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3D Generalisation of Building Components – An Initial Proof of Concept

Estibaliz Muñumer Herrero[1], Claire Ellul[1], Stefano Cavazzi[2]

[1] Department of Civil, Environmental and Geomatic Engineering, University College London, UK
(estibaliz.herrero.17, c.ellul)@ucl.ac.uk
[2] Ordnance Survey, Southampton, UK – stefano.cavazzi@os.uk

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Abstract

A varied range of applications make use of 3D models nowadays, for instance in urban planning, energy demand studies, solar irradiation, or noise estimation. Acquisition, maintenance, and production of 3D spatial data is costly and laborious, especially at a national level, a great challenge for National Mapping and Cadastral Agencies (NMCAs) – such as Ordnance Survey (OS) for Great Britain. Generalisation is designed to address this challenge, where new datasets are created from a single source by the selection of the desired information and reduction of the amount of detail and data volume. Extensive literature exists in the context of 2D generalisation and automated algorithms exist to remove unwanted detail, however, adding a third dimension complicates the process significantly. Here, a methodology to address this issue is proposed, where the façades of a 3D building are decomposed, rotated, and translated from 3D environment to 2D. Existing automated 2D generalisation operators are applied to building elements and once generalised, they are rotated back to 3D. The outer shell of the resulting generalised 3D building is reconstructed with the independently generalised façade. The results demonstrate a potential flexible, component-based method for 3D generalisation, that could benefit NMCAs.

1. Introduction

Collection and manipulation of 3D geospatial data have increased exponentially in the last decades, driven by the increasing availability of capture methods such as Light Detection and Ranging (LiDAR) and laser scanning, enabling the generation of detailed 3D representations at city or national scale (Li et al., 2016).

The availability of 3D models has in turn driven (and been driven by) applications that make use of the data to prepare a realistic impression of, and interactive visualisation of, cities for applications including navigation or virtual tours (Fino et al., 2022; Koch et al., 2014). Beyond using geospatial data for visualisation purposes, various other use cases make use of 3D models for their applications, for example in solar panel installations, energy simulations or urban planning (Eicker et al., 2015; Leszek, 2015; Wate and Coors, 2015).

For every application, the quantity of content and detail in the model varies – for instance, a tourism application will endeavour to display 3D models of the landmarks at the highest detail. From the generation to the management, and later use of the 3D city model, in order to make 3D city modelling efficient and reusable to address different user needs, many resulting products should be derived from a single detailed source.

In general, acquisition and processing geospatial data are of high cost, in particular at national scales. While specific expenditure on 3D city model creation is not listed, in their annual report, the National Mapping Agency for the UK, Ordnance Survey, presented the cost of sales for the period 2021-22 of £32.4 million and, £31.6 million for the period 2020-21(not including the operating costs of £130.7m for the first period) (Ordnance Survey Limited, 2022), from capturing, maintaining, and providing geospatial data and services.

Reusing data is a common exercise within NMCAs as a strategy to save costs, where maps at different scales and for different audiences are produced from the same data source. In traditional 2D cartography, generalisation is the process where unwanted detail is discarded and only the information of interest is maintained, abstracted and the detail reduced to derive into a coarser product to get a better understanding of it (Robinson et al., 1995). Historically, the NMCAs have benefited from this process and while extensive research has been done for the 2D domain, deriving small-scale products via 3D generalisation is its infancy (Stoter et al., 2017).

Given the cost of 3D data capture, NMCAs could benefit from flexible 3D generalisation approaches where multiple 3D city model outputs are obtained from their core datasets. However, in contrast to 2D, to date there are no clearly established methods of achieving this (see Section 2.3).

The approach presented in this paper explores the exploitation of 2D generalisation algorithms in a 3D context. We derive 3D generalised versions of buildings by decomposing them, extracting building components (e.g., windows), reducing detail by using existing 2D generalisation algorithms and then composing all the generalised building parts back together. This results in a simplified version of the original 3D building model.

Related work in the topic of 3D generalisation and level of detail is presented in Section 2. The data used in this study is presented in Section 3. The steps of the experimental methodology are described in Section 4, and the preliminary obtained results in Section 5. An interpretation of the results and discussion of the limitations is outlined in Section 6. Concluding remarks are enclosed in the last section, Section 7.

2. Related Work

2.1 2D Generalisation

As introduced briefly in Section 1, in the field of cartography, it is given the term generalisation to the process to categorise features and eliminate unwanted details to minimise visual complexity of the final product (Robinson et al., 1995). Years of traditional mapmaking enabled a better understanding of the purpose and process of generalisation: it ensures that the plotted map information is comprehensible for the map readers by preventing overcrowding the resulting map and emphasizing the relevant details. Regardless of the purpose, it enables maximising the return on investment in data capture by a *'create one, use many times'* approach (Ibid).

In the cartographic generalisation literature, Shea and McMaster (1989) proposed a logical framework of the digital generalisation where they aim to focus on the questions *why*, *when*, and *how* to generalise. The authors present a list of 12 generalisation operators - *simplification, smoothing, aggregation, amalgamation, merging, collapse, refinement, typification, exaggeration, enhancement, displacement,* and *classification*, which has been cited and applied by many authors since (Longley et al., 2015; Weibel and Dutton, 1999).

Digital generalisation is now extensively used in practice, with methods being nearly 100% automatic (Revell et al., 2011). The maintenance and updating of the geographic databases from which to produce maps is one major issue for NMCAs (Duchêne et al., 2014), as well as developing processes to where the human interaction is minimised (or even completely scrapped) on the automated generalisation processes (Stoter et al., 2013). Multi-scale maps are produced in a less complex manner via an automated generalisation, a direct benefit for NMCAs to directly reduce costs and time required (Stoter et al., 2017, 2010).

2.2 3D City Models and Applications

An increase of applications using 3D city models – such as air pollution and quality studies (Ghassoun et al., 2015; Kumar et al., 2017) or energy demand estimations (Kaden and Kolbe, 2014) to name a few – has directly impacted the demand for 3D city models.

In the latest decades, modelling real-world phenomena in three dimensions has increased in popularity. In particular for 3D representation of cities, many 3D building models are generated and exchanged based on CityGML, a conceptual model and exchange format issued within the international standard for spatial data agreed by the Open Geospatial Consortium (OGC) (Open Geospatial Consortium, 2021). 3D multi-scale modelling is differentiated in levels of detail (LoD0 to LoD3), where the quantity of information to geometrically portray the real world increase the higher the level of detail is.

A gap between the data needs of specific applications and the standard has led researchers within the field of 3D modelling of cities to present several proposals to enhance OGC's LoD classification in order to add flexibility through building components, to allow better specification of the data requirements of a specific task (Benner et al., 2013; Biljecki et al., 2013; Deng and Cheng, 2015; Löwner et al., 2016, 2013). A widely referenced improved LoD specification by Biljecki et al. (2016a) replaces the above-mentioned specification and supplements it by defining a set of 16 possible 3D representations of the exterior geometry of buildings (Figure 1).

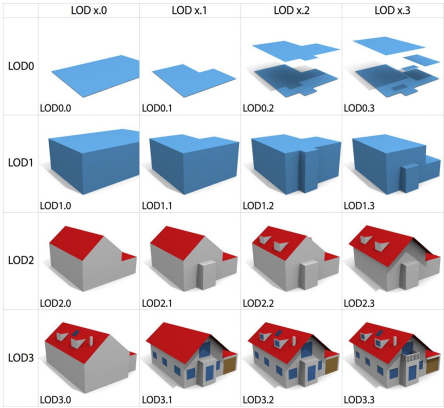

Figure 1. New set of 16 LoDs to define of the exterior geometry of a building (Biljecki et al., 2016a).

2.3 3D Generalisation

To date, the majority of the 3D generalisation approaches focus on automated generation of 3D models of lower LoD (Baig and Rahman, 2013; Forberg, 2007; Kada, 2002; Thiemann and Sester, 2004; Xie and Feng, 2016) and few consider the purpose of the final application (Grabler et al., 2008; Sester and Brenner, 2005). In regard to the façades, generalisation operators have been explored in approaches such as the one presented by Fan et al. where the exterior shell of the 3D building models is extracted and generalised by a typification process to the windows (Fan et al., 2009). Homogenization as generalisation operator is introduced by Guercke where similar object on the façade are detected and replaced by an arrangement in regular grid structure (Guercke, 2014).

In the field of computer graphics, extensive research to simplify 3D meshes exists – algorithms such as edge collapse (Heckbert and Garland, 1997; Hoppe et al., 1993) or vertex clustering (Rossignac and Borrel, 1993) reduce the number of geometric primitives into coarser versions. Salinas et al. present a structure-aware triangle mesh decimation by edge collapse where the model structures are preserved using planar proxies (Salinas et al., 2015).

In general, it is fundamental that automated approaches generate versions of the data that relate specifically to a given task or application (Baig, 2013), since each application will have specific detailed requirements for the generalised output (Wong, 2018).

3. Data

In order to explore the possibilities of the proposed approach, the input data consists of 3D buildings with detailed features on the façade, such as windows or doors, characteristics of an LoD3 building among the classification of levels of detail stablished for the CityGML conceptual standard (Open Geospatial Consortium, 2021). The initial building is a sample generated exclusively for this experiment (see Section 3.1), while the second belongs to the synthetic city *Random3Dcity* (Biljecki et al., 2016b) (see Section 3.2).

3.1 Input Data 1: Sample Building

The first input 3D building is a vector geometry (a set of points, lines, and polygons) created in a PostgreSQL relational database with the extension for spatial data PostGIS[1] (Figure 2).

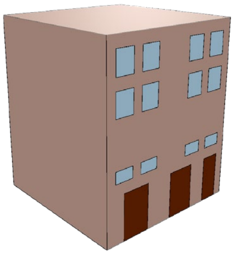

Figure 2. The original sample building with detailed windows and doors.

Since the proposed 3D generalisation approach is focused on building features on the façade, as starting point of exploration, the sample building consists of a flat roof. Aiming to depict a building of a high street, only the front façade of the building contains detailed features.

3.2 Input Data 2: *Random3Dcity* Building

As part of his PhD research, Biljecki (2017) released a project named *Random3Dcity* where a set of CityGML buildings in various LoDs are developed. This open source 3D dataset at level of detail LoD3.3 has been downloaded (Figure 3) and the first building from the top left of the set chosen as input for the presented methodology (Figure 4).

Figure 3. Some of the downloaded 3D buildings from *Random3Dcity* at level of detail LoD3.3 (Biljecki, 2017).

Unlike the other input building (see Section 3.1), the chosen building contains features on every façade (particularly windows).

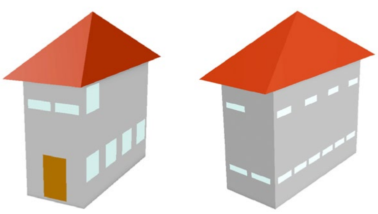

Figure 4. The chosen building, front (left) and back (right) perspective views (Biljecki, 2017).

[1] https://postgis.net/ Accessed 1st February 2024

4. Methodology

Extensive research into generalisation in 2D has provided for well-developed tools and algorithms for operations such as simplification (Douglas and Peucker, 1973) and aggregation (Bader and Weibel, 1997; Müller and Zeshen, 1992). As a stepping stone towards effective 3D generalisation algorithms (in particular in commercial software), previous research has exploited existing 2D generalisation operators, such as simplification and aggregation, to achieve generalisation in 3D, focussing on building footprints (Ellul and Joubran, 2012; Muñumer Herrero et al., 2018).

This research extends the 2D/3D concept. The proposed methodology aims to obtain a generalised version of a given 3D building via existing 2D generalisation algorithms, in a process split in five steps (see Figure 5) which are described in the sections below.

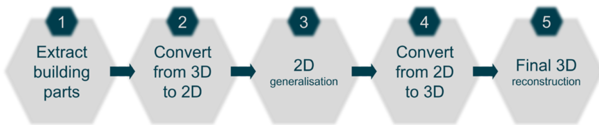

Figure 5. Steps involved in the proposed methodology.

4.1 Step 1: Extraction of Building Parts

Existing commercial software packages enable the visualisation and manipulation of 3D vector data. For instance, ArcGIS Pro facilitates manual and by-attributes selection, edit, and export[2] of the features of interest, which in this case are the façades and the components on those. Where a given 3D building model is in a format different to an ESRI Shapefile (for example, a CityGML building), the data type will be transformed into this format first. Commercial software such as FME[3] performs this transformation.

To facilitate the automation of the tasks that may be repeated for every building part, a Python[4] script is compiled, where the previously exported 3D polygon features (e.g., windows) are converted into a Pandas[5] data frame containing the information of every point such as identifiers, other descriptive attributes, coordinates, and spatial reference.

4.2 Step 2: Transformation From 3D To 2D

To ensure the verticality of the façade (or elements on it) exported on the previous step, a rotation matrix in Z axis, $R_z(\theta)$, is calculated, where the rotation angle θ is calculated by means of the points original XYZ coordinates.

$$R_z(\theta) = \begin{bmatrix} cos\theta & -sin\theta & 0 \\ sin\theta & cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (1)$$

where R_z = Rotation matrix on Z axis
θ = Rotation angle

[2] https://pro.arcgis.com/en/pro-app/latest/tool-reference/conversion/export-features.htm Accessed 1st February 2024
[3] https://docs.safe.com/fme/html/FME-Form-Documentation/FME-Form/Workbench/transforming-data.htm Accessed 1st February 2024
[4] https://www.python.org/ Accessed 1st February 2024
[5] https://pandas.pydata.org/docs/index.html Accessed 1st February 2024

By applying this rotation to every original node, possible inclinations disappear, and it is considered that all the points are on a vertical plane. As well as the original XYZ coordinates, the rotation angle, and the new coordinates of the rotated points (in Z axis) are stored.

Transformation from 3D to 2D implies plotting a vertical plane onto a horizontal plane. Therefore, a new rotation matrix is applied, in Y axis, and the rotation angle now being 90 degrees.

$$R_y(90°) = \begin{bmatrix} cos90° & 0 & sin90° \\ 0 & 1 & 0 \\ -sin90° & 0 & cos90° \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ -1 & 0 & 0 \end{bmatrix} \quad (2)$$

where R_y = Rotation matrix on Y axis

Following this step, a translation based on the minimum and maximum rotated coordinate values of the whole set of points is calculated and applied to get the new coordinates.

$$\begin{aligned} T_x &= -\min\left(X_{R_y}\right) \rightarrow X_T = X_{R_y} + T_x \\ T_y &= -\min\left(Y_{R_y}\right) \rightarrow Y_T = Y_{R_y} + T_y \\ T_z &= -\max\left(Z_{R_y}\right) \rightarrow Z_T = Z_{R_y} + T_z \end{aligned} \quad (3)$$

where T_x, T_y, T_z = Translations on axis X, Y and Z.
X_{Ry}, Y_{Ry}, Z_{Ry} = XYZ coordinates after $R_y(90°)$
X_T, Y_T, Z_T = XYZ coordinates after translation

Lastly, the translated coordinates of every node, along with other information such as identifiers and attributes are used to merge the points belonging to the same polygon and the geometry of those is calculated and stored in a geopandas dataframe[6], which can be exported to an ESRI shapefile for visual inspection in a GIS software.

4.3 Step 3: 2D Generalisation

ESRI's ArcPy is used for this process, which contains a set of modules to perform different geospatial analysis and data manipulation. Within the Cartography toolbox, some of 2D generalisation operators are included[7], enabling automatization. The 2D generalisation operator used to test in the proposed methodology is the aggregation of polygons with a tolerance of 1m. For this initial experiment, no minimum area or hole size has been set.

After running this operator, a smaller number of 2D polygons is expected. The rotation and translation values stored in the input 2D polygon feature class are stored in the aggregated polygon feature class too.

4.4 Step 4: Transformation From 2D To 3D

As well as geometry, the aggregated polygon feature class contains the translation values applied in Section 4.2 and the rotation angle in Z axis. All those attributes, along with the 90 degrees of rotation in Y axis, are stored into a dataframe and a composed Python script inversely calculates the 3D coordinates of those polygons as:

- An initial value of Z=0 is given to the aggregated polygons as they only contain XY coordinate values.
- To the XYZ coordinate values, the stored translation values are taken of so that the translated coordinates are calculated.
- A rotation in Y axis of -90º is applied and new XYZ_{Ry} are calculated, which means that the polygons are now on a vertical plane.
- Ensuring that any existing initial façade inclinations are restored, the saved rotation in Z angle is used to inversely rotate the vertical plane in Z axis. The 'rotated in Z' coordinates can be now considered as the generalised XYZ coordinates.

The dataframe containing the generalised coordinates is exported to a ESRI compatible point feature class, as well as converted into a geodataframe to convert the generalised XYZ values into point type of geometry. Then, identifiers and attributes for every point stored enable arranging and combining the points belonging to the same polygon and creating a polygon type of geometry. Lastly, the geodataframe is exported to an ESRI shapefile.

4.5 Step 5: Final Generalised 3D Building

The methodology process presented from Section 4.1 to Section 4.4 is run for every façade where the level of detail is to be reduced, and stitching all the façades together, a generalised 3D building is obtained.

5. Results

Both the sample (Section 3.1) and Random3Dcity (Section 3.2) buildings presented in the data section (Section 3) have been put to test the presented approach (Section 4). For this initial exploration, the façade elements chosen to inspect and generalise were windows.

5.1 Results of Input Data 1: Sample Building

Within ArcGIS Pro, the only façade containing windows is manually selected and the actual windows extracted by selection of attributes (Figure 6– output of step no.1 and input of step no.2). The resulting feature class is imported in the Python script (Section 4.1) and a dataframe listing the identifier, parent polygon, X, Y, and Z coordinates is obtained.

Because the original façade is vertical with no inclination, the angle to rotate around the Z axis is null. While rotating around Z axis is skipped, the vertical plane is shifted to the horizontal plane with a rotation of 90º in the Y axis. The translation values and the translated XYZ coordinates are calculated as in Equation (3) and grouping the points based on the parent polygon id, polygon geometries are generated and inspected in ArcGIS Pro (Figure 6 – output of step no. 2 and input of step no. 3).

The polygons located within a distance below the set threshold are aggregated together and from 12 initial polygons, 4 polygons are created, a reduction of around 33% (Figure 6 – output of step no. 3 and input of step no. 4). The saved translation values are now taken away from the aggregated coordinates and a rotation of -90º around the Y is applied to lift the polygons from a horizontal to a vertical plane. As a result, the generalised coordinates are obtained, and the geometry exported and visualised in ArcGIS Pro (Figure 6– output of step no. 4 and input of step no. 5).

[6] geopandas.org/en/stable/docs/reference/api/geopandas.GeoDataFrame.html Accessed 1st February 2024

[7] https://pro.arcgis.com/en/pro-app/latest/tool-reference/cartography/an-overview-of-the-generalization-toolset.htm Accessed 1st February 2024

https://doi.org/10.5194/isprs-annals-X-4-W5-2024-247-2024

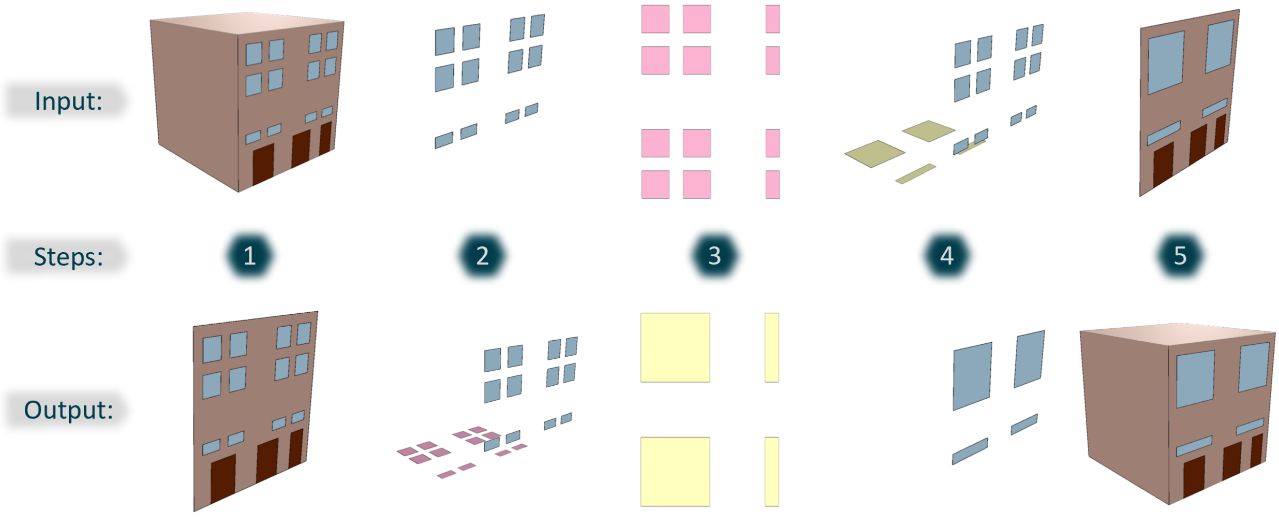

Figure 6: Results of every step of the methodology applied on the original sample building (Section 3.1) -top left. The extracted façade (Step 1) is transformed from 3D to 2D (Step 2) and the polygons in a distance below the threshold aggregates (Step 3). Lastly, the aggregated polygons are inversely transformed from 2D to 3D (Step 4), and together with the rest of the façade, a generalised 3D building is displayed -bottom right (Step 5).

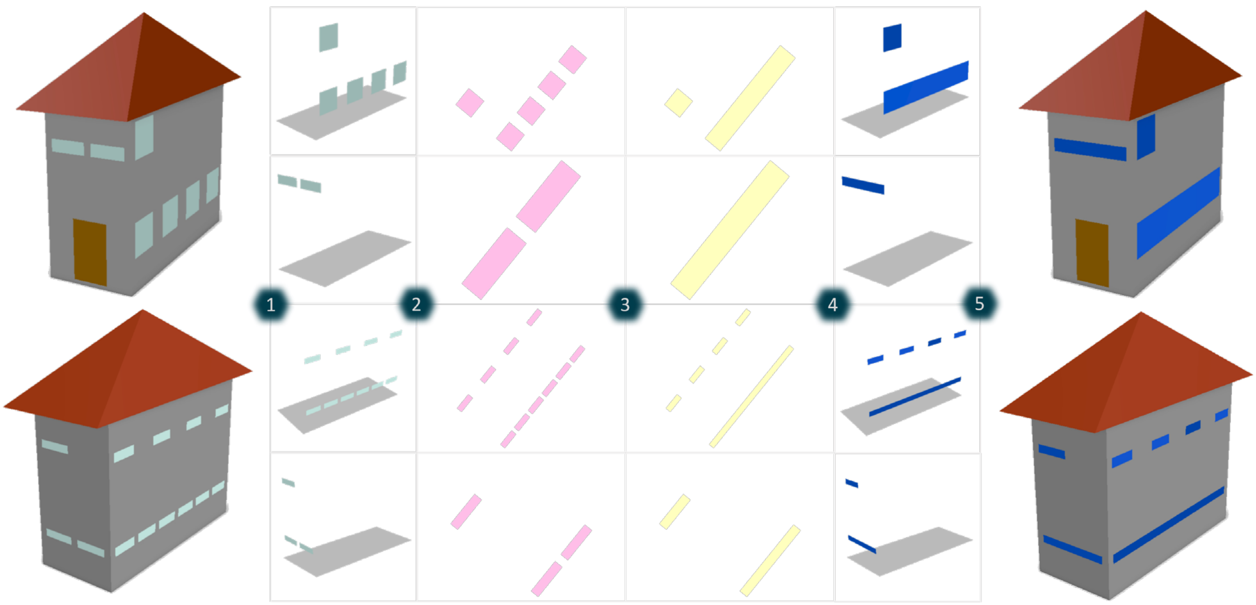

Figure 7. Random3Dcity original building (left) seen from the front and back. Each row from the grid of figures in the middle belong to one of the four walls of the input building, and moving from left to right, in every column the results obtained in every step of the methodology are displayed. The generalised windows (in yellow colour), after being transformed from 2D to 3D (in blue colour) and stitched together in the 3D environment, enable a 3D generalised building (right).

The generalised façade together with the original untouched facades are put together and a resulting 3D generalised building is displayed (Figure 6– output of step no. 5)

5.2 Results of Input Data 2: *Random3Dcity* Building

The downloaded Random3Dcity building is firstly transformed from CityGML to an ESRI shapefile with the commercial software FME, so that the file is in the correct input format to run the Python script (Figure 7 – top and bottom left). The methodology is run on every façade of the input building since they all contain windows, which are selected and extracted manually (Figure 7– first column of the grid - output of step no. 1).

On every façade, due to a slight inclination, a rotation angle around the Z axis and associated rotation matrix in Z are calculated. As a result, the vertical plane is prepared to apply a rotation angle of 90º around Y axis and moved the calculated constant translation distance in the three axes (Figure 7 – second column of the grid - output of step no. 2).

The window polygons in 2D plane ready to be used as input on the automated aggregation generalisation operator. Despite running each façade separately, the total 20 window polygons from the original 3D building were automatically generalised into 10, a reduction of 50% (Figure 7– third column of the grid - output of step no. 3).

The rotation angles and translation values obtained when transforming from 3D to 2D are now used in reverse to transform the generalised geometry from 2D to 3D (Figure 7– fourth column of the grid - output of step no. 4).

The generalisation outputs for every façade, together with other components in the façade (i.e., the door) and the detailed roof – which in the first step of the methodology were ignored as the focus was on windows – are all assembled together, resulting a generalised 3D building (Figure 7 – top and bottom right).

6. Discussion

The experiment carried out revealed promising results for a component-based 3D generalisation of a city building, after obtaining a reduction of detail on the façade components. Lacking in commercially accessible 3D generalisation algorithms, and based on the extensive literature, the proposed approach exploits existing 2D generalisation operators to reduce the level of detail.

Nowadays, commercial software packages offer well-developed tools to run some 2D generalisation operators such as simplification or aggregation. In this preliminary experiment, window polygons within a threshold of 1 meter are aggregated. As presented in Section 5.1 and 0, the number of window polygons on the generalised 3D buildings decreased significantly - a reduction of around 33% for the sample building (Section 3.1) and 50% for the *Random3Dcity* building (Section 3.2) compared to their original 3D versions. These statistics regarding the reduction of number of windows may be useful for some applications such as solar irradiation estimations or indoor illumination predictions.

No other 2D generalisation operator has been tested in the current experiment, partially due to the simplicity of the geometry of windows. In situations where the input features contain more detail, more operators may be considered to increase a reduction of detail. Moreover, only one specific distance tolerance has been explored. Deciding the elements to be generalised, the 2D generalisation operators, the sequence application order and the level of tolerances depend on the purpose and requirements of the final product, set by the use case. In other words, *one size does not fit all* when it comes to generalisation.

6.1 Future work

There is much room for improvement regarding the input data – using different original 3D buildings from different sources and typologies and at different levels of detail, as well as exploring different output variations when different building components are generalised.

We plan to evaluate the presented methodology with an LoD3 CityGML dataset comprising 50 building models from the German city of Ingolstadt[8], which not only plane polygon geometries are included but other more complex geometries such as multipolygons or donut and concave features too.

In relation to the 2D generalisation (Section 4.3), further work is planned to further reduce the amount of detail by applying other 2D generalisation operators – for example simplification or smoothing – which are currently automated and commercially available. Future investigations will include evaluating the results of these generalisation operators to assess whether important geometric properties, such as perpendicularity and spacing between objects, are maintained.

An assessment of whether the geometries of the outcomes of the proposed 3D generalisation approach are valid is required, a task that can be tested by deploying some existing open source validation tools such as *val3dity* (Ledoux, 2018) or *CityDoctor2*[9]. Besides the geometric perspective, validating whether the 3D generalised buildings are applicable to different scenarios such as shadow casting or energy modelling and assess the impact of the generalisation over the analysis is part of the future work. In addition, it has been considered to employ the proposed methodology on a specific use case of particular interest of the Ordnance Survey.

7. Conclusions

The results obtained from the proposed 3D generalisation approach demonstrate an adaptable, component-based method that could benefit NMCAs. The flexibility of the method in regards of the input features to be generalised, the generalisation operators to apply, and the amount of generalisation desired (tolerance) enable NMCA clients customised 3D outputs, specific to the requirements and purpose of the final application.

Moreover, obtaining different outputs from one single source is of great interest for the NMCAs. The opportunity to achieve different generalised 3D buildings automatically from a single source would benefit the NMCAs in cost, time, and workload. Based on that, they could focus on maximising the benefits from the investment in data capture such as aerial photography, LiDAR or laser scanning.

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