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3D Topological Validation of Compact Abstract Cell Complexes (CACC) Data Structure for Buildings in CityGML

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ABSTRACT

3D models without the preservation of 3D topological information hinders the ability of 3D models to serve its full potential in terms of 3D analyses. The support of 3D topology is crucial for analyses that requires information regarding adjacencies and connectivity. One of the ways to maintain topological information is by implementing a topological data structure such as the Compact Abstract Cell Complexes (CACC) topological data structure. This paper demonstrates the topological validation for the implementation of the CACC topological data structure for buildings in LoD2 CityGML. Directed graphs and adjacency matrices were constructed for the test datasets of buildings in CityGML. The in-degree and out-degree for all vertices were calculated based on the adjacency matrices. Based on the "Hand-shaking" theorem, the number of α_0-cycles of the CACC topological data structure which connects points to form 1D topological links was compared to the number of directed edges of the constructed directed graphs. Therefore, the implementation of the CACC topological data structure for buildings in LoD2 CityGML was found to be topologically sound.

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1. Introduction

One of the objectives of conveying information is to ensure the users' understanding regardless of the users' different backgrounds of knowledge. In the field of geoinformation, the manner in which the real world is represented is important to provide information that meets the requirements of the user or applications. A city is also known as an urban system of urban structures which is modelled or represented as a city model. A city model is defined as a representation of the urban structures and spatial properties that depicts the actual city (Billen et al., 2014). A city can be represented as a 3D city model or 2D representation. Generally, a representation of the real world (city) in 2D refers to a representation that is bounded by x and y coordinates. A few examples of 2D representations are maps, plans and computer-aided drawings (CAD). On the other hand, 3D city model or also known as virtual reality urban modelling represents cities with x, y and z coordinates. A 3D city model can also be defined as a model which represents a city with the usage of 3D spatial information as well as semantic information within a single framework (Chen, 2011). This allows the representation of a city as a 3D city model which is a mirrored image of the actual city but in a virtual environment. Therefore, a 3D city model is able to provide realistic simulations and accurate information for various applications such as cadastre, urban planning and navigation.

Given the many applications that may benefit from the use of a 3D city model, an international standard and open data model for 3D city modelling was introduced. CityGML is an international standard and open data model for 3D city modelling which was established by the Open Geospatial Consortium (OGC) (Gröger & Plümer, 2012). The development of CityGML was targeted to be a shared definition of entities, attributes and relationships within a 3D city model (Kolbe, 2009). CityGML encompasses five main aspects of a complete 3D city model which are 3D geometry, semantics, scale or level-of-detail (LoD), appearance and topology. The first aspect which is 3D geometry refers to the geometric properties of the features which is based on the Geographic Markup Language (GML) standard. Next, the semantics aspect deals with the semantic information or attributes of the features. The third aspect allows multiresolution modelling which represents the scale as LoDs where the coarsest LoD is LoD0 and the finest LoD is LoD4. The fourth aspect which is appearance handles how CityGML displays the 3D city model in terms of textures which differentiates between surfaces or facades. The final aspect is topology which refers to the mechanism used within CityGML to store topological properties of the 3D city model.

The real world is considered as a space or topological space whereby an object resides in the space. Kumar (2014) defined a natural geographic situation as a set {G, F, R} where G and F are two features and R is the relation between G and F. Topology can be defined as the adjacencies between objects residing in a space (McDonnell & Kemp, 1995). This means that topological properties of an object are properties that remain unchanged despite transformations of the space and define the qualitative properties of the object in terms of relationships to other objects. The way objects are related can also be described at a geometric level which describes the topology, projective geometry and Euclidean geometry (Clementini, 2019). Hence, a topological model can be defined as a schema which specifically represents the topological properties and relationships of spatial features (Ghawana et al., 2012; Lee & Kwan, 2005). In terms of city modelling, a city can be topologically represented as the adjacencies of objects. As a single building, the relations between building elements are able to describe the connectivity of building elements and the function of the building (Krämer & Huhnt, 2009; Xie et al., 2013). In order to maintain consistency and connectivity of elements in an object, a comprehensive 3D topology is required (Ellul, 2007). Furthermore, analyses involving exploration of building elements also requires a comprehensive preservation of topological properties (Isikdag et al., 2013; Hyeyoung et al., 2009). 3D topology is also required to support analysis which yields results in 3D as a 2D topology is will ultimately deliver results in 2D (Ellul & Hakley, 2006). Topological properties are able to support analyses such as adjacencies, intersections, connectivity, containment and disjointedness (Li et al., 2016). These analyses may appear simple yet supports more complex applications such as navigation and simulations (Salleh et al., 2018). The topological component of CityGML as the international standard for city modelling does not employ the topological model by GML3. This is due to the complexities of the topological model which will complicate the data model and physical entities within the CityGML model (Gröger & Plümer, 2012; Kolbe, 2009).

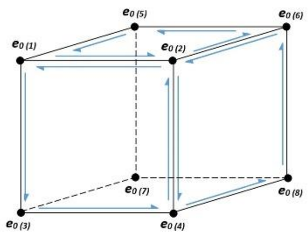
Generally, topology for city modelling can be divided into two subdivisions which are 2D topology and 3D topology. The type of topology currently used in CityGML is a 2D topology which is the topology-incidence (Li et al., 2016a). This topology is based on the relationships of surfaces whereby if an incidence occurred between two surfaces; the surfaces will be referenced to each other. The topological primitives approach is a 3D topology which maintains topological properties of features using the basic topological primitives similar to geometric primitives. This is different for the cell-based approach and boundary representation approach where the topological properties of features can be maintained based on the boundary of the features. However, none of these approaches were utilised in the maintenance of topology within CityGML.

The topological component of CityGML provides information regarding to related building elements in the form of simple relations such as doors belonging to rooms or building parts that make up a building. However, the topological component of CityGML does not support direct retrieval of topological relationships (Rook et al., 2016). This simple topological information is insufficient for topological analysis regarding 3D adjacencies and nearest neighbour (Ujang et al., 2019). The method of establishing topology by incidence can only be done with the explicit representation of the common surface as an individual geometry (Li et al., 2016). This is due to the inability of CityGML to support topological primitives and effectively build 3D topology (Boguslawski et al., 2011; Li et al., 2016). Moreover, this disadvantage also hinders the preservation of relationships between topological primitives in different dimensions (Ghawana et al., 2012).

This paper attempts to topologically validate a CACC topological structure implemented for buildings in CityGML. The CACC topological data structure is briefly explained in Section 2. The methods used for the topological validation is elaborated in Section 3. Subsequently, the results are presented in Section 4 which includes the topological validation results and a brief comparison of connectivity capabilities between the CACC topological data structure and existing CityGML topological mechanism. Finally, the paper is concluded in Section 5.

2. Compact Abstract Cell Complexes (CACC) Topological Data Structure

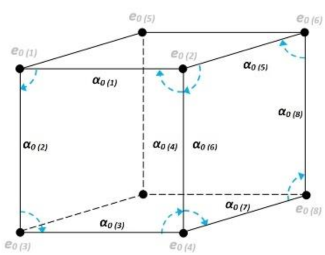
The topological data structure implemented in this study is the Compact Abstract Cell Complexes (CACC) data structure. This structure employs a compact yet abstract method of storing topology in which the topology is not limited to the bounds of a geometric space (Ujang et al., 2014). Moreover, CACC was found to be the most compact method of storing topological information in comparison to other topological data structures such as dual half-edge (DHE), cell tuple, G-Maps and others (Ujang et al., 2014). The concept of the CACC data structure which stores topology as atomic cycles made up of deconstructed parts of cycles allows navigation through the cycles. Each dimension is represented by a different cycle such as 0D points are connected to 1D edges in α_0-cycles, 1D edges are connected to form 2D faces in α_1-cycles, 2D faces are connected to form 3D volumes in α_2-cycles, and connectivity between volumes are represented as α_3-cycles (Ujang et al., 2014). Figure 1 depicts α_0-cycles as the blue markers which details the paths of 1D edges via 0D vertices.



α_0-cycles	Paths
$\alpha_{0(1)}$	$e_{0(2)}$ -> $e_{0(1)}$
$\alpha_{0(2)}$	$e_{0(1)}$ -> $e_{0(3)}$
$\alpha_{0(3)}$	$e_{0(3)}$ -> $e_{0(4)}$
$\alpha_{0(4)}$	$e_{0(4)}$ -> $e_{0(2)}$
$\alpha_{0(5)}$	$e_{0(6)}$ -> $e_{0(2)}$
…	…
$\alpha_{0(24)}$	$e_{0(8)}$ -> $e_{0(7)}$

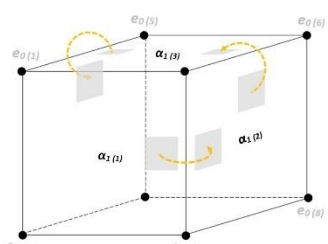
Figure 1 α_0-cycles and its paths (Ujang et al., 2014)

Figure 2 shows α_1-cycles that represents paths of connected 1D edges previously stored as α_0-cycles to form 2D faces. Meanwhile, the α_2-cycles are depicted in Figure 3 as paths between connected 2D faces previously stored as α_1-cycles to form 3D volumes.



α_1-cycles	Paths
$\alpha_{1(1)}$	$\alpha_{0(1)}$ -> $\alpha_{0(2)}$ -> $\alpha_{0(3)}$ -> $\alpha_{0(4)}$
$\alpha_{1(2)}$	$\alpha_{0(5)}$ -> $\alpha_{0(6)}$ -> $\alpha_{0(7)}$ -> $\alpha_{0(8)}$
$\alpha_{1(3)}$	$\alpha_{0(1)}$ -> $\alpha_{0(5)}$ -> $\alpha_{0(9)}$ -> $\alpha_{0(10)}$
…	…
$\alpha_{1(6)}$	$\alpha_{0(3)}$ -> $\alpha_{0(7)}$ -> $\alpha_{0(24)}$ -> $\alpha_{0(23)}$

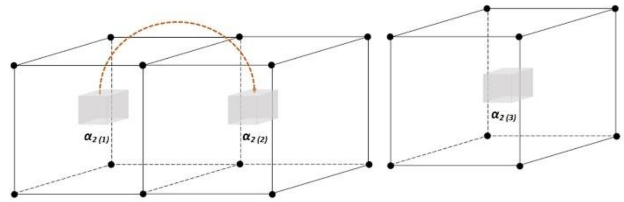
Figure 2 α_1-cycles and its paths (Ujang et al., 2014)



α_2-cycles	Paths
$\alpha_{2(1)}$	$\alpha_{1(1)}$ -> $\alpha_{1(2)}$ -> $\alpha_{1(3)}$ -> $\alpha_{1(4)}$ -> $\alpha_{1(5)}$ -> $\alpha_{1(6)}$

Figure 3 α_2-cycles and its paths (Ujang et al., 2014)

In addition, the adjacencies of 3D volumes are also represented by α_3-cycles as connectivity between 3D volumes as depicted in Figure 4.



α_3-cycles	Paths
$\alpha_{3(1)}$	$\alpha_{2(1)}$ -> $\alpha_{2(2)}$

Figure 4 α_3-cycles and its paths (Ujang et al., 2014)

The cycles of lower dimensions which act as the building blocks for higher dimension cycles ultimately provides support for connectivity across cycles and dimensions (Ujang et al., 2014). This also supports the traversing through connected elements in a 3D model which as a result also describes topological relationships between elements (Ujang et al., 2014). That being so, the retrieval and preservation of information regarding the connectivity of elements in a 3D model is also supported. Consequently, the preservation of topological information using the CACC data structure requires minimal storage which is practical for applications which deals with both geometrical and topological properties (Ujang et al., 2014)

3. Methodology

As this paper focuses on the topological validation of CACC topological data structure, the procedures carried out to implement the CACC topological data structure are not detailed. The general methodology of the CACC topological data structure implementation for buildings in CityGML are shown in Figure 5.

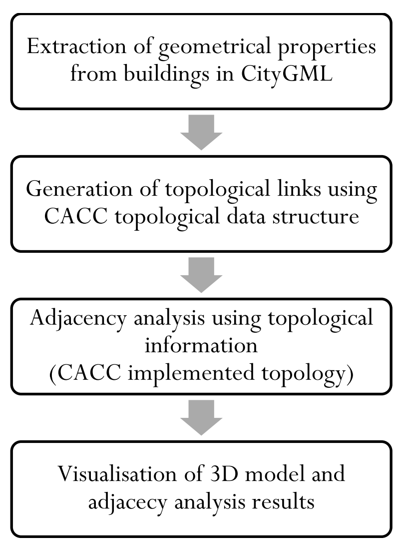


Figure 5 General methodology of CACC implementation for buildings in CityGML

In order to implement the CACC topological data structure for buildings in CityGML, the geometrical properties were extracted from the CityGML data. The geometrical properties included the points, lines and polygons which makes up the building in CityGML with the respective x, y and z-coordinates. The procedures executed to extract the geometrical properties are elaborated in Salleh and Ujang (2018). The geometrical properties act as a stand-in for the construction of CACC topological links explained in the previous section. The CACC topological data structure is implemented for buildings in CityGML by preserving comprehensive topological information in the form of CACC topological links. The construction of CACC topological links is detailed in Salleh et al. (2018). The topological information was used in the adjacency analysis which tested the connectivity of building elements using the CACC topological links and is elaborated further in Salleh, Ujang, Azri and Choon (2019).

The topological validation of the CACC topological links is pivotal in ensuring that the implementation of the CACC topological data structure for buildings in CityGML is topologically sound. The following section elaborates the methods carried out in validating the topology of the CACC topological data structure implemented.

3.1 Topological Validation of Implemented CACC Topological Data Structure for Buildings in CityGML

The topology of a structure can be represented as a directed graph or digraph which is homeomorphic to the structure. A digraph is defined as follows:

$$\vec{G} = (V, E, \eta) \quad (1)$$

where *v* is a vertex and *e* is an edge in the graph

$$v \in V$$
$$e \in E$$
$$\eta(e) = (v_i, v_j).$$

The equation above defines a digraph as a graph which consists of vertices, edges and edges with direction (η) which are ordered pairs of connected vertices. The ordered pairs can subsequently be used in an adjacency matrix which represents the connections of the digraph. Adjacency matrix is defined by Aldous and Wilson (2003) as follows:

Let G be a digraph with N vertices labelled $1,2,3,\ldots N$. The adjacency matrix A(G) of G is the $N \times N$ matrix in which the entry in row i and column j is the number of edges $N(\eta(e))$ joining the vertices (v) i and j.

The in-degree of a vertex can be defined as the number of directed edges where the specified vertex is the "head" of the edge. The in-degree of a vertex is denoted by the following equation:

$$d^-_{\vec{G}}(v_i) = N|\{e \in E : \eta(e) = (x, v_i) \text{ for some } x \in V\}| \quad (2)$$

As shown in the equation above, the in-degree of vertex i in a digraph is the number of edges such that the direction of the edge is going into the vertex i as the "head" of the edge. On the other hand, the number of directed edges of the direction that goes out of the specified vertex is defined as the out-degree of the vertex. The out-degree of a vertex is denoted by the following equation:

$$d^+_{\vec{G}}(v_i) = N|\{e \in E : \eta(e) = (x, v_i) \text{ for some } x \in V\}| \quad (3)$$

The equation above shows that the out-degree of vertex i in a digraph is the number of edges such that the direction of the edge goes out of the vertex i where vertex i is the "tail" of the directed edge. Based on the adjacency matrix, the total of in-degree and out-degree of a vertex can be calculated by:

$$\sum d^-_{\vec{G}} = \sum_{i=1}^{V} col_{v_i} \text{ and } \sum d^+_{\vec{G}} = \sum_{i=1}^{V} row_{v_i} \quad (4)$$

The total of in-degree of an adjacency matrix can be calculated by summing up the columns of the adjacency matrix while the total of out-degree of an adjacency matrix can be calculated by summing up the rows of the adjacency matrix.

4. Experiments and Results

The CACC topological data structure was implemented for buildings in CityGML, specifically buildings in LoD2. Two CityGML datasets were used where dataset A consists of two connected buildings and dataset B consists of two disjointed buildings as shown in Figure 6.

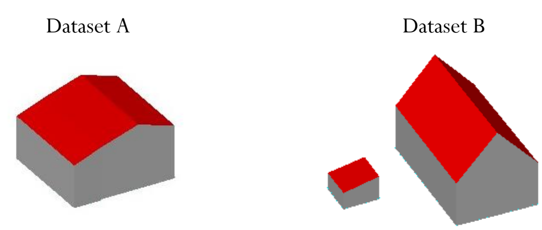


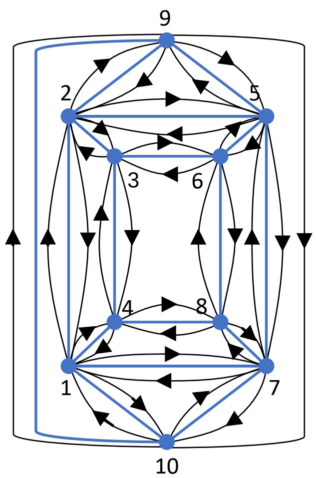
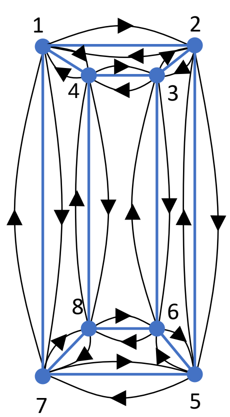
Figure 6 CityGML test datasets in LoD2

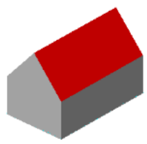
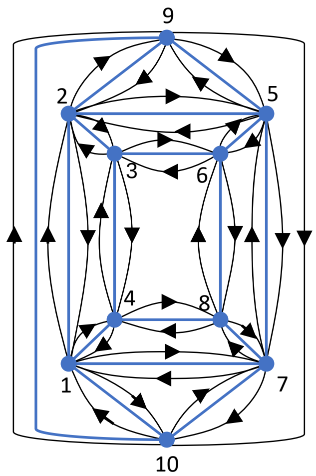
For the purpose of validating the topological information preserved for buildings in CityGML using CACC topological data structure, two simple cases of connected and disjointed buildings were used. This is parallel to the findings of Knoth, Atazadeh and Rajabifard (2020) whereby the key significant spatial relations of 3D buildings are 3D buildings can share boundaries (connected) and 3D buildings cannot penetrate each other (disjoint).

4.1 Topological Validation

Directed graphs and adjacency matrices were constructed for both datasets and are illustrated in Table 1. The arrows represent the topological connection between points of the buildings in CityGML which are based on the CACC topological links generated for the two datasets.

Table 1 Directed graph representation and adjacency matrix of buildings in LoD2 CityGML

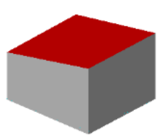
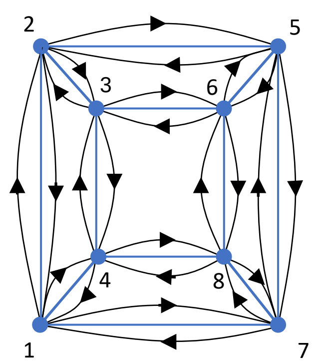
<table>
<tr><th>Building</th><th>Building Visualisation</th><th>Digraph Representation</th><th>Adjacency Matrix</th></tr>
<tr><td rowspan="2">Dataset A: Connected Buildings</td><td></td><td></td><td>$$\begin{array}{c} \\ v_1\\ v_2\\ v_3\\ v_4\\ v_5\\ v_6\\ v_7\\ v_8\\ v_9\\ v_{10}\end{array}\begin{array}{c} \begin{array}{cccccccccc} v_1 & v_2 & v_3 & v_4 & v_5 & v_6 & v_7 & v_8 & v_9 & v_{10}\end{array}\\ \begin{bmatrix} 0&1&0&1&0&0&1&0&0&1\\ 1&0&1&0&1&0&0&0&1&0\\ 0&1&0&1&0&1&0&0&0&0\\ 1&0&1&0&0&0&0&1&0&0\\ 0&1&0&0&0&1&1&0&1&0\\ 0&0&1&0&1&0&0&1&0&0\\ 1&0&0&0&1&0&0&1&0&1\\ 0&0&0&1&0&1&1&0&0&0\\ 0&1&0&0&1&0&0&0&0&1\\ 1&0&0&0&0&0&1&0&1&0 \end{bmatrix}\end{array}$$
$\sum d_{\vec{G}}^{-} = \sum_{i=1}^{10} col_{v_i}$
$= 4 + 4 + 3 + 3 + 4 + 3 + 4 + 3 +$
$3 + 3$
$= 34$
$\sum d_{\vec{G}}^{+} = \sum_{i=1}^{10} row_{v_i}$
$= 4 + 4 + 3 + 3 + 4 + 3 + 4 + 3 +$
$3 + 3$
$= 34$</td></tr>
<tr><td></td><td></td><td>$$\begin{array}{c} \\ v_1\\ v_2\\ v_3\\ v_4\\ v_5\\ v_6\\ v_7\\ v_8\end{array}\begin{array}{c} \begin{array}{cccccccc} v_1 & v_2 & v_3 & v_4 & v_5 & v_6 & v_7 & v_8\end{array}\\ \begin{bmatrix} 0&1&0&1&0&0&1&0\\ 1&0&1&0&1&0&0&0\\ 0&1&0&1&0&1&0&0\\ 1&0&1&0&0&0&0&1\\ 0&1&0&0&0&1&1&0\\ 0&0&1&0&1&0&0&1\\ 1&0&0&0&1&0&0&1\\ 0&0&0&1&0&1&1&0 \end{bmatrix}\end{array}$$
$\sum d_{\vec{G}}^{-} = \sum_{i=1}^{8} col_{v_i}$
$= 3 + 3 + 3 + 3 + 3 + 3 + 3 + 3$
$= 24$
$\sum d_{\vec{G}}^{+} = \sum_{i=1}^{8} row_{v_i}$
$= 3 + 3 + 3 + 3 + 3 + 3 + 3 + 3$
$= 24$</td></tr>
</table>

<table>
<tr>
<td rowspan="2">Dataset B: Disjointed Buildings</td>
<td></td>
<td>
</td>
<td>

$$\begin{array}{c|c} & v_1\ v_2\ v_3\ v_4\ v_5\ v_6\ v_7\ v_8\ v_9\ v_{10} \\ \begin{matrix} v_1\\ v_2\\ v_3\\ v_4\\ v_5\\ v_6\\ v_7\\ v_8\\ v_9\\ v_{10} \end{matrix} & \begin{bmatrix} 0&1&0&1&0&0&1&0&0&1\\ 1&0&1&0&1&0&0&0&1&0\\ 0&1&0&1&0&1&0&0&0&0\\ 1&0&1&0&0&0&0&1&0&0\\ 0&1&0&0&0&1&1&0&1&0\\ 0&0&1&0&1&0&0&1&0&0\\ 1&0&0&0&1&0&0&1&0&1\\ 0&0&0&1&0&1&1&0&0&0\\ 0&1&0&0&1&0&0&0&0&1\\ 1&0&0&0&0&0&1&0&1&0 \end{bmatrix} \end{array}$$

$$\sum d_{\vec{G}}^{-} = \sum_{i=1}^{10} col_{v_i}$$
$= 4 + 4 + 3 + 3 + 4 + 3 + 4 + 3 + 3 + 3$
$= 34$

$$\sum d_{\vec{G}}^{+} = \sum_{i=1}^{10} row_{v_i}$$
$= 4 + 4 + 3 + 3 + 4 + 3 + 4 + 3 + 3 + 3$
$= 34$

</td>
</tr>
<tr>
<td></td>
<td>
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<td>

$$\begin{array}{c|c} & v_1\ v_2\ v_3\ v_4\ v_5\ v_6\ v_7\ v_8 \\ \begin{matrix} v_1\\ v_2\\ v_3\\ v_4\\ v_5\\ v_6\\ v_7\\ v_8 \end{matrix} & \begin{bmatrix} 0&1&0&1&0&0&1&0\\ 1&0&1&0&1&0&0&0\\ 0&1&0&1&0&1&0&0\\ 1&0&1&0&0&0&0&1\\ 0&1&0&0&0&1&1&0\\ 0&0&1&0&1&0&0&1\\ 1&0&0&0&1&0&0&1\\ 0&0&0&1&0&1&1&0 \end{bmatrix} \end{array}$$

$$\sum d_{\vec{G}}^{-} = \sum_{i=1}^{8} col_{v_i}$$
$= 3 + 3 + 3 + 3 + 3 + 3 + 3 + 3$
$= 24$

$$\sum d_{\vec{G}}^{+} = \sum_{i=1}^{8} row_{v_i}$$
$= 3 + 3 + 3 + 3 + 3 + 3 + 3 + 3$
$= 24$

</td>
</tr>
</table>

The calculation of the total of in-degree and out-degree of vertices in the digraphs for all buildings using the adjacency matrix are shown in Table 1. The equation below denotes the "Hand-Shaking" theorem which proves that the amount of edges of a regular graph is equal to the total of vertex degrees for all vertices divided by two:

$$\sum_{v_i \in V(G)} d_G(v_i) = 2|E(G)| \qquad (5)$$

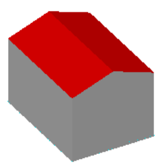
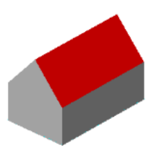
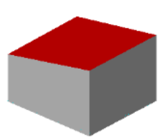
However, the graphs constructed to represent the topology of the buildings in LoD2 CityGML are directed graphs which represents the connectivity between points in the building. Hence, a theorem parallel to the "Hand-Shaking" theorem for digraphs is used as a means of topological validation of the CACC topological data structure implemented as defined below:

$$\sum_{v_i \in V(\vec{G})} d_{\vec{G}}^{-}(v_i) = \sum_{v_i \in V(\vec{G})} d_{\vec{G}}^{+}(v_i) = |E(\vec{G})| \qquad (6)$$

The previous equation (6) denotes that for a digraph; the sum of in-degree for all vertices is equal to the sum of out-degree for all vertices and is also equal to the number of directed edges of the digraph.

The results shown in Table 1 illustrates that the sum of in-degree and out-degree of all vertices for all digraphs are equal which results in the number of directed edges. Based on the CACC topological data structure, directed edges are represented as α_0-cycles which connects vertices to form edges. The number of α_0-cycles for each building are shown in Table 2.

Table 2 Number of α_0-cycles for each building

Building	Building Visualisation	Number of α_0-cycles
Dataset A: Connected Buildings		34
		24
Dataset B: Disjointed Buildings		34
		24

Based on Table 1 and Table 2, the number of directed edges of the digraphs are equal to the number of α_0-cycles for each building. This adheres to Equation (6) hence, proving that the CACC topological data structure implemented is topologically sound. According to Jahn et al. (2017), a topological representation of an object that is equal to its geometric properties is said to be topologically consistent and ensures the correctness of topological information retrieval as the topology of the model is bound to the Euclidean space.

5. Conclusion

One of the most important characteristics of an object is its location which describes its position within the space. The geometric components of the object also describe the form or shape of the object. This allows the determination of the spatial properties of the object and what the object looks like. Apart from the geometrical component of the object, the topological component is also important in the representation of the elements. 3D topology is required as a means of support for various 3D analyses for city modelling which produces 3D results. However, the topological component of CityGML as the international standard for city modelling remains in 2D with the utilisation of the simple topology-incidence mechanism. A comprehensive preservation of topological primitives is required to ensure the maintenance of connectivity information between buildings or building elements. 3D spatial queries and space segmentation are also important in the planning and management of building complexes for a sustainable development of cities. Individual units in a building complex can be represented as 3D blocks which are related. The use of topological relationships in 3D spatial queries allows the determination of common parts of an object. For example, a 3D query of other units that are related to a wall of a unit that is undergoing repairs can be retrieved and checked or given early warning.

This paper demonstrated a topological validation of the implementation of the CACC topological data structure for buildings in CityGML. Two CityGML datasets were used for testing which consisted of connected and disjointed buildings in LoD2. Directed graphs and adjacency matrices were constructed for each building to represent the topology of the building elements. The in-degree and out-degree of vertices were calculated. The "Hand-shaking" theorem which denotes that the sum of in-degree equals the sum of out-degree also equals the number of directed edges was used. The number of directed edges was found to be equal to the number of α_0-cycles of the CACC topological data structure generated for the building. Therefore, this verifies that the CACC topological data structure used to maintain topological information for buildings in CityGML is topologically sound. This study focused on the wall, roof and ground surfaces of a CityGML building in LoD2 and to other connected buildings. Future studies could attempt to implement the CACC topological model for buildings of higher LoD which could lead to the improvement of indoor navigation and other applications.

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