Automation in Construction 96 (2018) 236–249

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Review

Spatial compactness metrics and Constrained Voxel Automata development for analyzing 3D densification and applying to point clouds: A synthetic review

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ARTICLE INFO

Keywords:
Spatial metrics
Constrained Voxel Automata
Cellular automata
Lidar
Point clouds
Spatial data mining
3D discrete compactness

ABSTRACT

A construction operation is known as a complex system whose complicated components can be understood by applying spatial metrics to massive point-based data. Two and three-dimensional compactness metrics are critically reviewed based on the scale of urban modeling, application in urban studies and architecture, and the capability to model spatial and temporal urban changes. This review indicates that there is a lack of a uniform definition of compactness in urban, building and construction studies and a lack of 3D metrics to model spatial and temporal patterns of vertical building developments. To fill these gaps, a new definition of compactness for vertical building developments was developed based on elements of the compactness concept in the literature of urban form in highly dense urban areas by developments of high rise buildings. In addition, spatial data mining methods are suggested for deriving a spatial distribution pattern of building height; a new metric of A* was developed based on 3D Discrete Compactness for comparison of various 3D configurations of the buildings; and Constrained Voxel Automata and volumetric metrics were developed theoretically and proposed for future studies in characterizing spatial and temporal patterns of vertical building developments. It is found that there is a lack of appropriate methodologies to derive the patterns of vertical building development using 3D data such as airborne lidar to meet future needs.

1. Introduction

Automated and spatial modeling paradigms are critical for modeling complex systems and environments over time. Current methods of analyzing development changes are only planar (two dimensional) or a combination of space and time for compactness analysis at different scales of buildings and urban areas [1–3]. However, fully automated spatial modeling that integrates space and time for analyzing lidar point cloud data sets has been ignored in the field of construction and built environment, and is still embryonic in other disciplines [4]. There are ongoing attempts to utilize new class simulation techniques including voxel automata, by an array of advances in other disciplines [4–6], but these techniques have been widely ignored for building and construction change analysis. The main reason is the lack of metrics in the literature to analyze spatial components of the changing process and availability of required metrics. In general, lack of a widely accepted definition of building compactness, conflation of spatial compactness over time and building density, and disagreement about acceptable compactness metrics in the literature of the built environment, has limited the application of previous research findings to the topic.

Voxel automata is one of the main simulation methods among automated spatial modeling methods, and adopts the principles of location automata systems. The voxel in this approach represents the smallest 3D spatial unit of the selected objects where a pixel is the smallest unit of a 2D image. The voxelization concept, rather than pixelization, allows construction scholars to extensively and precisely study the macroscopic 3D spatial behavior of complex bridges, dynamic construction processes and the spatial development of civil infrastructure, floods, and pollution over time.

This paper aims to identify the gap in the literature in regard to a definition of compactness of buildings, construction objects and urban form in different scales of analysis, and to develop new metrics for 3D compactness assessments and vertical building developments. Based on the elements of compactness concept in the literature on spatial modeling and remote sensing, the paper presents a newly developed definition of compactness for analysis of vertical building developments.

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https://doi.org/10.1016/j.autcon.2018.09.018
Received 31 May 2018; Received in revised form 20 September 2018; Accepted 29 September 2018

Furthermore, the paper proposes methodologies to derive the patterns of vertical building development which can be applied on 3D data sets such as airborne lidar. The paper also explores the possibility of applying Spatial Data Mining (SDM) methods in modeling building height and 3D Discrete Compactness (3D DC) to derive spatial and temporal patterns of vertical building development, which have been ignored in construction and vertical urban development studies. This is a critical methodological model since point clouds are increasingly produced and used by construction practitioners. Following all previous developments of conceptual models, voxel automata including relevant metrics are developed theoretically for future applications.

2. Review method

This paper provides a thorough review of compactness metrics for analysis of buildings forms using lidar point cloud, as well as the role of spatial metrics in conceptual approaches to building progress modeling and 3D urban construction development modeling. The review approach is to identify frequently used terms in urban construction development studies to develop a unique, new concept of 3D spatial metrics. The review looks at different scales of analysis used for modeling spatial and temporal patterns in different disciplines of the built environment, identifies terms such as 'density' and 'compactness' which are used interchangeably in the literature, and describes the 2D and 3D urban metrics based on the scale of analysis. The review also investigates the concept of compactness in a broader context for characterizing horizontal and vertical urban development, and assesses its importance accordingly. Among the metrics, those characterizing compactness of urban building block form in metropolitan and local scales will be discussed. To detect the pattern of vertical compactness, the review explores the possibility of using SDM methods, 3D DC and Contact Surface (A^*) in relevant contexts. Mass and space index as well as voxel automata are also developed as the potential solution to fill the gap in future research.

Fig. 1 shows the four main elements required for spatial modeling in both horizontal and vertical developments. These elements are: information obtained from remote sensing (RS); metrics; pattern; and dimension. Building change metrics (BCM) for deriving the patterns of 3D building development are required to detect the areas with higher levels of concentration of vertical urban development, referred to as 3D compactness here. It is also important to separate *high* from *low* buildings in compactness assessments of vertical building development when determining which urban construction areas show a trend to *relatively higher* building development. Monitoring spatial and temporal change of 3D compact building developments and spatial patterns of vertical building developments is crucial for planning and management as it provides fundamental information to formulate strategies and policies for controlling vertical physical progress. As demonstrated in Fig. 1, spectral information from RS is used in landscape metrics and Cellular Automata (CA) for deriving the patterns of horizontal urban development, such as the compactness pattern of urban growth. For vertical urban building development modeling, building height information from 3D RS is required for appropriate 3D metrics. If the focus of research is to derive vertical urban building patterns, firstly information about building envelopes is required to be extracted, and secondly, heights of these buildings should be derived from 3D data.

The review also discusses the five main requirements to characterize 3D compactness, namely: determining the scale of analysis; concisely defining the concept of 3D building form compactness; quantifying urban metrics of 3D compactness; using clear methodologies for the application of proposed metrics; and incorporating suitable 3D data for extracting information based on an appropriate scale of analysis.

3. Conceptual approaches to modeling building changes

At the metropolitan scale, two main conceptual approaches to spatial and temporal urban pattern analyses can be recognized from traditional and modern perspectives. As Herold [7] discussed and illustrated in Fig. 2, in the traditional top-down approach (i.e. from process to structure), processes produce structures, while in the modern bottom-up approach (i.e. from structure to process), structures can be representative of processes. In these approaches, process refers to a series of socio-economic activities or policies and strategic plans to achieve a certain type of urban pattern. Urban structure also is referred to as the 2D spatial arrangement of urban elements such as open and public spaces. Major drivers and factors, such as economic forces, master plans and land demands that affect urban change over time, are investigated in a top-down approach. Indeed, the top-down approach explores how these processes produce a type of pattern for change in urban structures. For example, low fuel prices compared to housing rents may result in a sprawl form of urban development and in contrast, high fuel prices in conjunction with low housing prices near city centers could result in more compact development. As Fig. 2 shows, in the bottom-up view, to derive spatial and temporal patterns of urban structure and development, urban metrics are applied to remote sensing data [7]. Then the derived structure is used for investigation and analysis of the underlying processes. This modern view employs remote sensing data and spatial metrics for analysis of urban patterns whereas the traditional perspective believes that the socio-economic processes are the major drivers of the existing patterns of urban form and

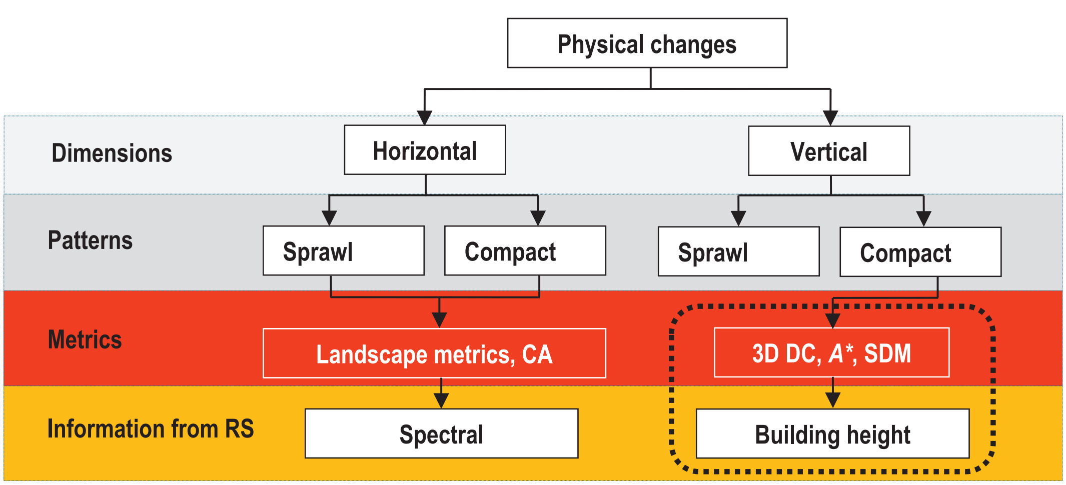

Fig. 1. Physical progress modeling in vertical and horizontal dimensions and demonstration of the research focus on proposing 3D metrics for characterizing compactness of vertical urban development using building height information from Remote Sensing.