VOXELIZATION TECHNIQUES: DATA SEGMENTATION AND DATA MODELLING FOR 3D BUILDING MODELS

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ABSTRACT:

Voxelization of data is discretizing the 3D space, in which the simplest form is a single voxel. There is a large number of publications that are related to voxelization. However, this paper focuses on the voxelization technique implemented in 3D building modelling. This paper aims to get the development idea of the voxelization technique throughout these past years to determine the suitable technique and method for including a 3D voxelized building model in Computational Fluid Dynamics (CFD). From the search and analysis, it is found that this technique is not only related to data modelling of the 3D voxelized model; the voxelization technique can also be utilized in the data segmentation process. First, for the data segmentation, the voxelization technique is implemented to manage the large amount of point cloud data that were obtained from the 3D scanner and sensors, which is done by reducing the number of data to avoid data redundancy and unused data using each of the voxels that exist in that environment. Second, for data modelling, popular input data to generate the 3D voxelized model is also in the form of a point cloud. However, there are still other forms, such as line and surface. Nevertheless, this paper reviews the voxelized technique in building modelling despite some data segmentation. The review shows various input data, applications, and techniques associated with the voxelization process based on building model generation. However, there is still room for improvement that allows the 3D model to be modelled in the voxelized form in the CFD domain.

1. INTRODUCTION

The three-dimensional (3D) based modelling is either represented using vector or raster technique. Vector techniques are widely utilized, particularly in 3D modelling. Numerous researchers have conducted 3D modelling (Mohd et al., 2017; Salleh et al., 2021; Ujang et al., 2018) and 3D spatial analysis (Azri et al., 2018; Azri et al., 2020; Ujang et al., 2013) in vector-based research. This includes using 3D vector models in the Computational Fluid Dynamics (CFD) application to model wind flow simulation (Ridzuan et al., 2022). Nevertheless, it differs significantly from the voxelization process. The voxelization technique is commonly used when the modelling utilizes the raster-based approach. In general, voxelization represents the model in pixel-like data, but as it is in a 3D environment, it is called a voxel. A voxel is a single sample in the 3D grid spaced uniformly throughout the model, and in a model, there are many voxels. Two fields apply this technique: the medical imaging domain (Joyce et al., 2022; Ma et al., 2019) and computer gaming (Bergs et al., 2021; Min et al., 2018).

From the perspective of the medical domain, the voxelization is used for a treatment plan, in which the data used is represented in a voxel, and it will then arranged and clustered by using isodose feature preserving (IFP) (Liu & Xing, 2018; Ma et al., 2019). Furthermore, apart from IFP, process such as light transportation in complex bio-tissues is also associated with voxel representation, where the existing tissue are presented in the voxel. In supporting the modelling, a voxel-based Monte Carlo method (VMC) is used (Phong et al., 2020; Yan & Fang, 2021). As mentioned in the research, the voxel data in IFP and VMC is for x-ray radiation therapy in the medical imaging field.

Besides the medical imaging scope, the computer gaming environment is another well-associated field. All the modelled data in voxel for this field are utilized in a gaming environment. Still, the difference is the model to be presented, such as game characters and building, and the different techniques to voxelized the data. Min et al. (2018) perform voxelization by using the 3D mesh data of gaming characters and building and using its silhouette to fit the voxel model for better voxelization representation of the data. A method such as detecting if the centre point of each voxel falls inside a model and determining the voxel's existence (Nuic & Mihajlovic, 2019) can also be implemented in generating voxel data in the gaming environment.

However, voxelization exists not only in these two fields: medical imaging and computer gaming. Other areas widely implement this voxelization, such as 3D building modelling, 3D printing (Ghadai et al., 2021), geoscience (Raeisi et al., 2012), photogrammetry (L. Wang et al., 2017), surgery simulator (Faieghi et al., 2020) and other fields.

Various fields use the voxelization technique in data representation, so to comply with the different nature and structure of the data and the suitability and applicability to be implemented, there are various techniques introduced by earlier researchers regarding the way of constructing the data in voxel form. So, this matter will be further discussed and reviewed throughout this paper.

This paper consists of four sections; this section describes and gives an overview of voxelization. Section 2 will be continued with the methodology of constructing and writing this paper, Section 3 is the review part, and Section 4 is for the conclusion.

2. METHODOLOGY

The methods for reviewing articles on the data voxelization technique are described in this section. The procedure includes an identification step, an eligibility phase, and a final selection phase (Figure 1).

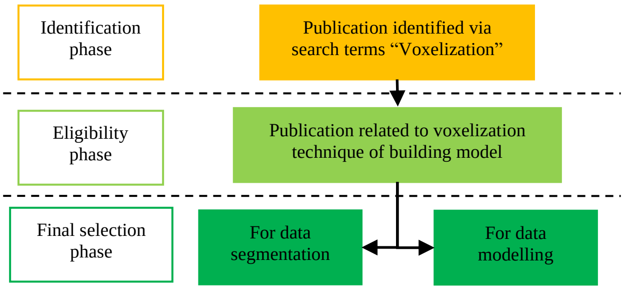

Figure 1. Flowchart of reviewing the data voxelization technique

2.1 Identification Phase

This identification phase involves collecting and searching for all the existing publications on voxelization topics from the last two decades. The search was done using the journal database with the search term "Voxelization". There are vast results produced using this search term. This shows that this technique is used in many different fields, and it is not only in the form of a journal and conference paper; there are also book chapters, reports, and many more.

2.2 Eligibility Phase

From all the publications, the ones related to the voxelization technique of the 3D building model are chosen. This is because this paper aims to review the voxelization technique of voxelized building modelling for implementation in a new area of study: CFD simulation surrounding the building model. So, with the earlier study, the drawbacks can be analysed, and the improvement can be implemented in future studies.

2.3 Final Phase Selection

Based on the selected scope, this paper will present the data segmentation and modelling using the voxelization technique in the related study. The major difference between these two is that when used for data segmentation, the method is utilized to group the data in a single voxel and generate new data to reduce the number of data. However, the resulting model is in 3D voxelized form for data modelling.

3. 3D BUILDING MODELLING: VOXELIZATION

Voxelization encompasses various topics, including voxel applications, the technique used to generate voxel objects, and many more. It varies in multiple scopes and exists in various fields of study, including medical imaging, 3D printing, computer gaming, etc. Because of this, many different types of research have been presented and studied in the last two decades; however, only the voxelization techniques related to 3D building modelling will be discussed in this part. There are two related topics reviewed here: the voxelization technique for data segmentation and the second one for data modelling. The data segmentation section provides an overview of the process; however, the data modelling part is discussed critically.

3.1 Voxelization Technique for Data Classification, Management and Segmentation

The research by Deschaud & Goulette (2010) used the voxelization technique for data management. As the data from the 3D scanner produce a large number of point clouds of the captured object, there is an algorithm called plane detection used to reduce data size. This is where the voxelization technique is implemented: voxel growing. It is carried out by searching for neighbors in constant time for each point using its 26 voxel neighbors, which results in a connected component of an empty set because the points have been added using linked voxels.

Hofierka & Zlocha (2012) introduced a vector-voxel approach for computing solar radiation concerning the 3D building model in urban areas. The voxelization is implemented in this study by applying the volume tessellation (Figure 2) to the study area extent using a voxel data structure, where the voxel resolution facilitates the rule and size of segmentation for the spatial polygons to define the surfaces of an object. Hence, allow each polygon to fit a unique voxel of the volume region.

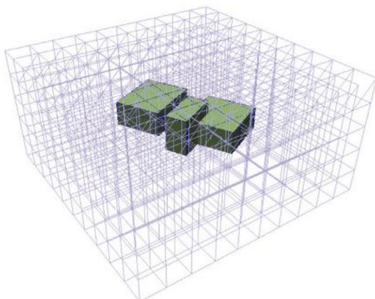

Figure 2. Volume tessellation of voxel data model and polygon surface segmentation (Hofierka & Zlocha, 2012)

Besides, for Xiong et al. (2013), the voxelization technique is used to process the point cloud data of the building model from a laser scanner to convert it to the real-world vector building model (Figure 3), where it provides space for point cloud discretization. This technique is utilized to reduce and distribute the point cloud uniformly.

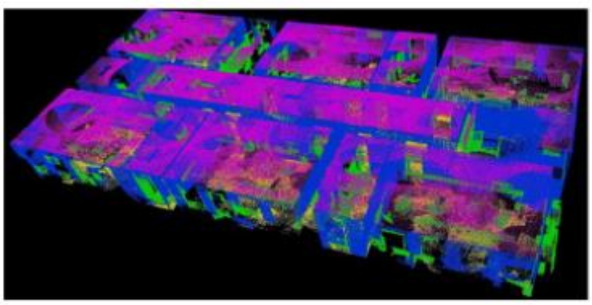

Figure 3. The result for the point cloud classification (X. Xiong et al., 2013)

Aijazi et al. (2013) used the data from the 3D point cloud of the LiDAR technique in the study. This point cloud is associated with the voxelization technique when it requires a segmentation process. The segmentation process in this research reduced the dense point cloud that is unuseful and redundant. The voxel size here refers to the maximum and minimum radius of neighboring points along an axis. The voxel then encapsulates the points to reduce the point cloud to form super-voxels, which are used for the later clustering by Link-Chain Method.

Furthermore, the voxelization technique for data segmentation is implemented in Vo et al. (2015) on point cloud data of a 3D building model. The method with octree structure is performed by determining the suitable voxel size to include the specific point and utilizing the region growing method for the same characteristics of the point cloud. The voxel of the same characteristics existed in the same colour (Figure 4).

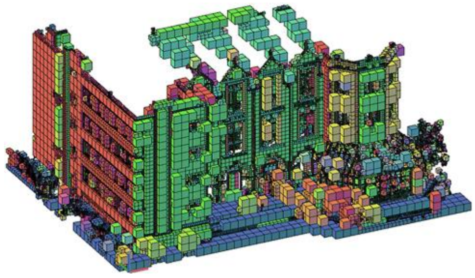

Figure 4. Data segmentation of point cloud data (Vo et al., 2015)

In addition, Wang et al. (2015) performed the automatic method to extract building geometries from the 3D point clouds, which exist in an unorganized structure collected from the Time of Flight (ToF) laser scanner. In this research, reducing the data is by importing the point cloud data to the 3D uniform voxel grid, and the data are placed into their corresponding voxels. The density of the data can be reduced by removing all the point cloud data present in the same voxel, and a new centroid point is generated to represent that voxel (Figure 4).

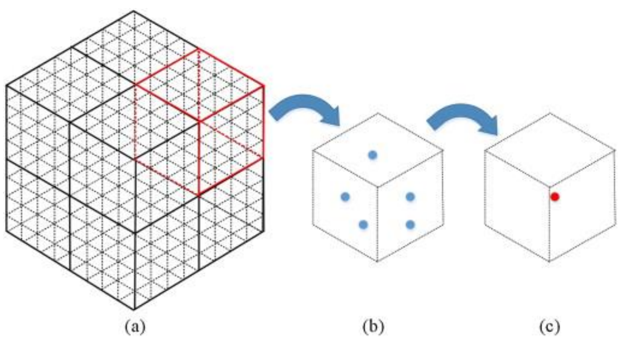

Figure 4. (a) 3D uniform voxel grid structure; (b) a voxel and the points located in it; and (c) one estimated point left after data downsizing (Wang et al., 2015)

In the study by Poux & Billen (2019), point cloud segmentation is done by using a specific depth level of octree-based voxel structure to support the feature-based point cloud parsing where each voxel space in the structure which consists of a grouped point, is characterized using shape and relationship-based feature extraction. There are several groups of point clouds exist, such as primary elements (PE), secondary elements (SE), transition elements (TE), and remaining elements (RE).

Furthermore, Bonczak & Kontokosta (2019) used aerial LiDAR data, city administrative property records, and building footprint shapefile to extract the physical and architectural building parameters. The voxelization technique was adopted in this study to calculate the building envelope surface area. Each building was treated as an object in a voxelized form consisting of $1m^3$ cubes. The calculation was then completed by associating the number of voxels to the height equal to Digital Surface Model (DSM).

Also, Saglam et al. (2020) performed the segmentation process of the 3D point cloud. It voxelized the raw, disorganized point clouds using the octree organization (Figure 6) and then calculated the centroids and normals of the points in the voxels (each voxel is represented as a segment) all at once, where it implemented the non-sequential region growing technique. Additionally, this method is friendly to the non-surface voxels that maybe exist.

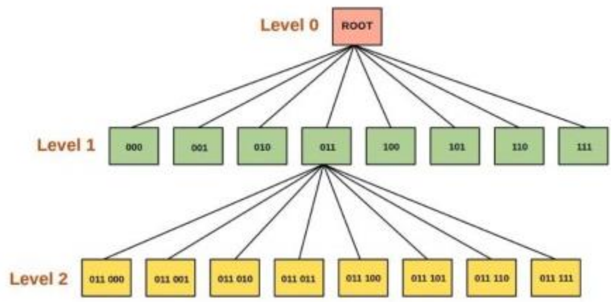

Figure 6. Octree organization of the voxelizing technique (Saglam et al., 2020)

Gezawa et al. (2022) studied point cloud categorization using data classification and segmentation networks. The enormous point cloud data is simplified into the voxelized grids with the support of the point quantization method to get the same number of points in each voxel. Each voxel is assigned as a primary feature of the voxel. The classification and segmentation process occurs when the voxel undergoes multiple convolutions to classify the feature and segment them to form the object parts.

This subsection shows that the voxelization technique is implemented for data segmentation and classification using several different techniques (Table 1). These are done to manage the point cloud in a high-density number of the point cloud by grouping it into a voxel of specific characteristics. As the volume for these point cloud data is too high, there is a need to reduce the volume and size to decrease computational time. Hence, the voxel-based classification and segmentation method provide the ability to classify data by specific feature selection and segment the point cloud following its suitable objects.

Table 1. Voxel-based data segmentation and classification.

Voxel-based Point Cloud Data Segmentation & Classification	
Publication	Voxelization Method
Deschaud & Goulette (2010)	Region growing
Hofierka & Zlocha (2012)	Volume tesselation
Xiong et al. (2013)	Region growing
Aijazi et al. (2013)	Link- chain method
Vo et al. (2015)	Region growing
Wang et al. (2015)	Region growing
Poux & Billen (2019)	Feature-based data parsing
Bonczak & Kontokosta (2019)	Space voxelization
Saglam et al. (2020)	Region growing
Gezawa et al. (2022)	Point quantization voxelization

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3.2 Voxelization of The Model

This subsection focuses on the voxelization techniques implemented in many studies to produce a 3D model. It relates the resulting modelling with a CFD environment that should exist in appropriate detailing design, and generation is based on a vector model.

Research by Glander & Dollner (2008) discussed how to generalize the 3D city model, and one of the techniques presented is voxelization. It is done by sampling the building geometry within a 3D grid. The resolution of the voxel follows the equation of resolution is equal to "real world units" divided by "grid unit". Each voxel is filtered using a box filter to better sampling quality. The Gaussian blur filter was also applied to the voxel model. As a result, the processed data is converted to polygonal representation, where the marching cubes are implemented to create the geometry model. Figure 7 shows the result of generalization using the voxelization technique. As the purpose of the study itself is a generalization, the resulting model cannot represent the building in the study area very well. This is because the model becomes simplified, and the building design details are missing in the final presentation.

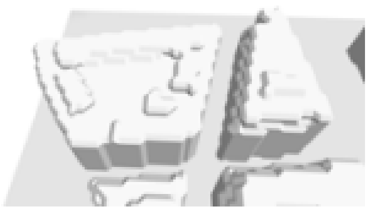
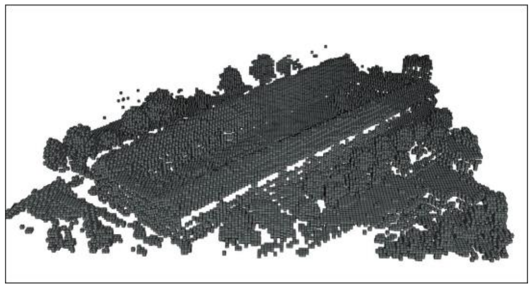


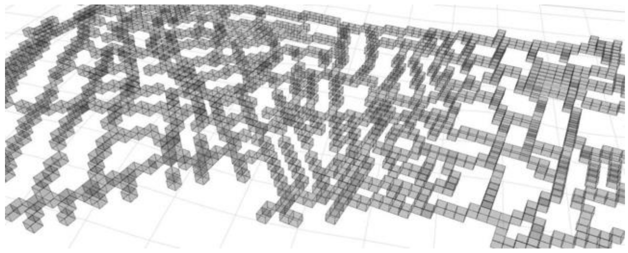
Figure 7. Voxelization of the building model (Glander & Dollner, 2008)

Another study applied this technique to support the construction of a 3D building model (Truong-Hong et al., 2013). The process is done by utilizing the voxelized technique with suitable voxel size and octree depth parameters and integrating it with the building façade to create the building façade. The voxelization is run by determining the bounding box of the captured data and the minimum voxel size depends on the minimum opening size. Also, boundary lines and openings can be detected through the study's applied algorithm. The input data is from the point cloud data obtained from the terrestrial laser scanning (TLS) data acquisition technique. However, this study only uses a small dataset in which it is more practical to process less dense data.

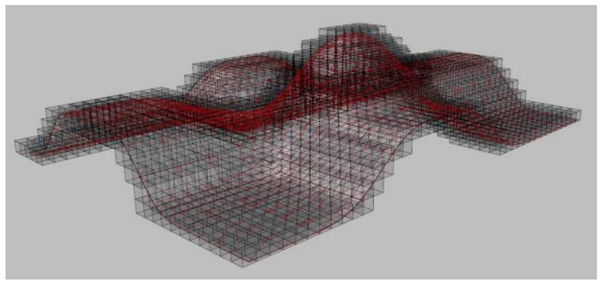
In a study by Nourian et al. (2016), they provided a method to make large-scale voxel models of the built environment that are spatially and topologically correct from the point cloud, curve, and surface objects. These input data are classified into different dimensions, where one point is zero-dimensional, and the other two are one-dimensional and two-dimensional. However, all inputs are embedded in three-dimensional Euclidean space. The resulting voxel models from these input data (Figure 8) were based on the intersection targets desired connectivity levels, such as 6 or 26 connected voxels. Nonetheless, the techniques implemented strictly applied to the input data instead of the entire 3D building model.



(a)



(b)



(c)

Figure 8. Voxelization result from a) point, b) curves, and c) surface object (Nourian et al., 2016)

Apart from that, Xiong et al. (2017) employed the triangle mesh building model to be voxelized. This voxelized model served as an input model for the extraction of interior space. Due to the input data being triangular meshes, the technique entails two stages: edges and triangular meshes voxelization. Additionally, the neighbouring search method combined the adjacent voxels produced by the edge and triangular processes. This study also included the semantics of six directions from six surfaces of each voxel to take into account the semantics information of the building in the newly developed model. Yet, the utilized technique requires the existence of edge and triangle data.

Moreover, the voxelized building model is also incorporated in the field of explosion simulation (Willenborg et al., 2018). No input data is used; however, the voxelized model was generated using the regular grid in the simulation domain. It is compared to the existing building model in City Geographic Markup Language (CityGML) standard. The voxels that have spatial relation to the CityGML model were determined using the PostGIS 3D intersection test procedure (implemented tree structure-based method) and were accumulated together to generate the finalized building model. However, as the voxelized model is generated in different domains, the accuracy of the inter-domain relation will affect the constructed model.

Gorte et al. (2019) presented a study on evacuation routes in a building using the 3D voxelized building model for an emergency response plan. The voxelized model of 4.55 cm voxel resolution is generated using floor, stairs, walls, and roofs. However, this research that used the dilation and erosion operation only remained with voxelized floor and stairs for the evacuation operation. Due to the specific application to implement the voxelized model, the resulting model is unsuitable for the study that requires the fully covered building model. The presented technique with dilation and erosion operation will affect the modelling of excluded connection structures such as stairs.

Likewise, Hübner et al. (2020) constructed a 3D voxelized building model (each voxel size of 5 cm) of floors, walls, wall openings, ceilings, and interior objects using triangle meshes. The region growing techniques are used in categorizing the ceiling and floor and extend to detect the room candidates. These room candidates are then assigned to the wall, wall opening, and the interior object using a rule-based voxel sweep algorithm. The concept of generating the voxelized indoor and outdoor models with several surfaces is adequately documented; however, the segmentation process following the normal direction of triangle meshes needs to be considered carefully when dealing with different input data.

Zhao et al. (2022) utilized the voxelization technique in the application of 3D pathfinding in terms of distance and cost, explicitly using several locomotive types. It is applied by putting the octree-based voxelization into practice on the geometry input. It can distinguish the steps and slopes in indoor modelling and fit with the locomotive types' movement behaviour criteria. Nonetheless, to match the pathfinding application, this study only focuses on the steps and slopes of indoor modelling. The partition process in creating the voxelized model is only considered on both characteristics.

This subsection concludes by presenting the second use of the approach, which is data modelling. Various methods and procedures were introduced (Table 2) in several applications; however, the documented method needs to be improved to make the voxelization technique suitable for the building model in the CFD wind simulation environment.

Table 2. Voxel-based Building Modelling

Voxel-based 3D Building Modelling				
Publication	Type of data	Application	Technique performed	Drawback
Glander & Dollner (2008)	Geometry data	3D building generation	Voxelization & Gaussian blur filtering	The generated model is too simplified with less detail of structure can be presented
Truong-Hong et al. (2013)	Point cloud	3D building generation	Octree-based voxelization	The acquired data is less dense point cloud data, which makes the processing technique better suited for the less dense point cloud data
Nourian et al. (2016)	Point cloud, curve and surface	General study	Voxelization with the combination with 6 or 26 connectivity of voxel	The presented technique focuses separately on the point, curve, and surface
Xiong et al. (2017)	Triangular meshes	Indoor building space extraction	Edge and triangular meshes voxelization & neighbouring search method	The processing method requires the input of edge and triangular data
Willenborg et al. (2018)	-	Explosion simulation	Regular grid-based voxelization & tree structure-based method	As the voxelized model is generated in different domains, the accuracy of the inter-domain relation will affect the constructed model
Gorte et al. (2019)	Floor plan	Evacuation operation	Voxelization with dilation and erosion method	The resulting model is not suitable for the study that requires the fully covered building model, and the presented technique with dilation and erosion operation will affect the modelling of excluded connection structures such as stairs
Hübner et al. (2020)	Triangular meshes	Indoor building construction	Voxelization & region growing technique	The segmentation process following the normal direction of triangle meshes needs to be considered carefully when dealing with different input data
Zhao et al. (2022)	Geometry data	3D pathfinding	Octree-based voxelization	The technique applied only focuses on generating the step and slope

4. CONCLUSION

This paper reviews the voxelization technique related to the 3D building model used in previous publications. From the review, it was found that the voxelization technique is utilized in two different conditions. The first one is for data segmentation and classification, and the second one is for data modelling. The method implemented throughout the data segmentation usually uses 3D point cloud data from TLS, ToF sensors, and other 3D scanners. All the studies discussed that using this specific voxelization technique reduces the point cloud data. This is due to the high density of the 3D point cloud data of objects or building models captured on the field. Reducing the density level of the data is vital as some of the data is unnecessary and introduces the redundant point cloud that can increase the computational time. Then, the second category of voxelization technique existed, data modelling. In this category, different techniques were used by researchers to produce the 3D voxelized model: some used point cloud data, line data, triangular meshes, etc. Nevertheless, not all the techniques can generate a good quality building model. Also, the input data plays the primary role in developing the 3D voxelized model. This is because different input data is suitable with varying techniques of voxelization. Yet, from the publications, the documented method needs to be improved to make the voxelization technique suitable for the building model in the CFD wind simulation environment.

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