Investigating the use of the Euler characteristic as part of fitness-for-purpose assessment of 3D city models

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Summary
Three-dimensional geospatial information is increasingly used for tasks beyond simple visualisation. There is a need to quantify and describe 3D datasets to users to enable an informed selection of datasets for specific visualisation or analytical tasks. This study investigates the suitability of the Euler characteristic as part of fitness-for-purpose assessment of 3D city. The metric was calculated for nine 3D city models. Four datasets contained over 70% buildings represented by closed, simple polyhedral, while the rest exhibited a range of different profiles. Though less visually appealing, the lower computational load required is better suited for 3D analyses.

KEYWORDS: 3D GIS, 3D geoinformation, 3D data quality, 3D city models, geometric errors

1. Introduction

Three-dimensional geospatial information (3D GI) is being increasingly used in a large range of tasks beyond visualisation, with an expectation of 3D capability both among specialist users and the public (Ellul and Wong, 2015). In recent years, governments and councils around the world have been extending their 2D GIS implementations in cities to 3D (Albrecht and Moser, 2010). These datasets, however, are created in isolation, by different producers, and may be created to a local specification for a specific purpose. This leads to variations in the models' geometric and semantic complexity, as well as the degree of deviation from the corresponding real world objects (Löwner and Gröger, 2016). Inconsistencies in 3D GI datasets may include: the choice of features modelled; the level of geometric detail features is modelled at; the level of semantics; the inclusion of textures; the choice of representation; the file formats used and the delivery mechanisms to potential users (Wong and Ellul, 2016). Biljecki *et al.* (2016a) find that existing 3D CityGML datasets without any geometric or semantic errors are rare and those that are nearly valid are mostly simple LoD1 models.

As 3D datasets vary intrinsically and extrinsically, there is a need to quantify and describe 3D datasets to users to enable an informed selection of datasets for specific visualisation or analytical tasks. Existing measures of 3D data such as CityGML's concept of level of detail (LoD) (Kolbe *et al.*, 2005) are perhaps only partially sufficient in fully communicating data quality and fitness-for-purpose as the specification is not unambiguous (Biljecki *et al.*, 2016b). Wong and Ellul (2016) explores the use of geometry-based metrics to provide users with additional information on 3D city models as part of fitness-for-purpose evaluations. It was further suggested to explore whether 3D data quality measure from other fields could be applicable in the context of 3D GI. Within geometry processing, the Euler formula or Euler characteristic (1) is used to calculate the genus of meshes (Botsch *et al.*, 2010). It utilises the relation between the number of vertices v, edges e and faces f such that topologically closed surfaces return a value of $2(1\text{-}g)$ where g is the genus.

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$$E = v - e + f \quad (1)$$

In this study, the use of the Euler characteristic to identify geometric errors in existing 3D city models is investigated. It continues work on geometry-based metrics developed by Wong and Ellul (2016) to analyse the variation of complexity within 3D city datasets. Here, it is assumed that users of 3D city models desire buildings which are composed of predominantly simple convex polyhedral or platonic solids with genus 0 ($E = 2$) using the fewest required vertices, edges and faces in the presentation. In contrast, non-simple polyhedral which may have holes and duplicate, redundant vertices, edges and faces are less desirable (Figure 1). It must be noted that this is an assumption – as the influence of errors and representations on specific spatial analyses has not been fully investigated (Biljecki *et al.*, 2016a). Volume calculations and rendering operations benefit from simple and closed polyhedral, with a defined inside and outside. The study considers whether the Euler characteristic can help identify and distinguish the level of geometric errors present with a dataset and provide users more information to allow for more effective assessment of fitness-for-purpose of the dataset.

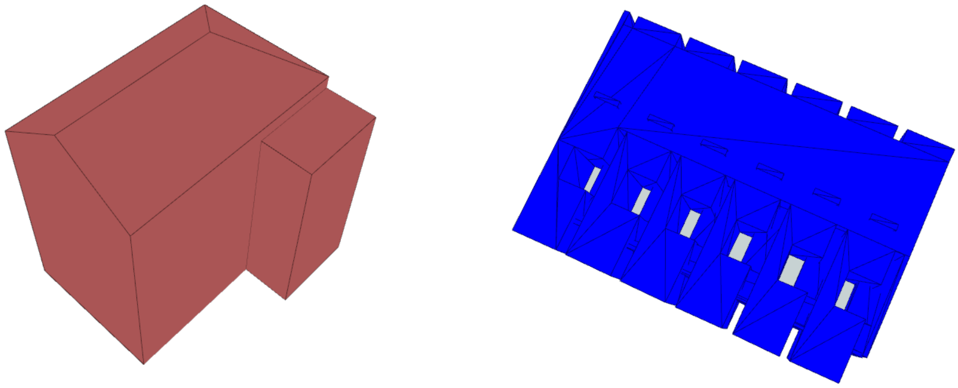

Figure 1 Simple (left) vs. non-simple polyhedral (right)

2. Methodology

2.1. Data

Nine 3D city datasets were selected and presented in this study. Due to the cost-prohibitive nature of commercial 3D datasets, the selection criterion was for the data to be freely available. The datasets include:

1) Berlin, Germany (Berlin Business Location Center, 2016);
2) Adelaide, Australia (Adelaide City Council, 2016);
3) Washington D. C., USA (District of Columbia, 2016);
4) Frankfurt, Germany [city centre only] (Stadtvermessungsamt Frankfurt am Main, 2016);
5) Rotterdam, The Netherlands (Geemente Rotterdam, 2016);
6) New York, USA [1] (Technische Universität München, 2015);
7) New York, USA [2] (NYC DoITT, 2016);
8) Montreal, Canada (Ville de Montréal, 2016);
9) Sheffield, UK (Ordnance Survey, 2014).

While it is recognised that this is not an exhaustive list of 3D datasets available, it provides an overview of the current datasets available to GI users. It must be noted that this study is not a judge on the quality of the 3D city models, but rather an investigation into the difference approaches and to quantify whether a consistent geometry-based metric can be used to describe them to users. Further details on the datasets such as delivery formats and method of reconstruction can be found in Wong & Ellul (2016).

2.2. **Method**

Each dataset was converted from its delivery format and stored in an Oracle Spatial Database 11g using FME 2014 SP1. The storage in a spatial database with a spatial index allowed for efficient interrogation of the geometry at the city scale while providing consistency between datasets when querying. Following conversion, a custom Java parser automatically generated the metrics individually for each building to calculate the Euler characteristic, storing the results back into the database.

3. Results

The results and the performance of the metric calculations are presented below (Tables 1 & 2).

Table 1 Performance of the metric calculations

Dataset	Total Rows	No. of buildings	Time taken (seconds)	Time per 1,000 entries (seconds)
Berlin	2,917,890	537,208	547.44	1.02
Adelaide	4,570	4,569	175.65	38.44
Washington	103,073	51,886	152.84	2.95
Frankfurt	143,284	10,588	9.22	0.87
Rotterdam	545,116	181,686	766.38	4.22
New York [1]	1,082,015	1,082,015	890.00	0.82
New York [2]	12,965,603	1,083,437	1,427.77	1.32
Montreal	36,516	12,051	85.44	7.09
Sheffield	5,034	1,678	6.42	3.83

Table 2 Euler characteristic of the city models by percentage of total buildings

E	**BER** %	**ADE** %	**WAS** %	**FRA** %	**ROT** %	**NY [1]** %	**NY [2]** %	**MON** %	**SHE** %
<-4	22.65	28.01	17.02	0.00	12.84	0.00	0.75	1.43	0.00
-4	0.15	2.04	2.91	0.02	3.26	0.00	0.57	0.31	0.06
-3	0.15	2.36	3.90	0.04	3.87	0.00	0.03	0.61	0.00
-2	0.42	2.52	5.37	0.09	5.74	0.02	5.22	0.73	0.25
-1	0.54	2.41	7.43	0.26	10.22	0.00	0.05	1.03	0.63
0	1.69	2.52	9.07	1.11	22.71	0.15	20.62	2.26	1.01
1	0.76	2.67	28.95	2.45	26.13	0.00	0.02	3.25	31.57
2	90.22	3.66	10.83	89.17	13.87	99.83	71.43	86.94	8.99
3	0.15	2.87	4.44	0.55	1.19	0.00	0.01	0.12	3.71
4	3.48	3.52	2.05	3.87	0.12	0.00	0.59	2.15	1.95
5	0.05	3.61	1.47	0.22	0.03	0.00	0.00	0.04	2.01
6	0.96	3.94	1.14	1.29	0.01	0.00	0.12	0.61	4.84
7	0.02	3.52	0.92	0.06	0.01	0.00	0.00	0.02	2.39
8	0.35	3.11	0.56	0.40	0.00	0.00	0.16	0.28	3.08
9	0.04	3.04	0.84	0.07	0.00	0.00	0.03	0.00	6.10
>10	0.79	30.20	3.10	0.42	0.00	0.00	0.39	0.22	33.40

4. Discussion

In general, Berlin, Frankfurt, Montreal and New York [1] and New York [2] returns the highest percentage of buildings where E = 2. Conversely, Adelaide presents some very extreme values, with almost 60% with E lower than -4 or higher than 10. Similarly, Washington present a range of Euler characteristic values. This may reflect the complexity derived from the choice of modelling tools as the datasets were created from Autodesk 3DS max models (Figure 2). Sheffield has 31.57% buildings with E = 1. Upon closer inspection, the buildings lack a ground surface and wall surfaces are extended to the ground (Figure 3). Rotterdam is evenly distributed between -4 and 2, although the source of the variety was difficult to determine.

4.1. Applying the metrics in practice

The datasets which consisted of a high number of closed and simple polyhedral should theoretically have a lower computational load as they contain fewer redundant detail for the same representation. Further, the ability to identify “inside” and “outside” of a polyhedral is beneficial for 3D analysis which require volumetric calculations such as flood modelling. As the data contain less geometric detail, the buildings may appear more generalised (LoD 1 and 2) and be less appealing for visualisation. However, for spatial analyses such as the application of 3D noise mapping, having more detailed and complex geometry is, in fact, not beneficial (Deng *et al.*, 2016). A trade-off must be made between the adequacy of 3D detail, the visual impact of the resulting 3D dataset, the suitability of the response times and the overall usability of the 3D model (Ellul and Altenbuchner, 2014).

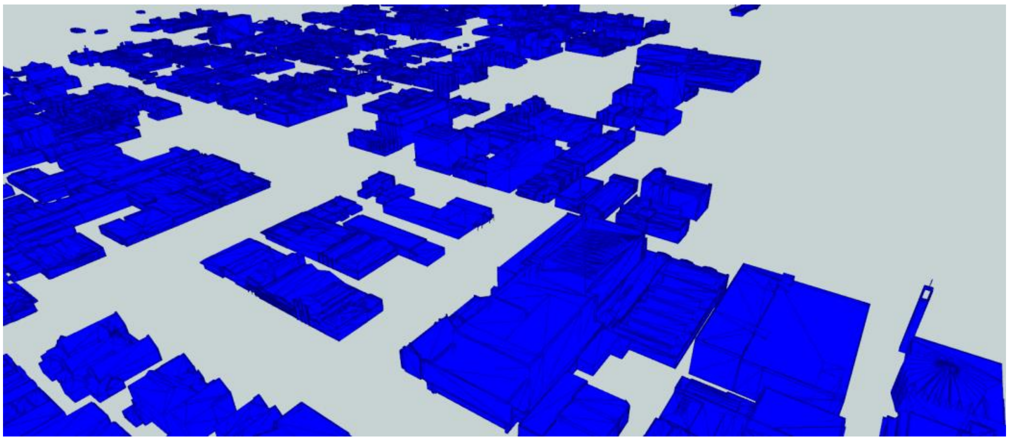

Figure 2 Geometric complexity of Adelaide 3D city model

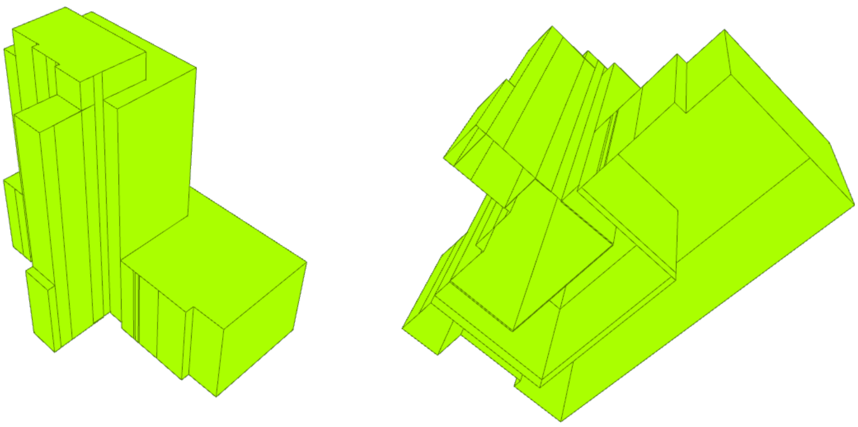

Figure 3 Sheffield – Example of walls extending down into the building

4.2. Recommendations and future work

Several recommendations arise from this study. There is a need to quantify the benefits of closed and simple polyhedral within spatial analyses. Investigation into the usefulness of other geometric measures (minimum height, minimum bounding volume, assessing surface normal vectors) along with the spatial variation of geometric complexity may also be of benefit

5. Conclusion

This study provides an investigation into the use of the Euler characteristic as an indicator of geometric errors within existing 3D city models. It demonstrates that automated geometry-based metrics can be used to quickly provide additional information on 3D city models. The Euler characteristic is useful for identifying 3D city models with a high number of closed and simple polyhedral which are best suited for analyses. The metric, however, cannot be used in isolation and without physical inspection of the data. What it provides is a complement to existing data descriptors if backed up with local knowledge, where possible.

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7. Biography

Kelvin Wong is an EngD research engineer at the UCL Centre for Virtual Environments, Interaction and Visualisation, Department of Computer Science, University College London. His research interests focus on the challenges of deploying 3D geographic datasets at a national level, with regards to 3D requirements gathering, 3D usability and 3D data quality.

Claire Ellul is a Lecturer in Geographical Information Science at University College London. Prior to starting her PhD, she spent 10 years as a GIS consultant in the UK and overseas, and now carried out research into the usability of 3D GIS and 3D GIS/BIM integration. She is the founder and current chair of the Association of Geographical Information's 3D Specialist Interest Group.

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