3D Generalization of Boundary Representation (B-Rep) of Buildings

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Key words: B-Rep, generalization, simplification

SUMMARY

Different organizations, users or applications demand different levels-of-detail (LoDs) of generalized buildings. Enhancement of relevant information and suppression of irrelevant information based on the applications or the user's demand is still subject to the research. Therefore, the size and shape of generalized models varies due to differences and incompatibility of data sets (models); generalization operators and rules. This shows that outcome of generalization strategies can be influenced by the type of input data model, generalization process (operation) and the intended LoD. Characteristics of spatial models and building blocks, based on which certain generalization strategy operate need to be specified. In this paper, generalization of 3D buildings represented as boundaries out of three categories of 3D representation: cell models; Constructive Solid Geometry (CSG); and boundary representations (B-Rep) is carried out. Additionally, characteristics and compatibility of 3D city models with certain generalization strategy, 3D representation and visualization standard for output, types of building models and level-of-details (LoDs) are taken into consideration. Results show that 3D generalization of B-Rep of buildings is simple and straight forward. Furthermore, reduction of data volume based on self-perceptual rules, generalization operators can affect size and shape of generalized objects and neighboring segments.

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1. INTRODUCTION

Automatically, lower LoD can be generated from higher LoD of 3D models by reducing data volume and storing generalized LoDs in multiple representation data structure but main characteristics of the building have to be preserved (Mao *et al.*, 2011). Technically, pre-requisites of 3D generalization are: methods to automatically generate different level of details (LoDs); multiple representations of LoDs; and functionalities to automatically select the optimal LoD for a given application; they have to be met to automate the generalization process with the aim of analyzing building models in different scales (Baig et al. 2013). However, many researchers have proposed generalization algorithms for individual cartographic operations to generate different LoDs. A number of existing generalization algorithms for 3D building models by different researchers fulfill the first generalization pre-requisite specifically to generate different LoDs. Some researchers proposed algorithms to fulfill the second pre-requisite using CityGML specification but still an efficient approach to reduce complexity of 3D buildings on demand and on-the-fly is subject to 3D generalization research.

Generalization strategy is designed based on geographic features of cities, which are abstractions of real world objects (Kolbe 2009). However, humans have spatial observation in 2D and 3D while computer does not. Therefore, geometric data is defined in one of three dimensions such as a single point (0-dimensional), lines (1-dimensional), areas (2-dimensional) and volumes (3-dimensional) in space. In GIS (Geographic Information System), a series of fundamental geometric primitives are used to represent city objects in a 2D or 3D space. These primitives include point (node), line (edge), and polygon (face). Node or point is fundamental building-block of city objects which can be described as end location of an edge. Points are described and stored with two numbers (x, y) coordinates in 2-dimensional space. While in 3D Euclidean space, every point can be determined by a triple coordinates (x, y, z) e.g. point cloud obtained from Terrestrial Laser Scanning or LiDAR etc. A line is a 1D shape that links two points with coordinates by a direct path therefore it is considered as a simplest type of segment. Volumetric geometries of 3D city models (e.g. buildings, trees, lampposts, etc.) are modeled using geometric primitives (points, edges, faces) and surfaces or solids is bounded by a closed surface.

Degeneration of 3D city models reconstructed from CAD drawings as generalization process is one of the earlier methods proposed by (Glander and Döllner 2007), (Kada 2007) and (Thiemann and Sester 2004). For this purpose, CAD drawings of 3D buildings are separated from 3D city models such as building models, lamp-posts, traffic light, and vegetations (trees). Based on dimensions of CAD drawings, geometries of the city objects are reconstructed / degenerated and arranged / re-arranged part by part. Out of generalization of such models can be exported into VRML / X3D or GML (Graphical Markup Language)

formats.
Generalization of 3D building models represented using three categories of 3D representation: cell models; Constructive Solid Geometry (CSG); and boundary representations (BRep) (Encarnação 1997) are different. Figure 2 shows a simple building is represented in three distinct representations (e.g. cell, CSG, and B-Rep). Location, size and shape of geometric features can be changed by applying certain generalization operations. For example, Euler operators are used to construct and generalize B-Rep models and they are not Computer-Aided Design (CAD)-type B-Rep. They are used to make or destroy or kill a number of vertexes, edges, faces, shell, and holes. These operators guarantee to preserve the connectivity during data modification.

In this paper, characteristics and compatibility of 3D city models, 3D representation, management and visualization standards, types of building models (e.g. structured geometry with and without semantics, etc.) are investigated. Additionally, generalization of 3D buildings represented as boundaries out of three categories of 3D representation: cell models; Constructive Solid Geometry (CSG); and boundary representations (BRep) is carried out.

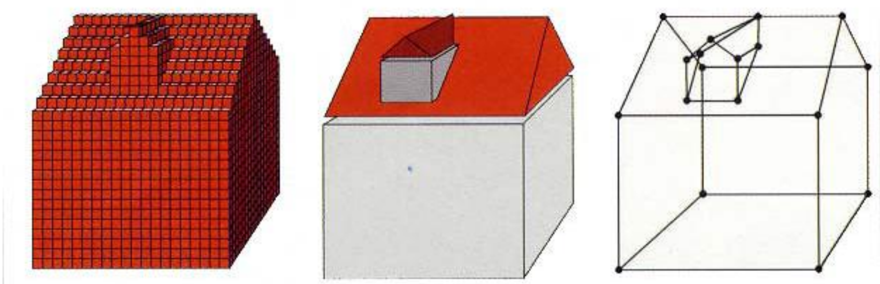


Figure 1. Modeling of a simple building model using cells (left), CSG (middle), and BRep (right) representations adopted from (Pfund 2002)

2. 3D MODELLING AND EXTRACTION

2.1 3D building Representation and Standards

Standards for presentation (visualization) and representation of 3D objects are different. KML (KML 2012) and Extensible 3D (X3D) are few of the examples of visualization standards while CityGM (Gröger et al. 2007) and Industry Foundation Class (IFC) (IFC 2009) are used for representation of 3D city models. But, (Kolbe 2009) at page 28 claimed that “CityGML is complementary to visualisation standards like X3D or KML”.
However, In April 2008, KML has been approved as a standard by OGC and described KML as an XML language focused on geographic visualization, annotation of maps and images. Additionally, KML is not designed for 3D visualization, it supports 3D model by COLLADA file (Mao 2010). X3D or Extensible 3D as ISO ratified open standard file format and runtime architecture proposed and managed by Web3D Consortium for representation and exchange of 3D city models(X3D 2012) Particularly, X3D is designed for visualization of 3D scenes in the Internet.
CityGML defines the concept of LoDs to represent different levels of details of buildings

(Gröger et al. 2007). It defines not only the shape and photo-realistic appearance of 3D building objects but also thematic properties, attached rich semantic information can also be stored in CityGML. These models are reconstructed and represented in different LoDs to be used for visualization purposes. There are two main advantages of CityGML. Firstly, components such as outer shell, openings (windows, doors), outer building installations, interiors (chair, table, fan etc) can be modeled, represented and stored in multiple LoDs. Secondly, generalization specifications provided for different LoDs are characterized by differing accuracies and minimal dimensions of objects. All object blocks as generalized features with ground plans of at least 6m x 6m have to be considered in LoD1 while 4m x 4m in LoD2. In the detailed model at LoD3, the minimal size of side of generalized object should be 2m x 2m. Simplification method described in next section follows these rules. But, CityGML doesn't provide any method to generalize LoDs automatically so needs to be done separately. Therefore, smaller components need to be simplified separately so that buildings at a certain LoD could be derived to be represented by an aggregate building at a lower LoD. Buildings modelled in CityGML are used for testing algorithms as part of this research.
Lastly, IFC is considered as neutral and open specifications, which facilitate interoperability in the building industry. This format is also being used commonly for Building Information Modeling (Eastman 2012).

It is important to distinguish different types of 3D city models with the aim to tailor generalization strategies. *Explicit* or *parametric* representations of the essential geometry of 3D city models are classified in (Guercke and Brenner 2009). The geometry is stored with the feature in *explicit models* so generalization strategies don't need to produce while the geometry is implicitly given through the parameters of the feature during generalization in *parametric models*. Following three types of 3D building models can be distinguished along with other models (Stadler and Kolbe 2007): geometric models without semantics; structured geometric models along with simple semantics; and structured geometric models along with rich semantics. Geometry models are purely geometric in nature and are modelled based on 3D graphic formats like X3D, KML, COLLADA or CAD format. Additionally, these models contain raw data or basic geometry which can be used for further data interpretations. Information such as meta-data cannot be represented along with geometry of buildings. However, these models are only useful only for visualization but not for representation of 3D city models so spatial analysis could not be carried out due to missing semantic information attached with city models. Geometry models with simple semantics e.g. name of the building which indicates only the existence of the building do not support further classification or decomposition based on semantics.
In geometry models with rich semantics, both, geometry and semantics are logically represented and linked on different LoDs so that relationship between geometry and semantic could be established. Structured geometry models with rich semantics comprised of ontological structure including thematic classes, attributes, and their interrelationships besides the spatial and graphical aspects (Kolbe et al. 2009). Such models are the most detailed thematic concept of CityGML (Gröger et al. 2007). An individual geometry representation is provided for each of the four levels of detail (LoD1 to LoD4). Structured geometric models along with rich semantics at different LoDs (LoD1 – LoD4) are presented in Figure 2.

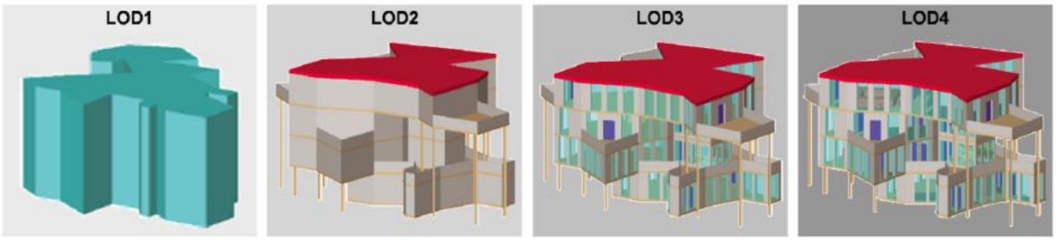


Figure 2. Examples of structured geometric models (Kolbe 2009) along with rich semantics at different LoDs (LoD1 – LoD4)

2.2 Extraction of B-Rep

Generalization of ground plans of buildings is one of the major parts of this thesis. CityGML schemas use the *groundsurface* type to define the ground plan of a building but it is necessary to find a method to create the ground plan from a simple surface set without any semantic information (Mao et al. 2011). The ground plan can be derived from the exterior shells of a building by projecting the wall on the ground and connecting the footprint into a closed polygon (Fan and Meng 2012). However, this method is based on the exterior shell generated by an algorithm which is quite complex and time consuming (Mao et al. 2011). This method is based on point clouds produced by converting walls from CityGML data set. In this method, average points of all centroids of the walls is represented as *Mi* = [*Mx* ,*My* ,*Mz*]*i* for each wall is calculated while an adjusting plane F_i (plane with more than one walls) is derived using Equation 2.1 (Fan et al. 2009). Angle between two planes is observed and resulting polygons are preserved or deleted based on their orthogonal structure and parallelism. Distance from greater centroid is calculated and maximum distance polygons are considered to be exterior shell of each wall, which is preserved.

$$F_i := A_i x + B_i y + C_i y + D_i = 0 \qquad (2.1)$$

Where

F_i = Plane with more than one walls

D_i = represents the nearest distance of the plane to the origin of the coordinate system (x, y, z)

[A_i, B_i, C_i] are the normal vector of the plane F_i

Each polygon which belongs to the same wall at a plane is calculated by providing the coordinates of all its vertices in the Equation 2.1 as input. Thus, the angle θ_{ij} between the planes can be derived by applying Equation 2.2 (Fan et al. 2009).

$$\theta_{ij} = \arccos\left(\frac{A_i A_{ij} + B_i B_{ij} + C_i C_{ij}}{\sqrt{A_i^2 + B_i^2 + C_i^2} * \sqrt{A_{ij}^2 + B_{ij}^2 + C_{ij}^2}}\right) \qquad (2.2)$$

Similar method is used to extract the exterior shell of roof structures. Plane is computed for each roof polygon. Those polygons which are orthogonal to ground plan are deleted and the remaining polygons are categorized into a number of clusters based on their position and orientations. Distances from greater centroid is calculated for each cluster thus maximum distance value specifies the polygons representing the exterior shell of roof and wall. Maximum distance is calculated with Equation 2.3 (Fan et al. 2009).

$$d_{m.ij} = \frac{|A_{ij}\ .\ X_m + B_{ij}\ .\ Y_m + C_{ij}\ .\ Z_m|}{\sqrt{A_{ij}^2 + B_{ij}^2 + C_{ij}^2}} \qquad (2.3)$$

Smaller components e.g. windows, doors of each wall are projected and reduced to planes on their exterior shell. Geometric characteristics of windows and doors within the wall are preserved by projecting them onto the exterior or outer shell using following Equation (2.4) (Fan et al. 2009).

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} projection = \begin{bmatrix} x_{wd} \\ y_{wd} \\ z_{wd} \end{bmatrix} + \left[-D_i^{ex} + (A_i^{ex}\ \ B_i^{ex}\ \ C_i^{ex}). \begin{bmatrix} x_{wd} \\ y_{wd} \\ z_{wd} \end{bmatrix} \right] . \begin{bmatrix} A_i^{ex} \\ B_i^{ex} \\ C_i^{ex} \end{bmatrix} \qquad (2.4)$$

In order to model a simple wall without any opening in LoD3, at least six polygons are required. Therefore wall, windows as well as door in LoD3 are modelled as cuboid presented in Figure 3.

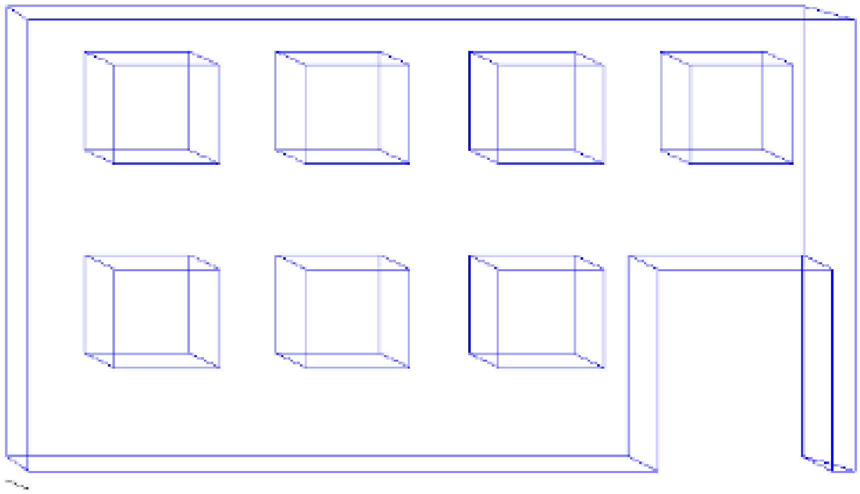


Figure 3. Windows, walls and doors are modeled as cuboid (Fan and Meng 2009).

2.3 Establishment of Topological Relationship

Only vertices of building exteriors are separated from these source files (CityGML datasets). A topological relationship is established between B-Rep of buildings and their corresponding vertices. For this purpose, two tables (e.g. B-Rep and vertices) are linked to each other shown in Figure 4.

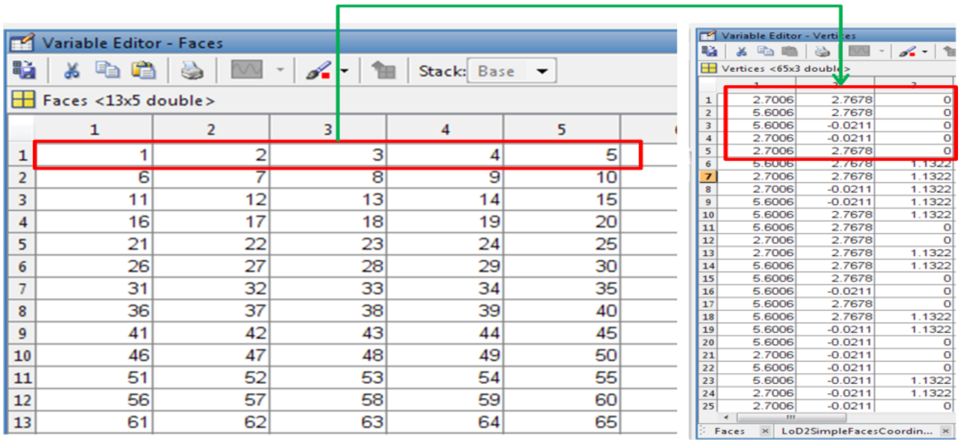


Figure 0. A topological relationship is established between boundaries of B-Rep (left) and their corresponding vertices (right)

Based on these vertices, the edges are generated to be used for simplification and aggregation purposes. Boundaries of buildings at LoD3 without windows and doors along with roof structures are projected onto the horizontal ground plan. However, the geometry in a CityGML data set in the form of nodes of surfaces can also be used.

In order to project extracted surfaces onto the ground, ‘z’ or elevation values of each node are removed. Roof structures are projected onto the ground while avoiding distortion in orientation, length and width of surfaces. The wall surfaces for most of the buildings are multi-polygons. Filling gap approach is applied to join two projected polygons with the aim to form a single large polygon. Empty space between two points, lines or areas may be produced due to projection onto the ground. This gap is filled by inserting additional vertices or points. Interpolation methods such as ‘rhumb’, great circle and ‘linear’ interpolation are few of valid interpolation methods being practiced to fill the gap between vector data coordinate points, lines and polygons. In order to fill the gap between two polygons, we used interpolation method and produced new latitude for a specified longitude. The longitudes must increase or decrease monotonically. The methods returns interpolated points that lie on the line and circles between input data. These interpolation method results in Linear or Cartesian between the numerical values entered (lat1, lon1) and (lat2, lon2). Linear data points can also be generated from interpolated points in reverse order. Figure 5 shows an illustration of projection of surfaces of a simple building onto the ground and reconnecting into a single polygon. The projection of flat roof outline and the ground plan are enclosed within each other.

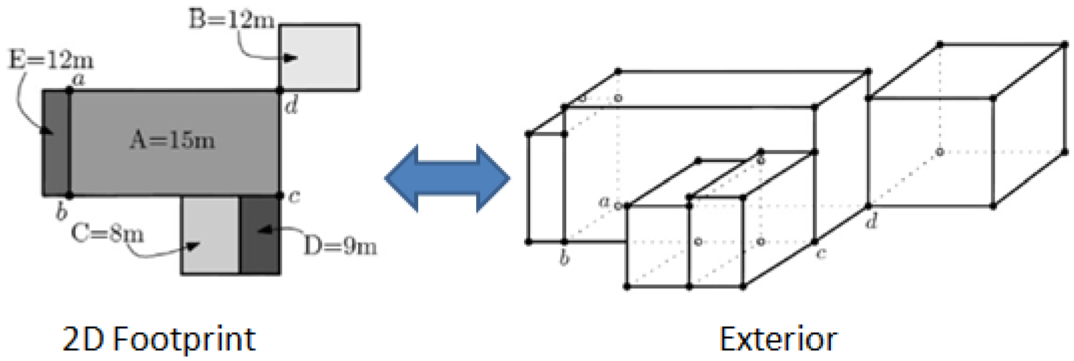


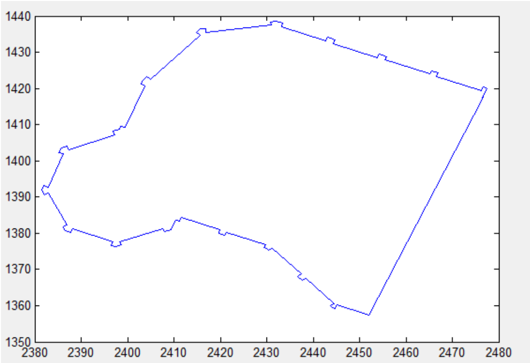
Figure 5. Building footprint and boundary representation (B-Rep) of outer shell of five buildings with flat roof adapted from (Gröger et al. 2012)

3. SIMPLIFICATION OF B-Rep

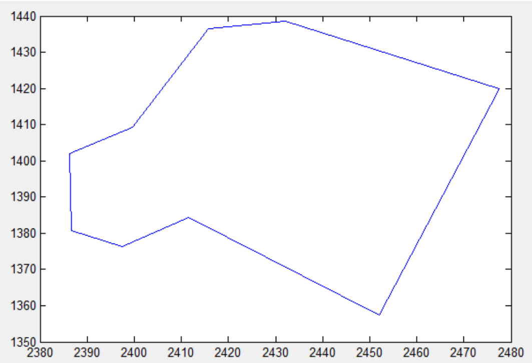
Elimination of insignificant curves, corners, and edges of B-Rep is one of important operations of generalization process. B-Rep of building is composed of a set of points in its closure without the interior points (Yevgeniya et al. 2009). The shape of the B-Rep can be considered only by its boundary and is represented by two-dimensional polygons. Polygons of walls, doors, windows and roofs can be projected onto the ground to draw their respective B-Reps in 2D space. The B-Rep of ground floor represents a bottom-most floor used to specify on the ground floor geometry while the B-Rep of the roof floor is independent of the ground floor plan.

The fundamental criteria to remove / adjust potential edges and polygons are still subject to the research. Simplification of edges of extrusion / intrusion and off-set was implemented and edges shorter than threshold value (t) were removed from B-Reps. For this purpose, methods proposed for removal/adjustment of shortest edge Sester and Brenner (2004); (Fan and Meng 2009; Mao et al. 2011; Fan and Meng 2012) and (Baig and Rahman 2013a) can be applied to simplify ground plans. An adoption of methods of Sester and Brenner (2004) (*Continuous generalisation for visualisation on small mobile devices*. Heidelberg, pp. 355–368, 2004) extended by Fan et al. (2009) (Lecture Notes in Geoinformation and Cartography, Advances in Giscience. Springer, Heidelberg, pp. 387–405, 2009) are modified to tailor based on different combination of adjustment of edges. For this purpose, before simplification process starts, length of each edge is calculated based on x and y coordinates of nodes applying Euclidian distance and temporarily stored in a variable. The length of each edge is tested to determine the shortest edge shorter than the tolerance (t) provided by a user through GUI. The length, position and association of neighbouring longer edges are determined. This process provides enough information, which edges should be extended and in what direction. The same process is applied in two iterations to remove asymmetrical edges similar to (Baig and Rahman 2013b). Coordinates of nodes of simplified polygons are stored in arrays to be used for reconstruction of building models.
Methods to eliminated intrusion / extrusion and offset were tested on footprint of a single building named *Jabatan Pendaftaran Negara (JPN), Putrajaya* city of Malaysia. Simplification algorithm was tested for 5m as threshold. However, the size and shape of

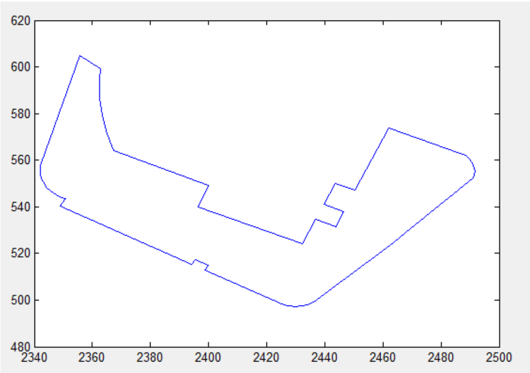
generalized surface depends on the threshold value (t=5m, 10m, 15m, etc.) value provided by user. Figure 6 shows the result of simplification of B-Rep of footprints of two buildings based on multiple parameters (t=5, 10, 15).



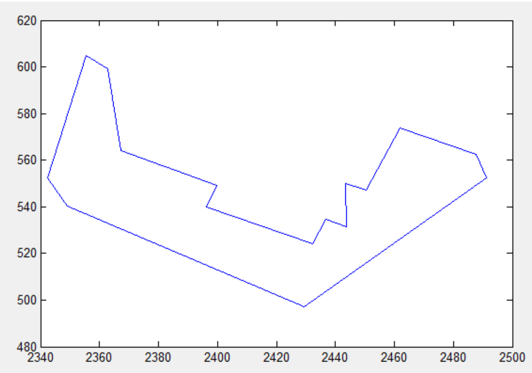
(a)



(b)



(c)



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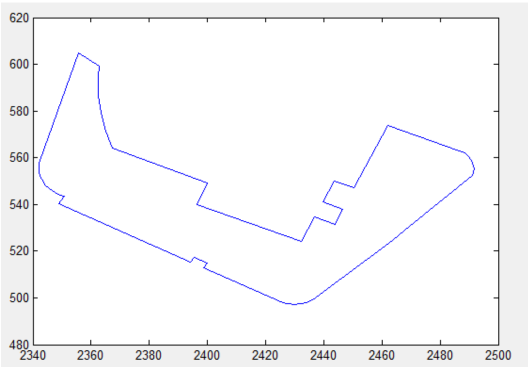
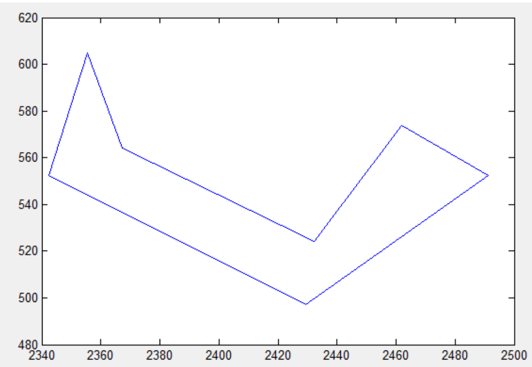


(e)



(f)

Figure 6. Result of simplification of B-Rep of building footprints: (a) original footprint (b) simplified at (t=5), (c) original footprint, (d, e) simplified footprints at (t=5 and t=10)

4. CONCLUSION AND DISCUSSION

The main focus of this paper was simplification of buildings represented as boundaries. For this purpose, new approaches are implemented to restrict number of edges, curves, and corners of ground plan of 3D building model on a certain LoD. Simplification of intrusion / extrusion, offset and corners was implemented and edges shorter than threshold value (t) were removed from ground plans by adopting methods proposed by Sester and Brenner (2004); (Fan and Meng 2009; Mao et al. 2011; Fan and Meng 2012) and (Baig and Rahman 2013a). The algorithms for derivation of LoD1 and LoD2 were tested for a small dataset containing 19 buildings at *Putrajaya* city of Malaysia.

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BIOGRAPHICAL NOTES

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