THREE DIMENSIONAL COMPACT ABSTRACT CELL COMPLEXES TOPOLOGICAL DATA STRUCTURE FOR BUILDINGS IN CITYGML

SYAHIIRAH MOHD SALLEH

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Philosophy

Faculty of Built Environment and Surveying
Universiti Teknologi Malaysia

FEBRUARY 2020

DEDICATION

To my father, who taught me that the sky is the limit.

To my mother, who has been my light throughout this journey.

To my brother and sisters. Do what you love and love what you do.

ACKNOWLEDGEMENT

I wish to express my sincere appreciation to my supervisor, Sr. Dr. Muhamad Uznir Ujang for his encouragement, guidance, patience, critics and friendship.

I would also like to thank Prof. Dr. Alias Abdul Rahman, Dr. Nor Suhaibah Azri, Dr. Muhammad Imzan Hassan, Dr. Ivin Amri Musliman, Dr. Nurul Hawani Idris, Dr. Mohammad Zakri Tarmidi and Dr. Azman Ariffin for their continuous support. Their invaluable views and advices are useful indeed.

I am also grateful to Universiti Teknologi Malaysia for the graduate research assistantship opportunity throughout the duration of this research.

My fellow postgraduate colleagues and 3DGIS lab members should also be recognised for their support. My sincere appreciation also extends to all my colleagues and others who have aided me throughout this journey. Unfortunately, it is not possible to list all of them in this limited space.

ABSTRACT

As the significance of visualising objects in three dimensional is now recognised, most city modelling approaches support 3D primitives in the construction (3D) of objects and visualisation. Although the visualisation of city models is in 3D, the topological information maintained remains in two dimensional (2D). This hinders the 3D model to serve its full potential, as the topological information that gives meaning to the objects is not preserved explicitly. The support of 3D topology is crucial for 3D spatial analysis that requires connectivity information and adjacencies in order to produce accurate output in 3D. This research investigates the implementation of a 3D topological model specifically using the Compact Abstract Cell Complexes (CACC) topological data structure for preserving the topological information of buildings in City Geographic Markup Language (CityGML). As the international standard for city modelling, the topological component of CityGML is in 2D via the simple topology-incidence. The use of the simple topology-incidence mechanism within CityGML allows only explicitly stored surfaces can be referenced. This then brings up the issue of inconsistent visualisation which is usually resolved by modelling the two buildings with two separate surfaces representing the common surface. However, the connectivity information between the two connected buildings are not preserved in CityGML as they do not share the same explicitly stored surface. Three objectives were established for the study namely to determine the specifications of a topological data structure for preserving topological information of buildings in CityGML, to implement a topological structure for buildings in CityGML that supports connectivity queries and adjacency analyses for city modelling, and to validate the proposed topological data structure in terms of geometric and topological properties in comparison to the existing CityGML topology mechanism. Several tasks were carried out to complete this research, including extraction of geometrical properties from CityGML, generation of topological links, adjacency analysis using topological information, and visualisation of 3D model and adjacency analysis results. The absence of a comprehensive topological model within CityGML made it necessary to use the geometric properties of the buildings in CityGML as a stand-in model to extract the topological properties that would subsequently be the basis for generating topological links. The CACC topological model preserves topological information by building topological links where points are connected to build alpha-0 links (1D lines), alpha-0 links are connected to build alpha-1 links (2D surfaces), alpha-1 links are connected to build alpha-2 links (3D volumes) and alpha-3 links represent the connectivity between 3D buildings. This allows connectivity between elements of different dimension as any link can be decomposed to its related lower dimension elements. Next, by implementing CACC topological model, the connectivity information for two buildings that are connected but modelled with two separate surfaces can be preserved. The support of topological information via the CACC topological model also allows the seamless execution of adjacency queries between building elements, including elements of different dimensions.

ABSTRAK

Memandangkan kepentingan visualisasi objek dalam 3D kini diiktiraf, kebanyakan pendekatan pemodelan bandar menyokong pengunaan primitif 3D dalam pembinaan objek dan visualisasi. Walaupun visualisasi model bandar berada dalam 3D, maklumat topologi kekal dalam 2D. Ini menghalang model 3D untuk menyediakan potensi sepenuhnya kerana maklumat topologi yang memberi makna kepada objek tidak dikekalkan dengan eksplisit. Sokongan topologi 3D adalah penting untuk analisis spatial 3D yang memerlukan maklumat kedekatan dan sambungan untuk mengeluarkan hasil yang tepat dalam 3D. Kajian ini mengkaji pelaksanaan model topologi 3D, secara khusus menggunakan struktur data topologi Kompleks Sel Abstrak Kompak (CACC) untuk mengekalkan maklumat topologi bangunan dalam Bahasa Markup Geografi Bandar (CityGML). Sebagai piawaian antarabangsa untuk pemodelan bandar, komponen topologi CityGML berada dalam 2D dengan menggunakan topologi-insiden mudah. Penggunaan mekanisme topologi-insiden mudah dalam CityGML hanya membenarkan permukaan yang tersimpan secara eksplisit dan boleh dirujuk. Ini kemudian menimbulkan masalah visualisasi yang tidak konsisten yang biasanya diselesaikan dengan memodelkan permukaan sama antara dua bangunan sebagai dua permukaan berasingan. Walau bagaimanapun, maklumat hubungan antara dua bangunan tersebut tidak dapat dikekalkan dalam CityGML kerana ia tidak berkongsi permukaan yang sama secara eksplisit. Tiga objektif telah digariskan dalam kajian ini iaitu untuk menentukan spesifikasi struktur data topologi yang boleh mengekalkan maklumat topologi bangunan dalam CityGML, untuk melaksanakan struktur data topologi bagi bangunan dalam CityGML yang menyokong pertanyaan kesalinghubungan serta analisis kedekatan bagi pemodelan bandar, dan untuk mengesahkan struktur data topologi yang dilaksanakan dari segi sifat geometri dan topologi berbanding dengan mekanisme topologi CityGML yang sedia ada. Beberapa tugasan telah dijalankan untuk menyelesaikan kajian ini yang merangkumi pengekstrakan sifat-sifat geometri dari CityGML, penjanaan pautan topologi, analisis kedekatan menggunakan maklumat topologi dan visualisasi model 3D dan keputusan analisis kedekatan. Ketiadaan model topologi yang komprehensif dalam CityGML menjadikannya perlu untuk menggunakan sifat-sifat geometri bangunan dalam CityGML sebagai model pendirian untuk mengekstrak sifat topologi yang kemudiannya menjadi asas untuk menjana pautan topologi. Model topologi CACC mengekalkan maklumat topologi dengan membina pautan topologi di mana titik dihubungkan untuk membina pautan alfa-0 (garisan 1D), pautan alfa-0 disambungkan untuk membina pautan alfa-1 (permukaan 2D), pautan alfa-1 disambungkan untuk membina pautan alfa-2 (isipadu 3D) dan pautan alfa-3 mewakili sambungan antara bangunan 3D. Ini membolehkan penyambungan antara unsur-unsur dimensi yang berbeza kerana mana-mana pautan boleh diuraikan ke elemen dimensi yang berkaitan dengannya. Seterusnya, dengan melaksanakan model topologi CACC, maklumat penyambungan untuk dua bangunan yang bersambung tetapi dimodelkan dengan dua permukaan berasingan boleh dikekalkan. Sokongan maklumat topologi melalui model topologi CACC juga membolehkan pelaksanaan analisis kedekatan yang berkaitan elemen bangunan termasuk elemen dimensi yang berbeza.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

0D	-	Zero Dimension
1D	-	One Dimension
2D	-	Two Dimension
3D	-	Three Dimension
XML	-	Extensible Markup Language
LoD	-	Level-of-Detail
GML	-	Geographic Markup Language
XML	-	Extensible Markup Language
CACC	-	Compact Abstract Cell Complexes
OGC	-	Open Geospatial Consortium
B-Rep	-	Boundary Representation
LADM	-	Land Administration Domain Model
DEM	-	Digital Elevation Model
FDS	-	Formal Data Structure
TEN	-	Tetrahedral Network
SSM	-	Simplified Spatial Model
DHE	-	Dual-Half Edge
OpenGL	-	Open Graphic Library
OpenTK	-	OpenGL Toolkit

LIST OF SYMBOLS

v	-	Vertex
E, e	-	Edge
f	-	Face
A	-	Adjacent Links
α_0	-	Alpha-0 Link
α_1	-	Alpha-1 Link
α_2	-	Alpha-2 Link
α_3	-	Alpha-3 Link
G	-	Graph
$\vec{G}$	-	Directed Graph

CHAPTER 1

INTRODUCTION

1.1 Introduction

The 21st century is known as the century of development where urbanisation is happening in countries all over the world. Existing cities are expanding while more areas are undergoing rapid development and growing into full-blown cities. Although there are numerous cities in a country let alone the world, each city is unique as it has its own physical and social elements (Horne, Thompson, & Podevyn, 2007). This shows the need for representing each city exclusively with respect to all elements of the city. Currently, more than fifty percent of the global population is residing in urban areas (Chen, 2011). Most often this occurs when residents from rural areas migrate to the city in hopes of a better quality of life (Ujang, Anton, & Rahman, 2013a). Hence, cities will continue to undergo changes as brought by the social and economic growth (Egger, 2006). In other words, changes in the structure of a city are unavoidable. Therefore, it is crucial that decision-makers are able to understand these changes and plan or resolve problems for a better city. Hence, each city must be represented as close to reality as possible to assist decision-makers in understanding the significant urban structures with regards to the issue at hand (Whyte, 2002).

1.2 Research Background

As an effort to model cities, computer-generated city models are being used as a means of visualisation for the representation of a city and its elements (Horne et al., 2007). So far, digitized representations of cities in two dimensions (2D) have assisted in the management and storage of information regarding the city’s components. The most common form of 2D city representations are maps, building or city plans and other forms of representation made up of geometries in 0D to 2D (Zhu et al., 2009).

However, the 2D representation of a city is only able to provide users with a rooftop view of the city which restricts the users' ability to understand and assess the effects of changes that occurs within the city at a scale appropriate to real life perspective (Thompson, Horne, & Fleming, 2006). Parallel to the advances in technology, city modelling has also shifted towards modelling in three dimensions (3D). This is due to the capacity of 3D modelling in offering a more realistic view of urban structures as compared to a 2D model (Ujang & Rahman, 2013b). A 3D city model refers to the integration of 3D geographical data and thematic characteristics of the urban structures within a geographic database (Chen, 2011). Besides that, Zhu et al. (2009) also defined 3D city model as a digital visualisation of a city in 3D which includes both geometric and semantic components. Apart from allowing users to experience a city model that is up to scale, a 3D city model also provides users with the means to envision and work with 3D information more effectively (Chen, 2011).

1.3 Problem Statement

As the significance of visualizing objects in 3D is now recognised, most city modelling approaches support 3D primitives in the construction of objects and visualisation. A volume representing a building complex can topologically contain multiple objects as building parts (Vitalis, Ohori, & Stoter, 2019). However, the building parts of the building complex are only represented geometrically as volumes without any description of how the building parts are connected. Therefore, the visualisation of 3D objects with accurate geometric data remains as a "graphical output" without the topological information to give meaning to it (Ujang, Anton, & Azri, 2019). In addition, without the support of 3D topology, the outcomes from analyses carried out will remain in 2D (Hyeyoung et al., 2009). Apart from that, 3D analyses regarding 3D proximity also rely on the support of a complete 3D topological structure (Moser, Albrecht, & Kosar, 2010). Topology also assists in describing the topological structure of an object which is important in supporting exploratory analyses (Ellul, 2007). This is supported by Isikdag, Zlatanova, and Underwood (2013) who stated that the maintenance of topological relationships which is also a topological property of the features will support exploratory analyses such as queries regarding related building elements. Analyses based on graphs which represent the connectivity of elements also necessitates topological relationships between elements as a prerequisite (den Duijn, Agugiaro, & Zlatanova, 2018). This shows that analyses are dependent on the supported dimensionality both geometrically and topologically. Hence, a topological model should explicitly define the relationships and adjacencies of objects or spaces (Karim, Rahman & Jamali, 2018). The absence of a 3D topological structure needed in a consistent 3D profile will also cause discrepancies and incomplete topological connectivity of objects which will hinder computational analysis (Xie et al., 2013). The implementation of a topological data structure that comprehensively describes the relationships and connectivity between geometric objects can also improve geometric processing performance (Vitalis, Arroyo Ohori, & Stoter, 2019). Therefore, a complete 3D data model requires consistent geometric primitives and 3D topological structure to support analyses as required by users.

An international standard for city modelling is CityGML which is also an open data model established by the Open Geospatial Consortium (OGC). This data model extends the international standard of spatial data exchange specifically for 3D city modelling (Open Geospatial Consortium, 2012). However, topological relationships is not supported by CityGML in situations such as relations between rooms or interior of buildings with the exterior (Boguslawski & Gold, 2015). The topological structure of CityGML is limited to the use of XML links or “XLink” mechanism which only relates explicitly stored objects (Yao et al., 2018; Kolbe, 2009). This is due to the absence of support for topological primitives within CityGML (Boguslawski, Gold, & Ledoux, 2011). Li et al. (2015) also found that conflicts occurred with the representation of shared surfaces due to the limited topology of the XLink mechanism. Therefore, CityGML is unable to relate between 0D, 1D, 2D and 3D primitives (Ghawana et al., 2012). In order to support topological representation within CityGML, the use of topological primitives are required (Kolbe, 2009). On top of that, clear storage of topological information in a topological data structure is preferable for extraction of connectivity information (Boguslawski et al., 2011). In general cases, the XLinks mechanism is capable of linking related objects as a consequence of implicit topological relationships between objects (Thomsen et al., 2008). Nonetheless, adjacent buildings that share a wall surface are commonly modelled using separate wall surfaces called “invisible” surfaces to ensure continuous and efficient visualisation (Gröger & Plümer, 2005). Terraced houses are henceforth not recognised as they are incorrectly represented as detached buildings (Braun et al., 2018). Consequently, the topological information and connectivity between objects are not preserved as objects hence they cannot be referenced to each other using the XLinks mechanism (Salleh & Ujang, 2018a).

1.4 Research Questions

The research questions of this study are as follows:

1. What are the specifications of a topological data structure for buildings in CityGML?

2. How to implement a topological data structure which can preserve topological information for buildings in CityGML?

3. How to evaluate the geometric and topological facets of the implemented topological data structure?

1.5 Aim of Research

The aim of this research is to implement a topological data structure for CityGML data that supports 3D visualisation and custom 3D analyses which involves adjacencies, and connectivity queries.

1.6 Research Objectives

The objectives of this research are as follows:

1. To determine the specifications of a topological data structure for preserving topological information of buildings in CityGML.

2. To implement a topological data structure for buildings in CityGML that supports connectivity queries and adjacency analyses for city modelling.

3. To validate the proposed topological data structure in terms of geometric and topological properties in comparison to the existing CityGML topology mechanism.

1.7 Scope of Research

The scope of this research is to implement a topological data structure for buildings in CityGML of LoD2 which includes only building parts and building elements such as wall, ground and roof surfaces. This research studied how the implemented topological data structure affects visualisation and 3D analyses by testing the model topologically and geometrically. This also included custom 3D analysis such as adjacencies, connectivity and queries. The implemented CACC topological model was developed as an external program outside of CityGML. Therefore, the CACC topological model was able to be implemented for CityGML data but not within the CityGML file.

1.8 Overall Methodology

Phase 1 of this research is the preliminary study in which a literature review was done. There are three main topics that were studied in the literature review. The first topic studied is GML or Geographic Markup Language which is followed by CityGML which included an explanation of CityGML components and topological capabilities as the second topic. Lastly, the third topic explored topology and existing topological structures in 3D. A good understanding of these topics are important in order to successfully carry out this research.

Phase 2 consists of data preparation and tools development. Suitable data is acquired from open source data websites which adhere to the CityGML 2.0 standards. The tools for extracting the building geometries from the data was also developed in this phase. Besides that, topology generating tools were also developed in this phase to generate topological links from the extracted geometries. The topology is generated based on the Compact Abstract Cell Complexes (CACC) topological data structure. The tools were developed using Microsoft Visual Studio 2010 (VB.net).

Phase 3 is composed of experimentation for generating topology in different cases such as connected buildings and disjointed buildings. The purpose of the experiments is to observe how topology for each case differs after generation of topology based on the CACC structure as the topological model. Adjacency analysis which included point-to-line, line-to-surface, surface-to-surface, and volume-to-volume adjacencies were also executed. This is crucial to assess the topological capabilities of CACC structure as a topological model for CityGML data.

Phase 4 is the development of the program for visualising the CityGML data after the implementation of topology based on the CACC structure. Due to the absence of a comprehensive topological model within the CityGML standard, the CityGML data with the CACC topology cannot be displayed using available CityGML viewers. The program developed in this phase acts as a viewer for CityGML data with the utilisation of CACC topology. This was also used to test the capabilities of the topological model in terms of geometric and topological properties.

Lastly, the final phase consists of analysis and thesis write-up process which is continuous throughout all phases of the research. The results of the experimentation and testing were analysed in this phase in terms of the geometrical and topological properties. A simple validation of the implemented CACC topological data structure was also carried out for both geometrical and topological properties of the CityGML data with the generated topological links This research is documented in the form of a thesis which consists of five chapters. The chapters consist of the introduction, literature review, methodology, results and analysis, and conclusion of the research. The flow of this research is summarised in Figure 1.1.

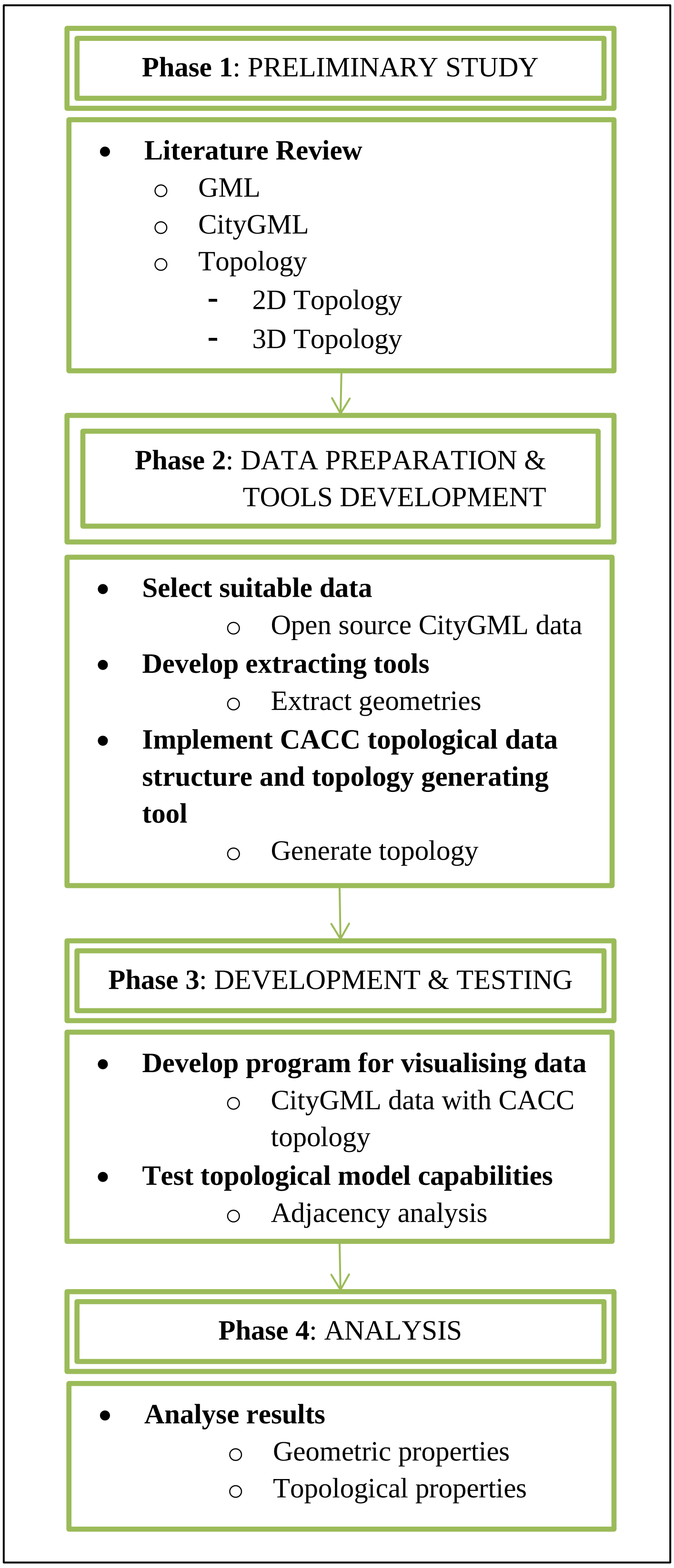

Figure 1.1 Research flowchart

1.9 Conceptual Framework

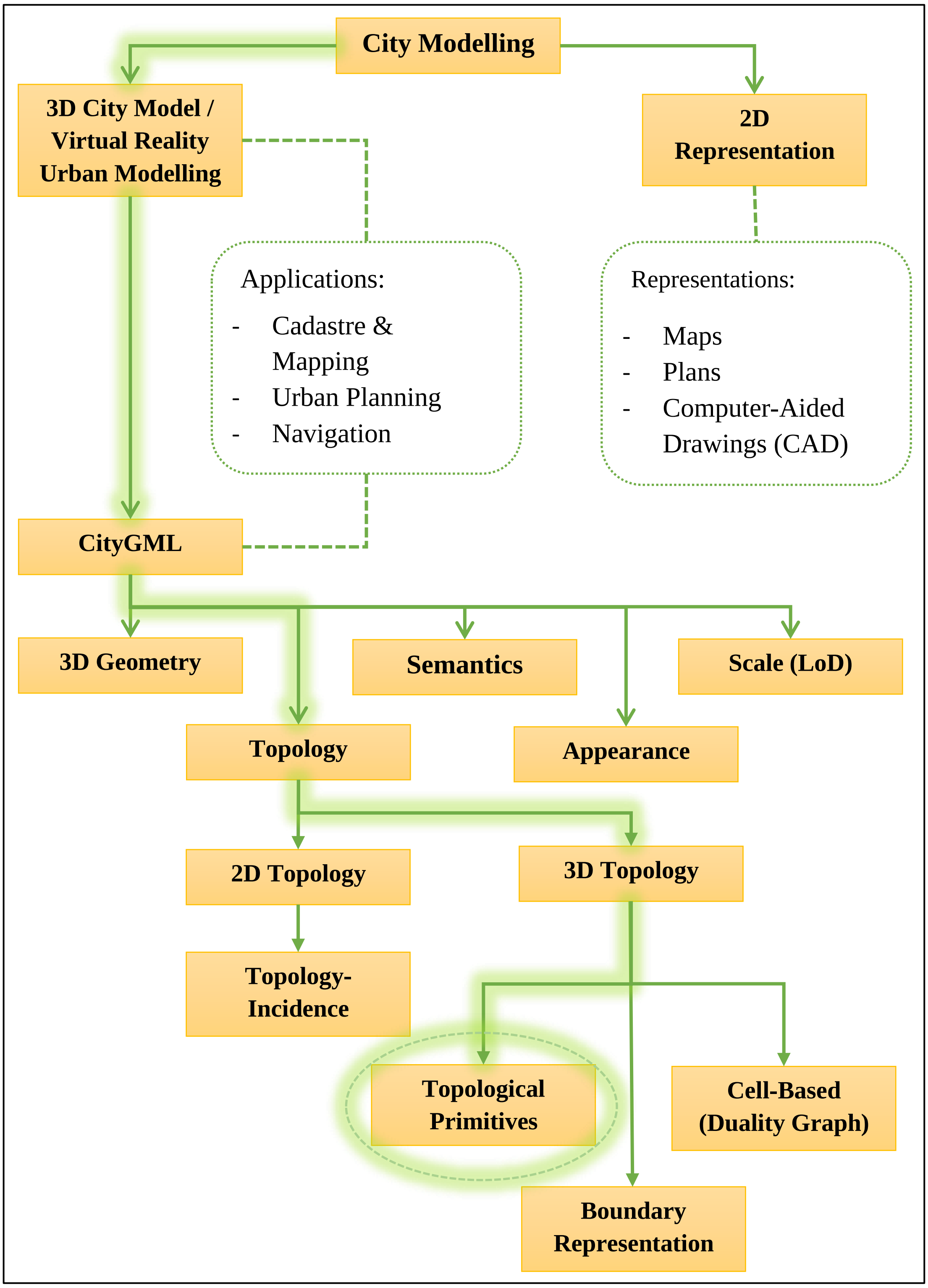

Figure 1.2 Conceptual framework of research

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. Though the representation of the real world can take many forms, accurate geo-referenced positions is one of the common priorities of any representation. Figure 1.2 illustrates the conceptual framework of this research which stems from the representation of a city as a city model. A city is also known as an urban system of urban structures which is modelled or represented as a city model.

A city can be represented in two ways which are shown in Figure 1.2 where city modelling is divided into 3D city model and 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. 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. The Open Geospatial Consortium (OGC) introduced CityGML to facilitate a standard for entities, attributes and relationships of 3D city models regardless of its specific application. Furthermore, CityGML encompasses various aspects or information of the city which are crucial to ensure an accurate and comprehensive 3D city model.

In order to provide a standard for a complete 3D city model, CityGML focuses on five main aspects as shown in Figure 1.2 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.

Generally, topology for city modelling can be divided into two subdivisions as shown in Figure 1.2 which are 2D topology and 3D topology. The type of topology currently used in CityGML is a 2D topology which is the topology-incidence. 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. On the other hand, a 3D topology can be further divided into three approaches which are topological primitives approach, cell-based approach and boundary representation approach. The topological primitives approach 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. Therefore, this study focused on the basic form of 3D topology which is the topological primitives approach.

1.10 Significance of Research

In CityGML, the topological information is not explicitly stored but connectivity information can be extracted if required by specific applications. However, it is very advantageous if the topological information is explicitly stored in a topological data model (Boguslawski et al., 2011). At the end of this study, a 3D topological data structure was implemented for users to store topological information and support topological primitives for buildings in LoD2 CityGML which is the international standard for city modelling. Besides that, the ability of the topological data structure to store topological properties also supported custom queries regarding adjacencies and connectivity.

1.11 Thesis Structure

At the end of this research, a thesis was produced to report the findings. The structure of the thesis is as follows:

i. **Chapter 1** - This chapter is the introduction of the study which briefly describes the overview of the research. This includes background of the study, problem statement, aim, objectives and the scope of the study.

ii. **Chapter 2** - This chapter is the literature review which consists of reviews of previous studies and writings on GML, CityGML and topology in three-dimensions.

iii. **Chapter 3** - This chapter represents the methodology which includes the workflow of this study, model design and model development. The processes executed in the developed tools are described using flowcharts and pseudocode.

iv. **Chapter 4** - This chapter comprises of the results of the generated topological links using the developed tools and adjacency analysis. The results are also visualised graphically. This chapter also details the evaluation of the topological model in terms of its geometric and topological aspects.

v. **Chapter 5** - This final chapter consists of the conclusion that will sum up the whole study and put forth the limitations of the study as well as recommendations for further study.

1.12 Summary

The ability to support topological primitives and maintain explicit 3D topology is crucial in the visualisation of 3D city models as well as performing custom analysis that requires connectivity information or adjacencies. This research focuses on the implementation of a 3D topological data structure for CityGML data. The support for topological primitives within this model is expected to assist in the ensuring of a continuous and unbroken visualisation of urban structures. Apart from that, the topological data structure is also important in maintaining 3D topology and performing 3D custom analysis. The implemented topological data structure was also evaluated geometrically and topologically as well as a comparison to the existing topology mechanism of CityGML. The outcome of this research is expected to provide users with an alternative for maintaining topological information for CityGML data.

REFERENCES

Agnarsson, G., & Greenlaw, R. (2007). *Graph Theory: Modeling, Applications, and Algorithms*. Pearson Education Inc.

Aldous, J. M., & Wilson, R. J. (2003). *Graphs and Applications: An Introductory Approach (Vol. 1)*. Springer Science & Business Media.

Arroyo Ohori, K., Ledoux, H., & Stoter, J. (2015). An Evaluation and Classification of n-D Topological Data Structures for the Representation of Objects in a Higher-dimensional GIS. *International Journal of Geographical Information Science*. 29(5), 825-849.

Biljecki, F., Ledoux, H., Du, X., Stoter, J., Soon, K. H., & Khoo, V. (2016). The Most Common Geometric and Semantic Errors in CityGML Datasets. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* 4(2W1), 13-22.

Biljecki, F., Stoter, J., Ledoux, H., Zlatanova, S., & Çöltekin, A. (2015). Applications of 3D City Models: State of the Art Review. *ISPRS International Journal of Geo-Information*, 4(4), 2842–2889. MDPI AG.

Billen, R., Cutting-Decelle, A.-F., Marina, O., de Almeida, J.-P., Caglioni, M., Falquet, G., Leduc, T., Metral, C., Moreau, G., Perret, J., San Jose, R., Yatskiv, I., & Zlatanova, S. (2014). 3D City Models and Urban Information: Current Issues and Perspectives. *Les Ulis cedex A*, France: EDP Sciences.

Boguslawski, P., & Gold, C. (2015). Buildings and Terrain Unified – Multidimensional Dual Data Structure for GIS. *Geo-spatial Information Science*. 18(4), 151-158.

Boguslawski, P., Gold, C. M., & Ledoux, H. (2011). Modelling and Analysing 3D Buildings with a Primal/Dual Data Structure. *ISPRS Journal of Photogrammetry and Remote Sensing*. 66(2), 188-197.

Braun, R., Weiler, V., Zirak, M., Dobisch, L., Coors, V., & Eicker, U. (2018). Using 3D CityGML Models for Building Simulation Applications at District Level. *2018 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC),* 1-8.

Breunig, M., & Zlatanova, S. (2011). 3D Geo-Database Research: Retrospective and Future Directions. *Computers & Geosciences*. 37(7), 791-803.

Chen, R. (2011). The Development of 3D City Model and its Applications in Urban Planning. *Proceedings of the 2011 19th International Conference on Geoinformatics.* 24-26 June. Shanghai, China, 1-5.

Clementini, E. (2019). A Conceptual Framework for Modelling Spatial Relations. *Information Technology and Control*, 48(1), 5-17.

den Duijn, X., Agugiaro, G., & Zlatanova, S. (2018). Modelling Below- and Above-Ground Utility Network Features with the CityGML Utility Network ADE: Experiences From Rotterdam. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 4(4/W7).

Döllner, J., Baumann, K., & Buchholz, H. (2006). Virtual 3D City Models as Foundation of Complex Urban Information Spaces. *11th International Conference on Urban Planning and Spatial Development in the Information Society*. 13-16 February. Vienna, Austria.

Egenhofer, M. J. (1989). A Formal Definition of Binary Topological Relationships. *International Conference on Foundations of Data Organization and Algorithms*, 457-472.

Egger, S. (2006). Determining a Sustainable City Model. *Environmental Modelling & Software.* 21(9), 1235-1246.

Ellul, C. (2007). *Functionality and Performance: Two Important Considerations when Implementing Topology in 3D GIS*. PhD Thesis, University College London, London.

Ellul, C., & Haklay, M. (2007). Requirements for Topology in 3D GIS. *Transactions in GIS.* 10(2), 157-175.

Ghawana, T., Aleksandrov, M., & Zlatanova, S. (2018). 3d Geospatial Indoor Navigation for Disaster Risk Reduction and Response in Urban Environment. *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci.*, IV-4, 49-57.

Ghawana, T., & Zlatanova, S. (2012). Increasing Significance of 3D Topology for Modelling of Urban Structures. *Geospatial World Forum 2012*. 23-27 April. Amsterdam, The Netherlands.

Gröger, G., & Plümer, L. (2005). How to Get 3-D for the Price of 2-D—Topology and Consistency of 3-D Urban GIS. *GeoInformatica*, 9(2), 139-158. doi:10.1007/s10707-005-6431-2

Gröger, G., & Plümer, L. (2011). Topology of Surfaces Modelling Bridges and Tunnels in 3D-GIS. *Computers, Environment and Urban Systems*. 35(3), 208-216.

Gröger, G., & Plümer, L. (2012). CityGML – Interoperable Semantic 3D City Models. *ISPRS Journal of Photogrammetry and Remote Sensing*. 71, 12-33.

Herring, J. (2001). The OpenGIS Abstract Specification, Topic 1: Feature Geometry (ISO 19107 Spatial Schema). *OGC Document*. Number 01-101.

Horne, M., Thompson, E. M., & Podevyn, M. (2007). *An Overview of Virtual City Modelling: Emerging Organisational Issues*.

Hyeyoung, K., Geunhan, K., Chulmin, J., & Hyunjin, Y. (2009). Comparing DBMS-based Approaches for Representing 3D Building Objects. *2009 Joint Urban Remote Sensing Event*. 20-22 May. Shanghai, China.

Isikdag, U., Zlatanova, S., & Underwood, J. (2013). A BIM-Oriented Model for Supporting Indoor Navigation Requirements. *Computers, Environment and Urban Systems*. 41, 112-123.

Jahn, M. W., Bradley, P. E., Al Doori, M., & Breunig, M. (2017). Topologically Consistent Models for Efficient Big Geo-Spatio-Temporal Data Distribution. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 4*, 65-72.

Kaňuk, J., Gallay, M., & Hofierka, J. (2015). Generating Time Series of Virtual 3-D City Models Using a Retrospective Approach. *Landscape and Urban Planning*. 139, 40-53.

Karim, H., Rahman, A. A., & Jamali, A. (2018). Unified Topological Framework for Retrieving 2D and 3D Multi-Scale Spatial Information. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 42*(4/W9).

Kolbe, T. H. (2009). *Representing and Exchanging 3D City Models with CityGML*, In J. Lee & S. Zlatanova (Eds.), *3D Geo-Information Sciences*. Berlin, Heidelberg: Springer Berlin Heidelberg, 15-31.

Krämer, T., & Huhnt, W. (2009). Topological Information in Geometrical Models of Buildings. *Computing in Civil Engineering*, 572-581. doi:10.1061/41052(346)57

Kumar, P. (2014). On the Topological Situations in Geographic Spaces. *Annals of GIS*. 20(2), 131-137.

Lee, J. (2008). *Spatial Data Analysis in 3D GIS*, In P. van Oosterom, S. Zlatanova, F. Penninga, & E. M. Fendel (Eds.), *Advances in 3D Geoinformation Systems*. Berlin, Heidelberg: Springer Berlin Heidelberg, 435-438.

Lee, J., & Kwan, M.-P. (2005). A Combinatorial Data Model for Representing Topological Relations Among 3D Geographical Features in Micro-Spatial Environments. *International Journal of Geographical Information Science*. 19(10), 1039-1056.

Lee, J., & Zlatanova, S. (2008). *A 3D Data Model and Topological Analyses for Emergency Response in Urban Areas*. In Zlatanova, S. & Li, J. (Eds.), *Geospatial Information Technology for Emergency Response.* CRC Press, pp. 159-184.

Li, L., Duan, X., Zhu, H., Guo, R., & Ying, S. (2015). Semantic Volume Texture for Virtual City Building Model Visualisation. *Computers, Environment and Urban Systems*. 54, 95-107.

Li, L., Luo, F., Zhu, H., Ying, S., & Zhao, Z. (2016a). A Two-level Topological Model for 3D Features in CityGML. *Computers, Environment and Urban Systems*. 59, 11-24.

Li, L., Wu, J., Zhu, H., Duan, X., & Luo, F. (2016b). 3D Modeling of the Ownership Structure of Condominium Units. *Computers, Environment and Urban Systems.* 59, 50-63.

McDonnell, R., & Kemp, K. (1995). International GIS dictionary. John Wiley & Sons.

Molenaar, M. (1990). *A Formal Data Structure for three-dimensional vector maps*, In L. Jiyeong & S. Zlatanova (Eds.), *3D Geoinformation Sciences.* Springer-Verlag Berlin Heidelberg.

Moser, J., Albrecht, F., & Kosar, B. (2010). Beyond Visualisation–3D GIS Analyses for Virtual City Models. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. 38(4), W15.

Open Geospatial Consortium. (2007). OpenGIS® Geography Markup Language (GML) Encoding Standard: Open Geospatial Consortium.

Open Geospatial Consortium (2012). *OGC City Geography Markup Language (CityGML) Encoding Standard.* Open Geospatial Consortium.

Pilouk, M. (1996). *Integrated modelling for 3D GIS.* PhD. Dissertation, ITC Netherlands.

Qiming, Z., & Wenjiang, Z. (2004). A Preliminary Review on Three-Dimensional City Model. *Geo-spatial Information Science*. 7(2), 79-88.

Rahman, A., & Pilouk, M. (2008). *Spatial Data Modelling for 3D GIS*. Springer Science & Business Media.

Rajabifard, A., Atazadeh, B., & Kalantari, M. (2018). A critical evaluation of 3D spatial information models for managing legal arrangements of multi-owned developments in Victoria, Australia. *International Journal of Geographical Information Science, 32*(10), 2098-2122.

Rikkers, R., Molenaar, M., & Stuiver, J. (1994). A Query Oriented Implementation of a Topologic Data Structure for 3-Dimensional Vector Maps. *International Journal of Geographical Information Systems*. 8(3), 243-260.

Rook, M., Biljecki, F., & Diakité, A. (2016). Towards Automatic Semantic Labelling of 3D City Models. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 4*(2W1), 23-30.

Salleh, S. & Ujang, U. (2018a). Topological Information Extraction from Buildings in CityGML. *IOP Conference Series: Earth and Environmental Science*, 169, 012088.

Salleh, S., Ujang, U., Azri, S., & Choon, T.L. (2018b). Cell Complexes Topological Links for Buildings in CityGML. *International Archives of Photogrammetry Remote Sensing and Spatial Information Sciences,* XLII-4/W10, 165-169.

Tang, L., Li, L., Ying, S., & Lei, Y. (2018). A Full Level-of-Detail Specification for 3D Building Models Combining Indoor and Outdoor Scenes. *ISPRS International Journal of Geo-Information*, 7(11), 419. MDPI AG.

Thompson, E. M., Horne, M., & Fleming, D. (2006). Virtual Reality Urban Modelling - An Overview. *CONVR2006: 6th Conference of Construction Applications of Virtual Reality*. 3-4 August. Florida, USA.

Ujang, U., Anton Castro, F., & Azri, S. (2019). Abstract Topological Data Structure for 3D Spatial Objects. *ISPRS International Journal of Geo-Information*, 8(3), 102.

Ujang, U., Anton, F., & Rahman, A. A. (2013). Unified Data Model of Urban Air Pollution Dispersion and 3D Spatial City Model: Groundwork Assessment Towards Sustainable Urban Development for Malaysia. *Journal of Environmental Protection*. 4(7), 701.

Ujang, U., & Rahman, A. A. (2013). Temporal Three-Dimensional Ontology for Geographical Information Science (GIS) - A Review. *Journal of Geographic Information Systems,* 5(3), 314-323.

Vitalis, S.; Arroyo Ohori, K.; Stoter, J. (2019). Incorporating Topological Representation in 3D City Models. *ISPRS International Journal of Geo-Information*, 8, 347-364.

Wang, Z., & Niu, L. (2018). A Data Model for Using OpenStreetMap to Integrate Indoor and Outdoor Route Planning. *Sensors, 18*(7), 2100.

Whyte, J. (2003). Virtual Reality and the Built Environment. *Presence: Teleoperators and Virtual Environments.* 12(5), 550-552.

Worboys, M. F., & Duckham, M. (2004). *GIS: a computing perspective*. CRC press.

Wu, M., Shen, J., & Wen, Y. (2009). A Hybrid Data Structure for Integrated Modeling of Geographic 3D Data. *2009 First International Conference on Information Science and Engineering*. 26-28 December. 1943-1946.

Xie, X., Zhu, Q., Du, Z., Xu, W., & Zhang, Y. (2013). A Semantics-Constrained Profiling Approach to Complex 3D City Models. *Computers, Environment and Urban Systems*. 41, 309-317.

Yao, Z., Nagel, C., Kunde, F., Hudra, G., Willkomm, P., Donaubauer, A., . . . Kolbe, T. H. (2018). 3DCityDB - A 3D Geodatabase Solution for the Management, Analysis, and Visualization of Semantic 3D City Models Based on CityGML. *Open Geospatial Data, Software and Standards*, 3(1), 5.

Zhu, Q., Hu, M., Zhang, Y., & Du, Z. (2009). Research and Practice in Three-Dimensional City Modeling. *Geo-spatial Information Science*. 12(1), 18-24.

Zlatanova, S. (2000). *3D GIS for Urban Development*. International Inst. for Aerospace Survey and Earth Sciences (ITC).

Zlatanova, S., Rahman, A. A., & Shi, W. (2004). Topological Models and Frameworks for 3D Spatial Objects. *Computers & Geosciences*. 30(4), 419-428.

LIST OF PUBLICATIONS

Indexed Conference Proceedings

1. **Salleh, S.** & Ujang, U. (2018). Topological information extraction from buildings in CityGML. *IOP Conference Series: Earth and Environmental Science*, 169, 012088. https://doi.org/10.1088/1755-1315/169/1/012088. **(Indexed by SCOPUS)**

2. **Salleh, S.**, Ujang, U., Azri, S., & Choon, T.L. (2018). Cell complexes topological links for buildings in CityGML. *International Archives of Photogrammetry Remote Sensing and Spatial Information Sciences*, XLII-4/W10, 165-169. https://doi.org/10.5194/isprs-archives-XLII-4-W10-165-2018. **(Indexed by SCOPUS)**

3. **Salleh, S.**, Ujang, U., Azri, S., & Choon, T. L. (2019). Spatial adjacency analysis of CityGML buildings via 3D topological data structure. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLII-4/W16, 573-579. doi:10.5194/isprs-archives-XLII-4-W16-573-2019 **(Indexed by SCOPUS)**

Non-Indexed Conference Proceedings

1. **Salleh, S.** & Ujang, U. (2017). A brief overview of topological requirements in 3D city modelling. *International Conference of Geomatics & Geospatial Technology.* 4-5 October, Kuala Lumpur, Malaysia. 285-290.