

# **An Approach of Instigating 3D City Models in Urban Air Pollution Modeling for Sustainable Urban Development in Malaysia**

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**Key words:** 3D City Modeling, Urban Air Pollution Modeling, Sustainable Urban Development.

## **SUMMARY**

Urbanization growth in Malaysia is like in any other developing countries, it contributes to the negative impact of the urban environment. As Malaysia is on its mission to be a developed country by the year 2020; it realizes that dealing with air pollution is one of the indicators headed towards it. Air pollution modeling is crucial for micro-scale environment area (i.e. high density urban area) since deploying air quality monitoring stations for area less than 2km is not practical and manageable. Instigating 3D city models for urban air pollution modeling seems promising for sustainable development planning and practice. It can expand the visualization and analysis capabilities of Geographic Information Systems (GIS) on cities, and they can be developed using web standards. However, these 3D city models with air pollution dispersion modeling consume much more storage compared to two dimensional (2D) spatial data. They involve with extra geometrical and topological information together with semantic data. Without a proper spatial data clustering method and its corresponding spatial data access method, retrieving portions of, and especially searching these 3D city models, will not be done optimally. In this research, we propose an apposite data constellation technique of space-filling curves for 3D city models data. We extend the Hilbert's space-filling curve to one higher dimension for 3D city models data implementations. The query performance was tested using a 3D city models dataset of 1,000 city objects and the results are presented in this paper. The advantages of implementing Hilbert curve for 3D city models data are that it improves data retrieval time by means of optimized 3D adjacency, nearest neighbor information and 3D indexing.

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## 1. INTRODUCTION

Urbanization process gives impacts in a range of economic, political, social, cultural, and environmental. Based on current and previous research works, negative impacts on the environment are taking place with poor development process and planning (Doygun and Alphan, 2006, Ramanathan and Feng, 2009, Wang et al., 2001). The urbanization process can be seen since 1950's, when the world's population increases to triple in 25 years (Berry, 2008). The world's population is projected up to 7.3 billion in 2015. Table 1 shows Asia is among the regions that indicate a drastic increase in urban percentage. Asia percentage for average annual rate of change for an urban area is 2.39% and for rural area it decreases 0.2%. On the other hand for Malaysia, the urban population rises from 1,244,000 in 1950 to 20,150,000 in 2010 (Figure 1).

**Table 1. World's Urban Population from 2011 to 2050 (United Nations, 2012)**

Country or area	Population (thousand)						Percentage Urban			Average annual rate of change (percentage)	
	Urban			Rural			2011	2025	2050	2010-2015	2010-2015
	2011	2025	2050	2011	2025	2050					
<b>World</b>	3632457	4642582	6252175	3341579	3360397	3053953	52.1	58	67.2	1.97	0.12
<b>Africa</b>	413880	642423	1264629	632043	774635	926970	39.6	45.3	57.7	3.23	1.63
<b>Asia</b>	1895307	2512033	3309694	2312140	2218097	1832526	45	53.1	64.4	2.39	-0.2
<b>Europe</b>	539010	566299	591041	200289	177591	128216	72.9	76.1	82.2	0.4	-0.71
<b>Latin America and the Caribbean</b>	472175	560030	650479	124454	118748	100476	79.1	82.5	86.6	1.42	-0.3
<b>Northern America</b>	285805	330040	395985	61758	58432	50878	82.2	85	88.6	1.13	-0.45
<b>Oceania</b>	26280	31758	40346	10895	12894	14887	70.7	71.1	73	1.49	1.38

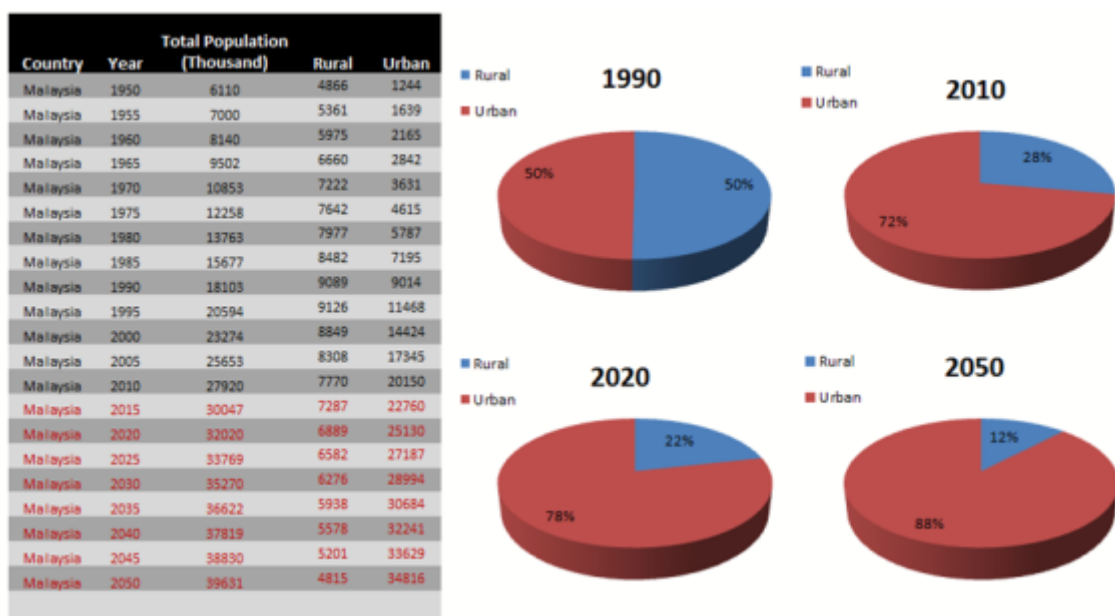
Realizing these challenges, major cities tend to minimize the negative effects and building the benefits (Yue Ray, 2011, Dayaratne, 2010, Fang et al., 2009). Therefore people are looking towards to sustainable urban environment in developing urban spaces that meet the standard for future generations and fulfill current development needs. Sustainable urban development can be described as development that improves the long-term health of social and ecological cities and towns (Wheeler, 2004). It reflects The Rio Declaration on Environment and Development, Agenda 21 by the United Nations, stated:

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*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.”*

In the current 10th Malaysia’s Plan, Thrust 4: “To Improve the Standards and Sustainability of Quality of Life” shows that Malaysia be present in positioning its part towards The Rio Declaration on Environment and Development, Agenda 21 by the United Nations. It can be perceived in policies on the subject of land use, climate change and green technology. As an example, for land use—National Physical Plan (NPP) and National Urbanization Policies (NUP); Climate change—National Policies on Climate Change and Road Map for Reduction of GHG Emissions; and Green technology National Green Technologies Policy. However, moving towards sustainable development for urban spaces is not an easy task. Despite the fact that policies regarding on the sustainable development are present, but to manage spaces with rapid development, active industrialization and high traffic volumes form a different scenario for the administration. Besides that, Vardoulakis, Fisher, Pericleous, and Gonzalez-Flesca (Vardoulakis et al., 2003) discovered that monitoring stations in urban areas are limited to a few sites and often it is located at airports. As for an example, the Malaysian Meteorological Department monitors 22 air pollution monitoring stations throughout the country (Figure 2). Meanwhile, Department of Environment Malaysia only has 15 continuous air quality monitoring stations in urban areas and their major focus is in Klang Valley whereby the capital city of Malaysia, Kuala Lumpur is located (Figure 3).



**Figure 1. Annual Percentage of Malaysia’s Urban Population (Source: Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, World Population Prospects: The 2006 Revision and World Urbanization Prospects)**



**Figure 2. Location of Air Pollution Monitoring Stations by Meteorological Department, Malaysia**



**Figure 3. Location of Continuous Air Quality Monitoring Stations by Department of Environment, Malaysia**

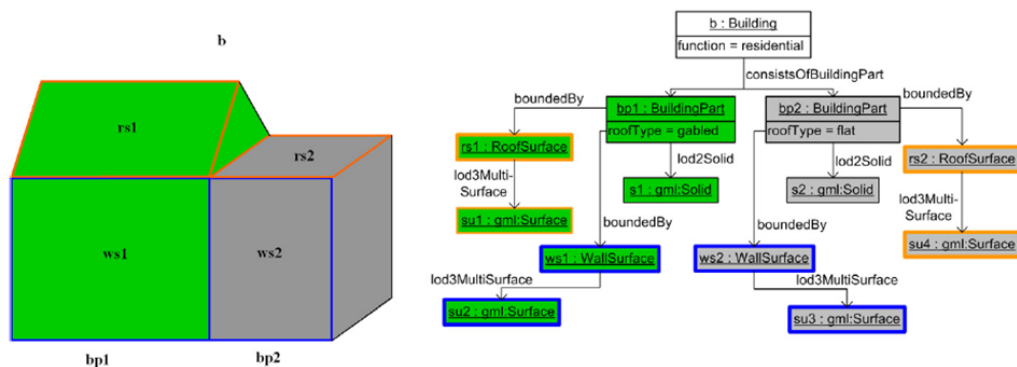
Conversely, in a high density of urban area the major source of air pollution are initiated by vehicle emissions (Rhy-Tyler et al., 2011). Heavy traffic and slow vehicle movements seem will trap the pollutant emission inside of the urban geometry. The circulation of pollutant between buildings will worsen if there is no natural ventilation or slow background wind speed. Based on Figure 2 and Figure 3 stations, they are basically based on regional scale model and did not focus on urban areas with less than 1km resolution. However it is crucial to monitor air pollution in urban cities in order to have a better and healthy living standard. Deploying monitoring stations at street level will affect the cost and maintenance. This is one of the reasons why it is difficult to have a micro scale model for air pollution monitoring in urban area (Anthony Steed et al., 2003).

Malaysia is on its mission to become a developed country by the year 2020. One of the indicators headed for that mission is to manage air pollution and its impact. Based on previous research, it shows that air quality in Malaysia play an important role on human health (Afroz et al., 2003). It is impossible to eradicate urban air pollution from the list. But the best way is to minimize the urban air pollution causes from urbanization.

Therefore in this research the discussion is motivated by author's previous research based on 3D city models as an input for urban air dispersion modeling (Uznir et al., 2013). Odds-on that urban air pollution dispersion modeling is one of the ways to upkeep the air quality monitoring in urban areas. Furthermore it will assist decision makers or planners in designing urban areas to meet the standard of sustainable cities. In this research, the highlights will be given onto the approach and performance issues of implementing 3D city models for urban air dispersion model. For an example in the next section, discussion will be made on the 3D city modeling trends, the CityGML standard and the storage comparisons between different Level of Details (LoD) concept. In sections 3, the implementation of 3D spatial indexing in urban air dispersion model will be explained with the general concept of Hilbert's Space Filling Curves. The Unified Modeling Language (UML) for implementing 3D city models with the dispersion model and experimented results will be shown in section 4 and this paper ends with section 5 as the conclusions.

## 2. DEVELOPMENTS IN 3D CITY MODELING

In commercial software development, companies are competing in developing tools that capable in managing 3D cities. ESRI (CityEngine), Bentley (Bentley's Map V8i) and Google (Google Earth) offer users the capability to create, visualize and measure for applications of 3D cities embedded in their products (Jazayeri, 2012).



**Figure 4. LoD2 building illustration: CityGML feature structure as UML instance diagram (Gröger and Plümer, 2012)**

Since quite a number of 3D city models format available, there is a need in standardizing the 3D city models for various applications. City Geography Markup Language (CityGML) is an example of an exchange standard format for 3D city models (Figure 4). It consists of different

Level of Details (LoD); LoD0, LoD1, LoD2 and LoD3. Different LoDs reflect different 3D spatial information details. The higher the LoD, the more object details and geometry included. This common information model is the first standard related to 3D city models (Jazayeri, 2012).

Users want to visualize and analyze their 3D city models (Over et al., 2010, Mao et al., 2011). Among the main step in analyzing 3D city models is the data retrieval for specific computing process. To seek specific information in a huge volume of data storage, a proper data constellation mechanism is needed. Although the data is retrievable with today's computer technology, but the data retrieval routine is not optimum and there is no reason to sacrifice the computational performance instead of using it for more intricate procedures.

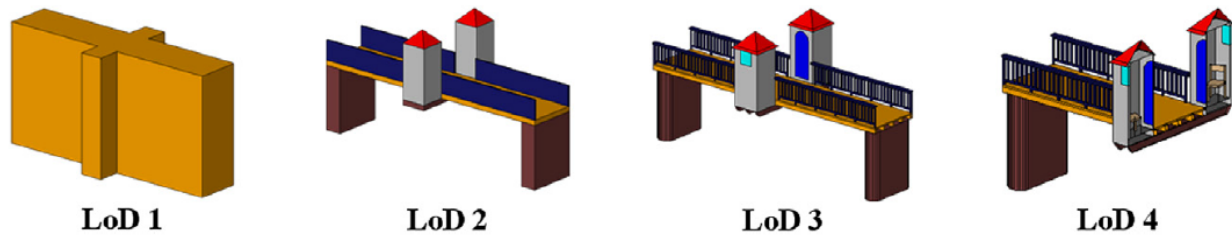
The construction of large-scale 3D city models with air pollution data faces the problem that the data is too huge, the mission is too heavy (load, manage and edit), and the development cycle is too long (Zhang and Shen, 2008). The major issue in using 3D city models data stated in the research on measuring the impact of 3D data geometric modeling on spatial analysis (Brasebin et al., 2012) is more complex data implies an increase in time and memory usage for the analysis (and calls for more research on the efficiency of the algorithms used).

Although a lot of problem arises, researchers put determination in improving the CityGML standard. Improving existing CityGML standard platform for practicality is better rather than starting from scratch as developing CityGML standard took many years of development. The next section describes the CityGML technical structures in brief.

## **2.1 City Geography Markup Language (CityGML)**

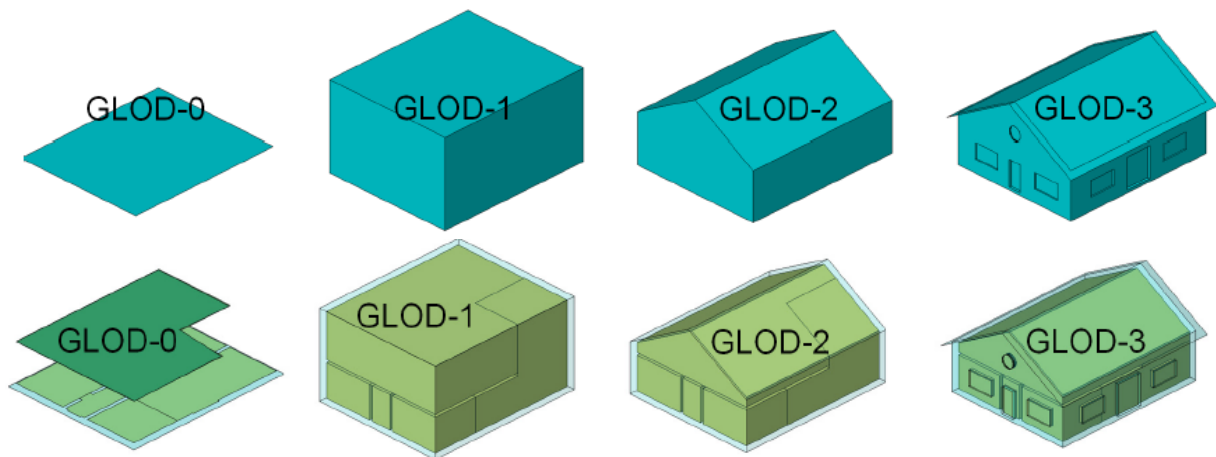
The City Geography Markup Language (CityGML) is an open standard for 3D city and landscape modelling that is recognized by the Open Geospatial Consortium (OGC) and the ISO TC211. The usage of CityGML standard can be seen in urban and landscape planning, 3D cadasters, environmental simulations, mobile telecommunications, disaster management, vehicle navigation, training simulators and mobile robotics. CityGML is an open data model and XML-based format for the storage and exchange of virtual 3D city models and it is implemented as an application schema for the Geography Markup Language version 3.1.1 (GML3).

CityGML implements different scales called the Levels of Detail (LOD). Each five LODs are based on specific model required in various applications. LOD1 is the well-known blocks model comprising prismatic buildings with flat roofs. Meanwhile, buildings in LOD2 have differentiated roof structures and thematically differentiated surfaces. LOD3 and LOD4 is more detailed city model designed for outdoor and indoor applications respectively, that requires higher accuracy for implementations (Figure 5).



**Figure 5. The Four Levels of Detail (LoD) Defined in CityGML (Gröger and Plümer, 2012)**

Recently, there is a new proposed concept for LoD that possibly could support more 3D applications in general (Löwner et al., 2013). This new concept omitted the previous LoD4 and embedded it in other LoDs. This new concept introduces separate LoD which is Geometric Level of Details (GLOD) and Semantic Level of Details which ranges from dimension 0 to dimension 3. This new concept will be in the consideration for the next version of CityGML (Figure 6).

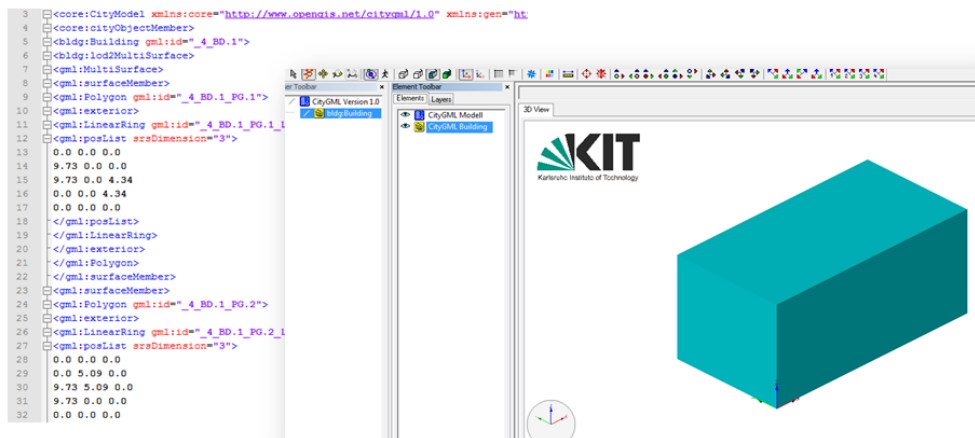


**Figure 6. The New Proposed Concepts of Geometric Levels of Detail (GLOD) in CityGML (Löwner et al., 2013)**

Technically, CityGML defines the classes and relations for objects in cities with respect to their geometrical, topological, semantical and appearance properties. This information is stored in a structured XML-based format with different tags for identifications. Figure 3 shows a representation of a single building in CityGML data. CityGML construct a building with four façade by having 6 polyhedral as 4 sets of coordinates (X, Y and Z) each. The 6 polyhedral can be identified as in <gml:Polygon> tags. Whereby each tag has its own unique gml:id attributes name identification. For each polyhedron, there is a sub-child tags named <gml:LinearRing> and <gml:PosList>. Information regarding coordinates are stored in <gml:PosList> tags in a sequence of counter clockwise as faces that is facing “outside” and clockwise coordinates sequence are faces with negative normal value. A four sided rectangle is



represented by 5 sets of coordinates (x, y and z). Usually the first and the fifth coordinate sets refer to the same coordinate values in order to create a boundary for the polyhedron. Basically this sequence is a list or cycle of coordinates (points). Polyhedrons that “belong” to a building are grouped in the same set. In the example, as shown (in Figure 7) the group can be identified as <bldg:Building> tags.



**Figure 7. Representation of a Building in CityGML**

However, CityGML requires 3.12KB size of memory disk storage for a building in Figure 7 (102 lines of tags and elements in XML structure). To differentiate, Table 2 shows the storage size for different numbers of LoD1 objects in CityGML. For retrieving information from CityGML data requires an XML tag list searching, comparison in Table 2 shows a total line of tags for each category for a number of buildings.

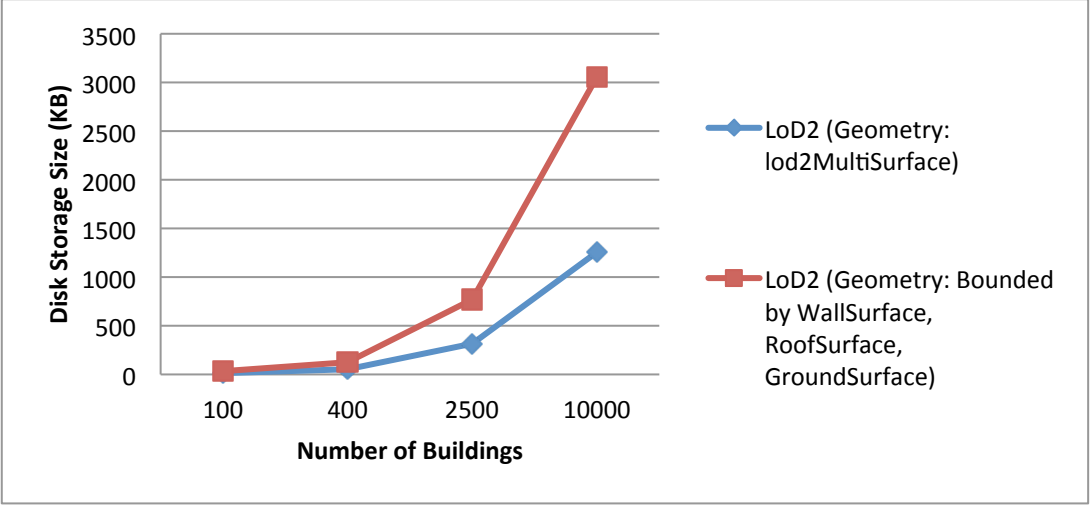
**Table 2. CityGML size (in KB) and Number of Lines Comparison Between Different Numbers of Buildings**

<i>Number of Buildings</i>	<i>Total</i>	<i>Size (KB)</i>	<i>Number of Lines</i>
2 x 2	4	17	708
10 x 10	100	394	17,412
20 x 20	400	1,592	69,612
50 x 50	2,500	10,084	435,012

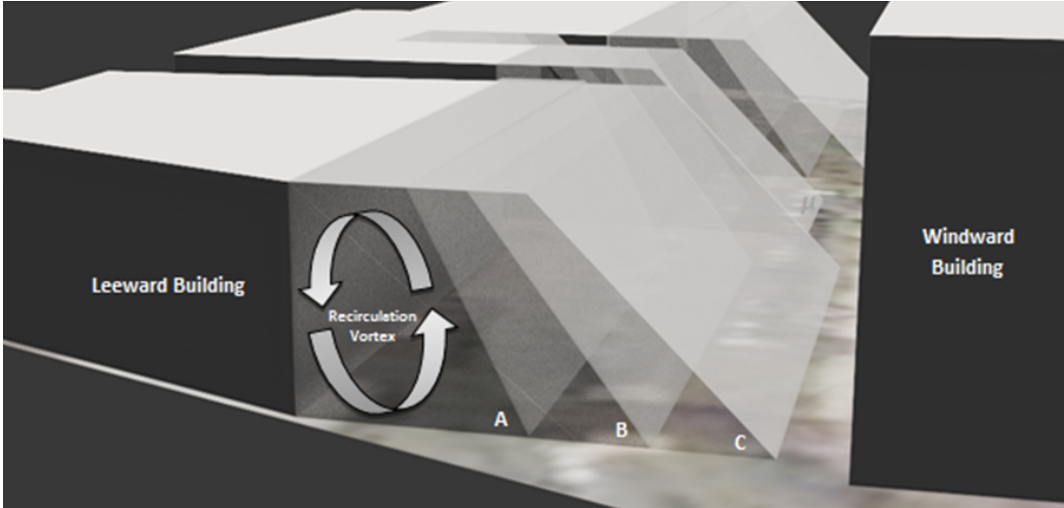
Meanwhile Figure 8 shows the disk storage comparison of LoD2 objects. Data used as a benchmark test in Figure 8 is downloadable at [www.citygmlwiki.org](http://www.citygmlwiki.org). Categorizations were made based on two categories which is LoD2 MultiSurface and LoD2 bounded by WallSurface, RoofSurface and GroundSurface. LoD2 bounded by WallSurface, RoofSurface and GroundSurface is a method of classifying the 3D objects into several parts such as wall, roof or ground surface of a building. This is a common way of describing CityGML data for



3D implementations. Based on Figure 8, it shows that the disk storage for LoD2 bounded by WallSurface, RoofSurface and GroundSurface rocketed more than double of LoD2 MultiSurface disk storage size. This graph indicates that it is vital to organize 3D city models data for optimizing 3D spatial queries search.



**Figure 8. Disk Storage Comparison Between Two LoD2 Categories**



**Figure 9. Recirculation Zone in The 3D Spatial City Model with Different Roof Wind Speed: (A) 1.0 mph, (B) 1.5 mph and (C) 2.0 mph**

Since 3D city modeling and air pollution data will involve with large amount of data, a method of organizing this data (technically) is proposed in this research. As for an example, different roof wind speed will affect the recirculation vortex in air dispersion model. Figure 9 shows the different values of roof wind speed implemented in 3D city models. There are two outputs from the computations of the recirculation zone in the air pollution model. The two

outputs are the length of the vortex ( $L_v$ ) and the length of the recirculation zone ( $L_r$ ). Below are the computations for  $L_v$  and  $L_r$ .

$$L_v = H_b \cdot r$$

Where  $H_b$  is the height of the leeward building and  $r$  is the wind speed dependent factor for the roof wind speed. With the street width ( $L$ ),  $L_r$  can be compute as:

$$L_r = \text{Min} (L, L_v \cdot \sin \varphi)$$

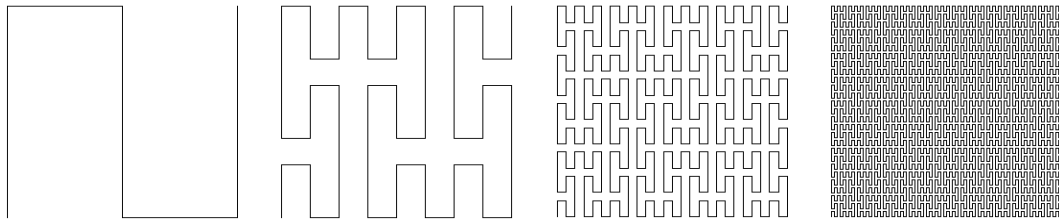
Therefore in the next section, the data constellation mechanism by using spatial indexing for 3D city models data is proposed. The data will be stored in a more structured way for implementation. At the same time it will provide advantages in terms of providing common spatial topology information such as 3D adjacency and nearest neighbor queries.

### 3. SPATIAL INDEXING

Spatial indexing is a technique to optimize query processing in spatial database by organizing records in memory space. Query performance is increased especially when dealing with many rows in a table. Number of rows will be reduced once the appropriate indexes are created and after that indexes will be executed for query processing. In traditional database system, data is ordered (or sorted) for efficient searching by using the ordering approach such as B-tree. But this approach is limited to one dimensional data such as text, numbers, strings and etc. For higher dimensional spatial data, memory space is utilized for organizing and sorting records in the database. According to (Rigaux et al., 2002), there are two main groups of index structures for spatial database which is space driven structure and data-driven structure. The usage between these two groups of indexing is constructed based on the application itself (Suhaibah et al., 2013).

#### 3.1 Space-Filling Curves and Hilbert curve

Space filling curve is a continuous function with its domain interval  $[0,1]$  and this range could be in 2D/3D topological or Euclidean space. Space filling curves allow a proximity problem to be reduced from higher dimensions to one dimension. Such problem usually involves query search and sorting in one dimensional space. Many applications can be benefited from space filling curve but the most common application of space filling curves is for storage and retrieval of multidimensional data in the database. A proximity problem for which space filling curve has been used regularly are approximate nearest neighbor searchers or finding closest points from one location. Until now, there are variants of space filling curves such as Hilbert curve, Dragon Curve, Gosper Curve, Moore Curve, Z-Order and many more.

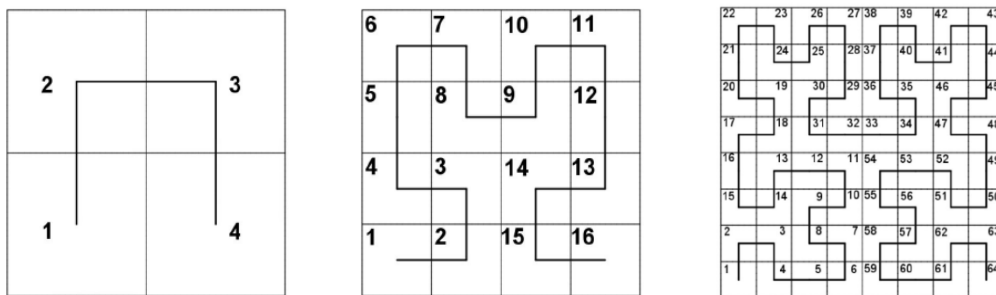


**Figure 10. First four iterations of Peano Curve**

The space filling curve was discovered by Giuseppe Peano in 1890 called Peano Curve. From his finding, a curve must pass through every point on a plane at least once. But, before his finding, in 1878, George Cantor has demonstrated a one-to-one correspondence between unit interval and unit square. A year after that, in 1879 Netto added that any such mapping could not be continuous. In 1891, David Hilbert discovered a curve structure which is a simpler variant of the same idea of Peano's. Hilbert curve subdividing squares into smaller squares instead of Peano's, nine smaller squares. Figure 10 shows four iterations of Peano Curve.

When David Hilbert discovered a variation of Peano's Curve, he divided each side of unit square into two parts equally. This yields the square into four smaller squares. From the divided squares, each of them is divided into another four smaller squares, and so on. For each part of this division, a curve will be traversed all the squares. Hilbert curve normally starts at the lower left division and end at the lower right division. According to its movement and process, Hilbert curve could be expressed in base 2.

Hilbert Space Filling Curve could be described as an underlying grid, an  $N \times N$  array of cells where  $N = 2^n$ . Hilbert's enumeration of the squares is shown in Figure 11 for  $n = 1, 2$  and 3. Note that the first square is always at the lower left corner and the last square is always in the lower right corner.



**Figure 11. The First Three Stages in Generating Hilbert Curve**

From the divided square, we assume that  $N \times N$  cells coordinates is  $(0,0)$  in the lower left corner. From the assumptions, Hilbert curve has corners at integers ranging from  $0$  to  $2^n - 1$  in both  $x$  and  $y$ . And if we took a positive direction along the curve the location from  $(x,y) = (0,0)$  to  $(2^n - 1, 0)$ .

### 3.2 Mapping points using Hilbert curve

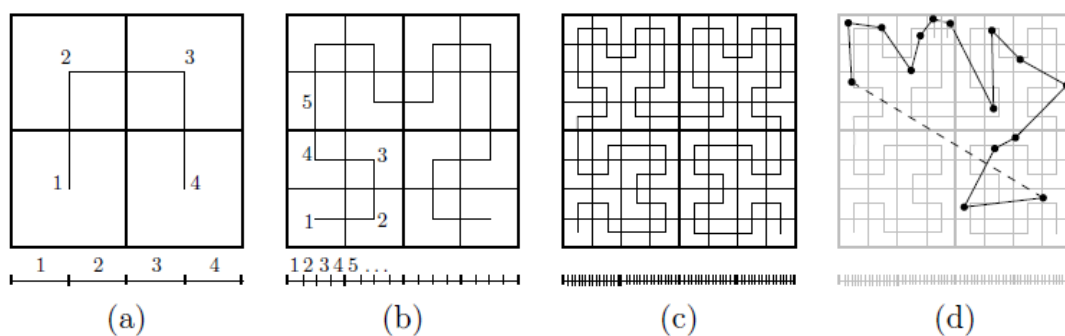
Figure 12 shows a set of point that will be used to demonstrate the space filling curve of 2D Hilbert curve.



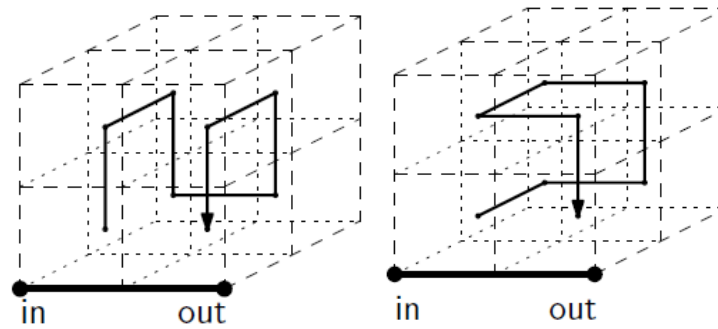
**Figure 12. Scattered Points (Kevin, 2008)**

The following constructions mapped the unit interval to a unit square of the Hilbert curve method.

- Each unit interval and unit square is divided into four intervals as shown in Figure 13. Every unit of intervals is assigned to one square. Figure 13 (a-c) shows the first three steps of this construction. In the limit this produces a subjective, continuous map from the unit interval to the unit square.
- Figure 13 (d) shows the resulting order of scattered points in Figure 12.
- Since the Hilbert curve starts in the lower left corner and ends in the lower right corner, the last edge of the round-trip (shown in Figure 13 (d) as dashed lines) seems to be long. Thus, the Hilbert curve is only suited for applications where a short path through the points is needed.

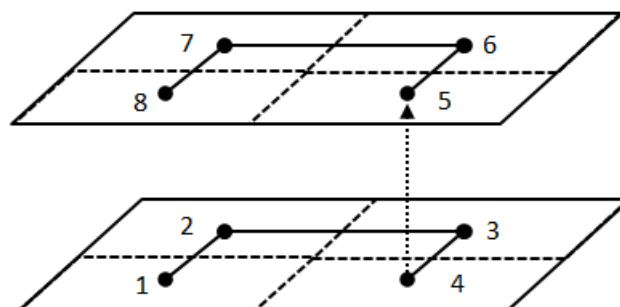


**Figure 13. Hilbert Curve and Order (Kevin, 2008)**



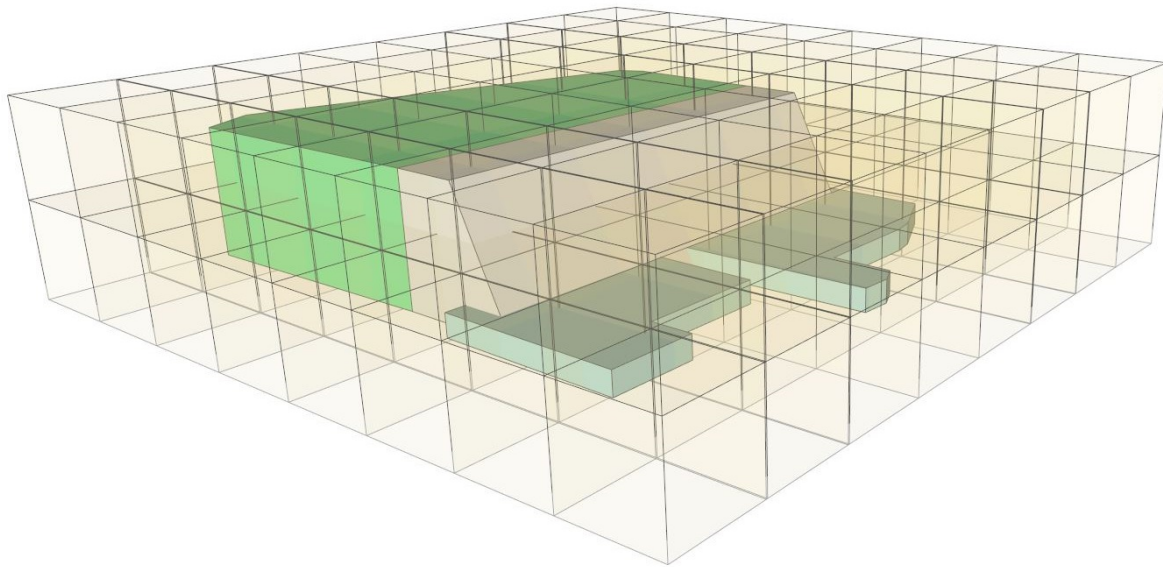
**Figure 14. Possible Approach of 3D Hilbert Order Where  $n = 2$  (Herman Haverkort and Walderveen, 2008)**

In this research, we adopt space-filling curves for the ordering in 3D city models. In mathematical analysis, a space-filling curve is a curve whose range contains the entire 2-dimensional unit square (or more generally an  $n$ -dimensional hypercube). This space filling curve visits every point in a square grid with a size of  $n^2$ . Space-filling curves in this research were used to compress the 3<sup>rd</sup> dimension models to 1 dimensional ordering. Based on previous research in implementing 3D Hilbert curve for spatial structures, there are 1536 diverse methods of 3D Hilbert curve implementation (Herman Haverkort and Walderveen, 2008). As an example, Figure 14 shows an identical  $2^n$  with different 3D Hilbert ordering approach.



**Figure 15. 3D Hilbert Order**

Meanwhile Figure 14 shows the 3D Hilbert curve implemented in this research with the rationalization of air pollution dispersion will not only move in horizontal direction but it will move vertically when the pollutant is trapped between buildings. In Figure 16, it illustrates the implementation of 3D Hilbert curve in 3D city models for urban air pollution modeling. The 3D city models demonstrated a 3D visualization of total immersion of recirculation zone scenarios occur in street geometry. The Hilbert cells is a  $2^n$  ( $n=2$ ) that encompasses the entire 3D city models. This approach can be expanded into large area of implementation. Results from the implementation of 3D Hilbert curve for 3D city models will be discussed in the next section while showing the advantages of less data retrieval time and processing.

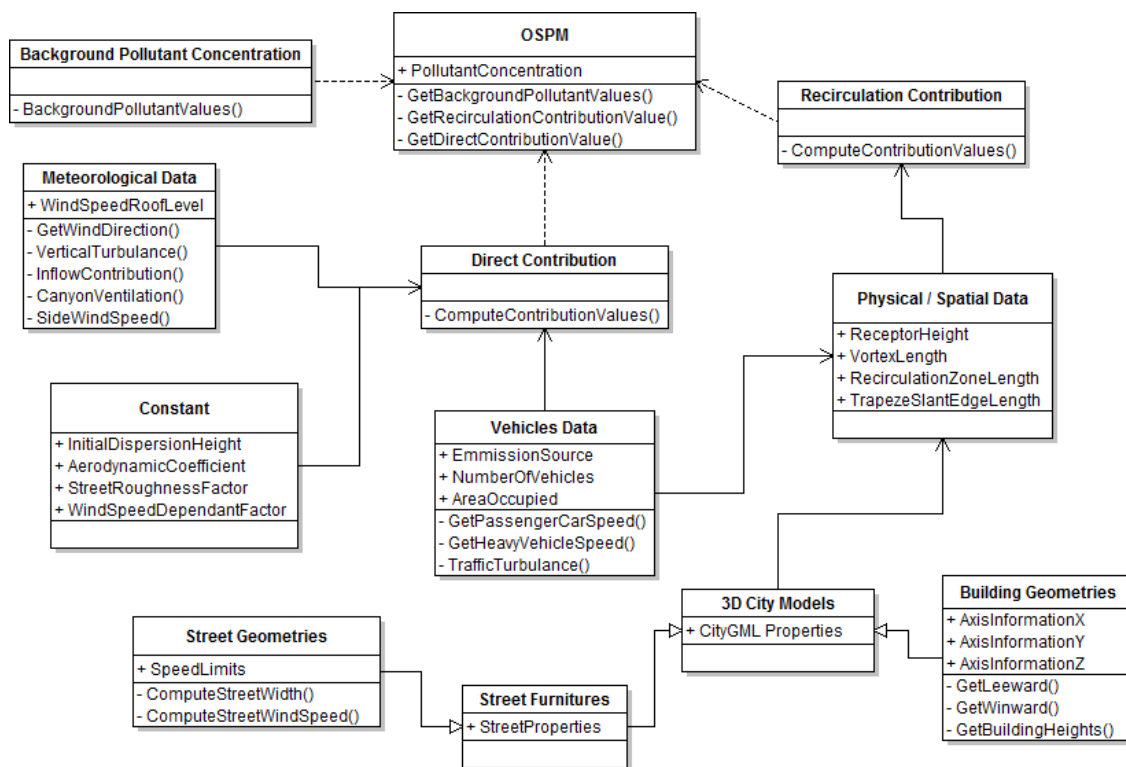


**Figure 16. 3D Hilbert Cells Implementation for Total Immersion of Recirculation Zone Situation**

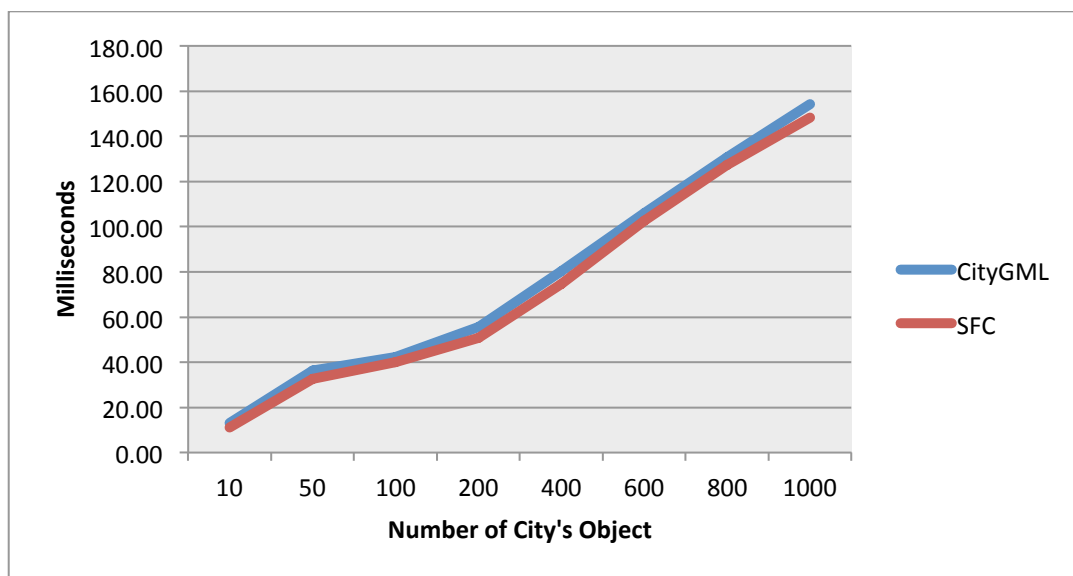
#### **4. ANALYSIS AND RESULTS**

This research used the approach of using 3D city models as a physical input data for air pollution dispersion modeling as described in the previous research (Uznir et al., 2013). Based on the Unified Data Model (UML) shown in Figure 7, it shows the possibility of simplifying the complexity of conducting air pollution dispersion modeling for high density urban areas or micro-scale environment.

As mentioned in the previous sections, indexing improves the data retrieval capabilities. For that reason, two types of search analyses were performed. Those analyses are *single object* search and *nearest object from target* search. The *single object* search usually is implemented in cases where the user wants to identify a single object from the 3D city models data. For an example in air pollution modeling, search based on leeward or windward building names or ID. Meanwhile *the nearest object from target* search is meant for queries like finding the adjacent buildings or building that affected from vehicle emissions. In the comparison, two analyses were prepared for different data sets of city objects (10, 50, 100, 200, 400, 600, 800 and 1000 objects). Data retrieval time is measured in millisecond and it was tested in a system using Intel Core i7 2.2GHz with 8GB memory.



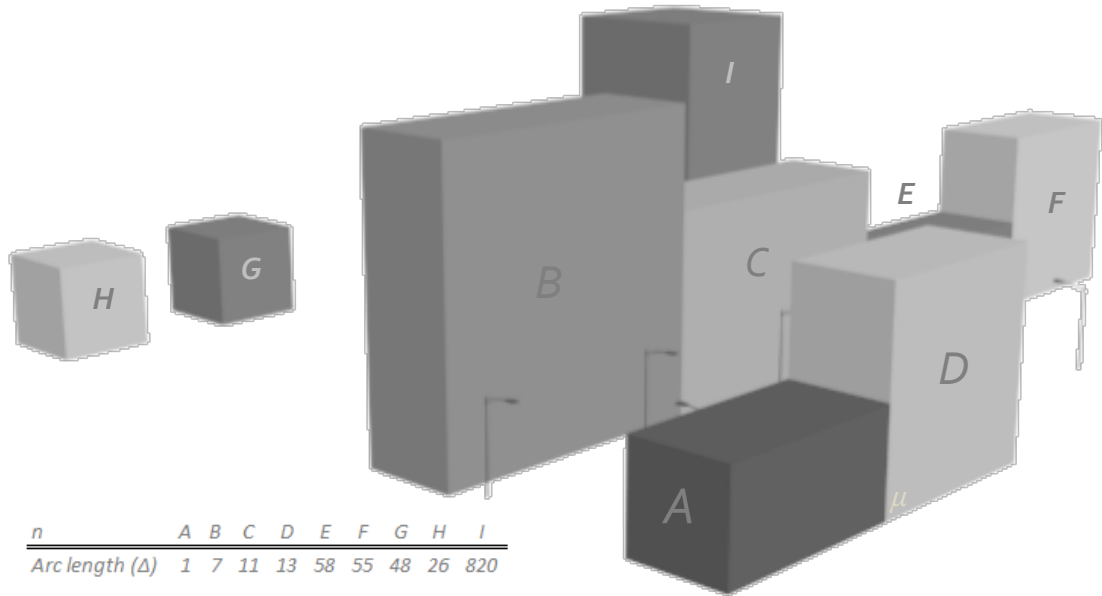
**Figure 17. The Unified Modeling Language (UML) for Air Dispersion Model with 3D Spatial City Model Integration**



**Figure 18. Single Object Search**

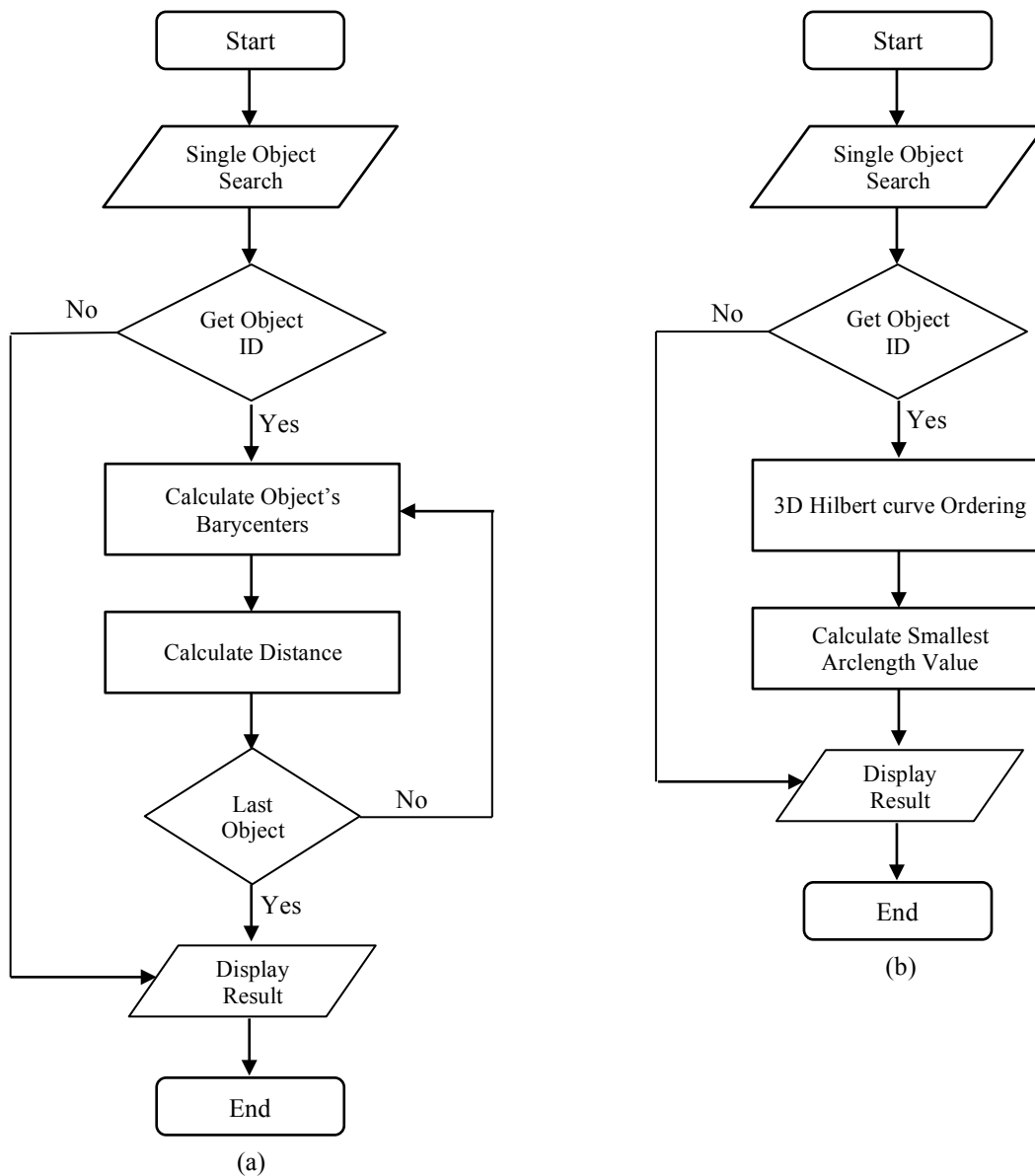


Graph in Figure 8 shows two types of 3D spatial data set used in the single object search, CityGML data and 3D spatial data with Hilbert curve implementation. The ordering is based on 3D Hilbert curve implementation. Eight data sets were prepared for each type respectively. From the figure shown, it indicates that for single object search, there is not much difference in time measured between both types of sets. This is due to the single object search routine is based on line tags list searching. Time measured in Figure 18 comprised of time for displaying tags that been traversed before getting to the target object.



**Figure 19. The Nearest Arc Lengths ( $\Delta$ ) from City Object A are B, C and D Respectively**

On the other hand, the advantage of space-filling curve operations can be seen in the consistency between neighboring pixels. In this case, the adjacencies between spatial objects were conserved and retrievable. The example shown in Figure 9 identifies objects that are located “near” to interest building. Since the Hilbert curve is organized into the one-dimensional structure, finding the nearest building to a specific building ( $n$ ) is by way of finding the nearest arc length to  $n$ . The bigger the difference ( $\Delta$ ) of arc length will identify the object’s distance from  $n$ .



**Figure 20. Flowcharts for Finding the Nearest Building for CityGML Data (a) and with 3D Hilbert Curve Implementation (b).**

Another experiment conducted in this research is to test the performance in data retrieval time for finding the nearest building from the target building. Figure 20 illustrates flowcharts in both implementations for comparison assessment. For this experiment, displaying the traversed tags is excluded and only finding the objects are the main objectives. Table 2 shows queries performed and measured for finding the nearest building to the target building.

**Table 3. Data retrieval time for nearest object from target search**

Target Object's ID	Nearest Object's ID	Time (milliseconds)		
		CityGML	Hilbert curve	Elapsed (%)
46	56	22	1	95.5
440	540	24	1	95.8
445	545	25	1	96.0
498	598	25	1	96.0
571	539	28	1	96.4
704	800	27	2	92.6
799	753	29	2	93.1
816	817	32	2	93.8
883	884	30	2	93.3
900	804	32	3	90.6
928	963	31	2	93.5
952	951	34	2	94.1
Average		28	2	94.2

Since the 3D city models data are based on XML structured ordering, searching the target objects are based on tags list and calculation are performed as in Figure20 (a). Results shown in Table 3 can be analyzed that buildings located farthest (i.e., object ID 1 is the closest meanwhile object ID 1000 is the farthest in XML structure) requires more time for data retrieval procedure. Contrariwise, the highlight should be given at the time elapsed between 3D city models with and without Hilbert curve implementation. On average Hilbert curve implementation boost up more than 90% faster compared to 3D city models data. It shows that 3D Hilbert curve in 3D city models capable in organizing data in a more efficient way. Hence, Hilbert curve implementation in large scale of data sets will optimize the data retrieval time while preserving the nearest neighbor information which is significant in geo-spatial analysis.

## 5. CONCLUSION

In this research, we have demonstrated the 3D Hilbert curve in 3D city models for optimizing query performance. We also validated the query performance comparison of 3D city object data set with and without 3D Hilbert curve implementation. From the test, we could see that the implementation of Hilbert curve method gives advantages in fast acquiring and information retrieval for 3D city models data. The advantages of Hilbert curve in preserving

neighboring information can be benefited for 3D city models application for air dispersion modeling. However, further studies need to be deliberated. This research only focused on buildings as the 3D city object. Since 3D city objects are becoming more sophisticated, therefore other relationship between city objects are needed. Experiment on street furniture and any other objects included in 3D city models should be implemented.

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