THREE-DIMENSIONAL GEOSPATIAL COMPACT ABSTRACT CELL COMPLEXES DATA STRUCTURE FOR URBAN AIR POLLUTION MODELLING

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To my wife, parents and ever-loving family…

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ABSTRACT

Understanding urban air pollution is important for sustainable urban development. Vizualization of urban air pollution modelling has been provided through the advancement of two-dimensional (2D) to three-dimensional (3D) Geographical Information System (GIS). However, current 3D GIS is still in its developing phase and focuses more on the geometry of the 3D city models. Presently, there have only been a few attempts in studying the topological relationships between 3D city objects as key elements in geospatial science. These topological relationships are vital for 3D traversal and 3D nearest neighbours information between 3D city objects in GIS. To address the lack of topological relationships in 3D GIS, Compact Abstract Cell Complexes (CACC) as a new topological data structure was developed in this research. CACC was developed by analyzing the existing data structure and identifying the limitations. Firstly, it was designed to store all the cycles that exist in different dimensions with the aim of articulating the connectivity in 3D city models. Secondly, it stored the nearest neighbours information by implementing the space-filling curve method called the Hilbert Curve. Functionally, CACC has the full traversal ability inside single and multiple connected components. Performance experiments proved that CACC requires 60% to 80% less disk storage as compared to other comparable data structures. The results have demonstrated that it is the most compact and requires minimal disk storage as well as being 90% faster in search queries of large 3D datasets. Upon validation, the implementation of CACC in urban air pollution modeling demonstrated the expediency of having a 3D topological data structure for 3D city models application. The research has developed and proved that CACC can identify topological relationships between 3D objects. Furthermore, its application can be extended to other 3D applications such as Building Information Model (BIM), Computer Aided Design (CAD), Computer Aided Engineering (CAE), web standards design, geospatial database design and disaster management and planning.

ABSTRAK

Kefahaman terhadap pencemaran udara bandar adalah penting untuk pembangunan bandar yang mampan. Visualisasi permodelan pencemaran udara bandar telah disediakan melalui kemajuan Sistem Maklumat Geografi (GIS) dua dimensi (2D) kepada tiga dimensi (3D). Walau bagaimanapun, GIS 3D kini masih di dalam fasa pembangunan dan tumpuan lebih diberikan pada geometri model bandar 3D. Pada masa ini, hanya terdapat beberapa percubaan dalam mengkaji perhubungan topologi di antara objek-objek bandar 3D sebagai elemen yang penting dalam bidang sains geospatial. Hubungan topologi adalah penting untuk penyusuran 3D dan maklumat kejiranan terdekat 3D di antara objek-objek bandar 3D dalam GIS. Bagi menangani kekangan perhubungan topologi di dalam GIS 3D, Kompleks Sel Abstrak Kompak (CACC) telah dibangunkan dalam kajian ini sebagai struktur data topologi yang baharu. CACC dibangunkan dengan menganalisis struktur data yang sedia ada dan mengenal pasti limitasinya. Pertama, ia telah direka untuk menyimpan semua kitaran yang wujud dalam dimensi yang berbeza dengan tujuan untuk menjelaskan perhubungan dalam model bandar 3D. Kedua, ia menyimpan maklumat kejiranan yang terdekat dengan melaksanakan kaedah lengkung ruang-pengisian yang dipanggil Lengkungan Hilbert. Dari segi kefungsian, CACC mempunyai keupayaan penyusuran penuh di dalam komponen tunggal dan komponen yang pelbagai. Eksperimen prestasi membuktikan bahawa CACC memerlukan storan cakera 60% hingga 80% kurang berbanding dengan struktur data lain yang setara. Keputusan telah menunjukkan bahawa ia adalah yang paling padat dan memerlukan storan cakera yang minimum dan juga 90% lebih cepat dalam pertanyaan carian set data 3D yang besar. Selepas pengesahan, pelaksanaan CACC pada pemodelan pencemaran udara bandar telah menunjukkan keperluan untuk mempunyai struktur data topologi 3D bagi aplikasi pemodelan bandar. Kajian ini telah dibangunkan dan telah membuktikan bahawa CACC boleh mengenal pasti hubungan topologi di antara objek-objek 3D. Tambahan pula, aplikasinya boleh digunakan untuk aplikasi-aplikasi 3D yang lain seperti Bangunan Model Maklumat (BIM), Reka Bentuk Berbantukan Komputer (CAD), Kejuruteraan Berbantukan Komputer (CAE), reka bentuk piawaian web, reka bentuk pangkalan data geospatial dan pengurusan dan perancangan bencana.

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LIST OF ABBREVIATIONS

2D	-	Two-dimensional
3D	-	Three-dimensional
APDM	-	Air Pollution Dispersion Models
AQE	-	Augmented Quad Edge
BIM	-	Building Information Model
CACC	-	Compact Abstract Cell Complexes
CAD	-	Computer Aided Design
DoE	-	Department of Environment
DHE	-	Dual Half Edge
GIS	-	Geographical Information System
G-Maps	-	Generalized Maps
GLoD	-	Geometric Level of Details
IG	-	Incidence Graph
JKR	-	Public Works Department (Jabatan Kerja Raya)
LoD	-	Levels of Detail
NUP	-	National Urbanization Policies
nD	-	Multidimensional
OUPP	-	Ontology of the Urban Planning Process
OSPM	-	Operational Street Pollution Model
SUD	-	Sustainable Urban Development
SCM	-	Street Canyon Models
SDHE	-	Simplified Dual Half Edge
SFC	-	Space-Filling Curves
UML	-	Unified Modeling Language

CHAPTER 1

INTRODUCTION

1.1 Research Background

During the last few decades population density has increased considerably making pollutions becoming more severe. This scenario has caused a growing understanding of managing pollutions, which has changed the way of human lives. This changed way of thinking necessitated United Nations to produce The Rio Declaration on Environment and Development, Agenda 21 that laid out sustainable development principles in many areas (United Nations, 1993). Principle 1 and Principle 3 of this declaration have stated:

- Principle 1: Human beings are at the center of concern for sustainable development. They are entitled to a healthy and productive live in harmony with nature.
- Principle 3: The right to development must be fulfilled so as to equitably meet the developmental and environmental needs of present and future generations.

Based on these principles, developments tend to lower the effects and mitigate the effects by doing assessments and modelling in order to understand the behavior of pollutions themselves. As development most likely to occur in urban areas compared to rural areas, more attention was given to understand urban form for future planning.

A lot of researches conducted have concluded that air quality is being the most pronounced urban problems (Metral *et al.*, 2008). Another fact revealed by statistical surveys is that more people are concerned about greenhouse effect rather than the hole in the ozone layer (Marquez and Smith, 1999) and more surprisingly, surveys on community attitudes showed that air pollution comes first into consideration and second to water pollution (ANOP, 1993). Bangkok with triple rate of lung cancer than the rest of Thailand, diesel exhaust emissions in Manila and Calcutta caused difficulties to breathe and Mexico City ozone increase rate triple compared to Melbourne (Manins, 1997). All of this showed the effects of air pollutions increase worldwide especially in major cities. Thus, it is crucial to put urban air pollution planning into considerations before further developments will take place.

Is it difficult to manage urban air pollutions? How to mitigate this event? Developed models show numerous efforts taking place to understand urban air pollution behavior. Geographical Information System (GIS) is one of the tools to achieve better understanding of these phenomena. Although GIS functions are as includes data processor and visualization, it also manages the relationship between spatial with semantic information. However, data input plays a vital role in producing more accurate output. Until recently, three-dimensional (3D) city modelling gives a new dimension to GIS in spatial applications. It stores geometrical information of 3D spatial objects for better understanding and visualization in various GIS applications. 3D city models could have understand better urban air pollution as a new data input and new aspect of pollution visualization. Metral *et al.* (2008) developed an ontology for integrating 3D city models with air quality models, and has stated that 3D city models can be used to provide more precise and effective air quality models that could benefit urban planners and stakeholders by providing information regarding the impact of the development plans on air quality evaluation.

However, 3D city modelling requires further research in order to understand and mitigate the effects of urban air pollution phenomena. For example, CityGML does not address the evolution of city models in a sophisticated manner and the representation of dynamic objects like moving objects is not yet included (Kolbe, 2010). Furthermore, visualization of 3D city models is based on a stationary framework. Although 3D static visualization in 3D city models is sufficient, dynamic 3D visualization could improve insight in understanding air pollution behavior. On the other hand, topological data structure for urban air pollution could enhance 3D city models for future application implementations.

This research has been motivated by an attempt to understand the behavior of urban air pollution by using 3D city models as a new spatial data input for air pollution modelling. Air pollution models in urban areas are significant tools to investigate, comprehend and forecast air pollution levels towards sustainable urban environment. Consequently, the new data structure proposed in this research is able to handle this phenomenon geometrically and topologically. In this study, the emphasis is put on the aspect of creating a GIS framework for urban development implementations that nowadays creates significant pollution problems in the urban communities. Therefore, discussions in this chapter have been organized in accordance with the following topics. This chapter presents the topic of this research and sets the outlines of the research. This chapter starts with a background description of the research (Section 1.1). In Section 1.2 the background of the problem is explained. The research questions are presented in Section 1.3, while in Section 1.4 the research approach compose of the research aim (Section 1.4.1), research objectives (Section 1.4.2), research methodology design (Section 1.4.3) and the research framework scope (Section 1.4.4) of this research are described. The contribution of this work is described in Section 1.5. This chapter ends with an overview of the thesis chapter's structure.

1.2 Background to the Problem

Pressure on land developments in urban areas has led to the poor air quality atmosphere. As discussed in Section 1.1, air quality impact in urban areas plays an important role in any mission towards sustainable urban environment, but it has often been neglected in urban development planning. In Malaysia, Section 34A of Environmental Quality Act, 1974 (NRE, 1974) requires developments which have significant impact to the environment to conduct an environmental impact assessment. Poor air quality in urban areas does not have an immediate impact, but it will reduce citizen's life quality in the long run (Sengupta *et al.*, 1996). Based on the 2008 Blacksmith Institute World's Worst Polluted Places report, urban air quality is listed as among the world's worst pollution problems (Ericson *et al.*, 2008).

Sustainable urban development can be defined as "development that improves the long-term health of Social and Ecological Cities and Towns" (Wheeler, 2004). Wheeler also stated that one of the major important characteristics of sustainable urban development is pollution and waste should be minimized. It is important to consider, in the planning process as early as possible, whether the proposed development will have a significant impact on air quality and will indirectly affects the urban community in terms of public health, loss of visual amenity or health damage (Marquez and Smith, 1999). Although these requirements on development have been realized, there has been limited progress in bringing this environmental planning into urban systems. Marquez and Smith (1999) addressed it as the cause of the absences of advance integrated environmental – transport modelling tools in analyzing the behavior of a complex and dynamic system.

In a practical approach, any urban air pollution models require several data as inputs for computations (Vardoulakis *et al.*, 2003). The geometry of an area being model is important in order to produce more accurate result. To date, there are complications in data acquisition for rapid development places. Building geometries (e.g. buildings height, width, and gaps) need to be collected from ground measurements and re-calculated with other inputs (e.g. street geometries) which change as development takes place. This information is important in any air pollution (dispersion) model and for planning purposes and this information should be made available before development take place.

Urban air pollution dispersion models involve both mathematical and physical information. According to (Vardoulakis *et al.*, 2003), five major parameters involved in most dispersion models are presented in Table 1.1 with together their dimensionality (2D and 3D).

Table 1.1 : Major inputs of air dispersion models

PARAMETERS	CATEGORIES	2D	3D
Meteorological Information	Wind Flow		/
	Wind Vector		/
	Windward		/
	Leeward		/
	Synoptic wind flow		/
	Local wind flow		/
Receptor			/
Traffic Volumes		/	
Emission Factors	Point-based	/	/
	Link-based	/	/
	Area-based	/	/
	Volume-based		/
Physical (Spatial)	Canyon Geometry • Short canyons • Medium canyons • Long canyons		/
	Building Geometry		/
	Aspect Ratio (H)		/
	Ventilation		/
	Building gap		/

Based on Table 1.1, urban air pollution dispersion models require more information in 3D forms. For an example, the physical (spatial) input requires the geometry that involves with three axes (x, y and z). In most air quality modeling, receptors parameter is used based on the location and its height from the street level, which again involves with 3D information. Therefore, the 3D information could provide precise and effective urban air quality models for future planning. And more, this 3D information is retrievable from 3D city models. However, even though it is retrievable from 3D city models, it is not a straightforward task. 3D city models framework like CityGML is intended for general application purposes (e.g. 3D data transfer, web-enabled) and are still at the construction phase for specific application implementation. Based on previous work, air pollution visualization in 3D is rather more complex than 2D visualization (Wang and Li, 2010). In addition, 3D city models only contain geometric and semantic information of the city without having a proper data structure and topological information. Whereby, topological information is important in urban air pollution dispersion models in order to execute the model calculation. Recently conducted research shows there is a possibility of implementing topology information for 3D city models (Boguslawski *et al.*, 2011, Gerhard and Lutz, 2009, Jiyeong and Sisi, 2008, Kolbe, 2009). Thus, the integration of urban air pollution model with 3D city models needs to be investigated to improve the applicability of modelling tools in analyzing air pollution behavior.

Conversely, in the aspects of 3D data structure, 3D city models are lacking in managing topological information (Arroyo *et al.*, 2013, Döllner *et al.*, 2006, Koussa and Koehl, 2009, Löwner, 2013). Thus as a result most researchers tend to improve the 3D city models structure framework. Geometrical visualization in computer graphics describes 3D data structures into two categories as shown in Table 1.2. The boundary model in the table exemplifies the 3D objects based on the boundary of the simplest cells. Meanwhile the solid model interprets 3D objects as pieces of volumes that resemble the whole object (i.e. tetrahedron). The most important models used in the spatial object representation were the Delaunay/Voronoi spatial model (Gold, 2005). Furthermore, 3D spatial environment requires manifold and non-manifold situations to be taken into consideration. Research on the Dual-Half Edge data structure (Boguslawski *et al.*, 2011) shows the implementation of a dual structure in non-manifold models. It enables path finding and planning for indoor navigation or evacuation route planning in 3D city models.

However, to shift the 3D data structure for "*movable*" objects situation, intensive data structure review is required. Current applications and frameworks for 2D and 3D spatial representations handle temporal dimension as 3D simulation (animation or video). This can be seen in many open source and commercial softwares (e.g. Google, ESRI, Bentley, MapInfo and Autodesk). As for moving objects, it requires locally updated topology whereby it should be addressed in 3D city models as the trends are demanding (see Chapter 2). Therefore, managing dynamic or moving 3D spatial events such as air quality monitoring for development planning is not sufficient with 3D simulation without having a proper topology information as suggested by many researchers (Kim *et al.*, 2010, Park and Lee, 2008, Thomsen *et al.*, 2008). More likely without having a proper topology information, its reconstructions need to be executed each time new events occurred whereby it is inefficient. Therefore, managing this event in 3D city models should be investigated and an applicable 3D data structure should be proposed in order to improve 3D city models for these events.

Table 1.2 : 3D data structures categories

Data Structure	Boundary Model	Solid (Volume) Model
Quad Edge	(Guibas and Stolfi, 1985)	
Half-edge	(Mantyla, 1988)	
Winged edge	(Weiler, 1988)	
GIS Topological Model	(Egenhofer and Franzosa, 1991)	
G-Maps		(Lienhardt, 1994)
Delaunay Tetrahedral		(Boissonnat *et al.*, 2002)
Augmented Quad Edge		(Gold *et al.*, 2005)

1.3 Research Questions

The questions that are addressed in this research are:

1. How 3D city models can help in describing urban air pollution behavior?
2. How 3D city models can have its own data structure that can preserve topological relationship and integrate it in the urban air pollution model?
3. How 3D city models are able to simulate dynamic 3D object's movements (urban air pollution) in 3D environment visualization?

Based on these main research questions, specific research questions are addressed as follows:

- Research Question 1:
  - What is the definition of urban air pollution?
  - How to relate urban air pollution with 3D city models as data input and visualization?
- Research Question 2:
  - What are the existing 3D data structures for managing 3D objects?
  - How to preserve geometry and topology information in 3D city models and integrate them in the urban air pollution model?
- Research Question 3:
  - How to visualize dynamic 3D geo-objects in 3D city models?
  - How to describe urban air pollution in 3D city models?

1.4 Research Approach

In this section the research aim, research objectives and research methods that were used to achieve these objectives are explained as follows.

1.4.1 Research Aim

The aim of this research is to propose and develop a three-dimensional (3D) data structure for 3D city models with the intention of describing urban air pollution visually and dynamically.

1.4.2 Research Objectives

The objectives in this research are described as follows:

1. To investigate the 3D city models in conjunction with the integration of urban air pollution dispersion models.
2. To propose and develop a 3D data structure that emphasis on geometry and topology for 3D city models in the urban air pollution model.
3. To apply and visualize dynamically the urban air pollution using the developed 3D data structure in a 3D city models environment.

1.4.3 Research Methodology (Design)

To answer the main research questions, the research design flow chart shown in Figure 1.1 is used. The flowchart illustrates six important stages which involves the Research Formulation phase (identifying the problems, research questions, aim and objectives), Literature Review phase (identifying the current scenario of urban air pollution and its model, current 3D data structures and 3D city modelling development), Design phase (the design and development of the new 3D data structure), Visualization phase (visualization development of the developed 3D data structure), Case Study phase (implementation in urban air pollution modelling case study) and concluded with Discussions, Conclusion & Recommendations phase.

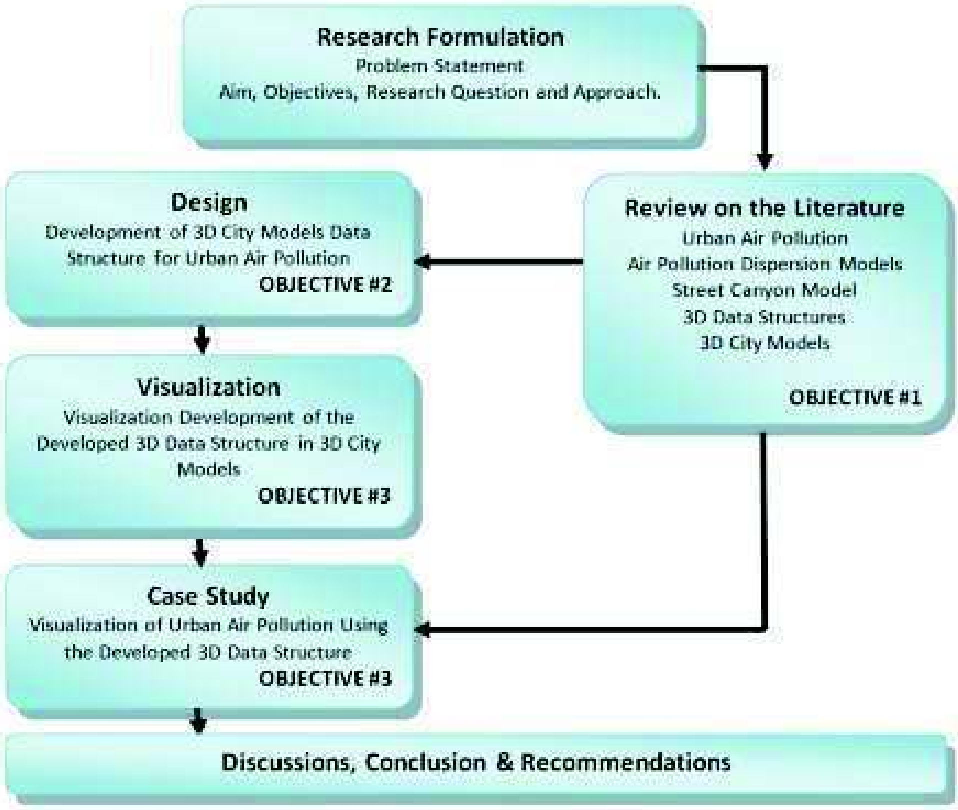

Figure 1.1 Research design flowchart

1.4.4 Research Framework

Based on the research design, the research framework illustrated in Figure 1.2 was used for structuring the general scope and the field of study. The research design is categorized into three main sections (Theories, Techniques and Development Tools). For instance, in the first section, urban pollutions issue is discussed comprehensively with the concern in outdoor air pollution situation. Furthermore, in the second category, the street canyon model for air dispersion modelling is selected for the urban air pollution modelling. Based on these two categories, the development tools section focuses on the integration of 3D city modelling as a physical data input in the air dispersion modelling.

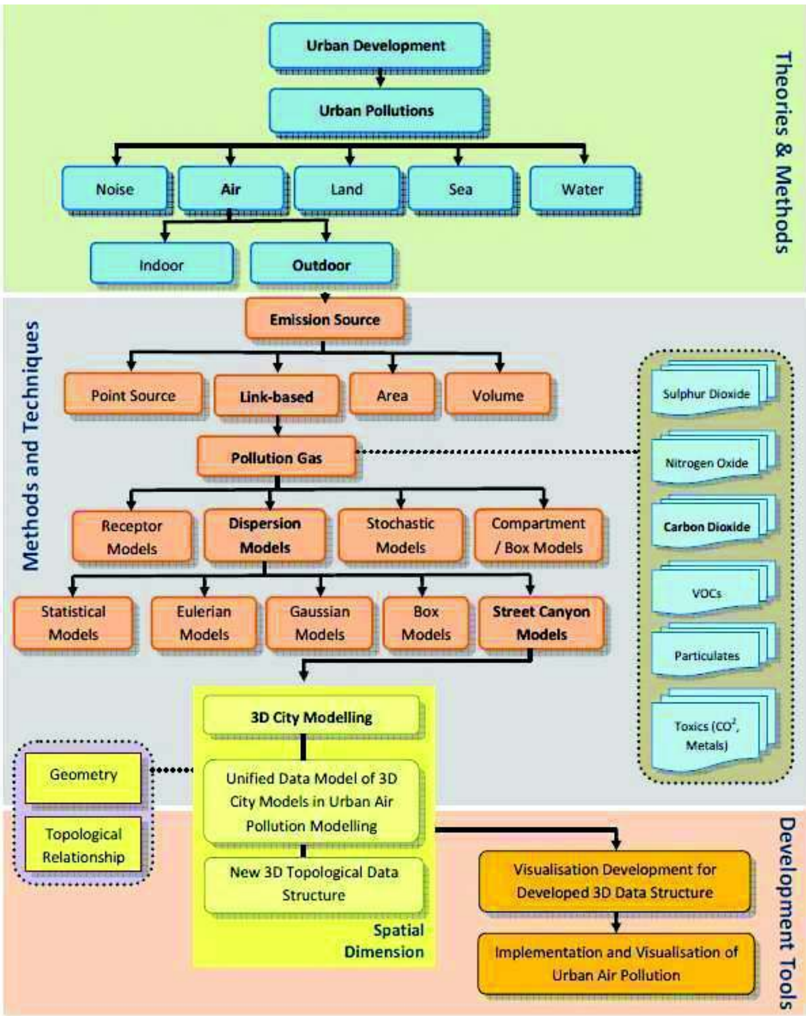

Figure 1.2 Conceptual Research Design

1.5 Contribution of this Work

The main contributions of this work can be summarized as follows:

i) Enabling the applicability of 3D city models in urban design and planning approach. This is an initial research on 3D city models in the urban development situations. Therefore this research has strong explorative characteristics resulting in a clear integration between 3D city models in urban design and planning.
ii) Current researches attempt to integrate air pollution models with 3D city models in the context of ontology. This work fills the gap between urban developments (air pollution models) with 3D city modelling by designing a specific 3D data structure for urban air pollution in 3D city models.
iii) In technical aspects, the outcomes of this research contribute to 3D GIS (3D city models), by answering the question of how to model dynamic spatial objects and to create topology information in 3D city models.
iv) There has been a limited approach to managing 3D objects in temporal dimension and most are based on animation and time-stamping approaches. This work contributes to a new method of handling 3D objects in temporal situation.
v) This work gives a diverse visualization of air pollution (dispersion) models with a better understanding of 3D air pollution movement.
vi) 3D city models for urban air pollution modelling can play an important role in urban design and planning for future sustainable urban development.

1.6 Organization of the Thesis

The thesis is structured as follows:

i) Chapter 1 – Introduction; this chapter introduces the background of the research, and the specific problem, the scope of the research, and defines some of the nomenclatures. Finally there is a summary, including the contribution of this research and an overview of the thesis.

ii) Chapter 2 – State of the Art: Urban Air Pollution Modelling in 3D City Models; this chapter describes the air pollution modelling used in the research and proposes the implementation of 3D city models as a new physical data input for air pollution modelling. The five Levels of Details (LoD) of 3D city models show the scale applicability for the dispersion model implementation. The proposed unified 3D data model for air pollution modelling can benefit in easy data acquisition, 3D visualization of air pollution dispersion and improves visual analysis of air quality monitoring in urban areas.

iii) Chapter 3 – Fundamentals of Three-Dimensional Data Structures; this chapter focuses on the trends in 3D GIS developments. In consequence, the implementations of topological data structures for 3D spatial objects and related data structures for this research were reviewed in this chapter.

iv) Chapter 4 – Compact Abstract Cell Complexes (CACC) Topological Data Structure: Design and Development; focuses on the information defined for 3D objects in the aspects of geometrical and topological information. This chapter proposed a new data structure called Compact Abstract Cell Complexes that is applicable for the urban air pollution model. In addition, this chapter demonstrated CACC topological data structure visualization and explained its features in identifying the topological relationships between objects.

v) Chapter 5 – Compact Abstract Cell Complexes (CACC) Verification and Evaluation; the purpose of this chapter is to examine how Compact Abstract Cell Complexes (CACC) topological data structure can be used to lever the topology of a 3D model in a more common approach (disk storage, response time and traversal). Comparison of CACC data with other topological data structures in 3D space has conducted. The results are presented as an indication of the CACC practicality for 3D spatial applications.

vi) Chapter 6 – CACC Implementation in Urban Air Pollution Modelling; CACC is used as a physical data input for Operational Street Pollution Model (OSPM). Several situations that most likely to occur in urban areas of air pollution modelling is shown and demonstrated using CACC. The technical feature of CACC that preserves the topological information is useful for classifying the buildings and finding the shared boundaries involved in OSPM computations.

vii) Chapter 7 – Conclusions, Recommendations and Further Research; concludes the thesis by summarizing the advantages of the developed data structure for urban air pollution, and by outlining the major contributions of this research. Recommendations for further research are also given.

REFERENCES

Abdul-Rahman, A. and Pilouk, M. (2008). 2D and 3D Spatial Data Representations. Spatial Data Modelling for 3D GIS. Springer Berlin Heidelberg. 25-42.

Afroz, R., Hassan, M. N. and Ibrahim, N. A. (2003). Review of air pollution and health impacts in Malaysia. Environmental Research, 92, 71-77.

Anjali Srivastava and Rao, B. P. S. (2011). Urban Air Pollution Modeling, Air Quality-Models and Applications. POPOVIC, P. D. (ed.) Air Quality-Models and Applications. InTech.

ANOP (1993). Community attitudes to environmental issues : ANOP report on 1993 National Research Program. Australia: Department of Environment, Sport and Territories, Canberra, Australia.

Anthony, S., Salvatore, S., Ben, C. and Greenhalgh, C. (2003). e-Science in the Streets: Urban Pollution Monitoring. 2nd UK e-Science All Hands Meeting 2003, 2003.

Arroyo, O. K., Ledoux, H. and Stoter, J. (2013). Modelling Higher Dimensional Data for GIS Using Generalised Maps. Murgante, B., Misra, S., Carlini, M., Torre, C., Nguyen, H.-Q., Taniar, D., Apduhan, B. and Gervasi, O. eds. Computational Science and Its Applications – ICCSA 2013. Springer Berlin Heidelberg. 7971, 526-539.

Ayhan, E., Erden, O. and Gormus, E. (2008). Three dimensional monitoring of urban development by means of ortho-rectified aerial photographs and high-resolution satellite images. Environmental Monitoring and Assessment, 147, 413-421.

Behley, J. and Steinhage, V. (2009). Generation of 3D City Models Using Domain-Specific Information Fusion. Fritz, M., Schiele, B. and Piater, J. H. eds. Computer Vision Systems, Proceedings. Berlin: Springer-Verlag Berlin. 5815, 164-173.

Berry, B. J. L., Marzluff, J. M., Shulenberger, E., Endlicher, W., Alberti, M., Bradley, G., Ryan, C., Simon, U. and ZumBrunnen, C. (2008). Urbanization: Urban Ecology.

Boguslawski, P. (2011). Modelling and Analysing 3D Building Interiors with The Dual Half-Edge Data Structure. PhD, University of Glamorgan.

Boguslawski, P., Gold, C. M. and Ledoux, H. (2011). Modelling and analysing 3D buildings with a primal/dual data structure. ISPRS Journal of Photogrammetry and Remote Sensing, 66, 188-197.

Boissonnat, J. D., Devillers, O., Pion, S., Teillaud, M. and Yvinec, M. (2002). Triangulations in CGAL. Computational Geometry - Theory and Applications, 22, 5 - 19.

Brandel, S., Schneider, b., Perrin, M., Guiard, N., Jean-Fran, Rainaud, O., Lienhardt, P. and Bertrand, Y. (2004). Automatic building of structured geological models. Proceedings of the ninth ACM symposium on Solid modeling and applications, 2004 of Conference Genoa, Italy. 1217886: Eurographics Association, 59-69.

Brisson, E. (1989). Representing geometric structures in d dimensions: topology and order. Proceedings of the fifth annual symposium on Computational geometry, 1989 of Conference Saarbruchen, West Germany. 73858: ACM, 218-227.

Cardoze, D., Miller, G. and Phillips, T. (2006). Representing Topological Structures Using Cell-Chains. Kim, M. S. and Shimada, K. eds. Geometric Modeling and Processing - GMP 2006. Springer Berlin Heidelberg. 4077, 248-266.

Comic, L. and Floriani, L. (2012). Modeling and Manipulating Cell Complexes in Two, Three and Higher Dimensions. Brimkov, V. E. and Barneva, R. P. eds. Digital Geometry Algorithms. Springer Netherlands. 2, 109-144.

Dayaratne, R. (2010). Moderating urbanization and managing growth: How can Colombo prevent the emerging chaos? World Institute for Development Economics Research, 2010. WIDER.

De, S., Michael, G. and Paul, L. (2007). Geospatial analysis: a comprehensive guide to principles, techniques and software tools. Troubador Publishing Ltd.

Dollner, J., Kolbe, T. H., Liecke, F., Sgouros, T. and Teichmann, K. (2006). The virtual 3d city model of berlin-managing, integrating, and communicating complex urban information. Proceedings of the 25th Urban Data Management Symposium UDMS.

Doygun, H. and Alphan, H. (2006). Monitoring Urbanization of Iskenderun, Turkey, and its Negative Implications. Environmental Monitoring and Assessment, 114, 145-155.

Duclaux, O., Frejafon, E., Schmidt, H., Thomasson, A., Mondelain, D., Yu, J., Guillaumond, C., Puel, C., Savoie, F., Ritter, P., Boch, J. P. and Wolf, J. P. (2002). 3D-air quality model evaluation using the Lidar technique. Atmospheric Environment, 36, 5081-5095.

Edelsbrunner, H. (1987). Algorithms in Combinatorial Geometry. Brauer, W., Rozenberg, G. and Salomaa, A. eds. Monographs on Theoretical Computer Science. Springer-Verlag.

Egenhofer, M. J. and Franzosa, R. D. (1991). Point-Set Topological Spatial Relations. International Journal of Geographical Information Systems, 5, 161-174.

Elbir, T., Mangir, N., Kara, M., Simsir, S., Eren, T. and Ozdemir, S. (2010). Development of a GIS-based decision support system for urban air quality management in the city of Istanbul. Atmospheric Environment, 44, 441-454.

Ellul, C. and Haklay, M. (2006). Requirements for Topology in 3D GIS. Transactions in GIS, 10, 157-175.

Entwistle, J. A., McCaffrey, K. J. W. and Abrahams, P. W. (2009). Three-dimensional (3D) visualisation: the application of terrestrial laser scanning in the investigation of historical Scottish farming townships. Journal of Archaeological Science, 36, 860-866.

Ericson, B., Hanrahan, D. and Kong, V. (2008). The World's Worst Pollution Problems: The Top Ten of the Toxic Twenty. Blacksmith Institute and Green Cross.

Evako, A. V. (2006). Topological properties of closed digital spaces: One method of constructing digital models of closed continuous surfaces by using covers. Computer Vision and Image Understanding, 102, 134-144.

Fang, M., Chan, C. K. and Yao, X. (2009). Managing air quality in a rapidly developing nation: China. Atmospheric Environment, 43, 79-86.

Ferradás, E. G., Miñarro, M. D., Morales Terrés, I. M. and Marzal Martínez, F. J. (2010). An approach for determining air pollution monitoring sites. Atmospheric Environment, 44, 2640-2645.

Fradin, D., Meneveaux, D. and Lienhardt, P. (2002). Sample space and hierarchy of generalized maps: application to architectural complexes. AFIG - French Association of Computer Graphics, December. 199-210.

Freitas, M., Sousa, A. A. and Coelho, A. (2009). Evaluation of Visualization Features in Three-Dimensional Location-Based Mobile Services. Setubal, Insticc-Inst Syst Technologies Information Control & Communication.

Fu, G., Jones, C. and Abdelmoty, A. (2005). Building a Geographical Ontology for Intelligent Spatial Search on the Web. In Proceedings of IASTED International Conference on Databases and Applications. 167-172.

Fu, L., Hao, J., He, D., He, K. and Li, P. (2001). Assessment of Vehicular Pollution in China. Journal of the Air & Waste Management Association, 51, 658-668.

Gerhard, G., T. H. K., Angela Czerwinski, Claus Nagel (2006). Candidate OpenGIS® CityGML Implementation Specification (City Geography Markup Language). Open Geospatial Consortium Inc.

Gerhard, G. and Lutz, P. (2009). Updating 3D city models: how to preserve geometric-topological consistency. Proceedings of the 17th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems, 2009 of Conference Seattle, Washington. ACM, 532-535.

Gerhard, G., Thomas, K., Angela, C. and Claus, N. (2008). OpenGIS® City Geography Markup Language (CityGML) Encoding Standard. Open Geospatial Consortium Inc.

Gold, C. M. (2005). Data structures for dynamic and multidimensional GIS. 4th ISPRS Workshop on Dynamic and Multi-dimensional GIS, Pontypridd, Wales, UK. 36-41.

Gold, C. M., Ledoux, H. and Dzieszko, M. (2005). A Data Structure for the Construction and Navigation of 3D Voronoi and Delaunay cell complexes. WSCG2005, Plzen.

Gold, C. M., Remmele, P. and Roos, T. (1997). Voronoi methods in GIS. Van Kreveld, M., Nievergelt, J., Roos, T. and Widmayer, P. eds. Algorithmic Foundations of Geographic Information Systems. Springer Berlin Heidelberg. 1340, 21-35.

Grasset-Simon, C., Damiand, G. and Lienhardt, P. (2006). nD generalized map pyramids: Definition, representations and basic operations. Pattern Recognition, 39, 527-538.

Guibas, L. and Stolfi, J. (1985). Primitives for the manipulation of general subdivisions and the computation of Voronoi. ACM Trans. Graph., 4, 74-123.

Haala, N. and Kada, M. (2010). An update on automatic 3D building reconstruction. ISPRS Journal of Photogrammetry and Remote Sensing, 65, 570-580.

Hong, Z., Cong, N., Zhang, L. and Ai, B. (2009). 3D monitoring of ice-snow in qinghai-tibet plateau - A case of geladandong. Chengdu.

Horna, S., Meneveaux, D., Damiand, G. and Bertrand, Y. (2009). Consistency constraints and 3D building reconstruction. Computer-Aided Design, 41, 13-27.

Jin, B. and Bian, F. (2006). Study on visualization of 3D city model based on grid service. Jisuanji Gongcheng/Computer Engineering, 32, 217-219.

Jiyeong, L. and Sisi, Z. (2008). A 3D data model and topological analyses for emergency response in urban areas. In Jiyeong, L. and Sisi, Z. eds. Geospatial information technology for emergency response (ISPRS book series). London, United Kingdom: Taylor & Francis. 143-168.

Karas, I., Batuk, F., Akay, A. and Baz, I. (2006). Automatically Extracting 3D Models and Network Analysis for Indoors. In Abdul-Rahman, A., Zlatanova, S. and Coors, V. eds. Innovations in 3D Geo Information Systems. Springer Berlin Heidelberg. 395-404.

Kim, T.-W., Lee, Y.-W. and Suh, Y.-C. (2010). A Literature Study on 3D Topology Models for the 3D Spatial Analysis.

Klette, R. (2000). Cell complexes through time. International Symposium on Optical Science and Technology. International Society for Optics and Photonics, 134-145.

Kolbe, T. H. (2009). Representing and Exchanging 3D City Models with CityGML. 3D Geo-Information Sciences. 15-31.

Koussa, C. and Koehl, M. (2009). A simplified geometric and topological modeling of 3D buildings: combination of surface-based and solid-based representations. ASPRS 2009 annual Conference: Reflection of the past, vision of the future.

Kovalevsky, V. (2003). Multidimensional cell lists for investigating 3-manifolds. Discrete Applied Mathematics, 125, 25-43.

Kovalevsky, V. A. (1992). Finite Topology and Image Analysis. Hawkes, P. ed. Image Mathematics and Image Processing. Academic Press. 84, 197 - 259.

Kremer, M., Bommes, D. and Kobbelt, L. (2013). OpenVolumeMesh – A Versatile Index-Based Data Structure for 3D Polytopal Complexes. Jiao, X. and Weill, J. C. eds. Proceedings of the 21st International Meshing Roundtable. Springer Berlin Heidelberg. 531-548.

Kunihiko, K. and Akifumi, M. (2006). Binary spatial operations on cell complex using incidence graph implemented at a spatial database system Hawk Eye. Progress in Informatics, 3, 19-30.

Ledoux, H. (2008). The Kinetic 3D Voronoi Diagram: A Tool for Simulating Environmental Processes. Oosterom, P., Zlatanova, S., Penninga, F. and Fendel, E. M. eds. Advances in 3D Geoinformation Systems. Springer Berlin Heidelberg. 361-380.

Ledoux, H. and Gold, C. M. (2007). Simultaneous storage of primal and dual three-dimensional subdivisions. Computers, Environment and Urban Systems, 31, 393-408.

Lee, J. (2004). A Spatial Access-Oriented Implementation of a 3-D GIS Topological Data Model for Urban Entities. Geoinformatica, 8, 237-264.

Lee, J. O., Yi, G. C., Kim, Y. S. and We, K. J. (2009). 3D wetlands classification mapping of eulsukdo area using LiDAR data. Journal of the Korean Society of Surveying Geodesy Photogrammetry and Cartography, 27, 639-647.

Lee, S. H. and Lee, K. (2001). Partial entity structure: a compact non-manifold boundary representation based on partial topological entities. Proceedings of the sixth ACM symposium on Solid modeling and applications, 2001 of Conference Ann Arbor, Michigan, United States. 376976: ACM, 159-170.

Lienhardt, P. (1991). Topological models for boundary representation: a comparison with n-dimensional generalized maps. Computer-Aided Design, 23, 59-82.

Lienhardt, P. (1994). N-dimensional generalized combinatorial maps and cellular quasi-manifolds. International Journal of Computional Geometry and Applications, 4, 275-324.

Liu, L. F. and Fang, J. Y. (2009). An Accelerated Approach to Create 3D Web Cities. New York, IEEE.

Löwner, M. O. (2013). On Problems and Benefits of 3D Topology on Under-Specified Geometries in Geomorphology. Progress and New Trends in 3D Geoinformation Sciences. Springer Berlin Heidelberg. 155-170.

Löwner, M. O., Benner, J., Gerhard, G. and Häfele, K.-H. (2013). New Concepts for Structuring 3D City Models – An Extended Level of Detail Concept for CityGML Buildings. In Murgante, B., Misra, S., Carlini, M., Torre, C., Nguyen, H.-Q., Taniar, D., Apduhan, B. and Gervasi, O. eds. Computational Science and Its Applications – ICCSA 2013. Springer Berlin Heidelberg. 7973, 466-480.

Manins, P. C. (1997). Transport -- the future is clearer. Outlook 97: proceedings of the National Agricultural and Resources Outlook Conference 1997 of Conference Canberra, A.C.T.: Australian Bureau of Agricultural Resources and Economics, 3, 85-93.

Mantyla, M. (1988). An Introduction to Solid Modelling. New York, USA, Computer Science Press.

Marquez, L. O. and Smith, N. C. (1999). A framework for linking urban form and air quality. Environmental Modelling & Software, 14, 541-548.

Metral, C., Falquet, G. and Karatzas, K. (2008). Ontologies for the Integration of Air Quality Models and 3D City Models. Ontologies for Urban Development: Conceptual Models for Practitioners, 2008 of Conference Chemin des Chevreuils, Liège 1, Belgium, 18 - 33.

Mostafavi, M. A., Beni, L. H. and Gavrilova, M. (2009a). 3D dynamic scene surveillance and management using a 3D kinetic spatial data structure. Cancun. 45-53.

Mostafavi, M. A., Beni, L. H. and Hins-Mallet, K. (2009b). Representing dynamic spatial processes using Voronoi diagrams: Recent developements. Copenhagen. 109-117.

NRE (1974). Environmental Quality Act 1974 [Act 127].

Over, M., Schilling, A., Neubauer, S. and Zipf, A. (2010). Generating web-based 3D City Models from OpenStreetMap: The current situation in Germany. Computers, Environment and Urban Systems, 34, 496-507.

Park, I. and Lee, J. (2008). Defining 3D Spatial Neighborhoods for Topological Analyses Using a 3D Network-Based Topological Data Model - CA-Based Building Evacuation Simulation. ISPRS XXXVII Congress (WG-II-2), Beijing, China.

Qu, H., Li, J. and Pan, M. (2010). Three-dimensional Urban Geological Modeling and its Applications. 18th International Conference on Geoinformatics, 18-20 June 2010 Beijing, China. IEEE, 1-6.

Ramanathan, V. and Feng, Y. (2009). Air pollution, greenhouse gases and climate change: Global and regional perspectives. Atmospheric Environment, 43, 37-50.

Rhys-Tyler, G. A., Legassick, W. and Bell, M. C. (2011). The significance of vehicle emissions standards for levels of exhaust pollution from light vehicles in an urban area. Atmospheric Environment, 45, 3286-3293.

Roberts, E. M. (1984). Design methodology for optimum dosage air monitoring site selection. Atmospheric Environment (1967), 18, 1243-1244.

Schulte, C. and Coors, V. (2009). Development of CityGML ADE for Dynamic Flood Information. Applied Geoinformatics for Society and Environment 2009, Universiti Teknologi Malaysia. 1-6.

Schulz, H. (2009). Polyhedral approximation and practical convex hull algorithm for certain classes of voxel sets. Discrete Applied Mathematics, 157, 3485-3493.

Sengupta, S., Patil, R. S. and Venkatachalam, P. (1996). Assessment of population exposure and risk zones due to air pollution using the Geographical Information System. Computers, Environment and Urban Systems, 20, 191-199.

Silva, F. G. M. and Gomes, A. J. P. (2003). Adjacency and incidence framework: a data structure for efficient and fast management of multiresolution meshes. Proceedings of the 1st international conference on Computer graphics and interactive techniques in Australasia and South East Asia, 2003 of Conference Melbourne, Australia. 604503: ACM, 159-166.

Sukhinov, A. I., Gadelshin, V. K. and Lyubomischenko, D. S. (2009). 3D model of pollution distribution in city air and its parallel realization. Antalya.

Tack, F., Buyuksalih, G. and Goossens, R. (2012). 3D building reconstruction based on given ground plan information and surface models extracted from spaceborne imagery. ISPRS Journal of Photogrammetry and Remote Sensing, 67, 52-64.

Thomsen, A., Breunig, M., Butwilowski, E. and Broscheit, B. (2008). Modelling and managing topology in 3D geoinformation systems. Advances in 3D Geoinformation Systems. Springer. 229-246.

Toshev, A., Mordohai, P. and Taskar, B. (2010). Detecting and parsing architecture at city scale from range data. San Francisco, CA. 398-405.

United Nations (1993). Earth Summit Agenda 21 - The United Nations Programme of Action from Rio. United Nations.

United Nations, D. o. E. a. S. A., Population Division (2012). World Urbanization Prospects, the 2011 Revision. New York: United Nation.

Vardoulakis, S., Fisher, B. E. A., Pericleous, K. and Gonzalez-Flesca, N. (2003). Modelling air quality in street canyons: a review. Atmospheric Environment, 37, 155-182.

Wang, G., Bosch, F. H. M. V. D. and Kuffer, M. (2008). Modeling urban traffic air pollution dispersion. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. XXXVII, 153-158.

Wang, L., Lyons, J., Kanehl, P. and Bannerman, R. (2001). Impacts of Urbanization on Stream Habitat and Fish Across Multiple Spatial Scales. Environmental Management, 28, 255-266.

Wang, S. and Li, W. (2010). The Implementation of 3D Scene Walkthrough in Air Pollution Visualization. International Journal of Information Engineering and Electronic Business 2, 44-50.

Webster, J. (2003). Cell complexes, oriented matroids and digital geometry. Theoretical computer science, 305, 491-502.

Weiler, K. (1988). The radial edge structure: a topological representation for nonmanifold geometric boundary modeling. Geometric Modeling for CAD Applications., 3-36.

Wheeler, S. M. (2004). Planning for Sustainability: Creating Livable, Equitable and Ecological Communities Routledge.

Wiederhold, P. and Morales, S. (2009). Thinning on cell complexes from polygonal tilings. Discrete Applied Mathematics, 157, 3424-3434.

Woo, J.-H., Kim, H., Lim, S., Kim, J. J., Lee, J., Ryoo, R. and Kim, H. (2010). AirScope: A Micro-scale Urban Air Quality Management System. Hsu, C. H., Yang, L., Park, J. and Yeo, S. S. eds. Algorithms and Architectures for Parallel Processing. Springer Berlin Heidelberg. 6081, 520-527.

Xu, Z., Xiaofang, W., Zhu, G. and Yan, H. (2008). 3D modelling of groundwater based on volume visualization technology. Tang, X., Liu, Y., Zhang, J. and Kainz, W. eds. Advances in Spatio-Temporal Analysis. Taylor & Francis Group. 5, 163-8.

Yamaguchi, Y. and Kimura, F. (1995). Nonmanifold topology based on coupling entities. Computer Graphics and Applications, IEEE, 15, 42-50.

Yue Ray, G. (2011). China's Future Requires Managing Its Urbanization "Right". 5th International Association for China Planning Conference (IACP), 17-19 June 2011. 1-8.

Zalama, E., Gómez-García-Bermejo, J., Llamas, J. and Medina, R. (2011). An Effective Texture Mapping Approach for 3D Models Obtained from Laser Scanner Data to Building Documentation. Computer-Aided Civil and Infrastructure Engineering, 26, 381-392.

Zhang, Z. P., Fang, J. T. and Jing, R. H. (2009). Interactive Visualisation of 3D City Models Based on Adaptive Streaming of 3D-GIS Data. Los Alamitos, IEEE Computer Soc.