Detecting, Modeling and Predicting Vertical Urban Growth: An exploratory review

Yuanyuan Huang*[12], Yan Liu[12]and Scott N. Lieske[1]

[1] School of Earth and Environmental Sciences, The University of Queensland, Brisbane QLD 4072, Australia
[2]Spatio-Temporal Analytics Research Laboratory (STAR Lab), The University of Queensland, Brisbane QLD 4072, Australia
*Email: yuanyuan.huang@uq.edu.au

Abstract

Cities across the globe have been growing both horizontally and vertically to accommodate growing populations within limited land. Despite extensive research on urban sprawl, contemporary research on vertical urban development remains limited. This paper presents an exploratory review of the literature on vertical urban growth (VUG) based on academic papers published over the past three decades. Three thematic areas were identified, including approaches defining and extracting VUG, the identification of factors driving VUG, as well as models simulating and predicting VUG. Our results show that a diverse range of methods exist in defining and measuring VUG, ranging from the use of building heights or building floors to urban intensity, floor-to-area ratio, and urban functional complexity. While some research used building information data over time to define VUG, the most commonly used data derives from remote sense imagery, including Synthetic Aperture Radar imagery and Lidar data. Recent research uses Google Earth and OpenStreetMap as source data to extract building heights or number of building floors. On the other hand, only limited work is available in understanding and modeling the driving factors that lead to vertical urban growth. Cellular automata (CA) modeling, which has been commonly used to simulate horizontal urban expansion over the past four decades, are beginning to be used to simulate VUG and generate future growth scenarios. We argue that future research in this field should address the challenges in modeling vertical urban growth, particularly reliable data to parameterization, the configuration and validation of the 3D urban models, and the simulation of VUG under different scenarios and driving factors. We also call for more research to simulate the processes of urban demolition and shrinkage in the vertical dimensions, as well as the underground expansion in our urban space.

Keywords: Vertical urban growth, 3D geosimulation, urban change modelling, cellular automata, exploratory review.

1. Introduction

It is widely accepted that the continuous growth of the global population leads to the growth of cities. Urban development is a multi-dimensional process that involves changes in urban form in both the horizontal and vertical dimensions. Historically, most cities have accommodated urban population growth by developing low-density buildings horizontally, often referred to as urban sprawl. With the conflict of continual population growth and limited buildable land, many cities are experiencing urban consolidation and densification processes with development in the vertical direction. There are examples in North America (Koziatek and Dragićević, 2017), East Asia (Zhang et al., 2018) and other cities worldwide (Steve et al., 2013). This type of vertical urban growth (VUG), a type of urban expansion into the third dimension, is featured by development of mid- to high-rise buildings or even skyscrapers, which supports urban compactness in contemporary urban development process. While considerable research has been conducted in understanding and modeling horizontal urban growth, which is the 2D urban expansion, only limited studies explore the third dimension of a city.

There is a long history of using urban models to understand the processes and dynamics of urban development. There are numerous types of models including transportation models, land-use change and urban growth models, cellular automata (CA) and agent based urban models. As models are not representations of reality but simplifications (DeMers, 2002), one of the major simplifications in land-use change and urban growth modeling is the emphasis on urban 2D space and general lack of explicit consideration of areas above and below ground. As urban space is 3D space, 2D research and modelling cannot reflect the real urban morphology and the temporal and spatial change characteristics of a city. In addition, urban microclimate, such as the heat island effect or urban light pollution result from the mid/high buildings. These issues cannot be fully addressed using 2D models. Research on the 3D space expansion of cities can detect and simulate 3D urban morphology changes more comprehensively and accurately. A full 3D model of a city will allow better understanding of the mechanisms of urban space expansion, and help predict 3D urban land use scenarios, which could provide critical information for urban planning.

This paper presents an exploratory review of the literature on VUG. Our aim is to identify gaps in the existing literature, particularly potential approaches to utilize VUG models that have not yet been considered and attempt to answer some questions that 2D (horizontal) modeling cannot do. We organize and analyse the literature from three perspectives: 1) How is VUG being perceived and detected? 2) What factors impacting VUG have been identified/modelled? 3) How are models developed and applied to simulate and predict VUG? The next section first introduces the methodology used to conduct this exploratory review, followed by results addressing each of the three perspectives. Discussions on the challenges of VUG are presented in Section 4, and we conclude by identifying future research directions.

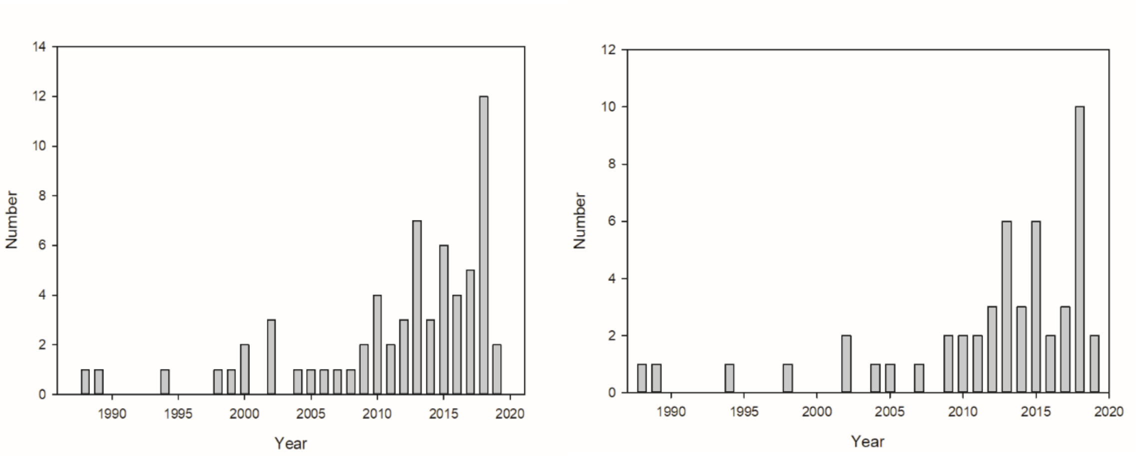
2. Methodology

We started the literature review by searching three databases: Science Direct, Scopus and Web of Science using synonyms in the search strings such as “vertical urban growth” OR “vertical urban development” OR “vertical urban sprawl” OR “vertical urban expansion” OR “vertical city growth” OR “vertical city development” OR “vertical city sprawl” OR “vertical city expansion”. We then refined our search results to be within the related disciplinary areas in geography, planning, urban studies, and manually removed duplications or news articles. We also searched from the reference lists of the selected articles to manually identify those related to VUG. This resulted in a total of 65 unique articles that are used as the subjects in this exploratory review. The date of these papers range for just over three decades from 1988 to 2019. After extracting all abstracts and keywords from the 65 articles being reviewed, we identified three key themes with each corresponding to our research perspectives.

3. Results

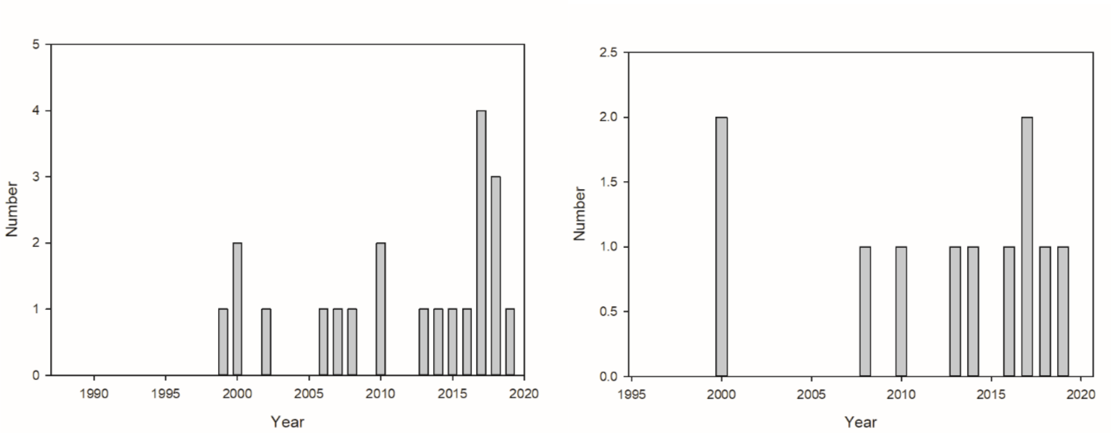
3.1. Number of publications by theme and over time

Out of the total 65 publications, 50 papers (or 76.9%) addressed the first theme on detecting VUG, 21 papers (or 30.8%) address the second theme on identifying and modeling the driving factors for VUG, and 11 papers (or 16.9%) address the third theme on developing 3D models to simulation the VUG. Figure 1 illustrates the total number of articles published in each year from 1988 to 2019 (a), number of articles under each theme (b-d), and different combinations of these three themes (e-h).



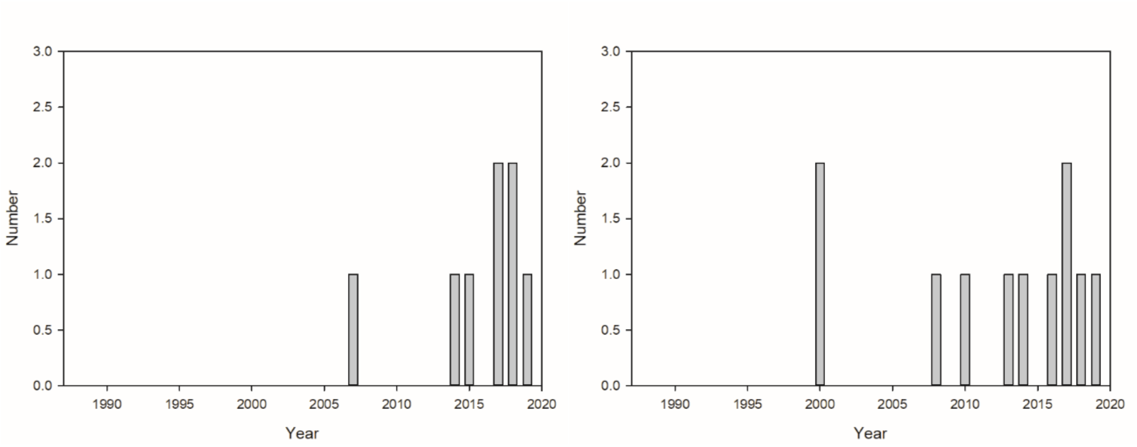
(a) All papers

(b) Theme 1 Detecting VUG

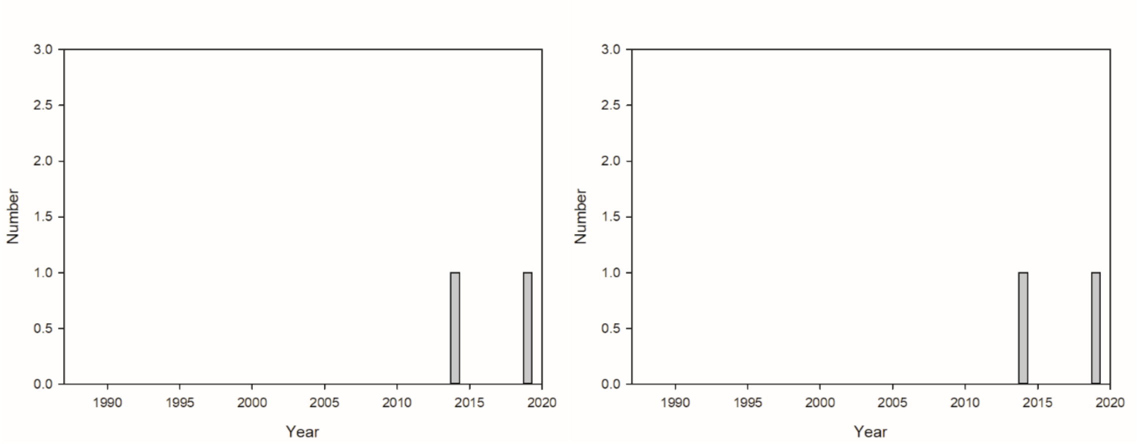


(c) Theme 2 Factors driving VUG

(d) Theme 3 Simulating VUG



(e) The combination of theme 1 and theme 2 (f) The combination of theme 2 and theme 3



(g) The combination of theme 1 and theme 3 (h) The combination of theme 1, theme 2 and theme 3

Figure 1: Number of publications on VUG.

The first paper on VUG was by Huertas and Nevatia (1988), which presents their work on detecting building heights using aerial images. Since then, an increasing number of articles have been published under this first theme, particularly after the year 2010. Research exploring the driving factors to VUG emerged much later, with the first article published by Fan (1999) which explored the driving forces of urban sprawl and vertical urban growth in China. Similarly, research on modeling and simulation of VUG also did not emerge until 2000 when Bell et al. (2000)and Semboloni (2000) published their work on modeling urban dynamic process and urban morphology which also depicts vertical growth. The figure shows that the combination of theme 2 and theme 3 has the same results as the single theme 3. Theme two identifies driving factors as a key component in comprehending and modelling urban development. Theme 3 identifies the same driving factors. Therefore, combining the results of theme 2 and theme 3 reveals these driving factors are critical for urban simulation

3.2. Theme 1: Understanding and detecting VUG

Our analysis of the literature show there is relatively little research on understanding and describing vertical change compared to 2D change in cities. Using the thematic analysis approach, we identified different ways of defining and measuring VUG (Table 1).

Table 1: Different definitions about VUG used in the literature.

Definitions	**Explanation**	**Examples**
Height definition	The change in building heights or number of floors of urban buildings	(Benguigui et al., 2008; Salvati et al., 2013; Zambon et al., 2019; Sanyal and Roychowdhury, 2017)
Building function definition	The increase in multiple functions (uses) of buildings such as commercial, residential and industrial	(Lin et al., 2014)
Building density/compactness definition	Increases in urban building density/compactness by developing medium and high-rise buildings	(Koziatek and Dragicevic, 2017)
Floor-to-area ratio definition	The agglomeration of population and economic activities leads to the increase of floor-to-area ratio, which leads to the vertical expansion of the city	(Zambon et al., 2019)
Building volume definition	The increase in building volumes reflects urban vertical and horizontal growth	(Wurm et al., 2013)

The most direct way to detect the vertical development of a city is to get the height data of city buildings through sources such as building height survey records (Salvati et al., 2013), authorized construction data from Local Urban Planning Bureau (Lin et al., 2014), official statistical sources such as the national census of buildings, building permit surveys and/or building registers (Zambon et al., 2019). More recently, Google Earth (Qi et al., 2016) and OpenStreetMap (Over et al., 2010) have been used as source data for extracting building heights or number of building floors. Apart from these data sources, the most commonly used data source for building heights and their change over time is remotely sensed data (Table 2).

Table 2: Remote sensing data used to detect VUG.

Sensors type	Data	Author/Year	Method
Active sensors/ Radar Remote Sensing	SAR imagery	(Brunner et al., 2010)	Using an iterative simulator and a matching learning function to estimate building heights
	Lidar data	(Rottensteiner and Briese, 2002); (Wurm et al., 2013)	Using directly observed point clouds data from LIDAR sensors to estimate building heights
	SeaWinds Scatterometer Active Microwave Data	(Steve et al., 2013)	Detecting VUG by using SeaWinds microwave backscatter power returned data
Passive sensors/ Optical Sensor	Aerial imagery	(Lin and Nevatia, 1998)	Estimating building heights from sun shadow information
	SPOT imagery	(Shettigara and Sumerling, 1998);	
	QuickBird satellite images	(Izadi and Saeedi, 2012); (Zhang, 2015)	
	IKONOS images	(Shao et al., 2011); (Qiao et al., 2015)	
	Chinese No. 3 Resource Satellite VHR image	(Wang et al., 2014)	
	Landsat image	(Zhang et al., 2017)	

3.3. Theme 2: Identifying driving factors to VUG

The vertical growth of cities is driven by many factors. Urban vertical development results from urban densification (Koziatek et al., 2016), which is highly correlated with population density. In addition, the construction of medium and high rise buildings is closely related to the accessibility of economic opportunities, transportation, services and facilities, financial feasibility, as well as land-use category (Leao et al., 2018; Koziatek and Dragicevic, 2017; Lin et al., 2014). Lin et al. (2014) grouped seven driving factors into three types, namely site-suitability, neighbourhood configuration and proximity extent. Our review of the literature indicates that other factors have also been identified and included as driving forces to VUG: population density, urban densification and land use/land cover change as the main driving factors leading to the increase in building heights (Table 3).

Table 3: Driving forces for VUG that are studied in the literature.

Author /year	**Site-suitability**									**Neighborhood**		**Proximity extent**				
	Population Density	**Total Population**	**Population growth**	**Resident inhabitants per dwelling**	**Economic factors**	**Land Use/Land Cover Class**	**Land Price**	**Exclusion and Limitations such as city Master Plan**	**Seismic hazards**	**Building heights**	**Buildings density**	**Distance to Transportation**	**Distance From Urban Center**	**Distance to Water**	**Public Service**	**Elevation**
(Benguigui et al., 2008)	○					○		○		○	○					
(Zhang, 2010)	○					○		○		○	○					
(Qin et al., 2013)	○					○		○		○	○	○	○			
(Zhang et al., 2017)	○	○			○											
(Zambon et al., 2019)	○	○	○	○	○											
(Koziatek and Dragicevic, 2017)	○				○	○		○		○		○			○	
(Lin et al., 2014)	○									○	○	○				
(Fan, 1999)			○		○			○								
(He et al., 2017)			○		○	○						○	○	○	○	○
(Perez et al., 2018)	○					○	○				○	○				
(Rashed et al., 2005)									○							

3.4. Theme 3: Simulating and predicting VUG

Geographic cellular automata-based modeling has been widely used in the simulation of various urban land use changes (Batty, 2007). The majority of CA models focus on the simulation of land change in two-dimensional space, and rarely involve three-dimensional urban space. Semboloni (2000) made a pioneering contribution by developing a 3D CA model to simulate the VUG by representing variation in land-use density and mixed land use. Benguigui et al. (2008) developed a quasi-3D cellular automaton (CA) simulation model of cities by using a 2D CA model including a cell attribute identifying building height information. However, this simulation lacks 3D visualization and neglects the regional heterogeneity in the built environment during research process. Building on the work by Benguigui et al. (2008), Zhang (2010) presented a 3D visualization, and conducted 3D space expansion scenario simulation by combining the Benguigui et al. (2008) model with an agent-based model. The previous two investigations studied cities as uniform units without considering spatial heterogeneity. Qin et al. (2013) added a centre distance parameter and a traffic distance parameter, resulting in a centre distance model and a transport distance model of three-dimensional urban growth. The results show that urban 3D spatial growth models are more consistent with real urban 3D spatial expansion process when incorporating spatial heterogeneity. Lin et al. (2014) also developed a CA modeling method for exploring the vertical complexities of urban high-rise building growth by implementing a series of “IF-THEN” rules. He et al. (2017) overcame the aforementioned shortcomings of traditional CA models by proposing a model based on a back propagation artificial neural network and case-based reasoning technology with sort cellular automaton.

Although the above five models identify locations of high-rise buildings, the results were expressed in two-dimensional raster grids with consistent cell sizes compatible with current geospatial data structures. However, urban land development, such as the construction of high-rise buildings, takes place on irregular size and shape properties rather than a regular grid. On the other hand, the procedural modeling approach in ESRI CityEngine is a three-dimensional method that can generate complex and detailed 3D buildings using programmatic rules based on existing vector geometry (Agius et al., 2018). CityEngine was used by Koziatek and Dragicevic (2017) to develop an iCity 3D geosimulation model to simulate vertical development scenarios. Nevertheless, the majority of model (although limited) still use grid-based CA approach to simulate VUG, possibly due to the difficulty in modeling the topological complexity should the irregular spatial units be used.

4. Discussion

This paper presents an exploratory review of literature on VUG published in mainstream academic outlets over the past three decades. Three thematic areas were identified – approaches defining and extracting VUG, the identification of driving factors to VUG, and models simulating and predicting VUG with some noticeable progress in the field particularly in the past 5 to 10 years. Our review also shows substantial challenges where some innovative breakthroughs need to be achieved by developing practical models to enhance our understanding and planning for VUG in the years to come.

Firstly, only limited work is available in understanding and modeling the driving factors that lead to VUG. Site-suitability, neighbourhood effect as well as spatial accessibility have been identified as key factors leading to VUG. Population density, urban densification and land use/land cover change were also recognised as the main driving factors leading to the increases in building heights.

Secondly, a few modeling approaches have been developed for the simulation of vertical urban development, most of them based on the CA principals. However, the calibration and validation of these models are largely limited. There are limited reliable data such as the vertical height of buildings over a longer period of time from real cities for model calibration and validation. In addition, limited effort in developing algorithms has been done to represent and simulation the driving forces that lead to vertical urban development. The work conducted by Zhang et al. (2017) is a good example that used historical Landsat image to obtain building elevation data of megacities, although their approach is only applicable to extremely high buildings in megacities with limited accuracy.

Lastly, the processes of urban shrinkage, demolition and redevelopment into the vertical dimension are also largely overlooked in the current research, so is the process for underground development such as underground rails and shopping malls which have been developing rapidly in many cities around the world. For example, the development of the underground railway network in Beijing, China, and in Tokyo, Japan, has greatly reduced the traffic pressure on the surface of the cities. Therefore, the combination of urban aboveground and underground built-up area expansion can be considered as a worthy part in the study of future urban vertical growth.

5. Conclusion

Globally, cities have been growing both horizontally and vertically to accommodate for the growing population and limited land. Despite extensive research on urban sprawl, contemporary research on vertical urban development remains limited. This paper presents an exploratory review of the literature on VUG based on papers published in mainstream academic outlets over the past three decades. Our results show that a diverse range of methods exist in defining VUG, and the most commonly used data are from remotely sensed images. Nevertheless, current research is largely limited by data available for calibrating and validating 3D urban models. Big data in the form of large quantity and individual level data from multiple sources such as social sensing has the potential to contribute to tackling the validation problem. For example, spatial big data contains the time-space behaviours information of a large number of people, and residential population information such as population density can indirectly reflect building size information.

If the geographic space be discretised into volumetric units as voxels, dynamic geographic objects could be simulated and analysed by voxel automata (Jjumba and Dragićević, 2016), like the cellular counterparts. Although voxels may also suffers from much of the drawbacks of raster, the vector-voxel approach applied in 3D solar radiation model (Hofierka and Zlocha, 2012), has great potential in urban simulation and this approach would eliminate the drawbacks from raster. However, until now, there has been limited exploration of using vector-voxel automata to simulate geographic processes such as three-dimensional urban expansion. Vector-voxel simulation could act as a new methodological approach for representing VUG in the four-dimensional (4D) space–time domain.

In sum, we argue that future research in this field should address the challenges in modeling VUG, particularly with regard to reliable data to parameterise the configuration and validation of the 3D urban models, as well as in the simulation of VUG under different scenarios and driving factors. We also call for more research to simulate the processes of urban demolition and shrinkage in the vertical dimensions, as well as the underground expansion in our urban space.

6. References

Agius T, Sabri S and Kalantari M. 2018. Three-Dimensional Rule-Based City Modelling to Support Urban Redevelopment Process. *ISPRS International Journal of Geo-Information* 7.

Batty M. 2007. *Cities and complexity: understanding cities with cellular automata, agent-based models, and fractals*: The MIT press.

Bell M, Dean C and Blake M. 2000. Forecasting the pattern of urban growth with PUP: a web-based model interfaced with GIS and 3D animation. *Computers, Environment and Urban Systems* 24: 559-581.

Benguigui L, Czamanski D and Roth R. 2008. Modeling Cities in 3D: A Cellular Automaton Approach. *Environment and Planning B: Planning and Design* 35: 413-430.

Brunner D, Lemoine G, Bruzzone L, et al. 2010. Building height retrieval from VHR SAR imagery based on an iterative simulation and matching technique. *IEEE Transactions on Geoscience and Remote Sensing* 48: 1487-1504.

DeMers MN. 2002. GIS modeling in raster (No. 910.285 D4G5). *New York: Wiley*.

Fan CC. 1999. The vertical and horizontal expansions of China's city system. *Urban Geography* 20: 493-515.

He QS, Liu YL, Zeng C, et al. 2017. Simultaneously simulate vertical and horizontal expansions of a future urban landscape: a case study in Wuhan, Central China. *International Journal of Geographical Information Science* 31: 1907-1928.

Hofierka J and Zlocha M. 2012. A New 3‐D Solar Radiation Model for 3‐D City Models. *Transactions in GIS* 16: 681-690.

Huertas A and Nevatia R. 1988. Detecting buildings in aerial images. *Computer Vision, Graphics, and Image Processing* 41: 131-152.

Izadi M and Saeedi P. 2012. Three-dimensional polygonal building model estimation from single satellite images. *IEEE Transactions on Geoscience and Remote Sensing* 50: 2254-2272.

Jjumba A and Dragićević S. 2016. Towards a voxel-based geographic automata for the simulation of geospatial processes. *ISPRS Journal of Photogrammetry and Remote Sensing* 117: 206-216.

Koziatek O and Dragicevic S. 2017. iCity 3D: A geosimualtion method and tool for three-dimensional modeling of vertical urban development. *Landscape and Urban Planning* 167: 356-367.

Koziatek O and Dragićević S. 2017. iCity 3D: A geosimualtion method and tool for three-dimensional modeling of vertical urban development. *Landscape and Urban Planning* 167: 356-367.

Koziatek O, Dragicevic S and Li S. 2016. Geospatial modelling approach for 3D urban densification developments. *XXIII ISPRS Congress, Commission II.* 349-352.

Leao SZ, Troy L, Lieske SN, et al. 2018. A GIS based planning support system for assessing financial feasibility of urban redevelopment. 83: 1373-1392.

Lin C and Nevatia R. 1998. Building Detection and Description from a Single Intensity Image. *Computer Vision and Image Understanding* 72: 101-121.

Lin J, Huang B, Chen M, et al. 2014. Modeling urban vertical growth using cellular automata—Guangzhou as a case study. *Applied Geography* 53: 172-186.

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

Perez RIP, Carballal A, Rabunal JR, et al. 2018. Predicting Vertical Urban Growth Using Genetic Evolutionary Algorithms in Tokyo's Minato Ward. *Journal of Urban Planning and Development* 144.

Qi F, Zhai JZ and Dang G. 2016. Building height estimation using Google Earth. *Energy and Buildings* 118: 123-132.

Qiao W, Liu Y, Wang Y, et al. 2015. Analysis on the characteristics of three-dimensional urban space expansion in Nanjing since 2000. *Geographical Research* 34: 666-676.

Qin J, Fang C and Wang Y. 2013. The three-dimensional urban growth simulating based on cellular automata. *Journal of Geo-Information Science* 15: 662-671.

Rashed T, Weeks JR, Stow D, et al. 2005. Measuring temporal compositions of urban morphology through spectral mixture analysis: toward a soft approach to change analysis in crowded cities. *International Journal of Remote Sensing* 26: 699-718.

Rottensteiner F and Briese C. 2002. A new method for building extraction in urban areas from high-resolution LIDAR data. *International Archives of Photogrammetry Remote Sensing and Spatial Information Sciences* 34: 295-301.

Salvati L, Zitti M and Sateriano A. 2013. Changes in city vertical profile as an indicator of sprawl: Evidence from a Mediterranean urban region. *Habitat International* 38: 119-125.

Sanyal J and Roychowdhury K. 2017. Tracking the relationship between changing skyline and population growth of an Indian megacity using earth observation technology. *Geocarto International* 32: 1421-1435.

Semboloni F. 2000. The growth of an urban cluster into a dynamic self-modifying spatial pattern. *Environment and Planning B: Planning and Design* 27: 549-564.

Shao Y, Taff GN and Walsh S. 2011. Shadow detection and building-height estimation using IKONOS data. *International Journal of Remote Sensing* 32: 6929-6944.

Shettigara V and Sumerling G. 1998. Height determination of extended objects using shadows in SPOT images. *Photogrammetric Engineering and Remote Sensing* 64: 35-43.

Steve F, Tom M, Karen CS, et al. 2013. A global fingerprint of macro-scale changes in urban structure from 1999 to 2009. *Environmental Research Letters* 8: 024004.

Wang X, Yu X and Ling F. 2014. Building heights estimation using ZY3 data—A case study of Shanghai, China. *Geoscience and Remote Sensing Symposium (IGARSS), 2014 IEEE International.* Quebec City, QC, Canada: IEEE, 1749-1752.

Wurm M, Taubenböck H, Esch T, et al. 2013. The changing face of urban growth: An analysis using earth observation data. *Urban Remote Sensing Event IEEE*: 1-4.

Zambon I, Colantoni A and Salvati L. 2019. Horizontal vs vertical growth: Understanding latent patterns of urban expansion in large metropolitan regions. *Science of The Total Environment* 654: 778-785.

Zhang L. 2010. Cellular automation and VR-GIS Technology based three dimensional dynamic simulation and application study of urban space growth. Ocean University of China.(in Chinese).

Zhang P. 2015. Spatiotemporal Features of the Three-Dimensional Architectural Landscape in Qingdao, China. *PLOS ONE* 10: e0137853.

Zhang W, Li W, Zhang C, et al. 2018. Analyzing horizontal and vertical urban expansions in three East Asian megacities with the SS-coMCRF model. *Landscape and Urban Planning* 177: 114-127.

Zhang WX, Li WD, Zhang CR, et al. 2017. Detecting horizontal and vertical urban growth from medium resolution imagery and its relationships with major socioeconomic factors. *International Journal of Remote Sensing* 38: 3704-3734.