2016 Asim IBPSA Asia Conference Jeju, Korea, November 27-29

Workflow for Generating 3D Urban Models from Open City Data for Performance-Based Urban Design

Kian Wee Chen[1,*], Leslie Norford[2]

[1] CENSAM, Singapore-MIT Alliance for Research and Technology, Singapore,
[2] Department of Architecture, Massachusetts Institute of Technology, USA

ABSTRACT

Urban designers gather and interpret data in the early design stages for two purposes: first, to study similar projects as precedents; and second, to better understand existing site conditions. Interpretation includes the running of environmental analysis on the collected data. The results of the analysis are used as references for a performance-based urban design process. City data are usually available in 2D but environmental analysis requires 3D city data. A method is proposed for calculating the building heights from 2D data for generating 3D urban model. The method uses building footprint and Floor Area Ratio (FAR) data. For Singapore, OpenStreetMap (OSM) has the building footprint data, and the Urban Redevelopment Authority provides the FAR data. The average building height of each plot is calculated from the method. A 3D urban model is generated by extruding the footprint by the calculated average height. The 3D urban model is then used for environmental analysis. The calculation and analysis are integrated into a workflow for urban designers. Designers gather and assemble these data on the QGIS platform. Once assembled, the data is passed to the appropriate tools for 3D generation and analysis. The 3D urban model is documented in CityGML format. The solar photovoltaic energy potential is calculated using the CityGML model with the Daysim lighting simulation. A case study is presented as proof of concept. The 3D urban model with predicted height is compared with the actual height model. The workflow over predicted the building heights by 20%. The PV potential results between the two models differ by 4.72%. Further improvements are suggested for the workflow. These include considering terrain data and having a more comprehensive set of analyses.

KEYWORDS

Performance-Based Design, CityGML, GIS, Open City Data, Workflow

INTRODUCTION

When urban designers embark on a design project they gather and interpret relevant data for two main purposes: first, the study of similar cases for use as precedents; and

* Corresponding author email: kianwee@smart.mit.edu, chenkianwee@gmail.com

second, to better understand the existing conditions of the site. The interpretation process includes performing environmental analyses of the collected data, such as shadow, solar and visibility studies. These analyses require 3D city data (Biljecki et al., 2015). Designers then use the analysis results as references for their design. This aids in setting up a performance-based urban design process and investigating design features of suitable precedents. The performances refer to the results of the analyses.

Data in 3D is not always available for environmental analyses. For example, most of the available urban data in Singapore are 2D. Data in 3D might be available in the future with The Virtual Singapore project (Cheng Wei, 2014), an ongoing project to map Singapore in 3D. It is unclear how the data will be disseminated to the public. An alternative way to obtain 3D data is from OpenStreetMap (OSM). In Germany, researchers have generated 3D urban models with data obtained from OSM (Over et al., 2010). Building footprints from OSM are extruded based on available building heights or storeys data. If no height data are available, a default value is used for the extrusion. The OSMbuildings website also generates 3D models from the height attribute (OSMbuildings, 2016).

The OSM data of Singapore do not have building height, except for a specific region in the city centre. The lack of building heights is a major obstacle in generating a 3D urban model for environment analysis. We proposed a method for calculating the average building height of each plot, using Floor Area Ratio (FAR) (referred as plot ratio in Singapore) and building footprints. Singapore's Urban Redevelopment Authority (URA) zoning master plan has the FAR data, and OSM has the building footprint data. Buildings in each plot are extruded based on the calculated average height. The 3D urban model is documented in cityGML format. Environment analysis is then conducted on the cityGML model. We conducted a solar analysis on the model using the Daysim lighting simulation (Daysim, 2016). The analysis assesses the solar photovoltaic (PV) potential of the buildings' surfaces. We then integrate the calculation and analysis into a workflow for urban designers.

The workflow is developed for generating a 3D model of residential new towns in Singapore. The new towns are 4-10km^2, and each plot is 2 – 10 hectare. We believe a 3D urban model generated from average building height of each plot, is sufficient for an assessment of its environmental performances. We compared the 3D model with the predicted height to a 3D model with the actual height to validate the workflow. This paper is structured as follows: the method section elaborates on the workflow. The workflow includes data collection, 3D urban model generation and solar analysis. The workflow is demonstrated on a case study and compared to a 3D model with actual heights. Lastly, the conclusion section looks at the limitations and further investigations of this workflow.

METHOD

The workflow relies on open and free tools so that it can be readily adopted by designers. It uses QuantumGIS (QGIS) and Pyliburo for the generation and analysis of a 3D urban model. QGIS is an application for sorting and assembling Geographic Information System (GIS) data. Python Library for Urban Optimsation (Pyliburo) is a python library developed by the authors. It uses open libraries such as pythonocc, lxml and pyshp. The library is available on https://github.com/chenkianwee/pyliburo. The pyshp package reads and writes shapefiles. We developed a python package pycitygml using lxml to read and write cityGML files. Another package called py2radiance is developed to facilitate the execution of Daysim lighting simulations. The pythonocc package is used for extruding the building footprint. As illustrated in *Figure 1*, the workflow is as follows:

1. Extract the region of interest from OSM using its export function. The OSM data can be directly imported into QGIS.
2. Download the region of interest of the zoning master plan from the URA website (URA, 2014). Import and georeference the raster image of the master plan in QGIS.
3. Once all the necessary data are sorted and assembled on QGIS, export all the data as shapefiles.
4. The module shp2citygml is written using pyshp, pytcitygml and pythonocc. Shp2citygml uses the shapefiles data to calculate the average height of each plot. The module extrudes the footprints and generates a 3D CityGML.
5. The module citygml2eval is written using py2radiance and pycitygml. Citygml2eval takes the Citygml file as input and executes the PV potential calculation.
6. We developed the workflow to account for the availability of 3D data. Pycitygml converts the 3D data into CityGML format for citygml2eval module to run the analyses.

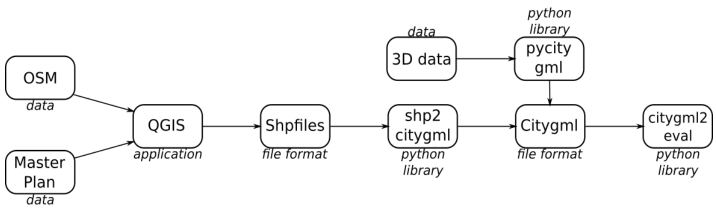

***Figure 1** Workflow summary*

Building heights calculation for generating 3D urban model

The OSM of Singapore provides building footprints, road networks, and public transportation network. Most of the buildings do not have height data. FAR and plot area data are available on the Singapore URA's zoning master plan. FAR is the ratio of Gross Floor Area (GFA) of all the buildings, $GFA_{total,}$ to the plot area, A_{plot}. It is shown in equation (1).

$$FAR = \frac{GFA_{total}}{A_{plot}} \quad (1)$$

Using data from the master plan, GFA_{total} is obtained by multiplying A_{plot} and FAR. The total building footprint area is the sum of all the footprint areas. The total footprint area excludes buildings that are not counted as GFA (URA, 2015). An example is a multi-storey carpark building. These buildings can be identified as most of the OSM building footprints are tagged with their building type. The average number of storeys of each plot, $n_{storeys}$, is calculated by dividing GFA_{total} by the total footprint area. It is shown in equation (2).

$$n_{storeys} = \frac{GFA_{total}}{TotalFootprint\,Area} \quad (2)$$

The multi-storey carpark heights are calculated based on the vehicle parking provision code (LTA, 2011). The minimum provision for carpark spaces is one parking space per residential unit. For commercial zones, it is one parking space per 450m^2 of building floor area. The average size of an apartment in Singapore, $A_{avgapartment}$, is 87.4m^2 (DOS, 2015). The number of houses on a plot, n_{houses} can be obtained by dividing the GFA_{total} by the average size, $A_{avgapartment}$.

$$n_{houses} = \frac{GFA_{total}}{A_{avgapartment}} \quad (3)$$

The parking provision does not specify the requirement of motorcycle lots. According to the census data, the motorcycle ownership, $O_{motorcycle}$, is 2.6 per 100 persons. The average household size, n_{hsize}, is 3.43. The plot population, P_{plot}, can be obtained by multiplying n_{hsize} and n_{houses}. The number of motorcycles parking for each plot, $n_{motorcycles}$, is calculated based on equation (4).

$$n_{motorcycles} = O_{motorcycle} x \frac{P_{plot}}{100} \quad (4)$$

A typical car parking size, A_{clot}, is 2.4m by 4.8m. A typical motorcycle parking size, A_{mlot}, is 1m by 2.5m. The total area required for parking, $A_{parking}$, can be calculated by equation (5), assuming every parking space is associated with the same amount of space for car circulation. Then with $A_{parking}$, the number of storeys for the car park can be calculated by dividing it by the carpark footprint area. This is shown in equation (2).

$$A_{parking} = (2x(n_{cars} x A_{clot})) + (n_{motorcycles} x A_{mlot}) \quad (5)$$

The building footprints are extruded based on the number of storeys. Floor-to-floor height is assumed to be 3m for residential building (HDB, 2014), 4m for commercial buildings (CTBUH, 2015) and 2.5m for multi-storey carparks (LTA, 2011). There are plots without FAR data. The footprints on these plots are extruded based on default height according to its land use. For example, a civic building is always four storeys. The generated 3D urban model is then documented as a cityGML.

Solar analysis for performance-based urban design – photovoltaic area index

The solar analysis is conducted using the GenCumulativeSky module (Robinson and Stone, 2004) in the Daysim lighting package (Daysim, 2016). The module calculates the cumulative solar irradiation falling on a surface over a given period of time. The analysis is conducted on the building façade and roof surfaces. The irradiation threshold value is the minimum amount of irradiation required for PV installation. For the façade area, the threshold value is 512kWh/m^2. For the roof surface area, the threshold value is 1280 kWh/m^2. As a rule of thumb, the thresholds are 80% of the annual irradiation falling on the roof and façade of a specific location. The annual irradiation falling on the roof is 1600kWh/m^2 and the façade receive about 40% of the roof irradiation (Luther and Reindl, 2013).

S_t is the surface area receiving irradiation equal or greater than the threshold. The PV area index, PVAI, is S_t normalised by the net surface area, S_n and expressed as percentage, as shown in equation (6). Both S_t and S_n include the surface area of the roof and façade. If only the façade or roof area is used for the calculation, it is referred as PV Façade Area Index (PVFAI) or PV Roof Area Index (PVRAI). The calculation is based on Compagnon, (2004) paper.

$$PVAI = \frac{S_t}{S_n} x100 \quad (6)$$

DEMONSTRATION

The workflow is demonstrated on a case study, Punggol New Town in Singapore. It is 9.34 km^2 and predominantly a residential area with a mix of commercial, education and civic buildings. The workflow generated a total of 579 buildings, one Mass Rapid Transport (MRT) station, seven Light Rail Transport (LRT) stations, 74 bus stops and roads. A step-by-step guide for generating and analysing the 3D model is available on https://www.gitbook.com/book/chenkianwee/generate-and-solar-analyse-urban-3d-model/details. *Figure 2* shows the generated 3D urban model for Punggol. The 3D model is used as input for the PVAI calculation. The results are shown in *Table 1*. The indices express the potential of an urban design to employ PV panels, as a reference point for comparison studies. It is possible to see how well a new design is performing as compared to an existing new town.

Table 1 *Results of the PVAI calculation on predicted level model*

	PVAI (%)	PVFAI (%)	PVRAI (%)
Predicted Level Model	50.38	42.62	95.10

Figure 2 *Punggol 3D model*

Validation of 3D urban model

In order to validate the method, we collected actual building storey data for 510 buildings from Punggol. The storey data was obtained from checking building lift lobbies, a more manageable task than measuring the building heights. The ratio of the predicted storeys to the actual storeys, $S_{predicted}/S_{actual}$, is calculated for the 510 buildings. The results are shown in *Table 2* 아래. The method over-predicted the building height by 20%, as shown by the $S_{predicted}/S_{actual}$ mean. There are 264 buildings that have predicted height within a 20% error range, $n_{buildings20}$. These buildings are mainly residential towers. The $S_{predicted}/S_{actual}$ median, maximum and minimum give a distribution of the errors within the buildings.

Table 2 *Results of the ratio of predicted storeys over actual storeys for the 510 buildings*

$S_{predicted}/S_{actual}$ Mean	$S_{predicted}/S_{actual}$ Median	$S_{predicted}/S_{actual}$ Minimum	$S_{predicted}/S_{actual}$ Maximum	$n_{buildings20}$
1.20	0.82	0.22	15.0	264

Most of the error in prediction is due to the mix of building heights within a plot. For example, there is a one storey club house building mixed with a series of 16 storeys residential block in a plot. The predicted average height is 15 storeys for all the buildings on the plot. As a result, the one storey clubhouse gave the maximum error of 15. Another cause of prediction error is due to the complex geometries of the buildings. These geometries include buildings towers on the podium and stepped buildings with varying heights. Building footprints extrusion are not capable of generating complex 3D forms.

A 3D urban model was generated using the actual building level information. The PVAI was calculated using the actual level model. As shown in *Table 3*, the PVAI is compared to the PVAI from the predicted level model in *Table 1*. We over predicted the PVAI by 4.72%, PVFAI by 2.29% and PVRAI by 12.83%. The over predictions are an acceptable trade-off. It is a huge amount of work to obtain the actual building level information. In this case, it took two weeks for a person to collect the building level information. It only took a day to download and prepare all the relevant information from the internet for the proposed workflow.

***Table 3** Results of the PVAI calculation on actual level model*

	PVAI (%)	PVFAI (%)	PVRAI (%)
Actual Level Model	45.66	40.33	82.27

CONCLUSION

This paper presented a workflow for rapid generation and analysis of 3D urban model from open city data. The demonstration showed the feasibility of the workflow by generating a 3D urban model from FAR and building footprint data. The generated 3D urban model is then analysed for its PV potential. We compared the results from the generated model to an actual height model. There were over predictions in the predicted height and the PV potentials. The over predictions were within an acceptable range. The over predictions due to the use of online open data were a reasonable trade-offs compared to the time required for on the ground data collection. The workflow uses open and free tools. All the information and tools can be downloaded online as stated in the previous sections. Urban designers can readily adopt the workflow without any extra monetary cost. They are able to quickly generate a 3D urban model for precedent studies or to better understand existing site condition.

Further investigations include solving two limitations mentioned in the validation section. First, account for height differences between buildings in a plot. This can be addressed by letting urban designers specify the building types on the plot. The height is then calculated according to the building type. The typical building storeys of a building type is taken into account when predicting the building heights. Second, generating buildings with complex 3D geometries. For example, if the tower footprint overlaps with the podium footprint, it is assumed that the building is a tower on a podium type.

Currently, the workflow does not consider terrain data. This is not critical for Punggol because the site is flat. However, for more hilly areas, terrain data will have a significant impact on the performances. Terrain data needs to be integrated into the workflow. Lastly, a more extensive set of environmental calculations is required, to aid urban designers in better assessing the urban design.

ACKNOWLEDGEMENTS
This research is supported by the National Research Foundation Singapore under its Campus for Research Excellence and Technological Enterprise programme. The Centre for Environmental Sensing and Modeling is an interdisciplinary research group of the Singapore MIT Alliance for Research and Technology. Thanks to Andrew Rouditchenko for the collection of Punggol building level data.

REFERENCES
Biljecki, F., Stoter, J., Ledoux, H., Zlatanova, S., Çöltekin, A., 2015. Applications of 3D City Models: State of the Art Review. ISPRS Int. J. Geo-Inf. 4, 2842. doi:10.3390/ijgi4042842

Cheng Wei, A., 2014. Interactive 3-D map of Singapore to be ready by 2017: National Research Foundation. Straits Times.

Compagnon, R., 2004. Solar and daylight availability in the urban fabric. Proc. Int. Conf. Sol. Energy Build. CISBAT 2001 36, 321–328. doi:10.1016/j.enbuild.2004.01.009

CTBUH, 2015. Height Calculator [WWW Document]. URL http://www.ctbuh.org/TallBuildings/HeightStatistics/HeightCalculator/tabid/1007/language/en-GB/Default.aspx

Daysim, 2016. Daysim Advanced Daylight Simulation Software [WWW Document]. URL http://daysim.ning.com/ (accessed 11.28.14).

DOS, S., 2015. Department of Statistics Singapore [WWW Document]. URL http://www.singstat.gov.sg/

HDB, 2014. Precast Pictorial Guide. Housing Development Board Singapore, Singapore.

LTA, S., 2011. Code of Practice: Vehicle Parking Provision in Development Proposals.

Luther, J., Reindl, T., 2013. Solar Photovoltaic (PV) Roadmap for Singapore (A Summary). Solar Energy Research Institute of Singapore (SERIS), Singapore.

OSMbuildings, 2016. OSMbuildings [WWW Document]. URL http://osmbuildings.org/

Over, M., Schilling, A., Neubauer, S., Zipf, A., 2010. Generating web-based 3D City Models from OpenStreetMap: The current situation in Germany. GeoVisualization Digit. CitySpecial Issue Int. Cartogr. Assoc. Comm. GeoVisualization 34, 496–507. doi:10.1016/j.compenvurbsys.2010.05.001

Robinson, D., Stone, A., 2004. Irradiation modelling made simple: the cumulative sky approach and its applications. Presented at the Plea2004 - The 21st Conference on Passive and Low Energy Architecture, Eindhoven, The Netherlands.

URA, 2014. Singapore Master Plan [WWW Document]. URL https://www.ura.gov.sg/uol/master-plan.aspx?p1=view-master-plan (accessed 6.21.16).

URA, S., 2015. Handbook on Gross Floor Area.