

Four-dimensional geospatial approaches for modeling vertical urban growth

by

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Abstract

Urban densification is a form of development that has been seen as more sustainable compared to urban sprawl, typical for North American cities. Urban modeling has been extensively researched and mostly focused on urban sprawl using methods based on raster geographic information system (GIS) data and for two spatial dimensions (2D). The objectives of this thesis are the 1) development of a spatial index for 3D urban compactness; 2) development of geosimulation approaches for modeling spatio-temporal dynamics of changes in 4D for vertical urban growth; and 3) implementation and evaluation of the proposed approaches using geospatial datasets for regional and municipal spatial scales for the Metro Vancouver Region. Several modeling scenarios have been created to represent 3D urban growth development over space and time. The obtained results indicate that the proposed 4D geospatial approaches have potential to be used in urban planning.

Keywords: 3D Geosimulation; vertical urban development; urban modeling; spatial index for 3D urban compactness; geographic information system (GIS); urban compactness

*To my loved ones, personal achievements reflect the
strength of those who support us, thank-you*

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Chapter 1.

Introduction

1.1. Introduction

The global population has been rapidly rising with most development occurring in urban regions (United Nations, 2002), exacerbating growth in the urban built environment. Traditionally, urban growth has expanded horizontally to accommodate the growing population, commonly known as urban sprawl. Cities that have experienced extensive urban sprawl were designed as an automobile-oriented dependent (Brunn et al., 2003). However, urban sprawl has been criticized as being an unsustainable form of growth (Johnson, 2001). Negative economic impacts of urban sprawl include the use of more resources across a wider horizontal area, increasing public expenditures (Carruthers & Ulfarsson, 2003). Urban sprawl affects social aspects of a region by disconnecting the residence from central community nodes, such as recreation and community centres (Burton, 2000). Numerous environmental impacts were studied with a focus on the consumption and degradation of the natural landscape, especially for lands designated for agriculture and ecological reserves (Livanis et al., 2006). Research has also been done on the negative impacts of urban sprawl and its effect on population health due to an increase of automobile use (Ewing et al., 2008).

Sustainable developments have been described by the World Commission on Environment and Development (1987) as a form of growth that meets the needs of the current generation without endangering the future generation's ability to meet their own needs through the degradation of the environment. Following this definition, there has been a push towards densifying the built urban environment that conforms and satisfies the commission's recommendations. The process of densifying a landscape has been termed urban compactness or a compact city (Burton, 2002). However, many definitions

of urban compactness exist as many researchers have their own interpretations (Burton, 2000). Densification in its simplest form is the increase of populations and built environment in a given area. An obvious and viable form of densification is through the development of mid- and high- rise residential buildings, which inherently compacts populations and residencies in the vertical direction. Mid- and high- rise buildings are also developed for economic office space and occur in Central Business Districts (CBD) in non-residential land use designations.

However, vertical growth through mid- and high- rise buildings requires planning consideration to establish good design for the impacted community (Al-Kodmany, 2011). Vertical growth often occurs in clusters of developments (Abdullahi et al., 2015) and the concentrations of high-rise buildings affects the local surroundings. Such affects include air pollution (Yuan & Ng, 2012), extreme events evacuations (Pelechano & Malkawi, 2008), and energy demands (Strzalka et al., 2011). Additionally, there is a need to densify urban regions to accommodate the increasing population in a more sustainable compact form of growth. For this reason, it is beneficial to develop analytical modeling approaches to represent urban densification and vertical urban development scenarios to better plan and mitigate potential problems. As with any form of urban growth, the growth of urban vertical profiles are spatio-temporal dynamic processes that operate in four-dimensions (4D), time and three spatial dimensions. Characteristics of urban growth phenomena are complex, dynamic, and non-linear spatio-temporal processes, suitable for geosimulation modeling.

Urban compactness, through the form of mid- and high- rise buildings, has become more apparent in large urban centres. Urban compactness development is common for many European and Asian cities because they have limited space for growth. Conversely, North American cities demonstrate massive urban sprawl growth because of available space for growth. However, with more concerns about urban sprawl, many North American cities are incorporating urban compactness in their future growth planning. Urban compactness is spatially organized across the landscape because it occurs near key services and amenities. Burton (2002) synthesized urban compactness as being a characteristic of density and mixed land use, which occurs through the process of urban intensification. Density is a key factor and is composed of

both population and built environment concentration. Mixed land use encourages heterogeneous developments in both height and in type, for example mixing mid- and high-rise residential buildings with retail shops at their base. Transportation networks are also key factors towards compactness (Frenkel, 2007) because they are the means that populations mobilize to jobs, recreation, and other services. Other factors that have been reported to affect urban compactness include access to job opportunity and recreation (Abdullahi et al., 2015).

The factors affecting urban compactness can be spatially analyzed to derive suitable locations for vertical growth of buildings. Urban compactness has been modeled and measured through methods such as principal component analysis (PCA) (Sani Roychansyah et al., 2005), regression analysis and descriptive statistics (Salvati et al., 2013), Pearson product-moment correlation coefficient (Chen et al., 2008), multi-nominal logit model (Frenkel, 2007), and multi-criteria decision models (Abdullahi et al., 2015), as few examples. Spatio-temporal approaches have further developed urban compactness modeling by deriving indices (Li & Yeh, 2004; Koomen et al., 2009). Use of cellular automata (CA) approaches were proposed to model forecasted vertical growth (Yeh & Li, 2002; Lin et al., 2014). However, these models were developed in two spatial dimensions using GIS-based raster regular spatial tessellations that may not fully represent intricate urban details at a cadastral lot resolution.

Urban growth phenomenon represents a dynamic process that is constantly shaping the built urban and natural landscapes, and are linked to economic, social, environmental, political, and other practices that together affect the overall progression of change (Batty, 2008). Various urban modeling methods, availability of geospatial data, and geographic information systems (GIS) have been used extensively to facilitate urban and regional planning and problems associated to land use and environmental impacts. Throughout the long history of urban growth modeling research, mostly GIS-based raster data has been used, also known as cells or regular spatial tessellations (Tobler, 1979; Batty, 2008). These modeling approaches had capabilities for simulating spatio-temporal urban growth dynamics but commonly in two spatial dimensions. With advancements in data collection and GIS software, research has also explored urban modeling approaches in multiple spatial dimensions (Shiode, 2000). These geospatial applications

revolving around urban phenomena have been incorporated in urban planning and management decision making procedures with more or less success (Couclelis, 2005). The developed methodologies focus around spatial indices, statistical GIS-based spatial analysis and modeling, which include geosimulation and geographic automata.

1.2. Theoretical Background and Research Problems

Spatial indices provide means of measuring specific characteristics of urban processes and are a form of spatial analysis. Spatial indices can be applied to urban landscapes to identify fragmentation, clustering, growth, and other urban features that are directly related to urban modeling. Moreover, land suitability indices have been derived to determine land selection comparison and possible future growth forecasts (Park et al., 2011). Indices for urban landscapes were commonly derived through imagery to determine morphological change over time as a means to measure and monitor past growth (Yang et al., 2005) through patterns such as composition and structure (Sudhira et al., 2004). Derived indices from imagery have also been used to detect change and project future growth (Herold et al., 2003). Additionally, 3D spatial indices were developed (Jjumba & Dragičević, in press) but are not yet suited specifically for urban analysis.

Urban suitability analysis has been documented extensively in GIScience literature and has supported regional planning and management (Hopkins, 1977; Voogd, 1983). Beginning in the early 1990's, GIS-based multi-criteria evaluation (MCE) approaches were used to assess multiple geospatial data to determine land suitability selection (Malczewski, 2004; Jankowski, 1995; Carver, 1991). In MCE approaches, input criteria is weighted against each other to derive suitability scores, providing ease to discriminate between high and low suitable locations across the geospatial extent (Malczewski, 2006). GIS-based MCE methods rely on analytical hierarchy process (AHP), logic-scoring preference (LSP), ordered weighted average (OWA), simple additive scoring (SAS), and weighted linear combinations (WLC) to incorporate weighting of criteria (Montgomery & Dragičević, in press). Suitability analysis methods have been applied to various urban contexts such as land conservations, land depletion,

agricultural land preservation, sustainable growth, regional growth, and other urban problems.

The next suite of approaches based on geographic automata and geosimulation were developed to represent urban growth dynamics across space and time, which can represent change of urban morphology and forecast various scenarios of growth (Benenson & Torrens, 2004). A compilation of datasets from previous years can be used to analyze and simulate the evolution of change of the urban landscape to help manage and mitigate urban and environmental problems. For more than two decades, urban modeling approaches including CA and agent-based modeling (ABM) (Batty & Xie, 1994; Matthews et al., 2007) have been used to show dynamics of urban growth (Clark & Gaydos, 1998; Batty, 2005). However, few CA modeling approaches have been developed to address urban compactness growth (Yeh & Li, 2014) and more specifically, high-rise building growth (Benguigui & Czamanski, 2008). ABM models have also been developed to show high-rise building growth (Broitman & Czamanski, 2012; Lin et al., 2014). However, most of the urban modeling approaches based on geographic automata were developed on homogenous, regular spatial tessellations limited to two spatial dimensions and time.

Regular spatial tessellations use GIS-based raster data due to mathematical operations that can be easily derived from various geospatial data sources. Many simulation models of urban morphology have used remotely sensed imagery (White & Engelen, 2000) because data can be easily obtained for different regions and for various years. Regular spatial tessellations may not properly represent local complexities for smaller extents or for more detailed spatial scales. Spatial tessellations are important in model design because urban planning is composed of various administrative boundaries that range in size and scales from regional, municipal, neighbourhood, block, cadastral lot, and building footprints. Cadastral lots, sometimes referred to as cadastral parcels, are public registrations that include details on ownership, taxation, and property lines. Cadastral lots are in a constant state of change as re-zoning and ownership transform the boundary lines to conform to new urban developments. Subdivisions of cadastral lots further complicate the morphology of the boundary lines and few have explored spatial methods to incorporate cadastral lot partitioning algorithms (Le Ber et al., 2009; Jjumba

& Dragicevic, 2012; Wickramasuriya et al., 2011) within different urban modeling procedures. The cadastral lots can be a very small spatial extent that may not be represented well through regular spatial tessellations, commonly used via GIS-based raster datasets. Conversely, land use designations are planned on a larger scale, usually on a regional or municipal extent, and are typically prone to change. They can be designated to protect important land for example, agricultural, aboriginal forest, or ecological land reserves. Land use designations delineate areas for specific type of urban growth such as low and high-density developments and may be placed to aid in organizing and containing urban growth. For these reasons, land use designations are not as dynamic as other urban units but continue to affect the type of development on local units, such as cadastral lots. Therefore, due to the variability of spatial resolution and shape of urban land use units, spatial tessellations should be considered in the model design.

Alternative spatial representations to the regular spatial tessellations are irregular spatial tessellations and are represented with GIS-based vector data. Urban modeling with irregular spatial tessellations have been explored to address common errors associated with the regular tessellations (Shi & Pang, 2000; Stevens et al., 2007). Irregular spatial tessellation can represent non-uniform boundary shapes with multiple vertices and non-angular geometry, unlike raster data. These spatial representations of phenomena may be more appropriate for high-resolution details such as urban cadastral lots and building footprints. However, GIS-based vector data present unique challenges due to their non-uniform, irregular spatial tessellations and categorical data structure, which can be composed of characters or numbers. These challenges associated with irregular tessellations have contributed to less research using this data form in urban modeling.

In reality, the built environment is inherently three-dimensional (3D), when considering spatial dimensions only. With increasing interest in vertical densification and 3D data becoming more available, urban researchers are emphasizing the need to model in the vertical dimension (Königer & Bartel 1998). There has been less research focused on 3D as opposed to 2D urban modeling because past geospatial data did not

contain much 3D information. Attributes and software capabilities may have provided challenges to compute and model the vertical dimension.

Additionally, it is important to differentiate between 2D, 2.5D, and 3D data representations. Where 2D represents a phenomenon in two spatial dimensions, 2.5D representations are assigned a single vertical value for each XY location (Bishop et al., 2000; Gröger & Plümer, 2005). The phenomenon may be extracted into the vertical dimension by this value but the geometry of the structure is simplified and restricted to the single height value. 'Real' 3D models preserve the intricate shapes of structures such as buildings by incorporating complex details including overhangs, balconies, and bridges (Gröger & Plümer, 2005).

GIS-based methods and geospatial data have been used towards 2.5D and 3D urban modeling. For example, geospatial data with height attributes have been represented in 2.5D through simple extrusions of the GIS-based raster cell or vector shape to the recorded height (Shiode, 2000). This approach is limited to block extrusions that do not represent the complexities of buildings or other landscape geometry. GIS approaches have also combined detailed 3D models from other research fields, such as computer-aided drafting (CAD) (Batty et al., 1998) and building information modeling (BIM) (Döllner & Hagedorn, 2007), and fused them with geospatial data. The 3D representations of current built environments have increased the development of spatial models with topics such as air pollution (Nichol & Wong, 2005) and visibility (Yang et al., 2007). Research has also presented methods of programming irregular spatial tessellations to refine the geometry and model 3D building objects at high-resolutions using geospatial data and software environments (Parish & Muller, 2001).

With recent advancements in remote sensing and GIS capabilities, it has been easier to incorporate geospatial and remotely sensed data into 2.5 and 3D urban modeling. Satellite and aerial imagery has provided 3D built environment modeling through methods such as triangulation (Wang, 2013). The introduction of Light Detection And Ranging (LiDAR) technologies has increased 3D data availability that can represent the built environment with intricate details (Shiode, 2000; Zhou et al., 2004). Remote sensing research has developed 3D urban spatio-temporal representations of change

detection to monitor land use (Brook et al., 2013), built environment (Stal et al., 2013), and coastal erosion (Ford, 2011). Spatio-temporal remote sensing approaches can derive high-resolution 3D models but tend to be limited to the number of years for which data has been collected.

Research in modeling 3D vertical urban development has been limited so far. A spatial index for urban compactness in 3D was developed to evaluate city growth efficiency and morphology by combining multiple indicators (Qin et al., 2015). A volumetric index was also developed to measure and monitor building height development in coastal areas using remotely sensed and geospatial data (Magarotto, 2016). However, the derived indices for 3D representation were not described to address temporal dimension of urban landscape change over time.

In literature, it was found that more 3D geospatial modeling approaches towards the development of building models have been prevalent through the incorporation of procedural modeling. Parish and Muller (2001) presented work using geospatial data representing urban landscape GIS-based vector shapes and mass generating 3D building objects. The introduction of procedural modeling capabilities, including quick and easy mass generation using a program that can stochastically generate 3D objects at various levels of details, has impacted the geospatial field concerned with urban modeling. More recent research presented by Xu and Coors (2012) and Moura (2015), developed suitability analysis maps that guided 3D modeling approaches on topics related to sustainability assessment and landscape change scenarios. Weber et al., (2009) also introduced a 4D city model incorporating a spatio-temporal component. However, these 3D modeling efforts set to answer specific urban spatial problems but did not report using existing urban policies or city by-laws for forecasting or developing scenarios of vertical urban development growth.

Urban modeling has explored various modeling approaches, spatial and temporal resolutions, and data formats for horizontal 2D growth. Not many research efforts have incorporated these important variables simultaneously, and even less have addressed a vertical urban growth context. Therefore, there is a need to develop geospatial modeling approaches to represent the patterns of vertical urban development growth at higher

spatial and temporal resolutions by combining GIS-based raster and vector data formats that can better represent the built environment. The geospatial modeling approach should represent the spatio-temporal morphology of the urban landscape changing in 3D over time.

To achieve detailed urban models that can represent spatio-temporal 3D vertical urban developments as part of geospatial procedures and that can aid in regional or local sustainability planning, the following research questions have been developed to guide the proposed research thesis:

1. Can a set of geospatial approaches be used to identify and measure locations of 3D vertical urban developments?
2. Can geospatial and geosimulation modeling approaches be used to represent and simulate 3D vertical urban developments across space and time?

1.3. Research Objectives

To answer these research questions, the main research objective is to develop a series of GIS-based modeling approaches for high-resolution 3D geospatial vertical urban developments. This research aims to develop a suitability analysis approach to identify urban compactness locations then explore various high-resolution 3D modeling approaches to represent the urban vertical growth over space and time.

The following research objectives aim to answer the outlined research questions:

1. To develop a GIS-based spatial index for 3D urban compactness
2. To develop a 3D geospatial model to simulate the spatio-temporal dynamics of vertical urban developments
3. To implement and evaluate the developed geospatial and geosimulation modeling approaches at different spatial scales and with different 3D growth scenarios

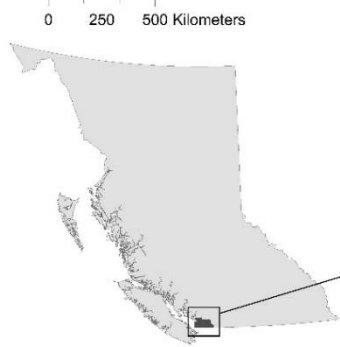
Previous research has explored combining commonly used GIS modeling approaches to generate high-resolution models but this thesis research aims to extend the work by incorporating geospatial and geosimulation modeling approaches to represent spatio-temporal vertical urban development growth in 3D.

1.4. Study Sites and Datasets

The Metro Vancouver Region in B.C., Canada (Figure 1.1 a and b), is experiencing an increased population growth with estimates of 3.2 million inhabitants by 2040 (Metro Vancouver, 2016). The region encompasses approximately 2800 km² and is surrounded by water bodies and mountains, limiting land for development. Additionally, the land is confined to an urban containment boundary, placed to protect agricultural and ecological reserves (Metro Vancouver, 2016). The region is also under an implemented sustainable growth plan that has goals, including urban densification to achieve compactness and prevent urban sprawl into valuable agricultural and forestlands. The City of Surrey is a municipality within the Metro Vancouver Region (Figure 1.1 c) and is also the sub-study for some aspects of this research. The City of Surrey is one of the fastest growing cities in the region and in Canada (City of Surrey, 2016). The City of Surrey also has a well-defined sustainable growth plan to accommodate the expected population growth.

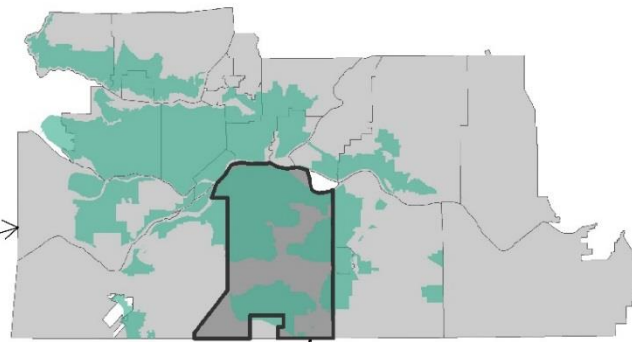
In order to implement the developed modeling concepts, various geospatial datasets are needed to satisfy the factors affecting urban compactness growth. They were obtained from local (City of Vancouver, 2015; District of North Vancouver, 2015; Surrey Open Data, 2015), regional (Metro Vancouver Open Data, 2015), provincial (DataBC Open Data, 2015; GeoBC, 2015), and national organizations (GeoGratis, 2015). Population densities were obtained for the Metro Vancouver Region at the highest resolution, the Dissemination Area, for the year 2011 (Statistics Canada, 2011). The geospatial data includes detailed cadastral lots, land use designations, and building footprints, provided by the City of Surrey (2015).



A. British Columbia



 Metro Vancouver Region

B. Metro Vancouver Region



 City of Surrey
 Urban Containment

C. City of Surrey

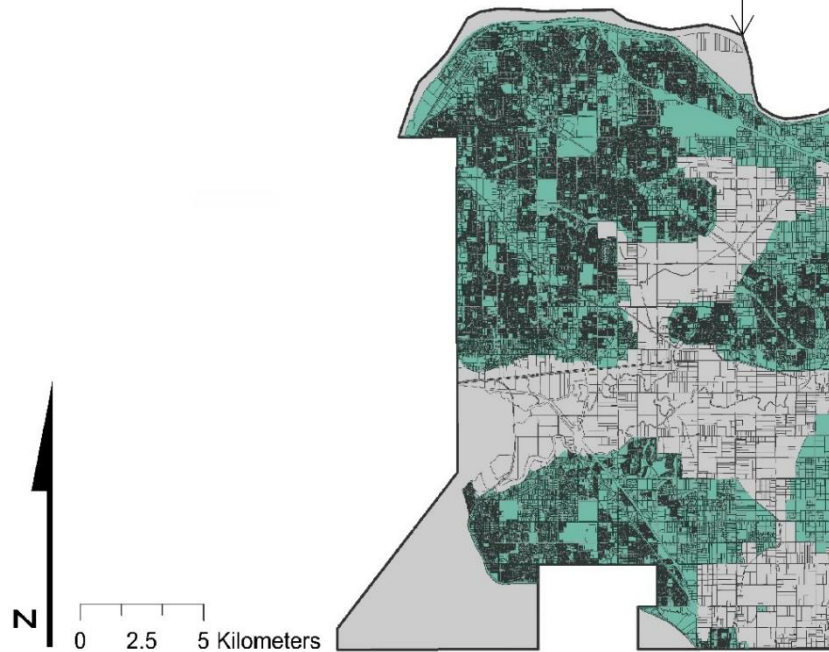


Figure 1.1. Study Areas: A. The Province of British Columbia; B. Metro Vancouver Region; and C. City of Surrey, Canada, with Cadastral Lots

1.5. Thesis Overview

This thesis contains five chapters. Following the introduction, chapter two presents the rationale and development of a spatial index for 3D urban compactness. In this research, although the results are extruded as 2.5D representations, the term '3D' is used to represent the derived index values of building heights in third vertical dimension. The presented spatial index for 3D urban compactness was derived from the development of three parameters: 1) Suitability Analysis; 2) Land Designation; and 3) Average Building Height. The Suitability Analysis Parameter was based on the key indicators affecting locations of urban compactness and fuzzy membership functions were used with the geospatial datasets. The Land Designation Parameter assessed land use designations and assigned an availability for development. Finally, the Average Building Height Parameter was compiled from sample building heights from geospatial data for the region and was spatially joined with the land use designations to determine the mean maximum building height per designation. The Spatial Analysis and Land Designation Parameters were iterated to incorporate spatio-temporal growth for the spatial index for 3D urban compactness, which was applied to the Metro Vancouver Region study area. However, the spatial index for 3D urban compactness was applied onto a cadastral lot level of detail, meaning that, it extruded each developable lot to the calculated building height. This showed volumetric lot extrusions that did not represent building level-of-detail. Chapter three combines the suitability analysis presented in Chapter two and further refines the results to a building level-of-detail.

Chapter three presents the developed 3D geospatial modeling approach that combined the raster suitability analysis map with vector GIS-based data through programmed rules using the Computer Generated Architecture (CGA) language. The 3D geospatial modeling approach incorporated municipal by-laws and plans to refine the suitable areas into high-resolution irregular tessellations, with subdivisions, that represent cadastral lots. The model also utilized real building height ranges that were assigned to specific land use designations to generate 3D developments. The generated 3D buildings were programmed using the CGA language in ESRI's CityEngine 2014 (ESRI, 2014). The study was focused only on Guilford Centre, in the City of Surrey, and did not address spatio-temporal change.

Chapter four presents the 3D geosimulation modeling approach that enhanced the geospatial model presented in Chapter three, by incorporating a temporal component and two growth scenarios for sub-areas in the City of Surrey. The 3D geosimulation modeling approach retained the programmed municipal by-laws and plans as developed in the geospatial model but also developed a series of suitability analysis maps that represent vertical urban growth for the years 2011 to 2040. The time-series suitability maps were developed for a normal and transportation expansion growth scenario. The transportation growth scenario was based on a real rapid rail expansion that was proposed by the City of Surrey. The 3D geosimulation was also programmed using the CGA language and operationalized in ESRI's CityEngine 2014 (ESRI, 2014).

The thesis is concluded with chapter five, a summary of the methods and obtained results for the presented research. Limitations and possible future work directions are also outlined in this chapter.

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Chapter 2.

Development of a Spatial Index to Represent 3D Urban Compactness

The version of this chapter co-authored with S. Dragicevic will be submitted to the Environment and Planning B journal.

2.1. Abstract

Urban regions around the world are developing in a more compact form to mitigate sustainability concerns, land depletion, and population growth demands. Urban compactness is a more sustainable form of development that occurs through densification and mixed land use practices through spatial indicators that intensify the landscape. Urban modeling has been used extensively to aid in regional planning and can be used to project future urban compactness growth scenarios. The objective of this research was to develop a spatial index for three-dimensional (3D) urban compactness growth that can be applied to an urban region to project future vertical development growth. The index was composed of three parameters accounting for land suitability, land use designation, and regional average building height. The study area chosen for this research was the Metro Vancouver Region, in BC, Canada, which is a growing urban area with a regional compact growth plan. The derived index was applied to the region for the years 2011 to 2040 with a 10-year time iteration. Presented results suggest that concentrations of urban compactness growth are near densely populated and transportation-oriented locations. The presented research aims to aid local governments in future planning processes related to regional sustainable development growth.

2.2. Introduction

Regional urban planning concerned with demanding growing populations is experiencing challenges to develop in a sustainable form. According to the United Nations (2002), population growth is expected to decline in rural areas but rise in urban regions, adding pressure on cities. Traditional urban development has occurred in the horizontal direction, commonly known as urban sprawl. Urban sprawl has been characterized as a relatively wasteful form of low-density urbanization growth (Torrens & Alberti, 2000). Urban sprawl has been attributed to many negative sustainable consequences in environmental (Johnson, 2001), economic (Carruthers & Ulfasson, 2003), health (Ewing et al., 2008), and social (Burton, 2000) sectors. Low-density developments grow horizontally across the landscape and consume more land, which encourages populations to travel further to gain access to services and to Central Business Districts where many economic opportunities are located. Additionally, the consumption of land negatively affects important and valuable agricultural land reserves, generally by consuming the land for developments (Livanis et al., 2006). Globally there are many cities exemplifying low-density growth but North America contains more cities with urban sprawl such as Chicago, Los Angeles, Detroit, and Phoenix, which are oriented around the automobile (Brunn et al., 2003). In general, consensus suggests that planning practices should try to mitigate the undesirable results of urban sprawl (Dieleman & Wegener, 2004) as it is an unsustainable form of urban development (Johnson, 2001).

Sustainable development has been defined as meeting current needs through practices that do not endanger natural systems that support life, and therefore, future generation's ability to meet their own needs (World Commission on Environment and Development, 1987). Population and development densification in urban regions can mitigate many of the concerns attributed to urban sprawl. This form of densification is commonly known as urban compactness or compact cities and has been determined to be a more sustainable form of urban growth (Burton et al., 2003), despite being contested by some (Neuman, 2005). In theory, urban compactness growth may decrease car dependency as access to services and resources may become more readily available (Jenks et al., 1996). Additionally, positive correlations between urban

compactness and sustainability have been reported, for example reduced CO₂ emissions (Liu et al., 2014).

Interest in urban compactness development has been concentrated in more developed countries such as the US, Japan, and Australia (Burgess & Jenks, 2002). However, due to exceptionally high population growth and the depletion of available land, Shanghai and Hong Kong are examples of compact cities (Burgess & Jenks, 2002). Other global cities such as Portland and Toronto, which do not have as demanding population growth as cities in Asia, are encouraging urban compactness growth for environmental and social concerns (Brunn et al., 2003).

An urban compactness design has been described by Burton (2002) as high-density concentration and mixed land use, driven by a process of intensification. In this context, density is understood as both population and built environment while mixed land use suggest land designations supporting residency, facilities, retail, commercial, and other activities. The intensification process enabling the development of density and mixed land use has strong relations with demographics such as population density (Burton, 2002) and other socio-economic factors (Koomen & Rietveld, 2009). Transportation nodes, including major roads and public stations, are networks also attributed to urban compactness (Abdullahi et al., 2015). Burton (2002) states that land use is important for urban compactness and helps plan and develop the built environment landscaped (Frenkel, 2007), another key indicator. Access to services, recreational amenities, and job centres (Sani Roychansyah et al., 2005; Abdullahi et al., 2015) are also attractive locations for urban compactness development. These indicators affecting urban compactness are all spatial entities that shape the three-dimensional (3D) landscape of the urban built environment. For this reason, there is a need for urban compactness analysis methods, scenario-based models, and tools to be developed to aid sustainable urban planning.

The objective of this research, therefore, is to develop a spatial index for 3D urban compactness applicable for a region-wide urban landscape to demonstrate spatio-temporal forecast of urban growth. The spatial index for 3D urban compactness consists of the development of three key parameters combined to produce a 3D spatio-temporal

model of the urban landscape. The three parameters developed for the spatial index include: 1) Suitability Analysis; 2) Land Designation; and 3) Average Building Height. In this research, the proposed spatial index for 3D urban compactness was applied to a regional scale for Metro Vancouver, Canada.

2.3. Theoretical Background

Urban compactness has been explored through various modeling methods using spatial indicators. Chen et al. (2008) compared urban compactness of 45 Chinese cities through the Pearson product-moment correlation coefficient to derive a summarized index to compare the cities. Urban compactness was measured and compared for multiple mid-sized European cities to identify the significance of the spatial indicators for the large-scale study (Stathakis & Tsilimigkas, 2015). Frenkel (2007) presented work on the spatial distribution and concentration of vertical developments based on a multinomial logit model. A multi-criteria decision-making and Bayes theorem approach was used to measure urban compactness across eighteen regional zones in Malaysia. Principal component analysis (PCA) was used to compare various urban compactness indicators by Sani Roychansyah et al. (2005), Li and Yeh (2004), and Salvati et al. (2013) alongside other statistical methods including descriptive statistics, regression analysis, and supervised classification. However, the morphology of urban compactness within a region is equally important for assessing spatio-temporal change.

Spatio-temporal approaches have been explored by Li and Yeh (2004) by using PCA, compactness index, and entropy measurement to provide further insight on urban morphology. Koomen et al. (2009) presented work on an urban-volume indicator that was used to spatio-temporally quantify urban extension and intensification through a self-organizing map approach. Similarly, Min et al. (2010) used various indices to measure urban compactness for spatial carrying capacity, spatial form, and spatial function. Although these studies succeeded in demonstrating change for past years, they did not forecast future changes to the landscape. However, Mubareka et al. (2011) derived a single composite index, from four morphological indicators that determined compactness and sprawl, to demonstrate how an index can be derived and applied to a large urban zone and simulating projected urban scenarios. A cellular automata (CA)

approach was used to compare various urban density scenarios (Yeh & Li, 2002) and to simulate building heights (Lin et al., 2014) and land use patterns. The research was based on vertical measurements, such as building heights, but did not include 3D representations of the spatio-temporal changes on urban landscapes.

Urban compactness has inherently 3D occurrence as it is developed in the vertical dimension. For this reason, measuring and forecasting urban compactness can be applied through 3D indices. Not much work has focused on this aspect but advancements in remote sensing, especially with LiDAR technologies, have increased the ability to more easily gather and measure the built environment in the vertical dimension (Chen et al., 2014). Additionally, remote sensing techniques can provide quantitative measurements for built environments that can better represent the compactness of a region (Yoo et al., 2009). 3D spatial indices to extract volume of buildings has been researched using LiDAR data (Tompalski and Wezyk, 2012). LiDAR data was used in research by Santos et al. (2013) to derive a volumetric density with 3D indicators that were applied to urban compactness modeling and by Stal et al. (2013) on LiDAR change detection of 3D urban areas. Pollard et al. (2010) presented an automatic volumetric change detection for urban land use.

Although remote sensing and other methods have begun to explore 3D urban morphology of the built environment, less work has focused on a spatio-temporal urban compactness index for 3D representations. A 3D urban expansion measure to evaluate growth efficiency using four indicators accounting for morphology, intensity, and fractal dimension measurements was presented by Qin et al. (2015). The research provided 3D building height models for two time periods to assess the efficiency and intensification of a Chinese city. Magarotto et al. (2016) derived a volumetric index to evaluate building height growth for over 30 years based on remote sensing imagery and spatial data. However, these examples were not able to provide insight into future urban compactness forecasts using the derived 3D indices.

There still exists a need to develop 3D urban compactness indices and test them in the context of spatio-temporal changes. The objective of this research is to develop the spatial index for 3D urban compactness for an urban region to evaluate forecasted

urban compactness growth. The proposed index includes a Suitability Analysis, Land Designation, and Average Building Height Parameter. The proposed modeling approach aims to be used as tool for planning efforts towards more sustainable and compact urban growth.

2.4. Methods

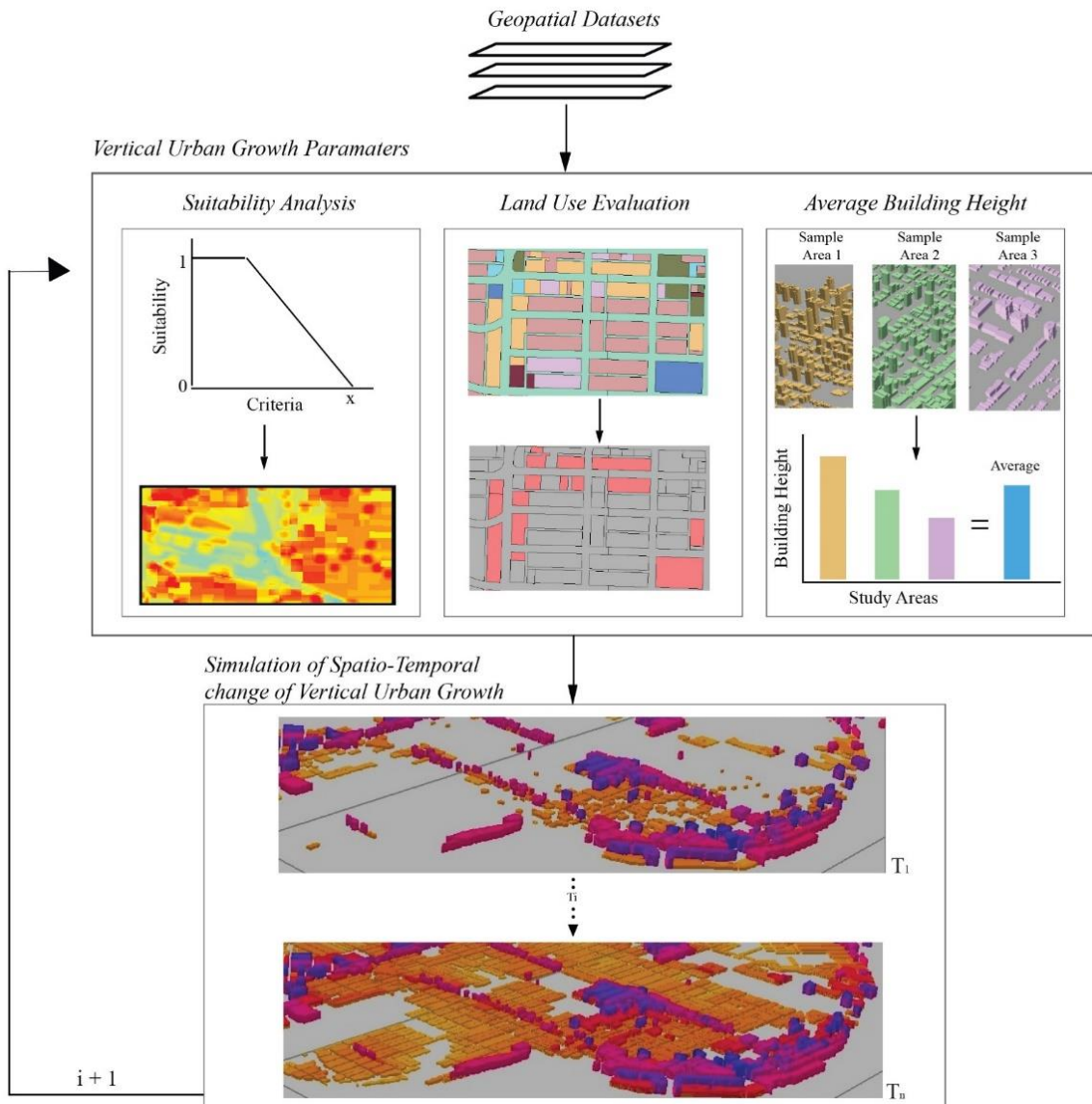


Figure 2.1. The Spatial Index for 3D Urban Compactness Derivation Overview

The presented spatial index for 3D urban compactness was derived and applied to regional geospatial datasets to forecast urban compactness growth. Figure 2.1 presents the overview of the methodology developed. The spatial index was a product of three parameters: 1) a Suitability Analysis Parameter using the key indicators for urban compactness; 2) a Land Designation Parameter that classified designations as developable and non-developable for vertical urban growth; and 3) an Average Building Height Parameter that determined height values using sample data sites. The spatial index for 3D urban compactness was applied to the Metro Vancouver Region to forecast vertical urban growth change over space and time. The presented work was operationalized in ESRI's ArcMap 10.2 and ArcScene 10.2 software (ESRI, 2013).

2.4.1. Study Area and Data

The Metro Vancouver Region is a rapidly growing area with populations expected to grow to 3.2 million people by 2040, adding an approximate 570 thousand new dwelling units (Metro Vancouver, 2016). This region, encompassing 21 municipalities, covers approximately 2 800 km² land area (Statistics Canada, 2012). However, the region's urban area is further restricted by the surrounding natural geography including water bodies and mountains, and an administrative urban land containment boundary that includes agricultural land and forest reserves (Figure 2.2). Therefore, the study areas for this research were confined to the developable regions within the Metro Vancouver urban containment boundary to model urban compactness. The City of Surrey, District of North Vancouver, and City of Vancouver, are municipalities within the Metro Vancouver Region and were used as samples for the average building height data. These municipalities were selected based on their difference in population and building heights to provide a more representative sample of the region.

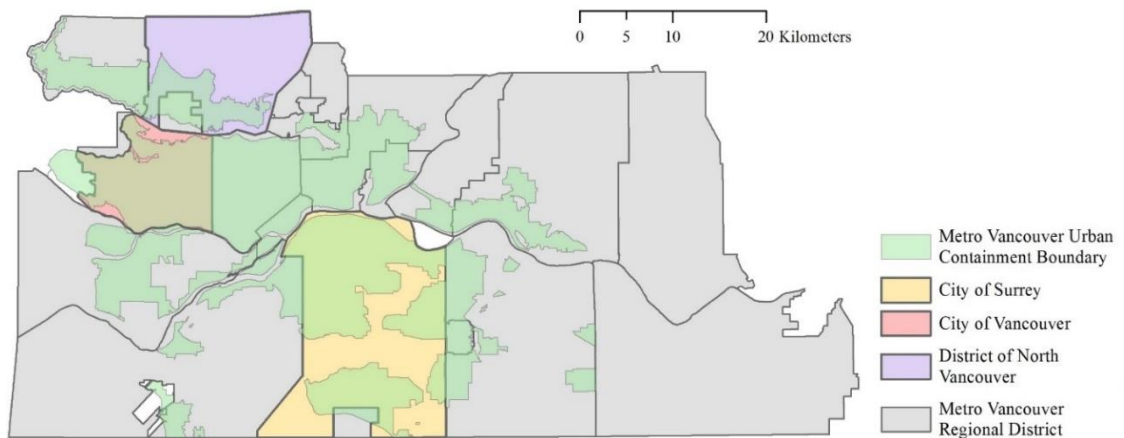


Figure 2.2. The Metro Vancouver Study Area and the Three Municipalities used to Derive Building Heights

Metro Vancouver is the political body for the Metro Vancouver Region and has developed sustainable growth plans in past years. In 1997, Metro Vancouver developed the Livable Region Strategic Plan (LRSP) concerned with protecting green zones, building complete communities, achieving a compact metropolitan region, and increasing transportation options (Holden, 2006). The LRSP was replaced by the Sustainable Region Initiative (SRI), a framework, vision, and action plan that encourages economic growth, community development, and environmental responsibility (Holden, 2006). Since the introduction of the SRI, Metro Vancouver has been responsible for core services, political forums, and policy through a sustainability assessment using metrics, targets, and deliverables (Metro Vancouver, 2010). Metro Vancouver has presented five goals it aims to achieve by 2040: 1) to create an urban compact area; 2) to support a sustainable economy; 3) to protect the environment and respond to climate change impacts; 4) to develop complete communities; and 5) to support sustainable transportation practices. The sustainability driven planning is also prevalent in residing municipalities through initiatives like the City of Vancouver's *Greenest City Action Plan* and the City of Surrey's 40-year *Sustainability Charter*. In whole, Metro Vancouver's urban planning and development has much consideration for sustainable and compact growth, a reason it was selected for the presented research.

The required data for this research included regional spatial datasets satisfying the urban compactness indicators and municipal building heights. Data satisfying the

suitability analysis indicators included: roads, bus and rapid rail stations, hazardous and restricted land, schools, walking and biking routes, community centres, hospitals, water bodies, and Central Business District (obtained from Metro Vancouver Open Data, 2015; DataBC, 2015; GeoBC, 2015). Population densities were calculated at the Dissemination Area (DA) level, from 2011 census population totals (Statistics Canada, 2011) and area. Slope was derived from a 10 m cell resolution Digital Elevation Model (DEM) dataset (GeoGratis, 2015) with a 0 to 40 degrees that are adequate slopes for building construction (Hatch et al., 2014). A land use designation spatial data set was obtained for the Metro Vancouver region, essential for the Suitability Analysis, Land Designation, and Average Building Height Parameters.

The data required for the Average Building Height Parameter included building footprints and heights for the City of Surrey, District of North Vancouver, and City of Vancouver municipalities obtained from: District of North Vancouver GEOweb, (2015a), Surrey Open Data (2015), and the City of Vancouver Open Data Catalogue (2015). These municipalities were selected because they represent very high (City of Vancouver), medium (City of Surrey), and low (District of North Vancouver) high-rise buildings in the region. The City of Vancouver building footprint data contained the height values for each establishment current to the year 2009. The obtained building footprint data for the City of Surrey, first published in 2014 and updated monthly, was joined with the available 2013 LiDAR dataset to derive approximate building height values. The District of North Vancouver building footprint data did not contain a building height field but provided building storey counts. The municipality building requirements state that all residential buildings cannot have storeys higher than 2 meters (District of North Vancouver, 2015 b). However, storeys are defined by the district as “that portion of a building which is situated between the surface of any floor and the surface of the floor next above it, and if there is no floor above it, that portion between the surface of such floor and the ceiling above it” (District of North Vancouver, 2015 b), meaning, they do not account for the structural material between each storey. Given this, a value of 3 m was deemed suitable to multiple each storey to obtain an approximate height. Additionally, a value of 3 meters was used by Magarotto et al. (2016) and Santos et al. (2013) in their research when calculating the height of each building floor.

2.4.2. 3D Urban Compactness Model Analysis

The spatial index for 3D urban compactness (3DI) was derived by multiplying the suitability analysis (P1), Land Designation (P2), and Average Building Height (P3) Parameters. The Suitability Analysis and Land Designation Parameters were updated for each time iteration but the Average Building Height remains a constant value.

$$3DI_{Ti} = (P1 \cdot P2 \cdot P3)$$

Where:

3DI	Spatial index for 3D urban compactness
Ti	Number of time iterations
P1	Suitability Analysis Parameter
P2	Land Designation Parameter
P3	Average Building Height Parameter

The spatial index for 3D urban compactness was applied to the study area and each pixel was assigned a value representing building height in meters. The index was updated for each iteration to project future growth in the study area. The values were extruded in 3D to present an alternative perspective of the projected vertical urban landscape growth.

2.4.3. Parameter 1: Suitability Analysis

Suitability analysis approaches have been used through various multi-criteria evaluation methods to rank spatial data layers to determine optimal suitability locations (Malczewski, 2004). They have been used for different land selection and scenario modeling (Jankowski, 1995) and have incorporated fuzzy membership approaches (Jiang & Eastman, 2000). Additionally, suitability analysis has been used on regional sustainability assessments by Kropp et al. (2012).

The presented work develops a Suitability Analysis Parameter that weights the various spatial indicators to identify suitable locations for urban compactness. Based on the literature, the indicators selected to represent urban compactness for this study are presented in Table 2.1 and is comprised of transportation, environment, land use, services and amenities, population density, recreation and community, and job opportunity information. To satisfy the indicators the data obtained for this study includes: roads, bus and rapid rail stations, slope, land use designations, schools, population census, walking and biking routes, community centres, and Central Business District, as few examples. Once obtained, the spatial data sets were converted to grid format, necessary to perform the suitability analysis.

Indicator	Intensification Process	Literature
Demographics	Population density	Burton (2002); Abdullahi et al., (2015); Lin et al., (2014); Roychansyah et al., (2005); Stathakis & Tsilimigkas (2015); Koomen & Rietveld (2009); Min et al., (2010)
Transportation	Major roads, public transportation	Burton (2002); Abdullahi et al., (2015); Lin et al., (2014); Roychansyah et al., (2005); Koomen & Rietveld (2009); Min et al., (2010)
Environment	Slope, undevelopable land	NA
Land Use	Zoning, land use designations	Burton (2002); Abdullahi et al., (2015); Frenkel (2007); Roychansyah et al., (2005); Stathakis & Tsilimigkas (2015); Koomen & Rietveld (2009); Min et al., (2010)
Services and Amenities	Schools, hospitals, shopping centres	Abdullahi et al., (2015); Roychansyah et al., (2005)
Recreation and Community	Walking and biking routes, parks, fields, recreation and community centres, library	Burton (2002); Abdullahi et al., (2015); Roychansyah et al., (2005)
Access to job Opportunity	Central business districts, urban centres	Burton (2002); Abdullahi et al., (2015); Frenkel (2007); Roychansyah et al., (2005)

Table 2.1. Urban Compactness Indicators, Intensification Process, and Literature Sources.

The Suitability Analysis Parameter was calculated through an analytical hierarchal process (AHP) of the spatial dataset. Suitability functions ranging from 0 to 1 were applied on the urban geospatial datasets, representing non-suitable and highly suitable locations respectively. Table 2.2 presents information used for describing each indicator used to build the compactness index, corresponding weights, and suitability function break points. Transportation values were assigned from recommendations of the regional public transportation authority (Translink, 2011) and other studies (Hatch et al., 2014). Access to services and job opportunities were assigned values from the Metro Vancouver Regional Growth Strategy (2016). Values for community and recreational services were obtained from the City of Surrey's Official City Plan (2014) recommendations. Hatch et al. (2014) also provided values for the environmental indicators specific to the Metro Vancouver Region. For indicators that had no values provided, Google Earth imagery was referenced to find average distance from the indicator to the nearest residential development. Land use and population density were not assigned suitability functions but were reclassified into 0 to 1 values of the other indicators.

Various literature reports that population demographics, transportation networks, and land use designations are highly influential indicators of urban compactness (Burton, 2002; Frenkel, 2007) and in this study, these indicators were weighted highest (Table 2.2). These indicators were also highly regarded in the Metro Vancouver Region's urban growth goals for 2040. Abdullahi et al. (2015) provided weights for urban compactness indicators in their research, and these values were considered in the indicator value assignment for this research. For indicators that no values were provided, a sensitivity analysis method was used by assigning weights.

Indicator	Data	Weights within Indicators (%)	Total Weights (%)	Fuzzy Functions (m)
Demographics	Population density	NA	15	NA
Transportation	Rapid rail stations (public)	20	35	Linear; min (*), max (400)
	Frequent bus stations (public)	20		Linear; min (*), max (400)
	Rail stations (Public)	20		Linear; min (*), max (400)
	Rail	10		Linear; min (40), max (100)
	Highway	20		Linear; min (200), max (800)
	Arterial	10		Linear; min (100), max (500)
Environment	Slope	50	10	Linear; min (40), max (20)
	Local Hazards (floods, landslides, etc.)	50		Linear; min (10), max (50)
Land Use	Zoning, land use designations	NA	15	NA
Services and Amenities	Urban centres	45	10	Linear; min (*), max (800)
	Schools	55		Linear; min (*), max (800)
Recreation and Community	All forms of routes (walking, greenways)	30	5	Linear; min (*), max (600)
	Parks and recreation centres	70		Linear; min (*), max (600)
Access to job opportunity	Urban centres	50	10	Linear; min (*), max (800)
	Commercial centres	25		Linear; min (*), max (800)
	Industrial regions	15		Linear; min (50), max (150)

Table 2.2. Suitability Analysis Indicators, Weights and Functions

The Suitability Analysis Parameter requires an update to show spatio-temporal land use change. The first derived suitability analysis map represents the initial land

suitability for the year 2011, the same year of the Canada census data. Literature reported urban compactness tends to cluster through growth (Abdullahi et al., 2015) and for this reason, suitable locations determined from the first suitability analysis were used as a new indicator in the following iterations.

2.4.4. Parameter 2: Land Designation

Land use designation data were used in this study because the data was less likely to change boundaries, unlike zoning boundaries that change often. In this respect, they can be more stable and, therefore, can be more appropriate for spatio-temporal modeling. Although each municipality has its own detailed land use designation, a region-wide land use designation for Metro Vancouver was used instead to ensure a consistent representation and extent. Of the regional land use designations, only six were deemed acceptable to develop mid- and high- rise buildings: Residential – Townhouses, Residential – Low - rise Apartment, Mixed Residential Commercial – Low – rise Apartment, Residential – High – rise Apartment, Commercial, and Mixed Residential Commercial – high – rise Apartment. These developable land use designations were assigned a value of 1, while non-developable designations were assigned 0 to define no urban compactness growth.

As urban compactness develops across the region, land use designations bordering the perimeter of suitable locations can evolve to accommodate mid- and high-rise developments. The presented work incorporates a land use update for each iteration to accommodate this growth. Residential Single Detached designations within 50 meters of the initial developable land use designations were re-assigned to Residential Low-rise apartment. This distance was selected because it encompassed near neighbouring lots without including too many adjacent lots for future mid- and high- rise developments. Only Residential Single Detached designations were considered because other designations were not fit to develop. As the time iterations progressed, more Single Residential Detached designations within the neighbourhood were added to the developable land classifications.

2.4.5. Parameter 3: Average Building Height

The Average Building Height Parameter was a derived spatial layer that contained height values for each developable land use designation. To derive building height values for each designation, spatial building datasets were obtained and joined to the Metro Vancouver Region land use dataset. To ensure a representative sample, three different municipalities were used to average the building height values. Building heights, in meters, were filtered and extracted from the City of Vancouver, the City of Surrey, and the District of North Vancouver building datasets. Next, the highest building within each land use designation was extracted for all three municipalities and averaged to get the mean building height value. The highest buildings were selected because they represent the current maximum height of buildings that are allowed, however, these values are refined by the other parameters. As the focus of this study is on urban compactness through vertical developments, land use designations that typically do not contain mid- and high-rise developments were assigned 0 as a building height value.

2.4.6. Spatio-temporal Change

This research incorporated spatio-temporal change from the years 2011 to 2040 with a 10-year incremental temporal resolution, denoted as T_{initial} , T_1 , T_2 , and T_3 respectively. The spatio-temporal change occurs in the Suitability Analysis and Land Designation Parameters. Suitable locations were identified for the year 2011 in the first Suitability Analysis Parameter iteration. These identified suitable locations for urban compactness were extracted and added to the next time iteration as a new indicator. The Land Designation Parameter also incorporated a spatio-temporal component by updating more available cadastral lots to become developed for time iterations T_{initial} , T_1 , T_2 , and T_3 .

The Average Building Height Parameter was combined with the Land Designation Parameter by matching designations. As the Land Designation Parameter updated newly available land suitable for development, the Average Building Height Parameter updated the corresponding building heights. Each time iteration incremental advanced the assigned building heights of the land use designations to the next highest building average height.

2.5. Results

The derived spatial index for 3D urban compactness was applied the Metro Vancouver Region for the years 2011 to 2040 with a 10-year time interval. Each parameter and the resulting index was represented by a regular spatial tessellation representation using GIS-based raster datasets with a 10-meter spatial resolution. The urban compactness index was constricted to land deemed developable within the urban containment boundary identified by Metro Vancouver.

2.5.1. Parameter Application for the Metro Vancouver Region

The Suitability Analysis Parameter was applied to the Metro Vancouver Region to derive suitable locations for urban compactness growth (Figure 2.3). The locations identified as most suitable for urban compactness (values closer to 1) are seen in red and least optimal locations (values closer to 0) are in blue. The locations in shades of red occur closer to transportation nodes and higher densities as these are key indicators affecting urban compactness.

The derived Metro Vancouver Region suitability analysis map for the year 2011, was overlaid and compared to Google Earth's imagery and 3D building model (Figure 2.4). The results show Google Earth's mid- and high- rise buildings residing within areas identified as suitable locations for urban compactness. The spatial distribution of suitable urban compactness locations, in shades of red, occurs near transportation nodes and densely populated areas.

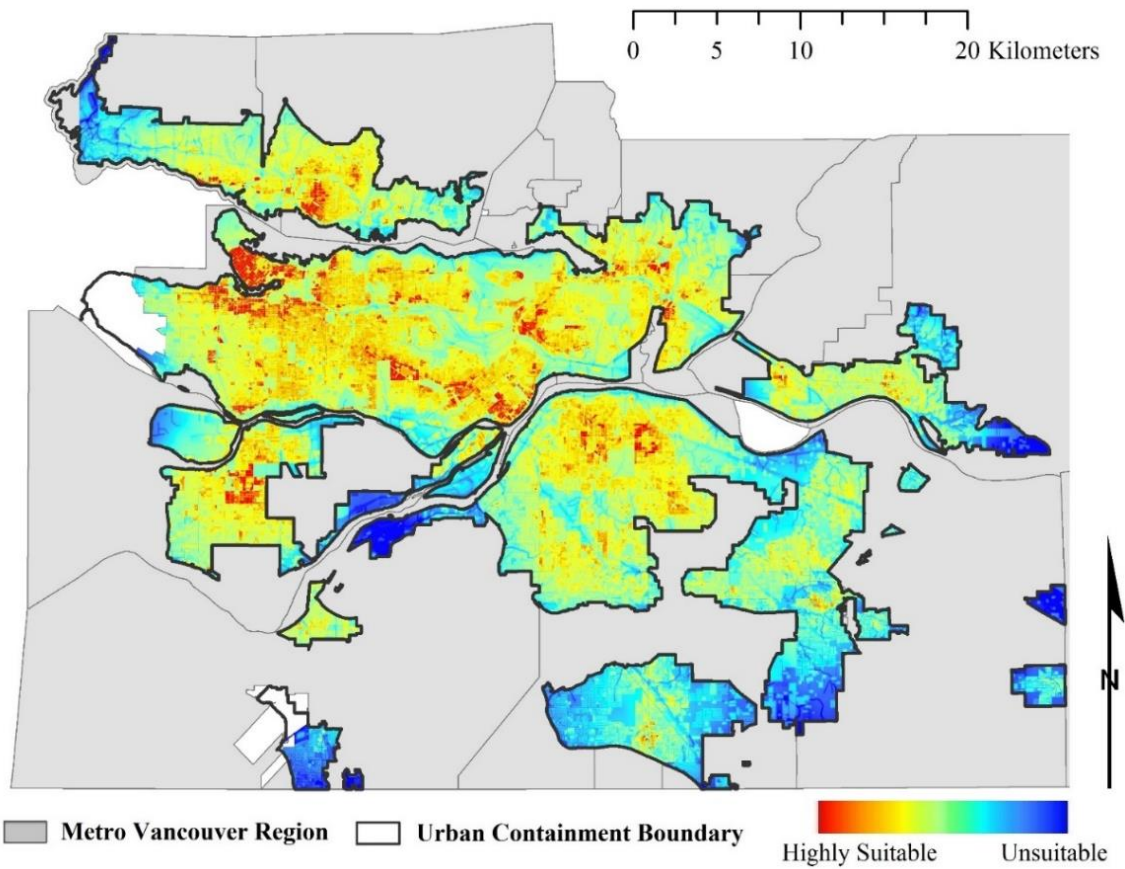


Figure 2.3. The Suitability Analysis Parameter for the Metro Vancouver Region

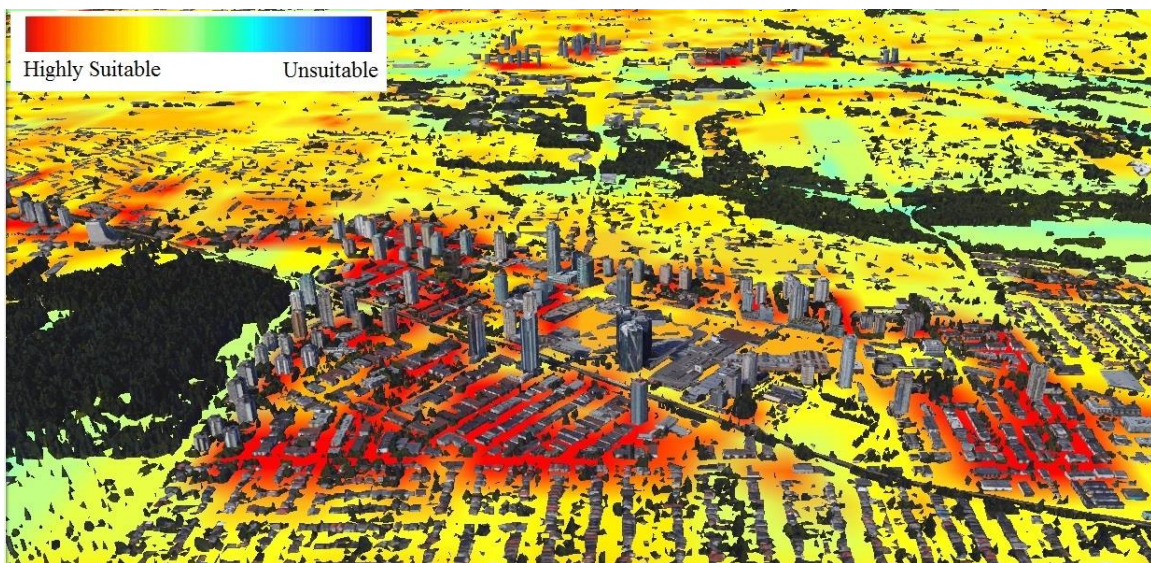


Figure 2.4. A Section of the Metro Vancouver Region Suitability Map with Identified High-Rise Building Locations

The Land Designation Parameter was applied on the Metro Vancouver Region land use spatial dataset. Figure 2.5 shows a composite of all Land Designation Parameter iterations symbolized to show the spatio-temporal growth, beginning with the initial 2011 year ($T_{initial}$) and increasing incremental by 10 years (T_2 , T_3 , T_4) to the final forecasted year of 2040. Darker red areas shown are land use designations deemed acceptable to have urban compactness development in the first iteration. The other colours represent the following iterations and the new land that becomes acceptable to develop.

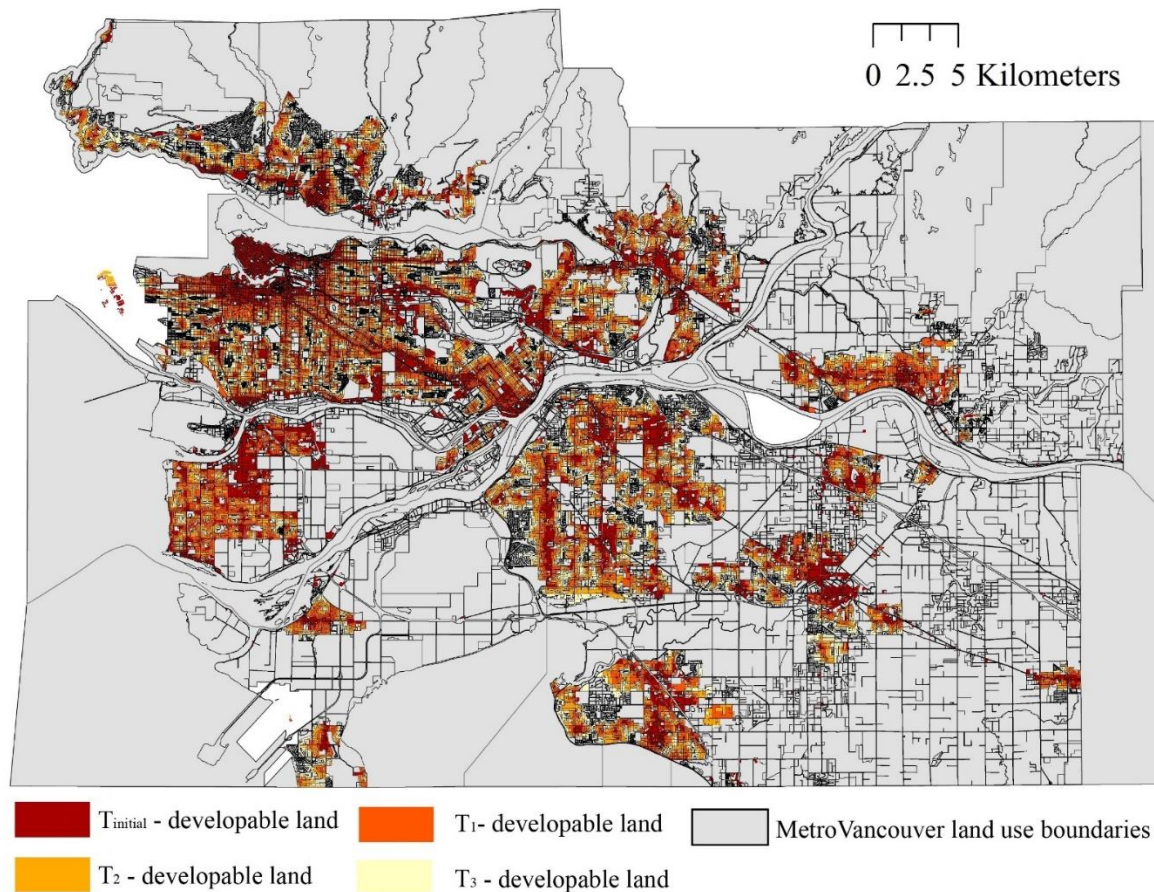


Figure 2.5. Land Designation Parameter Applied onto the Metro Vancouver Region for 2011 ($T_{initial}$), 2020 (T_2), 2030 (T_3), and 2040 (T_4)

The Average Building Height Parameter for the Metro Vancouver Region was derived from the City of Surrey, District of North Vancouver, and City of Vancouver's building average heights per each suitable land use designation. Each municipality and the averaged maximum building height are presented in Figure 2.6. The City of

Vancouver has a significantly higher building height maximum compared to the City of Surrey and even more than the District of North Vancouver. The derived average building heights were assigned to the 6 land use designations for the Metro Vancouver Region that were deemed developable. Figure 2.7 presents the initial spatial distribution of the Average Building Height Parameter for the Metro Vancouver Region.

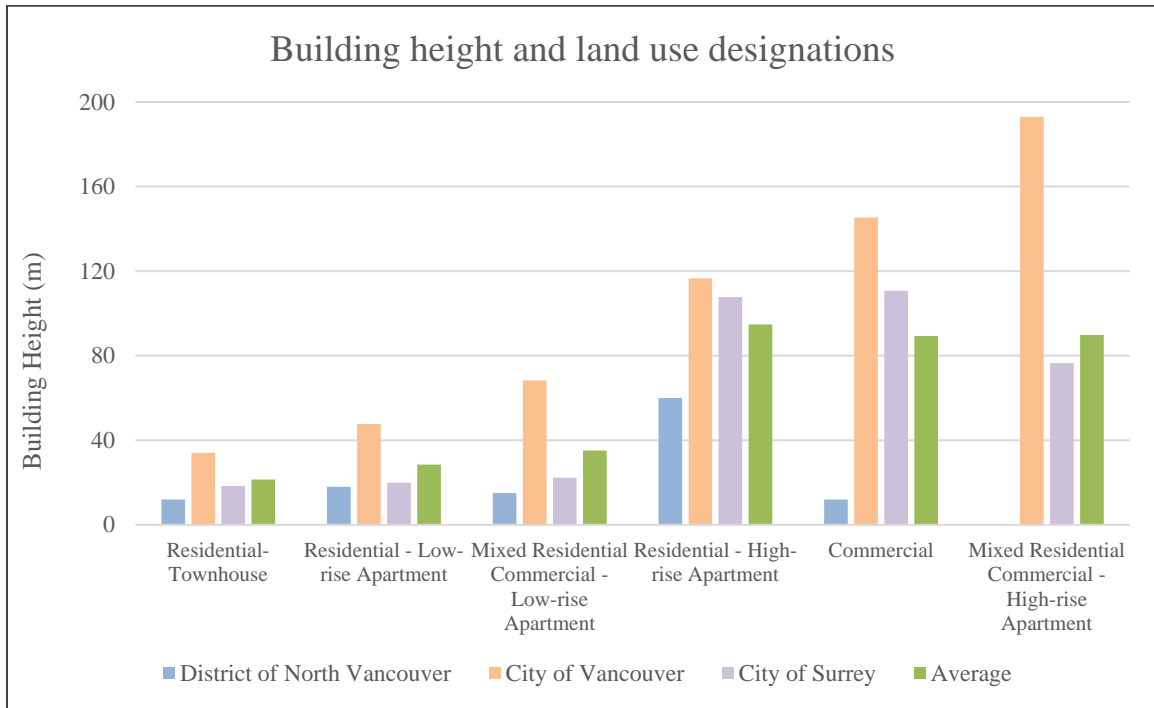


Figure 2.6. Maximum Building Height (m) for Three Municipalities for Land Use Designations in the Metro Vancouver Region and the Average Heights

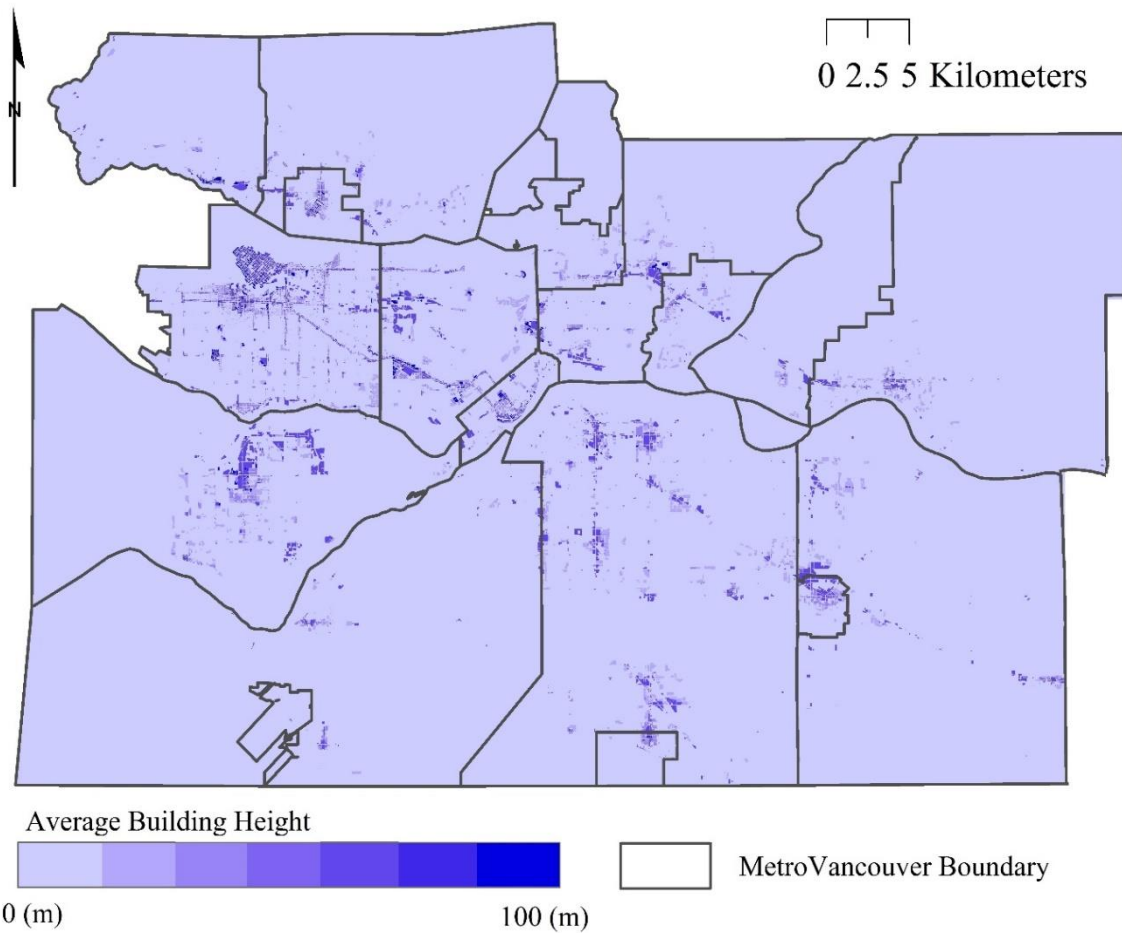


Figure 2.7. Derived Average Building Height Parameter for the Metro Vancouver Region

2.5.2. A Spatial index for 3D Urban Compactness Growth for the Metro Vancouver Region

The presented parameters were combined to derive a spatial index for 3D urban compactness, which was applied to the Metro Vancouver Region to show spatio-temporal change for vertical urban growth. Figure 2.9 shows the spatial index for 3D urban compactness on a perspective view for a section in the Metro Vancouver Region. The height values calculated by the spatial index for 3D urban compactness were extruded for the 2011, 2020, 2030, and 2040 years. As the time iteration progressed, urban compactness growth developed in the vertical and horizontal direction.

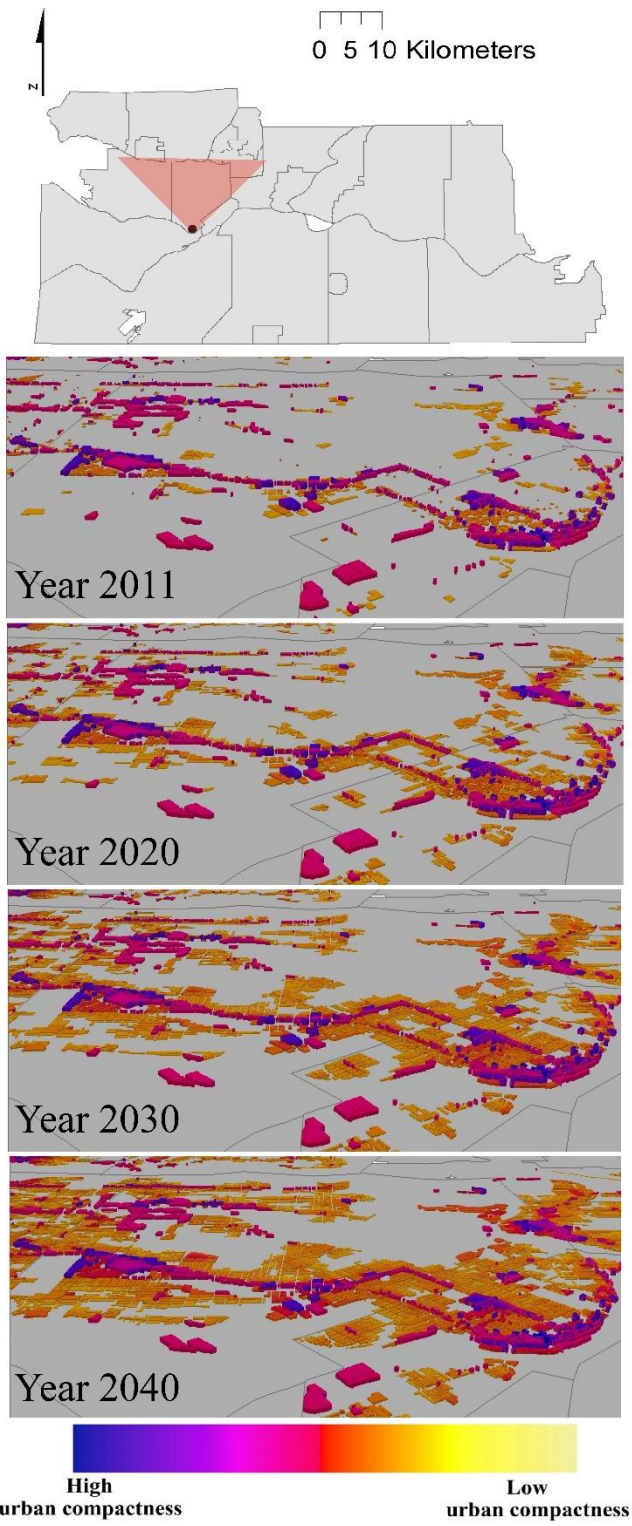


Figure 2.8. A 3D Perspective View of Urban Compactness Growth for Years 2011 to 2040 on a Section in the Metro Vancouver Region

2.6. Discussion

The Metro Vancouver Region is an example of a landscape that is already experiencing urban compactness growth with encouragement of sustainable development from the regional and municipal governments. Figure 2.9 shows the derived spatial index for 3D urban compactness for the region with four selected urban centres: A) Downtown Vancouver; B) Metrotown Centre; C) Coquitlam Centre; and D) Surrey Centre.

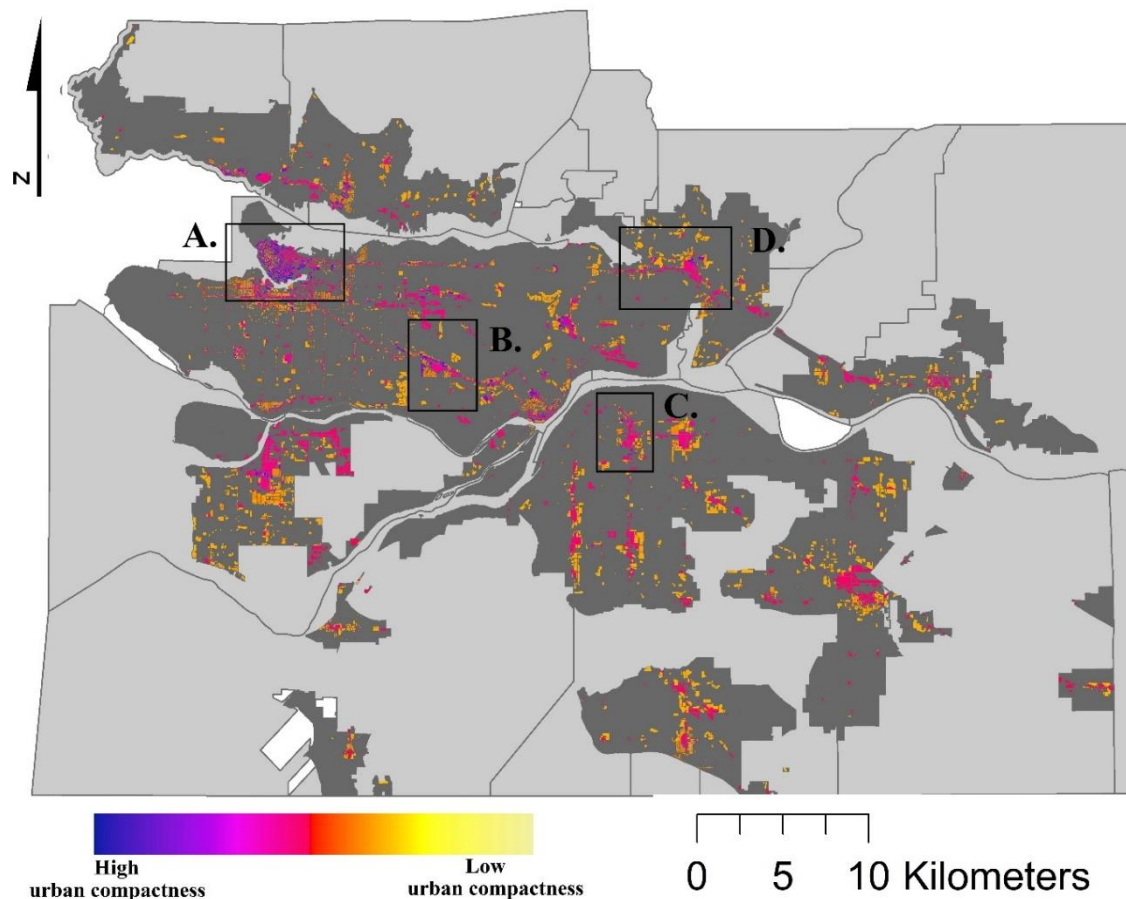


Figure 2.9. The Urban Compactness Index Results with Focus on A) Downtown Vancouver, B) Metrotown Centre, C) Surrey Centre, and D) Coquitlam Centre

Downtown Vancouver has the tallest and greatest amount of high-rise buildings in the entire Metro Vancouver Region. It is the largest Central Business District in the region with many employment opportunities. The high-rise buildings within Downtown

Vancouver are a mix of commercial and residential developments. Downtown Vancouver has a well-developed public transportation system including frequent buses, rapid rail, and water ferries.

Metrotown Centre resides within the City of Burnaby municipality and has the largest shopping centre in all of B.C. It also has a large park and many walking trails in close proximity. The centre also has a rapid rail and bus network that connects residents to Downtown Vancouver in approximately 30 minutes. Most of the mid- and high- rise developments in the area are residential, with a few commercial buildings.

Similarly, the City of Surrey is also connected to the same rapid rail line that connects to Downtown Vancouver. Unlike Metrotown, Surrey Center is located close to a major highway enabling faster travel to Vancouver. The City of Surrey is experiencing a great population growth and is forecasted to be one of the fastest growing cities in the region. With aims to develop a strong Central Business District, Surrey Centre may rapidly develop a more compact centre.

Coquitlam Centre has less mid- and high- rise buildings than the other three centres. However, the high-rise developments occurring next to the shopping and large transportation hub have been mostly developed over recent years. Although not currently connected to the rapid rail network, the development of such connection is expected to be completed by the year 2017 and this may be a strong indicator as to why these buildings have been more recently developed at this location.

As presented in this research, the urban compactness index has identified locations for urban compactness growth. These four examples demonstrate the spatial correlation of urban compactness to major transportation networks, more specifically to the rapid rail stations in the Metro Vancouver Region. As the rapid rail transportation continues to branch out, alongside other services, more sub-centres of urban compactness can be expected to develop in the Metro Vancouver Region. The presented spatial index can be applied to future growth scenarios, such as proposed transportation expansions, to aid in regional planning.

2.7. Conclusion

The presented research derived a new spatial index for 3D urban compactness equation and method to be used for regional spatio-temporal vertical growth modeling across the landscape. The index was derived from three parameters, a suitability analysis, land use evaluation, and average building height. The parameters were combined to produce an urban compactness index that was applied to the Metro Vancouver Region for the years 2011 to 2040. The model results presented locations deemed suitable for urban compactness and provided a vertical height index. A 3D extrusion of the vertical heights presented a perspective view on the regional spatial distribution of urban compactness. As discussed, the urban compactness index identified centres within Metro Vancouver that are already experiencing vertical growth through mid- and high- rise building developments.

The presented work has potential to aid in regional urban and sustainable planning. The projections can provide insight on urban compactness hot-spots, important for planning scenarios such as transportation, view-obstruction, energy efficiency, and pollution concentrations, as few examples. Planning for such demands can ultimately aid in designing a more sustainable and efficient built environment. Additionally, the presented spatial index for 3D urban compactness can be refined to municipal level scales that can utilize their own data, such as building height and land use designation, to provide more detailed results. Conversely, the methods presented can be applied to other growing regions with few refinements unique to each geographic locations.

2.8. Acknowledgments

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Chapter 3.

Geospatial Modeling Approach for 3D Urban Densification Developments

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3.1. Abstract

With growing populations, economic pressures, and the need for sustainable practices, many urban regions are rapidly densifying developments in the vertical built dimension with mid- and high-rise buildings. The location of these buildings can be projected based on key factors that are attractive to urban planners, developers, and potential buyers. Current research in this area includes various modeling approaches, such as cellular automata and agent-based modeling, but the results are mostly linked to raster grids as the smallest spatial units that operate in two spatial dimensions. Therefore, the objective of this research is to develop a geospatial model that operates on irregular spatial tessellations to model mid- and high-rise buildings in three spatial dimensions (3D). The proposed model is based on the integration of GIS, fuzzy multi-criteria evaluation (MCE), and 3D GIS-based procedural modeling. Part of the City of Surrey, within the Metro Vancouver Region, Canada, has been used to present the simulations of the generated 3D building objects. The results show development of mid – and high – rise buildings near transportation networks and densely populated areas. The proposed 3D modeling approach was developed using ESRI's CityEngine software and the Computer Generated Architecture (CGA) language.

3.2. Introduction

The global population is increasing rapidly and placing pressure on urban development. Cities are challenged by opposing economic and sustainable development demands. Urban growth sometimes identified as urban sprawl, means that development is occurring more in the horizontal direction. Sustainability concerns pressure urban planners and developers to consider alternative urban growth strategies, such as vertical and compact development, to augment the urban population densities and to reduce the adverse environmental impact of urban sprawl.

Current literature indicates that three-dimensional (3D) vertical urban growth models have been developed using spatial statistics and remote sensing approaches but with little temporal consideration. Remote sensing imagery and recently LiDAR data have been used mainly for urban vertical change detection (Wang, 2013). Spatial distribution of high-rise buildings was modelled using multi-nominal logit (Frenkel, 2004), three-tiered decision making approach (Tamošaitienė et al., 2013), and descriptive statistics coupled with regression analysis and principal component analysis (Salvatié et al., 2013). Cellular automata (CA) geosimulation approaches have been extensively used to model space-time dynamics of urban sprawl processes in the last two decades (Batty, 1999; White and Engelen, 1993) but the built environment was presented in two spatial dimensions. Benguiui and Czamanski (2008) and Li et al. (2014) proposed CA models to address urban densification and vertical growth. However, these approaches resulted in low-resolution regular grid distributions, not representative of the shape and size of typical irregular cadastral lots. Although advancements have been made on irregularly shaped grids in urban CA modeling (Stevens et al., 2007), more work is necessary to improve compatibility and ease of these approaches. Cadastral lots are fundamental units in planning; therefore, modeling vertical urban growth would be more useful if the shape and size of these units are represented.

The main goal of this research study is to propose a geospatial modeling approach to represent the urban densification process in 3D by generating urban development in the form of mid- and high-rise buildings. Integration of geographic information science (GIS), multi-criteria evaluation (MCE), and procedural modeling

have been used to develop the model. This proposed approach addresses the concerns surrounding low-resolution regular grid models by projecting scenarios of 3D building developments on irregular cadastral lots.

3.3. Methods

3.3.1. 3D Growth Parameters

Factors affecting urban densification and vertical urban growth have been studied by Burton (2002), Frenkel (2007), Mubareka et al. (2011), Sani Roychansyah et al. (2005), and Turskis et al. (2006). Urban densification, often named urban compactness, occurs in areas of higher population density and is often correlated to locations of mid- and high-rise buildings. The identified key factors contributing to vertical urban growth are related to population demographics and growth, economic opportunities, availability and accessibility to transportation networks, social and environmental services and activities, and land use designations. Main factors used in this study are population density, land use, distance to local services and amenities, transportation, job centres, and community and outdoor activities.

3.3.2. Study Site and Data Sets

The Metro Vancouver Region in Canada has a growing population with development constrained by water, mountains, agricultural land reserve, and forests. The City of Surrey was selected as a study area because it is characterized as one of the fastest growing cities in Canada and the Metro Vancouver Region (City of Surrey, 2016), and offers accessible geospatial data. Particularly, this study focused on the Guilford Town Centre as sub-study area of the City of Surrey (Figure 3.1a). GIS data sets such as city lots, buildings, land use designation, parks, schools, transportation networks, hazardous lands, and city centres were obtained from the City of Surrey's Open Data website (City of Surrey, 2016b). Population data was obtained from census records for year 2011 (Statistics Canada, 2011) at the dissemination area level. The raster GIS data layers used for the land evaluation analysis were at 10 m spatial resolution.

3.3.3. Modeling Approach

The proposed geospatial modeling approach integrates GIS based fuzzy multi-criteria evaluation (MCE) method and procedural modeling, which is accomplished in two steps. The first step is related to the evaluation of suitable locations for vertical urban growth. The MCE methods are well known decision-making approaches that have been used for different geographical applications in land site selection, agricultural land preservation, and urban and regional planning (Voogd, 1983; Carver, 1991; Malczewski, 2004). The fuzzy MCE method was used to provide suitability scores ranging from 0 to 1 where 0 indicates unsuitable and 1 indicates highly suitable locations for a vertical development. The MCE criteria were selected from the factors that were identified as the main contributors to vertical urban growth such as importance of recreation and green space, economic opportunity, distance to transportation, services and amenities, land use type, and population density. The MCE criteria were represented by fuzzy suitability functions to include planning strategies described in the City of Surrey by-laws (City of Surrey, 2014). The ESRI ArcGIS 10.2 software (ESRI, 2013) was used to combine multiple GIS data layers and implement the MCE method. Once the locations of potential suitable sites for vertical growth were identified, the results were utilized in the second stage consisting of a 3D GIS-based procedural model to generate building objects.

The procedural modeling approach creates 3D objects from the existing geometry based on the refinement rules (Parish and Müller, 2001). This geometry is extracted from existing vector based GIS data that represents irregular spatial tessellations, which creates 3D objects based on L-system grammar. The procedural rules encompass regional and urban building development policies and city by-laws, including the size of land subdivisions and cadastral lots, building types, set-backs, and heights. This second step was operationalized by using ESRI's City Engine 2014.0 software (ESRI, 2014) as the 3D GIS-based procedural modeling environment, using Computer Graphic Architecture (CGA) shape grammar language in order to program rules. CGA rules are applied using architecture design and object transformation rules such as scale, rotate, translate, and add (Halatsch et al., 2008). The refinement rules were programmed to generate vertical urban growth based on the following hierarchy: 1) creating subdivisions of existing cadastral lots into smaller lots based on surface area

parameter specifications; 2) assigning buildings' floor heights, setbacks, and colour to each land use designation using the land use reference script; 3) assigning land use designation to each cadastral lot determined by spatial alignment using the land use reference script; and 4) linking the cadastral lots to the obtained suitability scores and restricting growth to optimal locations.

3.4. Results

The Guilford Town Centre, within the City of Surrey, is a well-known shopping and expanding business district, and was selected for the implementation of the developed geospatial modeling approach. The perimeter of this location is 1.3 km by 2 km and encompasses an approximate 2.6 km² area (Figure 3.1 a). The obtained suitability values from the GIS-based MCE methods in the first step of the modeling process are presented in Figure 3.1 b, overlaying the values on the Google Earth 3D map. The values of highest suitability scores are in red, and the lowest in dark blue. The Google Earth 3D mid- and high- rise buildings reside within the suitable locations, which indicates that the MCE stage of the model has provided appropriate suitability values.

Stage two of the proposed geospatial model is related to the 3D GIS-based procedural modeling approach. The land use designations and existing cadastral lot subdivisions from the City of Surrey (Figure 3.2) have been further subdivided for the vertical growth. The land use designations determine the type of buildings that can be generated on each new lot. Three scenarios have been designed to represent slow, moderate, and fast growth speeds for the 3D vertical urban developments to accommodate diverse population influx in the city. These growth scenarios were determined by using three different values for MCE suitability scores, which generated maps of varying building development land constrictions. The obtained modeling results are presented for slow (Figure 3.3 a), moderate (Figure 3.3 b) and fast growth (Figure 3.3 c).

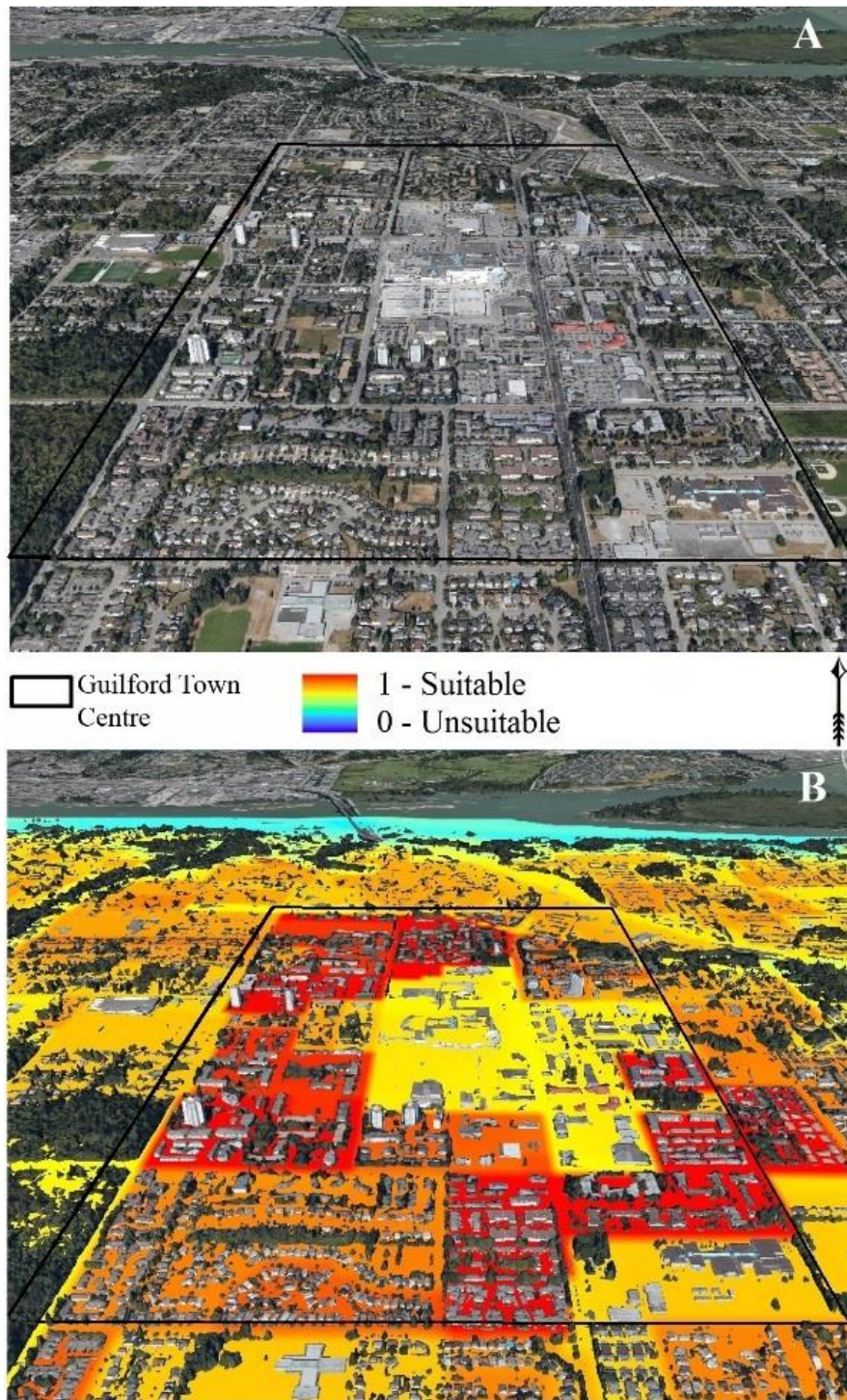


Figure 3.1. Guilford Town Centre, City of Surrey, Canada as (a) Study Area using Google Earth 3D Building Representation and (b) with Obtained GIS-MCE Map for Vertical Growth Suitability

The generated building objects in each scenario are colour-coded according to the land use designation of the developed lot. The generated three growth scenarios are presented through a different perspective angle (Figure 3.4). The current city skylines with real extruded building footprint geometry are shown in dark grey (Figure 3.4 a). The simulated development for slow (Figure 3.4 b), moderate (Figure 3.4 c), and fast growth (Figure 3.4 d) are presented in designated building colours. The modeling results indicate that the locations where the projected 3D growth occurred on the subdivided lots for each scenario. There is a noticeable increase in building densification surrounding the Guildford Town Centre, which is linked to the increased growth speed.



Figure 3.2. The City of Surrey Land Designations and Existing Cadastral Subdivisions Defining the Building Types

3.5. Conclusion

The developed geospatial vertical urban growth modeling approach utilizes the GIS-based fuzzy MCE method in combination with procedural modeling to project future urban densification. The model was implemented on cadastral lots of irregular shapes and sizes at high-resolution, overcoming past limitations of raster based models. The three growth scenarios demonstrated a realistic progression of urban densifications for the study area. The fast growth scenario presented more mid- and high-rise buildings for the urban and town centre designated lots. The developed geospatial vertical urban growth model has the ability to generate buildings governed by the suitability values and procedural rules and can be applied to other study areas.

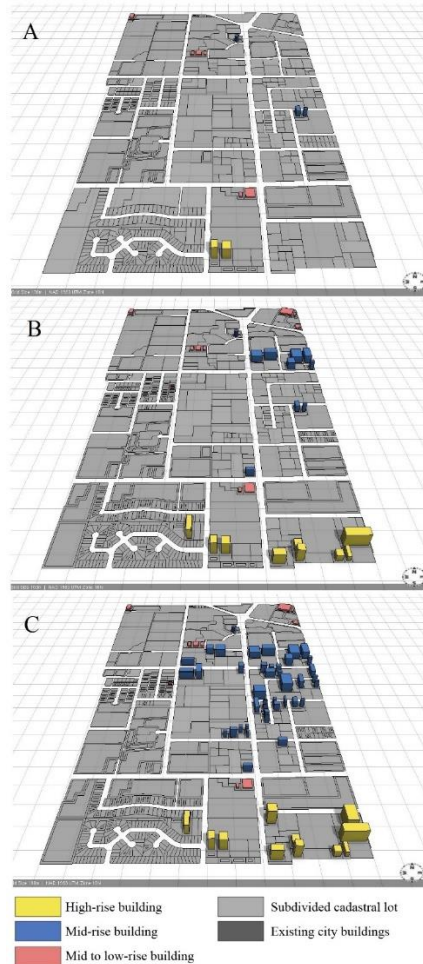


Figure 3.3. Modeling Results for the Vertical Urban Development Obtained for Three Scenarios (a) Slow (b) Medium and (c) Fast 3D Growth

This proposed geospatial modeling approach can be used by city planners to design and visualize various urban scenarios. Future work can incorporate more detailed building object designs, a temporal component, and other 3D development scenarios.

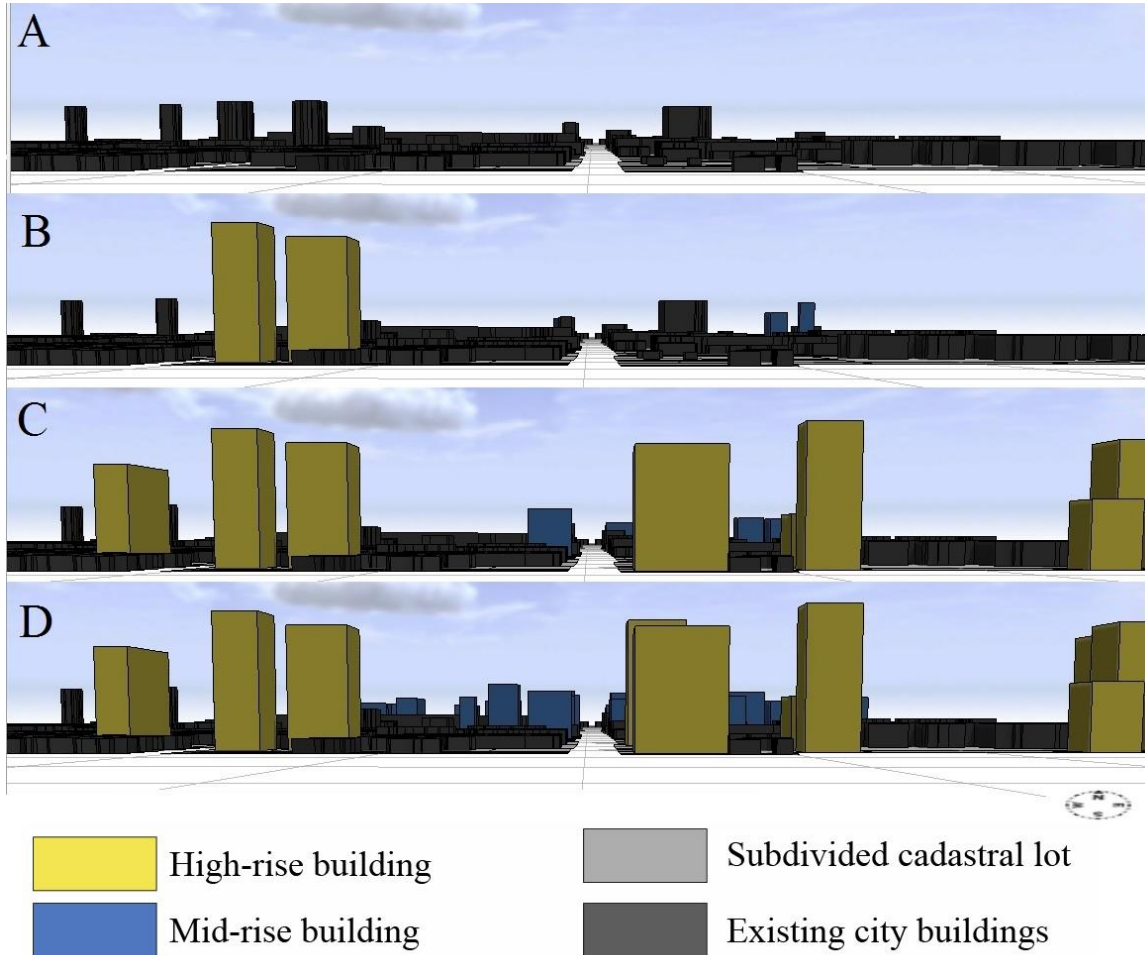


Figure 3.4. Visualization of the Urban Landscape (a) Under Current State, and as Simulated for (b) Slow (c) Medium and (d) Fast Vertical Growth Development Scenarios

3.6. Acknowledgments

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Chapter 4.

The 3D Geosimulation Approach for Vertical Urban Expansion

The version of this chapter co-authored with S. Dragicevic will be submitted to the Landscape and Urban Planning journal

4.1. Abstract

Urban growth is a three-dimensional (3D) spatio-temporal process that, due to growing populations, is experiencing densification vertically. Landscape planning for urban intensification and optimization is becoming more important and urban modeling methodologies and tools can aid in decision-making. Land use designations, population densities, and locations of basic services are all attributes for optimal locations for vertical expansion and can be used to model future mid- and high- rise building growth. The objective of this research is to develop a 3D geosimulation model to simulate the growth of optimal vertical expansion locations. This geosimulation model consist of two stages: the vertical growth land suitability analysis stage for finding optimal growth locations, and the 3D geosimulation stage to refine the suitability results on a cadastral lot resolution with 3D buildings. The proposed 3D geosimulation model was developed using ESRI's CityEngine software with the Computer Generated Architecture (CGA) language. The results of the simulation indicated that the augmented mid- and high- rise 3D building objects generated from 2011 to 2040 were clustered near urban centres and transportation networks. The geosimulation approach was applied to the City of Surrey, BC, Canada and an additional transportation scenario is presented to demonstrate the presented models ability to accommodate tangible planning contexts.

4.2. Introduction

It is widely accepted that the increasing global population heightens sustainability concerns in the environmental, economic, and social sectors (Turner, 2007), and adds pressure to city planning in rapidly growing regions. Historically, most cities adapted to urban population growth demands by developing low-density buildings in the horizontal direction, known as urban sprawl. Urban sprawl has been criticized in research as it causes more environmental degradation given the inefficient, constant and uniform low urban spread (Torrens & Alberti, 2000). This process negatively impacts environmental sustainability (Johnson, 2001), social equity (Burton, 2000), and proximity to transportation and other social services (Carruthers & Ulfasson, 2003). Rapidly growing cities are addressing unsustainable urban sprawl growth by increasing population density in the vertical dimension. Vertical urban development (VUD) can occur in the form of mid- and high- rise buildings, intensifying and optimizing the built environment.

Placement and design of high-rise buildings need consideration by city planners in order to build better cities (Al-Kodmany, 2003). The development of new high-rise buildings can drastically change the built-up environment that may affect variables such as urban air temperature (Chen et al., 2012), pollution and ventilation (Hang et al., 2012; Moonen et al., 2013; Yuan & Ng, 2012), and energy demands (Strzalka, et al., 2011). Models can help facilitate decision-making processes by showing landscape patterns and forecasted growth scenarios (Couclelis, 2005).

Spatial approaches have long been used for two-dimensional (2D) urban landscape modeling, commonly through cellular operations (Tobler 1979; Couclelis, 1985; Batty & Xie, 1994). Urban modeling approaches including cellular automata (CA) (Batty et al., 1999) and agent-based modeling (ABM) (Matthews et al., 2007) have been used to incorporate spatio-temporal dynamics in forecasted scenarios. Other approaches focus on land suitability evaluation based on criteria and include methods such as analytical hierarchy process (Hossain et al., 2007), logic-scoring preference (Hatch et al., 2014), ordered weighted averaging (Malczewski, 2006), simple additive scoring (Ligmann-Zielinska & Jankowski, 2012), and weighted linear combination (Carver, 1991), as few examples.

Typically, urban models are produced on GIS-based raster datasets due to ease, mathematical operations, and compatibility with other spatial data such as remote sensing and other GIS datasets. Although this may be appropriate for regional scale land use modeling, regular grids do not fully address the intricate complexities found on local scales, particularly complexities found within cadastral lots. Cadastral lots are high-resolution urban units, composed of an irregular size and shape grid distribution. This has been a challenging limitation to overcome because of conventional approaches that preform iterative operations on regular grids (White & Engelen, 2000). Approaches including spatial Voronoids (Shi & Pang 2000), raster-based partitioning algorithms (Morgan & O'Sullivan 2009), and irregular spatial tessellations (Stevens et al., 2007) attempted to address the regular grid limitation. The creation of spatial sub-units on cadastral lots is further complicated through subdivision processes and a few have incorporated subdivision algorithms in various landscape contexts (Le Ber et al., 2009; Wickramasuriya et al., 2011; Jjumba & Dragičević 2012). Despite the recent work, there still exist a need to incorporate modeling operations on irregular tessellations with more compatibility and ease.

Additionally, little research has concentrated on modeling urban densification or VUDs over time, although a few have started (Benguui and Czamanski, 2008; Lin et al., 2014). Urban compactness, a potential indicator for mid- and high- rise developments (Tsai, 2005), is spatially distributed on key parameters attractive to urban planners, developers, and buyers. Such parameters identified in literature (Burton, 2002; Frenkel, 2007; Turkis et al., 2006) include population density, access to services, and land use designation. These parameters can be used in spatial modeling approaches to project suitable VUD locations over time and various growth scenario simulations.

An additional limitation to urban modeling, specifically to mid- and high- rise growth, is refining projected growth to a building-scale resolution in 3D. This is important because building footprints equate to less area than a cadastral lot, a significant difference in area. Additionally, little research has modeled building dynamics in 3D to visualize urban growth through a different perspective and to calculate change in built volume. Such 3D high-resolution urban modeling is scarce in literature but research has

had advancements in architecture, computer science, urban, and GIS fields by using techniques such as CAD models, LiDAR, and simulation environments (Shiode, 2000).

The *iCity* modeling tool, presented by Stevens and Dragičević (2007), was developed to operate on an irregular vector tessellation and CA land use change simulation. Further, Jjumba and Dragičević (2012) developed *Agent iCity* to simulate land use change on irregular vector tessellations using an agent-based modeling (ABM) approach to incorporate various stakeholder's interests in urban scenarios. However, *iCity* and *Agent iCity* do not incorporate the third spatial dimension in their modeling approaches. Although they operate on a high-resolution cadastral lot shape and size, the results are limited to these vector boundaries.

The objective of this research, therefore, was to develop the 3D geosimulation modeling approach to represent 3D VUD growth on irregular spatial tessellations over space and time. The 3D geosimulation was developed on a high-resolution building scale. The proposed spatio-temporal model for suitable VUD locations was based on two parts: first, a vertical growth land suitability analysis approach; second, 3D geosimulation to subdivide cadastral lots, assign land use building attributes, and generate 3D building objects based on programmed rules reflecting city policies at optimal locations. The proposed model was then applied to a normal growth and transportation expansion scenario to present forecasted 3D VUD growth.

4.3. Theoretical Background: High-resolution 3D Urban Modeling

Little research has been done on urban modeling with focus on identifying and forecasting locations suitable for vertical densification, and more specifically for mid- and high-rise buildings. A statistical composite index was developed for urban compactness through regression analysis of imagery supplemented by PCA and cluster analysis (Mubareka, 2011). Salvati (2013) presented a morphological indicator created through descriptive statistics, regression analysis, and PCA for urban vertical profiles to demonstrate temporal growth. Research presenting approaches specifically addressing high-rise building growth included, multi-nominal logit models (Frenkel 2004), self-

organizing map (Koomen, 2009), and a combination of SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis, expertise input, and the SAW (Simple Additive Weighting) (Tamošaitienė et al., 2013) methods. However, these approaches did not represent VUDs on irregular spatial tessellations nor in 3D.

Remote Sensing has been used extensively in 3D urban volumetric construction (Wang, 2013), including aerial and satellite imagery, and more recently LiDAR approaches (Sridharan & Qiu, 2013), as well as a combination of both methods (Zhou et al., 2004). Research has (Brook et al., 2013) also focused on spatio-temporal modeling and monitoring of the urban built environment. Stal et al. (2013) utilized photogrammetry and LiDAR to identify buildings and show change detection of building heights through pixel subtraction. After filtering out other environmental noise, a 3D building change model was used to provide insight of height change between the two time periods. Despite the advancements in building identification, 3D modeling, and change detection over time and space, not much has been done through remote sensing towards forecasting future high-density or high-rise developments.

The CA modeling approaches have been used extensively for several decades to model various urban land use changes (White & Engelen, 1993; Batty, 2005; Sante et al., 2010) but mostly in two spatial dimension over time. CA simulates a spatial change by iterating and updating cell values, typically operating on a regular raster grid. A CA approach was applied to urban density by Yeh and Li (2002) to promote sustainable and compact development. The simulation was based on monocentric and polycentric urban forms and found that compact growth tends to show concentrations of high-density developments. CA modeling approaches specific to high-rise building growth have been explored by Benguigui & Czamanski (2008) and Li et al. (2014). Although the models presented projected locations of high-rise buildings, the results were in 2D and in the conventional regular spatial tessellation representation. Even with high-resolution grid cells, the size and shape of the cell and neighbourhood filter may still not fully represent an irregular cadastral lot distribution.

Broitman and Czamanski (2012) presented research using an agent-based modeling (ABM) approach to show developer competition towards high-rise buildings

and to demonstrate the 'leap-frog' phenomenon of emergent developments or sub-centres. Although their research focused specifically on high-rise developments, their approach was modeled on a 2D low-resolution regular spatial tessellation. Another ABM approach presented by Torrens (2013) modeled an earthquake evacuation that deployed agents evacuating 3D built environment scenarios. Despite the work presented, there is still a need to merge both urban modeling approaches, such as CA and ABM, with 3D environments.

Other advancements in 3D modeling utilize a procedural modeling approach, using programmed grammar rules on existing geometric vector shapes to refine appearance and model new objects in 3D (Parish & Muller, 2001; Talton et al., 2011). The derived 3D objects can be generated from existing geometry, such as GIS-based vector data that can represent irregular spatial tessellations of cadastral lots. Procedural modeling was proposed by Parish and Muller (2001) using an L-systems approach to generate roads, lots, and building objects with textures and a 3D urban procedural modeling approach, called *CityEngine*, was introduced by Muller et al. (2006). Since these urban procedural modeling developments, researchers have adopted the approach for various 3D urban modeling and visualizations problems, including new street modeling (Chen et al., 2008), modeling spaces at pedestrian scales (Koltsova et al., 2012), ecosystem trade-offs for urban planning (Gret-Regamey et al., 2013), and sustainable smart cities (Vihol et al., 2015).

Xu and Coors (2012) proposed the GIS System Dynamics approach for a sustainability assessment of residential urban development. Indicators were investigated and used to create 2D maps of projected growth. The derived maps of growth were used to visualize the results in 3D through a procedural approach. Similarly, a geodesign procedural modeling approach for urban landscape change was adopted for a small study area in Brazil (Moura, 2015). The approach included the original landscape, a multi-criteria analysis model to show potential change, and a 3D urban model of the potential future planning through a procedural approach. The integrated suitability analysis with procedural modeling approach was also taken by Neuenschwander et al. (2014) for quality target scenario based urban planning. These models did not incorporate an iterative temporal land use change, however, Weber et al. (2009)

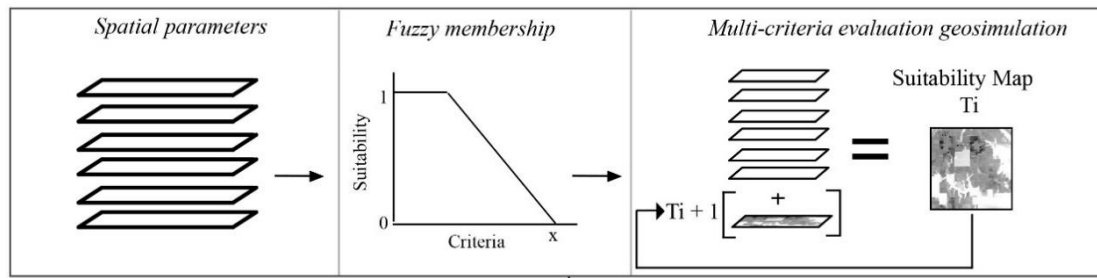
presented an interactive geosimulation of 4D cities. The spatial procedural modeling research did not include land selection approaches explicit to VUDs nor did they focus on building attributes specific to land use designations.

There is an obvious need for research to develop a robust 3D VUD high-resolution geosimulation approach to help understand the urban densification process and its impact on urban landscapes. This study, therefore, aims to integrate land selection evaluation and spatial procedural modeling approaches on an irregular spatial tessellation to advance 3D geosimulation modeling of VUD process over space and time. The model components include: 1) land selection evaluation utilizing key parameters that identify suitable location for VUDs; 2) spatial-temporal simulations that operate on high-resolution irregular spatial tessellations; and 3) visualization of projected growth in a 3D manner.

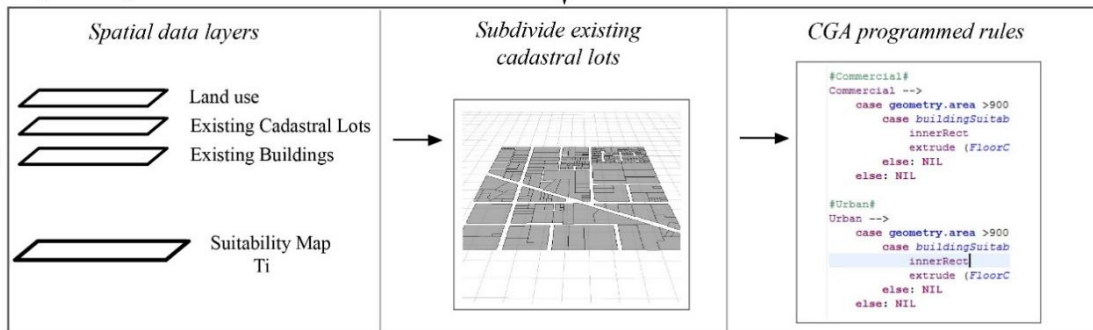
4.4. Methods

The 3D geosimulation model consists of two stages: 1) using key parameters in the vertical growth land suitability analysis stage, to identify optimal locations for mid- and high-rise buildings; and 2) a 3D geosimulation to generate building objects derived from programmed rules that incorporate land use designations, building policies and by-laws, and suitability maps. The geosimulation can incorporate several growth time iterations by evaluating and updating new suitable locations for the vertical growth land suitability analysis stage. The updated VUD suitability maps are utilized in the 3D simulation model stage and new building objects are generated for a normal and transportation expansion growth scenario. Figure 4.1 provides a model overview.

Stage 1: Vertical growth land suitability analysis



Stage 2: 3D geosimulation



Scenarios

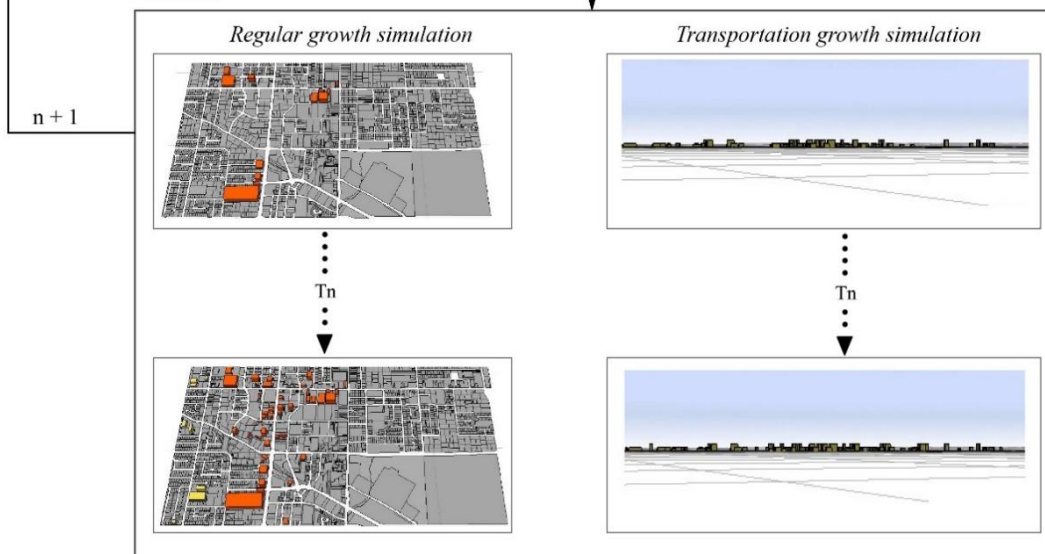


Figure 4.1. The 3D Geosimulation Model Overview

4.4.1. Stage 1: Vertical Growth Land Suitability Analysis

The vertical growth land suitability analysis stage operates on spatial datasets within six identified criteria that influence urban intensification and optimization,

significant for mid- and high- rise developments. Population demographics have been identified as a key criterion for VUD and encompasses socio-economic dispersions across the land, such as population density and household incomes (Burton, 2002; Koomen et al., 2009). Transportation networks including roads and public transport, such as rapid rail and buses, have also been used in urban densification research (Abdullahi et al., 2015; Frenkel, 2007). Land use, specifically designations encouraging densification and mixed use, highly contribute to densification growth (Burton, 2002). Population demographics, transportation, and land use criteria are commonly identified and used in density research, but to a lesser extent, services and amenities (Sani Roychansyah et al., 2005), recreation and community (Abdullahi et al., 2015), and access to job opportunities (Frenkel, 2007) have also been identified as influential criteria. An environmental land constraint criterion is also included to restrict growth in undevelopable locations due to factors such as but not limited to water bodies, steep slope, and flood hazardous. The spatial criteria datasets were standardized using fuzzy membership, operationalized in ESRI's ArcMap (2013).

The standardized criteria datasets were weighed against each other through a multi-criteria evaluation analysis. Multi-criteria evaluation approaches are well used models for decision-making based on various criteria (Voodg, 1983; Malczewski, 2004). These methods rank spatial layers accordingly and have been used widely in land selection modeling and urban planning (Carver, 1991; Jankowski, 1995). Additionally, multi-criteria evaluation approaches have been supplemented with fuzzy membership (Burrough et al., 1992; Jiang & Eastman, 2000) to assign suitability scores through standardized non-Boolean means. Multi-criteria evaluation and fuzzy membership modeling approaches typically operate on regular raster grids due to the mathematical calculations applied on the spatial layers.

The standardized criteria were weighed through a hierarchal structure beginning with individual criterion and ending with a final combination of all criteria. The rationale for the hierarchal weighing design was to account for the simulation updates in following iterations, which requires a change in weight values. The first suitability map derived from the multi-criteria evaluation analysis, T_i , represents the initial time scenario for the geosimulation. As noted in literature (Burton, 2002), urban compactness is highly

correlated to density and VUDs occur in clusters (Abdullahi et al., 2015; Yeh & Li, 2002). Due to these findings, the model derives projected growth maps by including T_{i+n} into proceeding iterations, altering the initial suitability weights to accommodate the new criterion.

4.4.2. Stage 2: 3D Geosimulation

The 3D geosimulation incorporates stage 1 results and other land use spatial data to refine and augment 3D VUD results through the spatial procedural modeling approach. Procedural modeling generates 3D objects from existing vector geometry (Parish and Muller, 2001). In an urban modeling context, 3D building objects can be generated from vector data such as land use and cadastral lots. This is created by writing a program with a set of rules that iteratively refine the model from a general to more detailed shape. This stage requires programming rules written in the Computer Generated Architecture (CGA) shape grammar language, developed to sequentially apply architectural design with general rules that add, scale, translate, and rotate the shape (Muller et al., 2006; Halatsch et al., 2008). The language operates on an object's bounding shape, its 'scope', by refining and generating it in 3D.

The 3D geosimulation stage was operationalized using ESRI's CityEngine 2014.0 (ESRI, 2014) software environment to program and generate the 3D geosimulation. The software imports and displays spatial layers, has a script editor, and can mass generate models all within the single program. In this research, the programmed rules were designed around a combination of city by-laws, suitability maps, object appearance, and user enabled options.

GIS vector shapes representing cadastral lots, existing building footprints, and land use designation were used in this stage. Cadastral lots were the fundamental vector geometries used to subdivide and generate 3D building objects. In cities, cadastral lots are constantly manipulated to conform to developmental demands. Undeveloped cadastral lots can encompass large areas until a development plan is requested for the location, at which time the cadastral lot may be subdivided into a smaller area specific to

the type of development. In this study, the existing cadastral lot shape geometry underwent a subdivision process as the initial geometry refinement.

Shape grammar rules, programmed in the CGA language, were implemented on the subdivided cadastral lots to further refine the geometry and to generate new building objects. Programmed rules applied on the cadastral lots included: land use building reference, stochastic lot omission, land suitability maps, and building object visualization. The land use building reference rule was programmed to assign building floor-height and setbacks. Next, a stochastic lot omission rule was added to restrict the amount of growth for cadastral lot development because in reality optimal land for urban growth does not all get developed at once.

The final cadastral lot refinement requires the program to evaluate the various cadastral lots and generated the building object based on the suitability maps generated in stage 1. If the lot is on an optimal cell, the building object's assigned height is multiplied by 1 and extrudes in the vertical dimension. Oppositely, if the lot is on a restricted cell, the building objects is multiplied by 0 and no growth occurs.

The land use reference script assigns floor parameters to each building object, however, floors cannot be observed through exterior building walls. For this reason, three visualization options were programmed to allow the user to toggle between building exterior walls, floors exclusively, and semi-transparent exterior walls with floors inclusively. Each building is colour-coded by an assigned colour to the land use reference rule.

4.5. Results

4.5.1. Study Area and Data

The Metro Vancouver Region is a growing urbanized area encircled by environmental constraints of water, mountains, and agricultural land reserves. The City of Surrey (Figure 4.2) resides within the Metro Vancouver Region and, based on the 2011 Canada census, is forecasted to become one of the fastest growing cities

nationally (City of Surrey, 2016 a). The city encompasses approximately 320 km² and has a diverse range of environmental heterogeneity including various land cover, hazardous flood plains, and steep slopes. Additionally, this study area was chosen because the City of Surrey has an active sustainable growth plan to accommodate the expected population growth. Due to computation restrictions, the normal vertical growth geosimulation was confined to the City Centre region and the transportation scenario confined to the Proposed Transportation Corridor.

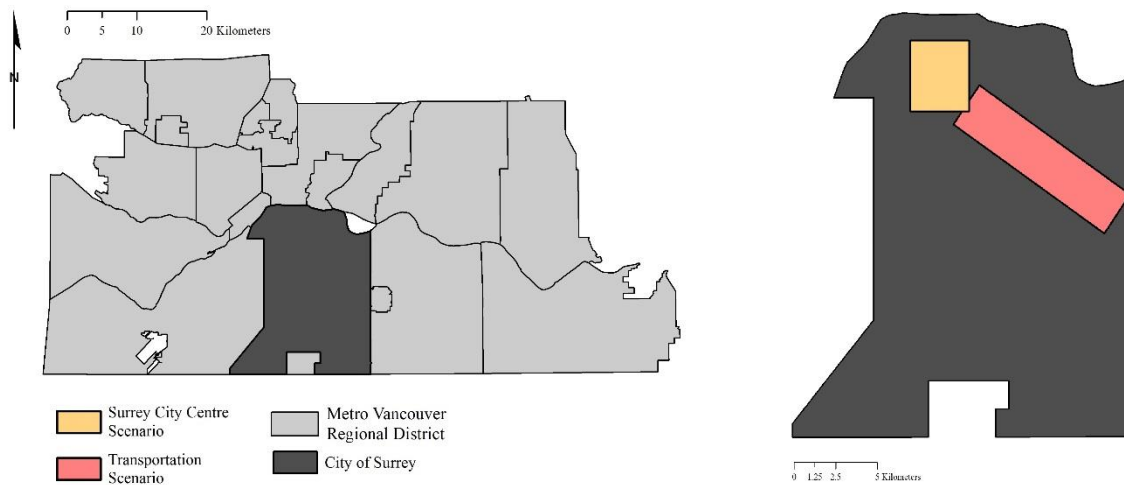


Figure 4.2. City of Surrey in Metro Vancouver, BC, Canada with the City Centre and Proposed Transportation Corridor

This City of Surrey was also selected as the study area because of the accessibility of geospatial data that satisfied the necessary criteria for VUD growth including population demographics, transportation, land use, services and amenities, recreation and community, access to job opportunity, and environmental constraints (obtained from City of Surrey, 2016 b). To satisfy the transportation criterion major roads (highways, freeways, and arterial), rail, and bus stations data sets were consolidated. Data sets including schools, libraries, community centres, and other facilities were used in conjunction with urban centre locations to fulfil the services and amenities criterion. Sport centres and fields, golf courses, recreational centres, community centres, heritage sites, walking routes or trails, and parks were consolidated under the recreation and community criterion. To account for the access to job opportunity criterion, commercial, industry and job centre (urban centres combined with Central Business District) land use

designations were obtained. Land use designation were obtained for the entire city as it provided insight on the various development regulations. A spatial data set of an urban containment boundary and hazardous lands (e.g. landslide and flood risks) were used as developmental constraints. Additionally, cadastral lots and building footprint vector data were obtained for the 3D geosimulation stage. Urban population data was gathered from Statistics Canada 2011 census at the highest resolution, the dissemination area (DA), and a population density was calculated for the study area. All spatial datasets were in 10 m raster grid resolution and confined to the municipal boundary extent.

4.5.2. Implementation of the 3D Geosimulation Model

The spatial criteria were standardized through fuzzy memberships presented in Figure 4.3. Membership values assigned for rapid rail and bus stations, recreation paths and facilities, and all community regions of interest were obtained from the City of Surrey's Official City Plan (2013). The membership for the major road network criterion was assigned based on a value provided by Hatch et al. (2014) and was doubled for the highway network criterion. Job centres and commercial land use criteria were assigned a membership from recommendations found in the Metro Vancouver Regional Growth Strategy (2014) documentation. The local facilities and services criteria were given memberships obtained from the City of Surrey's Community Energy and Emissions Plan (2014). Railroads, industry land use, and hazardous lands memberships were assigned based on distance measurements observed in Google Earth imagery within the City of Surrey boundary. Two spatial criteria omitted from fuzzy membership standardization, land use and population density, were reclassified into 10 categories to ensure values range incrementally between 0 and 1 as the other membership spatial criteria.

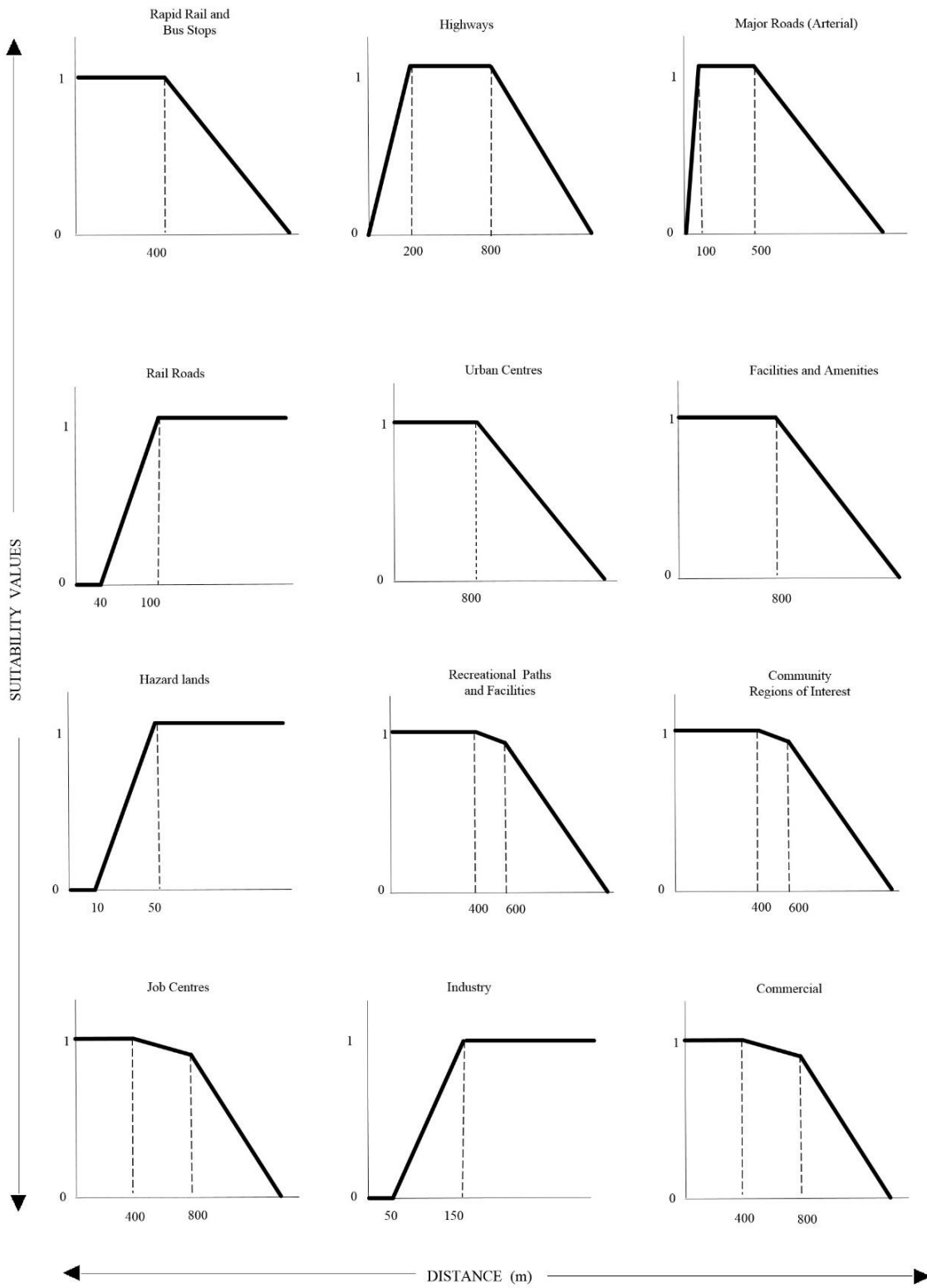


Figure 4.3. Fuzzy Membership for VUD Criteria

The spatial criteria for the City of Surrey were weighed through a hierarchical process to derive the vertical growth land suitability maps, Table 4.1 presents the assigned weights. As reported in literature (Burton, 2002; Abdullahi et al., 2015; Frenkel, 2007), land use, population demographics, and transportation criteria are significant contributors to urban compactness, and for this reason, were weighed higher. The remaining criteria were assigned lower values as they are not as influential to VUD and were referenced to Abdullahi et al. (2015) proposed weights. Final weight allocations were adjusted through the model calibration.

Criteria	Data	Weights for Data	Weights for T_i	Weights for $T_1 - T_3$
Recreation and Community	Regions of interest	35	5	45
	All routes (hikes, greenways, etc.)	30		
	Parks and recreation	35		
Access to Job Opportunity	Urban town centres	40	10	
	Commercial	20		
	Industrial	10		
	Empty lots	30		
Services and Amenities	Regions of interest	35	10	
	Schools	40		
	Urban town centres	35		
Transportation	Rapid rail	30	35	
	Frequent bus stops	30		
	Rail	10		
	Highway	20		
	Arterial	10		
Environmental Land Constraints	Hazardous lands	NA	10	
Land Use	Land use designations	NA	15	25
Demographics	Population density	NA	15	15
Previous suitability map (T_n)	Suitability VUD locations	NA	NA	15
TOTAL	-	-	100	100

Table 4.1. Criteria, Data, and Weights for the Vertical Growth Land Suitability Analysis Stage

The vertical growth land suitability analysis stage derived suitability maps for the City of Surrey under a normal growth scenario. The geosimulation time iterations represent a temporal unit of 10 years. T_i represents the suitability map with suitability values for 2011 determined by the census data of that year, and the T_3 iteration represents the projected growth for the year 2040. T_i suitability results were used to update the geosimulation for time iterations Time - 1, Time - 2, and Time - 3 on Figure 4.4. The areas in darker blue have values approaching 0 and are considered least suitable for VUD. Contrastingly, the areas in shades of red have values approaching 1 and are considered highly suitable for VUD growth. Distinct angular boundaries are evident in the results and this is partially because no fuzzy memberships were applied to the population density DAs. As expected, areas most suitable are closest to transportation networks, higher population densities, and urban centres.

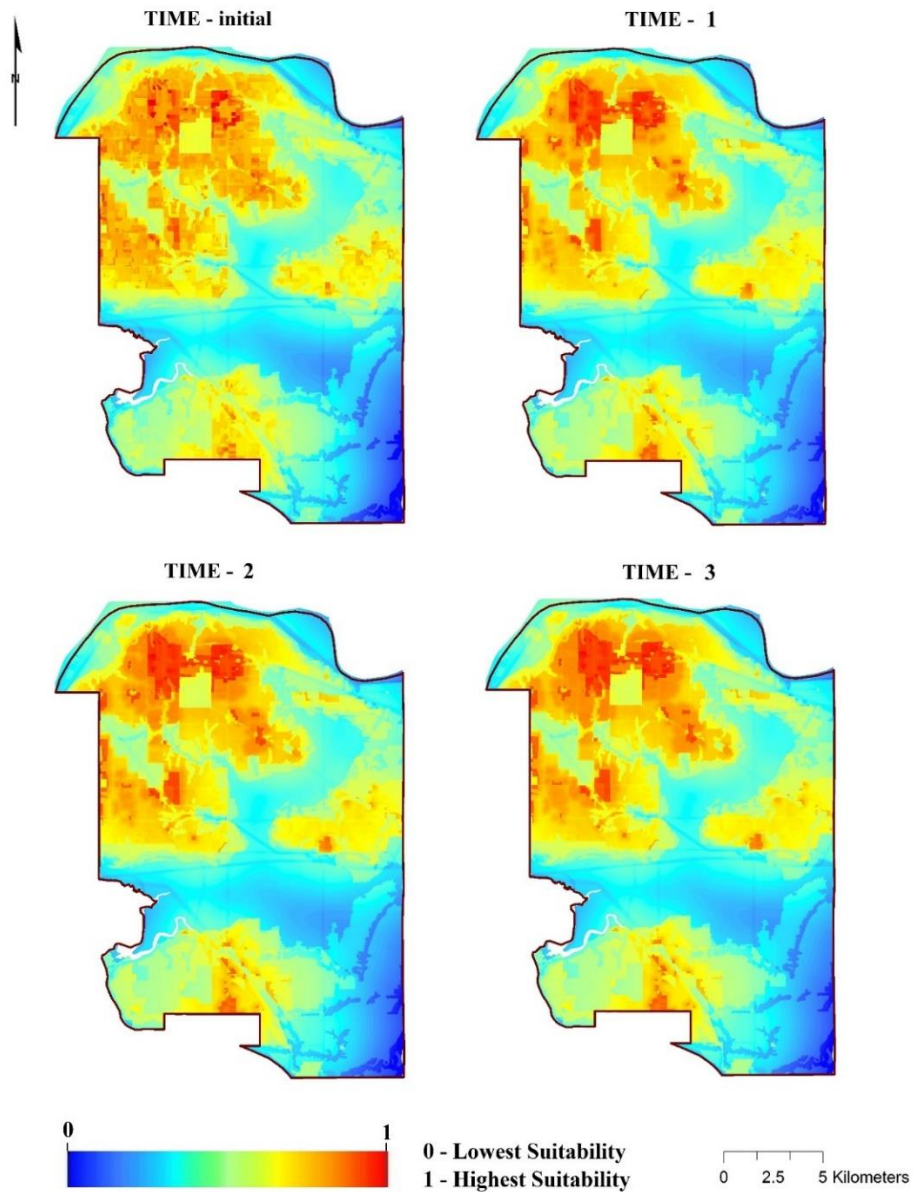


Figure 4.4. Suitability Values for Three Temporal Iterations for the Normal Growth Scenario

The presented vertical growth land suitability analysis approach was also used to generate a VUD suitability map for a transportation expansion scenario. The data for this scenario was digitized from a real City of Surrey proposed transportation expansion for rapid rail. The expansion station and route data was added to the existing transportation data set and the standardization and multi-criteria evaluation iterations were regenerated. Figure 4.5 shows the proposed transportation expansion locations overlaid

on the generated model at the end of the T_3 iteration. As expected, more suitable locations emerge around the proposed transportation stations than in the normal modeling scenario.

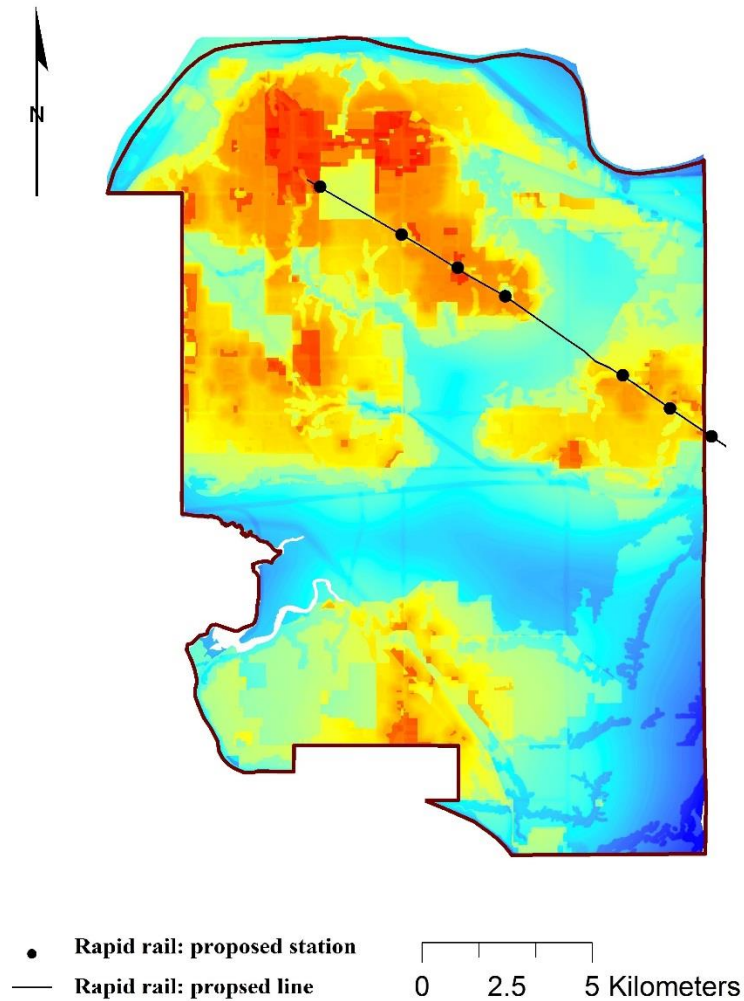


Figure 4.5. Suitability Values for the Transportation Expansion Scenario with the Proposed Rapid Rail Stations and Route for Time Iteration T_3

The City of Surrey produced a planned population density growth map for 2040 through a Community Energy and Emission Plan (City of Surrey, 2014a). The City of Surrey's projected map was used to compare this study's transportation geosimulation modeling results as a means of model validation (Figure 4.6). The geosimulation results obtained for Scenario 2 indicate more realistic results of VUD growth and is in

accordance with the City of Surrey planned population distribution growth. Simulation results for both scenarios indicated that high suitable locations are near transportation corridors.

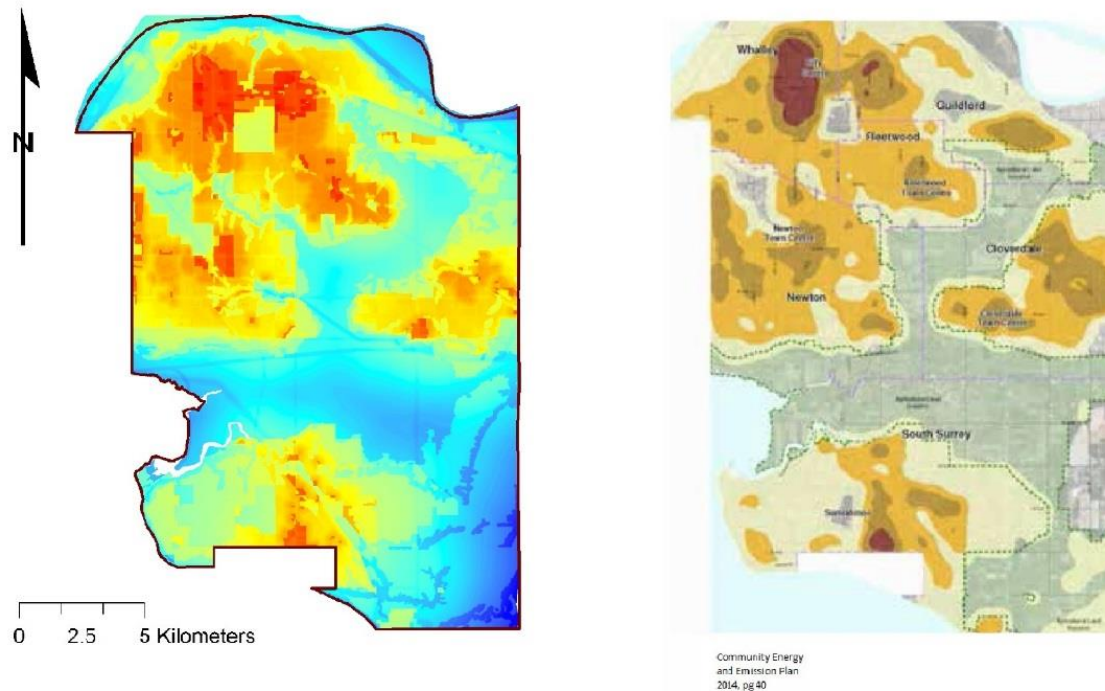


Figure 4.6. Suitability Values for the Transportation Expansion Scenario and the City of Surrey's Planned Growth

4.5.3. 3D Geosimulation for the Normal VUD Growth Scenario Results

The 3D geosimulation operates on three spatial datasets: land used designation, cadastral lots, and building footprints. The program was designed to only develop VUDs on land use designations deemed developable for VUD growth, and for the City of Surrey that included: Central Business District, Commercial, Multiple Residential, Mixed Employment, Town Centre, and Urban (see Table 4.2). Developments were further confined to cadastral lots, the fundamental vector geometry that refines the 3D building objects. Cadastral lots greater than 2000 m² were subdivided into new lots with a minimum area of 1000 m² and a maximum area of 1500 m². These values were determined by calculating the average of existing mid- and high- rise building cadastral lots for the City of Surrey. To determine approximate building floor heights, LiDAR data

was spatially joined to an existing building footprint dataset. The data was spatially joined to the land use dataset and averaged to determine a mean value per designation. Building set-backs were determined by averaging the distance of building footprints to the cadastral lot boundary datasets, then spatially joined to the land use to derive values for each designation.

Land Use Designation	Building Height Average (m)	Building Height range (m)	Lot Area Average (m ²)	Setbacks Average (m)	Floor Height (m)	Colour
Urban	7.54	24.38 – 1.73	1050.70	7.5	3	Yellow
Multiple Residential	8.10	67.54 - 2.48	2920.02	7.5	3	Purple
Commercial	7.78	32.99 - 2.76	5613.93	7.5	3	Pink
Mixed Employment	7.20	37.01 - 2.39	11506.34	7.5	3	Light Purple
Town Centre	8.37	65.52 - 2.99	3785.92	7.5	3	Blue
Central Business District	10.91	110.67 - 2.79	2454.39	7.5	3	Orange

Table 4.2. Land Use Designation and Assigned Development Attributes

The 3D geosimulation under a normal growth scenario was restricted to the City Centre, which has residing Central Business District, Multiple Residential, Urban, Mixed Employment, and Urban land use designations. The results of the geosimulation from T_1 to T_3 on the newly subdivided cadastral lots are presented in Figure 4.7. The 3D generated buildings are colour coded to the corresponding land use designations, and in the presented scenario, Urban and Central Business District designated buildings are evident. Due to the presented scale, buildings are visualized to show only exterior walls for better viewing but have the potential to show individual floors for user preference. The generated buildings appear to cluster near larger arterial roads. The large cadastral lots in the bottom right corner were not subdivided as they reside within a recreational park land use designation where no development is permitted. Other empty lots in this area are either set aside for future time interval development or coincide on currently non-suitable land dictated by stage 1 suitability maps.

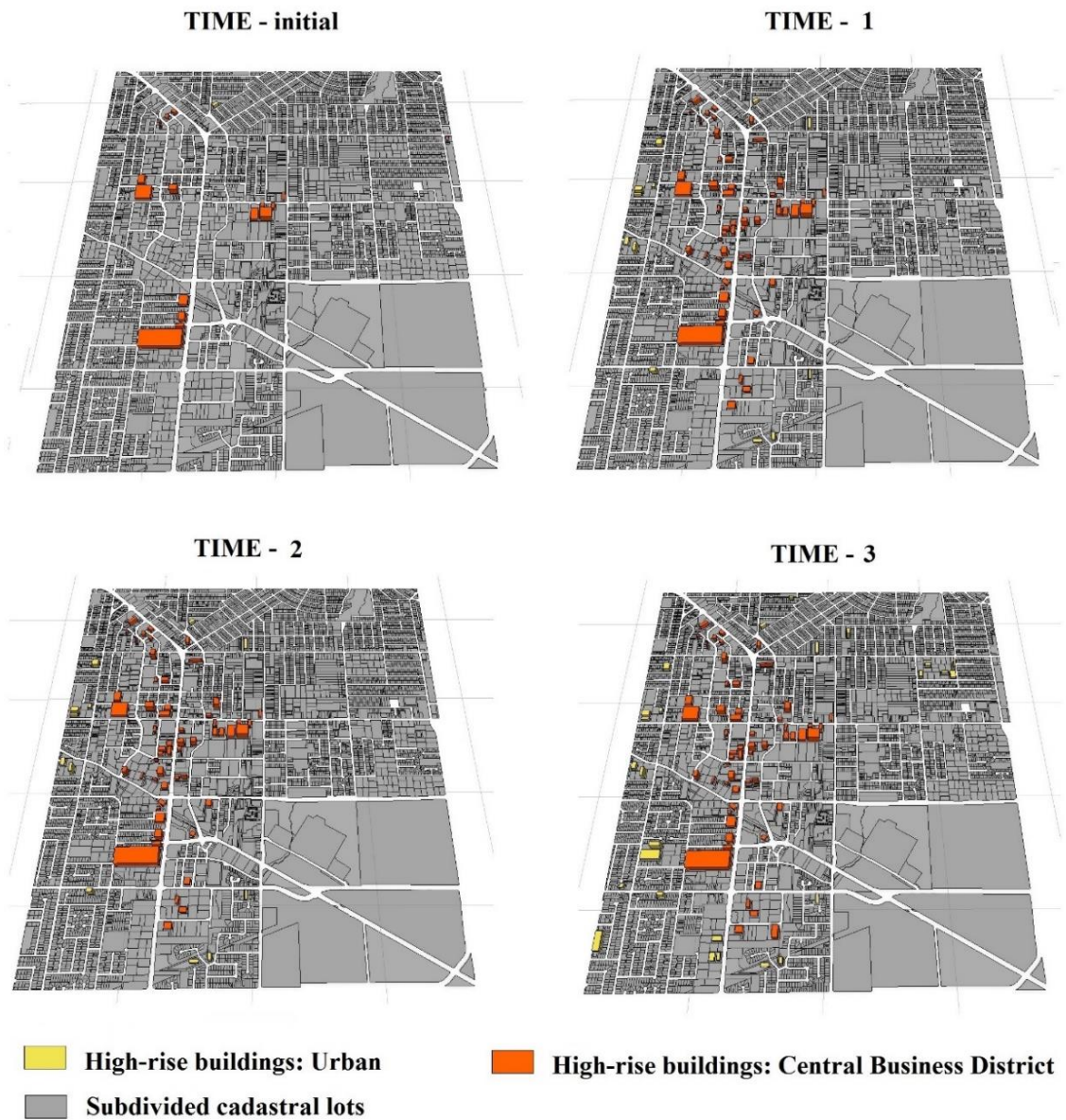


Figure 4.7. 3D Geosimulation of Normal Growth Scenario for the City Centre Study Area

4.5.4. 3D Geosimulation for the Proposed Transportation Corridor Scenario Results

The 3D geosimulation approach was applied to a transportation scenario along the City of Surrey’s proposed rapid rail expansion corridor for T_i to T_3 . Figure 4.8 presents a perspective north-east view of the generated building objects in ArcScene

(ESRI, 2013). The generated 3D buildings are colour coded to represent each time iteration, with dark red representing the year 2011 and yellow representing the year 2040. The spatial distribution of the 3D building developments present growth occurring near the new transportation stations in clusters as time iterations progress and new cadastral lots are updated as suitable for development. The updating, re-generating, and exporting of this transportation scenario is an example of how this presented 3D geosimulation can easily facilitate future urban scenarios with ease and compatibility.

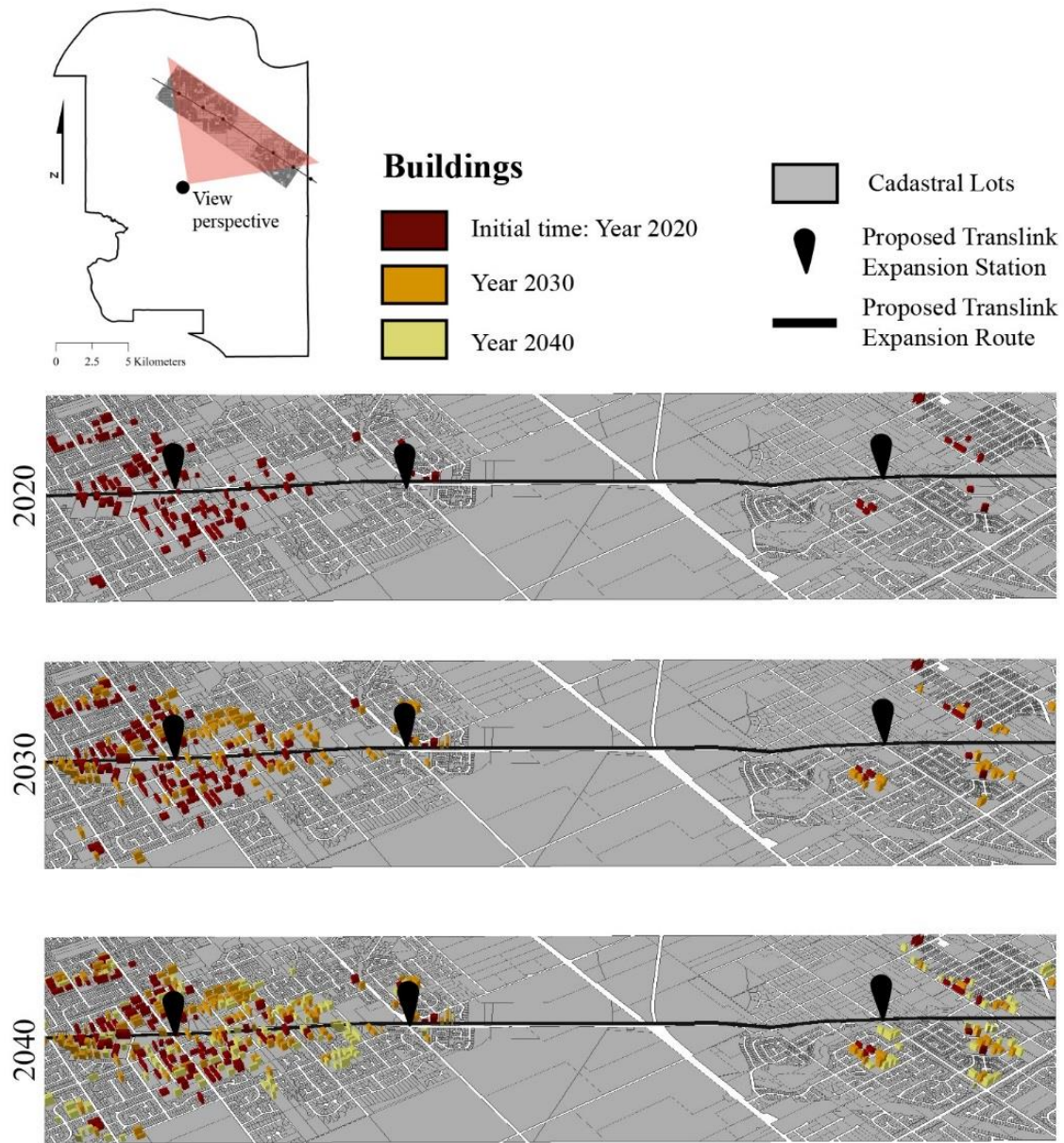


Figure 4.8. A Perspective View of the 3D Geosimulation of the Transportation Expansion Scenario for the Years 2011 (Top) to 2040 (Bottom)

4.6. Conclusion

This research study utilized a 3D geosimulation modeling approach for simulation of 3D high-resolution VUDs on irregular cadastral lots. The model derives suitable building locations based on criteria influencing urban compactness. The model is

iterated for the years 2011 to 2040 to show projected growth of the suitability locations over time and shows reasonable results when compared to the study area's, the City of Surrey, planned density growth. The derived suitability maps are used as land restrictions in the developed 3D geosimulation stage in conjunction with programmed rules. Land use designations were assigned building attributes derived from existing spatial data sets. The rules were programmed to reflect regional and city by-laws to further refine the cadastral lot suitability results to a building resolution, then augmented into the third spatial dimension. Three time iterations, approximately 10 years apart, were generated to show the projected 3D growth.

Additionally, this research demonstrated how the presented model can be directly applied as a tool in urban planning by incorporating a real transportation expansion scenario proposed by the City of Surrey. The model updated the transportation criteria by incorporating the proposed rapid-rail stations and regenerated the two stages. The outcome provided insight on projected VUDs near the proposed stations. This exemplifies the capability and ease of the 3D geosimulation model for various urban planning scenarios. The rapid and easy mass generation of 3D building objects can be updated on a local or global scale by the user. This research can be applied to various tangible urban scenarios such as visibility analysis and traffic planning. Additionally, once programmed, the updating flexibility enables planners to quickly view future scenarios without needing knowledge on how to program.

The procedural model also enables the user to visualize the generated building objects in various forms (mass, floors, or both) to further explore individual interests. Additionally, a report on building area, floor count, and floor height, is generated for each building, which users have access when selecting any building object. This allows for quick and easy evaluation of change for each time iteration.

Future work can aim to focus on obtaining a validation data set to assess suitability accuracy. Also, alternative urban growth modeling approaches, such as ABM or CA, can be simulated to compare method results. Future work can also leverage the higher level of detail capability inherent in procedural modeling. This can also include

transportation road networks that can be further expanded procedurally to help guide future cadastral lot subdivision.

4.7. Acknowledgments

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Chapter 5.

Conclusion

5.1. Thesis Conclusions

Urban growth occurs as a complex and dynamic four-dimensional process. Its representation has been extensively modeled but little work has focused on the development of 3D GIS-based methods for vertical urban development. The focus of this research thesis, therefore, was to develop a high-resolution 3D geosimulation modeling approaches to measure and represent vertical urban development growth. At the core of the research, multi-criteria evaluation (MCE) methods were used to select suitable locations for vertical growth at an urban regional and municipal scale. This suitability analysis method was developed using key factors specific to urban compactness growth identified from the literatures. Three approaches were developed to model 3D vertical urban development growth: the spatial index for 3D urban compactness, the 3D geospatial model, and the 3D geosimulation model.

The first research objective was to develop a GIS-based spatial index for 3D urban compactness and was applied to the datasets for the urban developments in Metro Vancouver Region. The approach was focused on the development of an index from Suitability Analysis, Land Designation, and Average Building Height Parameters. The Suitability Analysis Parameter was developed from geospatial data that represented urban compactness factors including: transportation nodes, population demographics, land use designations, access to jobs, environmental constraints, recreational and community centres, and access to services and amenities. The spatial index for 3D urban compactness was applied to the data for Metro Vancouver Region for the years 2011 to 2040, reflecting the date of the latest available Canada census data (Statistics Canada, 2011) and the region's Growth Strategy plan (Metro Vancouver, 2016). The

geospatial data were standardized using fuzzy membership functions to ensure values reflected from 0 to 1, where 0 meant no and 1 meant highest suitability of land for urban compactness growth. The standardized geospatial data, the factors, were combined through assigned weights to produce the Suitability Analysis Parameter and the developed maps were used in updating successive maps to achieve spatio-temporal suitability growth for various time iterations.

The second parameter, Land Designation, was derived from a land use designation geospatial dataset, which was classified into developable and non-developable designations. The initial land use evaluation map was used to update the successive maps for this parameter by assessing the neighbouring land use designations. The last parameter, Average building Height, was based on geospatial building height datasets for three sample cities within the study area and derived a maximum mean building height value for each developable land use designation. Finally, the three parameters were combined to derive an index that was applied to a regional urban scale. The spatial resolution used was 10 meters, which is an acceptable level for representing regional urban development and for planning. The projected urban compactness growth was extruded in the vertical dimension by the derived index value, which represented the maximum building height in meters, as volumetric blocks. The modeling approach was operationalized using ESRI's ArcGIS suite (ESRI, 2013).

The proposed urban compactness index was applied to the Metro Vancouver Region and the obtained results indicated that the vertical urban development growth was concentrated near urban centres, transportation nodes, and at locations with higher population densities. Downtown Vancouver, Metrotown Centre, Richmond Centre, Brentwood Centre, and Coquitlam Centre, were locations found to exhibit high scores for urban densification. These four locations were selected to compare the obtained results with the real built environment to show current mid- and high-rise developments residing at these locations. The modeled results presented 3D block extrusions of vertical urban developments at a land use designation resolution, and for this reason, the second objective was pursued to develop a high-resolution 3D building model.

To achieve the second objective of this research, a 3D geosimulation model was developed to represent the spatio-temporal dynamics of low- to high- rise buildings as vertical urban densification. The geosimulation 3D modeling approach focused on the development of a methodology that combined raster GIS-based data characterized as regular spatial tessellation with high-resolution vector GIS-based data as irregular spatial tessellations in 3D. The City of Surrey was selected as the study area because of the municipality's rapidly increasing population and the implemented sustainable growth planning strategy. The geosimulation 3D model was confined to the Guilford Town Centre in Surrey because it had low- to high- rise development land use designations and due to computational ease. The proposed 3D model combined GIS-based data representing factors affecting vertical urban development to develop a raster suitability analysis map. The suitability map was combined with subdivided cadastral lots and land use designation geospatial data using the Computer Generated Architecture (CGA) language to refine suitable land and to generate 3D building objects for the Guilford Town Centre. The programmed rules were designed to reflect the City of Surrey's municipal by-laws by assigning building floor heights, number of floors, and set-backs determined by land use designations. They were then applied to cadastral lots where generated 3D building objects occurred only where land suitability permitted. ESRI's CityEngine (ESRI, 2014) software was used to program and model the vertical urban development growth for the 3D urban modeling. The results from the geosimulation model are locations of mid- and high- rise building objects on the subdivided cadastral lots. The scenarios that simulated vertical urban densification growth at a slow, medium, and fast rate were forecasted for high-rise, mid-rise, and mid- to low- rise building developments. The simulated growth scenarios demonstrated a reasonable urban growth scenario occurring in the Guilford Town Centre area.

The more advanced 3D geosimulation modeling approach was developed to enhance the presented geospatial modeling approach by adding a spatio-temporal method and developing projected growth scenarios. The 3D geosimulation model incorporated a spatio-temporal method by developing a series of suitability analysis that were derived for the years 2011 to 2040, for the City of Surrey. The programmed rules combined the suitability analysis map series into the methodology to develop multiple 3D building object series, representing vertical urban development growth for the sub-study

area City Centre, City of Surrey. The 3D geosimulation modeling approach also developed a series of 3D vertical urban development simulations of a transportation expansion scenario for the years 2011 to 2040. The transportation expansion routes represented a real rapid-rail proposal by the City of Surrey and the proposed stations were incorporated in the suitability analysis maps. The transportation scenario was developed on a transportation corridor sub-study area for the City of Surrey.

The obtained results from the 3D geosimulation modeling approach for the normal growth scenario presented urban densification of mid- and high- rise building objects within Surrey City Centre. Specifically, high-rise buildings in the designated Urban and Central Business District cadastral lots densified near transportation nodes and where more populations inhabit. The results obtained for the transportation expansion growth scenario showed 3D vertical urban developments clustering near the proposed transportation stations. As the simulation progressed, new mid- and high- rise buildings developed on available cadastral lots. Modeling approaches were evaluated and implemented to develop different 3D growth scenarios as part of the last thesis objective.

5.2. Future Research Directions

Although the presented modeling approaches have satisfied the outlined research questions and their objectives providing realistic urban 3D growth over time, there still exist several modeling limitations that can be improved in future research. Firstly, the land suitability analysis for urban compactness growth used in both modeling approaches, was developed using a MCE for deriving suitability scores with key factors indicative of vertical growth. The factors selected and the corresponding assigned weights were determined using findings from scientific literature. However, concrete factors and weight values were challenging to source in several instances. Future research should explore methods that aid in criteria selection and their significance towards the phenomenon because MCE approaches are sensitive to small criteria changes (Chen et al., 2010). Methods to reduce error in criteria selection and weighing include principle component analysis (PCA), sensitivity analysis, and adding stakeholders into the process. PCA was used by Roychansyah et al. (2005) to

discriminate criteria and weights specifically in an urban compactness modeling context. Ligmann-Zielinska and Jankowski (2008) presented a framework to assist in the selection of an appropriate sensitivity analysis method and technique for specific MCE methods. Ligmann-Zielinska and Jankowski (2012) developed the proximity-adjusted preference (PAP) approach to show spatial bias of the weighting of evaluation criteria in MCE methods. The PCA, sensitivity analysis framework and PAP approach can be incorporated in future research. Moreover, applying a more complex method based on logic scoring preference (LSP) could be used for suitability analysis (Montgomery & Dragičević, in press; Hatch et al., 2014). The proposed thesis approach can also be enhanced by incorporating experts, city planners, and other stakeholders in the decision making process to assign fuzzy membership functions and MCE weights to each factor.

Secondly, model design usually should incorporate full model testing procedures with model calibration and validation to provide an accuracy assessment of the represented phenomenon. In the presented thesis, calibration was achieved through sensitivity analysis by comparing obtained vertical urban development suitability analysis results with Google Earth imagery and actual developments of high rise buildings in the region. Augmented 3D buildings in Google Earth imagery coincided with obtained suitable vertical urban development locations. To achieve validation procedures, multiple datasets representing multiple time snapshots are needed. Ground-truthing can also be incorporated by collected real *in situ* data for locations of emerging high-rise buildings for various years. Collected ground-truthed data can then be compared to the results obtained by the presented geospatial modeling approaches. In this thesis, validation was not fully performed due to limited data availability. Moreover, there is a need for new methods that can compare images that represent features in 3D to be able to fully test and validate the model. However, the 3D geosimulation results were compared to projected urban population growth maps provided by the City of Surrey, which identified similar spatial distributions of population growth for the year 2040 as with the presented results. Future work can apply the presented modeling approaches to regions that have several datasets of growth over past time.

Results obtained by the presented thesis research indicated that transportation networks are key factors affecting vertical urban development. As transportation

networks develop, they provide access to more land available for urban densification. Parish and Muller (2001) presented work on urban models that incorporate road networks that can be automatically grown based on programmed rules. Therefore, thirdly, the growth of the road networks should be incorporated in the modeling procedures for the growth scenarios in regions not yet developed. Such model design can be implemented in the presented 3D geosimulation approach in future work.

Finally, further advancements in 3D urban modeling indicate that building structures can be presented at more detailed levels (Dollner & Buchholz, 2005). Intricate building detail can be important for modeling high-resolution urban phenomena such as pollution and view obstruction analysis. Future work can be based on the increased level of detail (LOD) for the generated 3D building objects. This can include parts of building envelope structure and basic interior architecture. ESRI's CityEngine has the capability to mass generate such building designs and this advantaged should be leveraged to provide a higher LOD to the generated buildings. Research should also incorporate the current buildings, using methods such as LiDAR, to provide a greater understanding of how the derived 3D buildings may affect the current built environment.

5.3. Thesis Contributions

This thesis and the presented 3D geosimulation modeling approaches aim to contribute to the field of GIScience. The presented methods contribute to research focusing on spatial analysis related to the spatial index for 3D urban compactness derivation and spatio-temporal modeling related to 3D geosimulation approaches proposed. Methods developed are based on high-resolution regular and irregular spatial tessellation of available geospatial data. Further, the developed methods included a spatio-temporal component to show the dynamics of growth on regional and municipal scales. More specifically, the 3D geosimulation model contributed work towards the field of geosimulation by presenting vertical urban growth in spatial contexts and using high-resolution urban units such as cadastral lots for changes presented for multiple years. Additionally, this thesis research focused on exploring urban geosimulations in 3D, contributing to the development of 3D GIS. Approaches presented in this thesis were

capable of simulating vertical urban development growth in 3D with representations of actual building heights.

The presented research also aims to provide contributions to the field of geography and urban modeling. Urban development is an important process in geography because it affects the physical and human environment through implications such as sustainability, policies, social connections, access to services, and others. Urban modeling has been long researched for various urban context, including urban sustainability and compactness. However, urban compactness is a relatively new form of growth for North American cities and research efforts should continue to improve modeling of vertical growth. The spatial index for 3D urban compactness and the 3D models aim to provide new approaches that can be implemented and further developed in different geographical regions and scales, to aid in research pertaining to the studies of sustainable city development. Urban models can be used as tools for urban and land use planning and this research assist in providing insights on possible future urban growth scenarios in 3D. Therefore, this research also contributes to the urban planning field as new approaches and modeling tools for vertical urban development for regional and municipal scales.

5.4. References

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