developed system, the solar photovoltaic generation change of a city block has been simulated by performing land readjustment and changing the shape of buildings, ordinary roofed houses or double shed roofed houses suitable for efficient PV generation. This simulation reveals that double shed roofed houses have greatly improved solar photovoltaic generation.

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