Reasoning Spatial Relationships in Building Information Models using Voxels

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This paper investigates a voxel-based approach to automate the space construction of an ill-defined building information model, namely, a building model without specific spatial definitions. The objective is to provide a simplified representation through clustering voxels to reconstruct spaces, with which a spatial topological algorithm is designed to infer the implicit connectivity. This approach is treated as the first step to automate building information exchange for building performance simulation and knowledge-intensive reasoning.

Keywords: *Building information modelling, voxel, automatic building information exchange, topological spatial relationship*

INTRODUCTION

Building information modelling (BIM) has been increasingly used in the Architecture, Engineering and Construction (AEC) industries throughout the whole building life cycle, ranging from early conceptual design, construction, operation, to post-occupancy phases. A building information model is essentially a digital information repository with a pre-defined meta-data schema articulating how building data should be organised and structured to represent the whole building design. The objective is to manage three dimensional (3D) conceptual geometry, as well as functional and physical attributes, of a building using a relational database approach (Eastman, 1999).

For the past decade or more, the major development has been focused on the data schema and guidelines, by which the objective is to afford the flexibility, expandability and interoperability using a clearly defined data structure [1]. A commonly used non-proprietary data model is IFC-Industry Foundation Class [2]. Various tools have been developed to support IFC model creation and conversion (Bazjanac, 2009; [3]). Such guidelines and standards are essential to assure the quality of the data; however, it is still heavily relies on users' discretion for data input.

With the increasing popularity of using BIM in AEC practices, it provides a huge potential for integrated information applications; for instance, automating code checking for compliance with building regulations and sustainable rating standards (Biswas et al., 2013). Recent studies from Borrmann and Rank (2009) in spatial reasoning on building information models presented a semantic-rich language system for qualitative spatial query and reasoning. This approach demonstrated capabilities to uncover hidden spatial semantics, which might be implicitly modelled with building components. For instance, room adjacency can be reasoned through examining shared wall components. By aggregating these discrete relations, knowledge-intensive reasoning can be automated. The fire escape route planning is an example that can be automated and checked against the governing regulations. Nonetheless the strengths of proposed approaches in formulating computable representation, they are still very limited at the application level due to the complexity of the language itself and the pre-defined relations at a fine-grained level from the given building information models.

Automatic Data Exchange for Simulation

In addition to knowledge-intensive reasoning using BIM, there is a growing interest in automating BIM for building performance simulation. Among these, numerous researches investigate how conceptual geometry could be systematically restructured to form, for instance, thermal geometry for energy simulation in an automatic fashion (Bezjanac, 2009; Hitchcock and Wong, 2011; Jones et al., 2013).

Maile et al. (2013) pointed out the difficulties in providing error-free information during the conceptual design phase. For instance, formulating an accurate thermal geometry model for a building design is very different from the models that a designer used to represent design ideas. At the early conceptual design phase, it is challenging, and sometimes impossible, for designers to supply precise information while iteratively altering their design to meet various requirements. Most of the time, conceptual geometry contains ill-defined information due to many uncertainties at this stage. The implication of the uncertain nature of the conceptual design leads to the imperfections in models such that gaps in geometry and overlapping entities are more likely to occur. For instance, Figure 1 illustrates a commonly seen example of overlapping geometry, in which a column clashed with a beam component. Under this circumstance, it is often very difficult to formulate spaces as watertight enclosed volumes, which are essential for thermal geometry modelling and energy simulation.

In a general sense, data contained in a building information model is never complete and the amount of data continues evolving as the project progresses. Therefore, it is of the great interest in this paper to investigate a more generic and simplified method to capture underlying spatial relationships starting from the early conceptual phase. As the project progresses, the spatial network would evolve along with the required level of the granularity and changes could then be propagated effortlessly through various design, construction and operational phases.

Given a BIM model, the explicitly prescribed relationships between building components, or, sometimes, implicitly inferable spatial intelligence within the model could play an important role in successful data interoperation. As such, this paper proposes a generic voxel-based workflow to enable spatial reasoning on building information models. Our intention is that the proposed voxel-based methodology will demonstrate a simplified, yet efficient, approach of modelling and representing spatial topological relations. The expected contribution is to facilitate better communication among conceptual modelling, building information modelling and energy modelling.

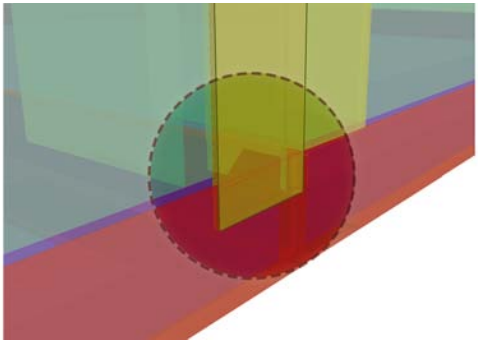

Figure 1
Overlapping geometry

RESTRUCURING SPACES USING VOXELS

This paper presents the work-in-progress development of reconstructing spaces given a coarse design geometry. Similar to Jones et al. (2013), the objective is to automate space construction of a 3D building model and one of the potential applications is to automate geometry preparation for building performance simulation and analyses. In this paper, we propose to use voxel, a three dimensional volumetric entity, to approximate given building information models. Through the simplified voxel-based representation, special information will be reconstructed and reasoned. This approach is expected to afford a foundation to infer implicit spatial relations embedded in the BIM models, in particular, during the early conceptual phase.

We intend to utilise voxels to examine building information models starting from the conceptual design phase. Given that any models provided at the conceptual design phase are more likely to be incomplete, we propose to start with the native geometric data from BIM models, namely, the polygonal representation of the building model, a mesh with triangular faces. Through a simplified volumetric representation of polygonal objects, we first construct the spatial objects, zones, and reason the underlying adjacency relationships among them.

Voxelisation

A voxel could be treated as an extruded pixel with an extra dimension in a three-dimensional (3D) environment. Voxelisation therefore describes a process of translating source data, a polygonal mesh, into three-dimensional volumetric data sets. In computer graphics, volume graphics is an important subfield aiming at the study of the modelling, manipulation, and analysis of spatial objects in a true 3D fashion (Chen, Kaufman, and Yagel, 2001). In this paper, we expand the volume graphics technique for spatial reasoning on complex building information models. In particular, we investigate how void (space) and solid (building component) objects can be better represented using a discrete set of voxels. Through aggregating voxels at various scales, we can extract abstract spatial relations at a customisable resolution without relying on any pre-defined geometrical relations.

To start with, we develop a volumetric parser taking into account the spatial occupancy to produce voxels with distinctive binary attributes, 0 for 'void' and 1 for 'solid'. Each voxel at its inception will be tested against with the given building components. When the union of a unit volumetric entity with the input building objects is not empty, a 'solid' voxel is constructed with an occupancy channel equal to 1; otherwise, a voxel with an occupancy channel equal to 0 and therefore 'void'. The entire voxel grid system will be based upon the bounding box calculated from the input building information models.

Voxel Definition. When a voxel is created, it will be assigned with a unique identification number (ID), which pertains information in relation to where this voxel is located in relation to the prescribed 3D voxel grid system. The formula for voxel ID, *V_ID*, calculation is as follows:

$$V_{ID} = X_{ID} + Y_{ID} \cdot Dim_X + Z_{ID} \cdot Dim_X \cdot Dim_Y \tag{1}$$

X_ID, *Y_ID*, and *Z_ID*, respectively represent the indices along the X, Y, Z directions of the 3D grid system.

Figure 2 illustrates an example of finite voxels in a prescribed volumetric space from a building box, specified with a minimum bounding box corner vertex, *BBox_MIN* and a maximum bounding box corner vertex, *BBox_Max*. Currently in this figure, only solid voxels were visualised and shown shaded grey.

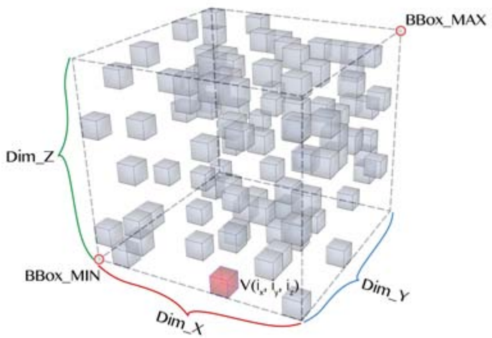

Figure 2
Voxelisation within the Bounding Box

Figure 3 demonstrates the creation of voxel models using two different resolutions. In this example,

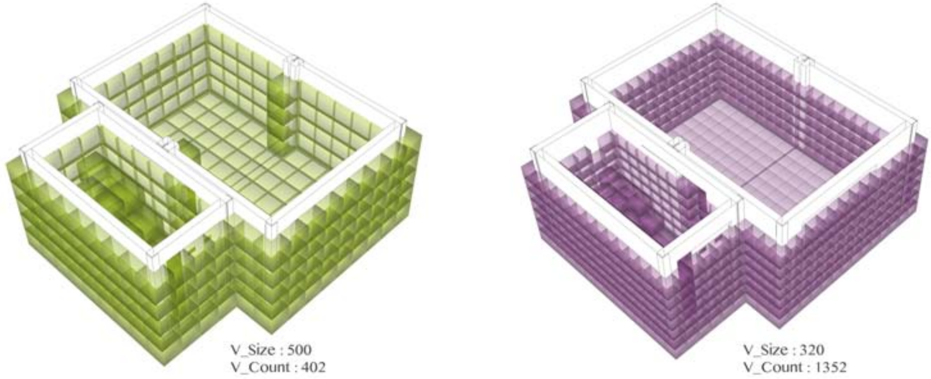

Figure 3
(Left) Low resolution voxelisation (Right) High resolution voxelisation

only partial models were used for the visualisation purpose.

Automating Space Construction

Once the finite set of voxels was generated, the inherit connectivity of each voxel will then be used to identify space clusters. For each voxel, there are in total six directly and twenty indirectly connected neighbours. Figure 4 illustrates the central voxel, shown in shaded red, has directly connected voxels shaded in blue and indirectly connected ones shaded in green. This relationship provides an important cue for the next spatial topology reasoning.

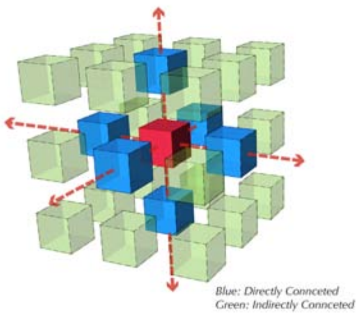

Figure 4
Voxel connectivity

In the following, we describe an algorithmic approach to formulating clusters through examining the connectivity between voxels. The procedure initiates the search from the directly connected neighbours at a given voxel, iterates through next connected neighbours at a time, and terminates as all valid voxels are exhausted. By iterating through all 'void' voxels at once, the clustering outcome approximates the building information models with distinct spaces. Spatial connectivity can then be reasoned through examining the boundaries of these spaces. The pseudo code for the space construction using clustering is as follows:

```
[SPACE_CONSTRUCTOR]
# VVS: Void Voxel Set for Search   #
# TVS: Temp Empty Voxel Set        #
# Curr_VC: Current Voxel Cluster   #
# EVC: Existing Voxel Cluster      #

1. FOREACH V in VVS:
2.   Add V to Curr_VC
3.   GET CV = CONNECTED_Voxels at V
4.   FOREACH V1 in CV:
5.     IF V1 NOT in EVC:
6.       Add V1 to TVS
7. Update VVS ← TVS
8. RETURN Curr_VC, if VVS is Empty
```

Figure 5 illustrates the space construction using the low-resolution voxel model given in Figure 4. Two

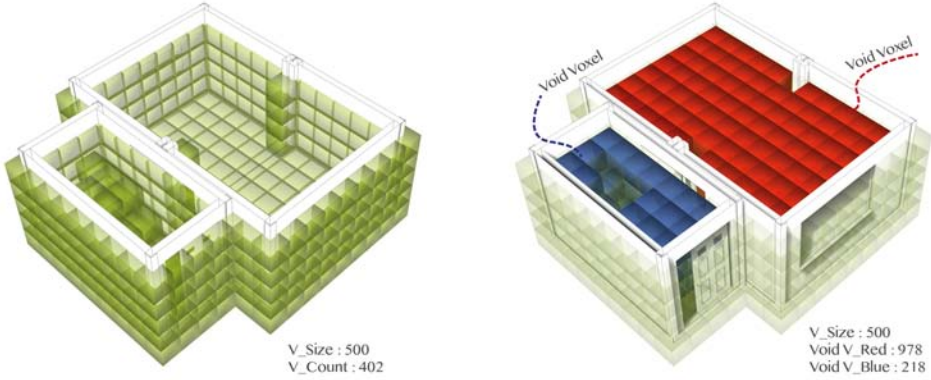

Figure 5
Reconstructing spaces by clustering void voxels

voxel clusters were identified at the ground level and they are shown shaded red and blue respectively.

With the space clusters ready, a topology solver is then triggered to interrogate the spatial connectivity among them. This solver starts by first extracting the boundary of each space cluster. Different from the voxels contained in the cluster, the boundary layer only consists of solid voxels, which surround and enclose the entire space. The adjacency relationship between two spaces is therefore inferable through examining these boundaries only. Figure 6 demonstrates an example of a modular house consisting of five spaces.

Voxel Object Data Structure and Representation

Voxel objects are created to represent given building information models. To fully parameterise voxel objects and voxel-based entities, a set of required data elements were proposed, including the bounding volume of the voxelisation, the voxel unit size, and the binary occupancy map, etc. These data elements, as shown in Table 1, were designed to describe the finite set of voxel objects within the bounding volume that enclose the whole building geometry.

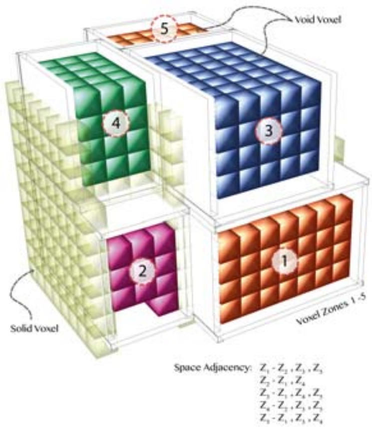

Figure 6
Space adjacency analysis

Figure 7 illustrates three voxel models with same bounding box, same voxel unit size, yet with different voxel binary map.

CONCLUSION

With the evolutionary nature of design, the amount of data continues growing across various design, construction, and operation phases. To facilitate such an information-intensive process, this paper investigates a generic voxel-based workflow to enable spatial reasoning on any given building information models. The objective is to capture underlying spa-

File Structure	Definition
OBJSOURCE *[Optional: SOURCE FILE NAME]*	The Input geometry source
BBOX_MIN *[X_COORD, Y_COORD, Z_COORD]*	The bounding box vertex with minimum X-, Y-, and Z-coordinates
BBOX_MAX *[X_COORD, Y_COORD, Z_COORD]*	The bounding box vertex with maximum X-, Y-, and Z-coordinates
V_SIZE *[NUMBER]*	Voxel unit size
V_DIM *[X_DIM, Y_DIM, Z_DIM]*	Voxel dimension along X-, Y-, and Z- Axis
VB_MAP *[Optional: Binary MAP]*	Voxel binary map representing either 'Solid' or 'Void'
V *[X_COORD, Y_COORD, Z_COORD]*	Voxel centre (X, Y, Z)

Table 1
Voxel data file structure

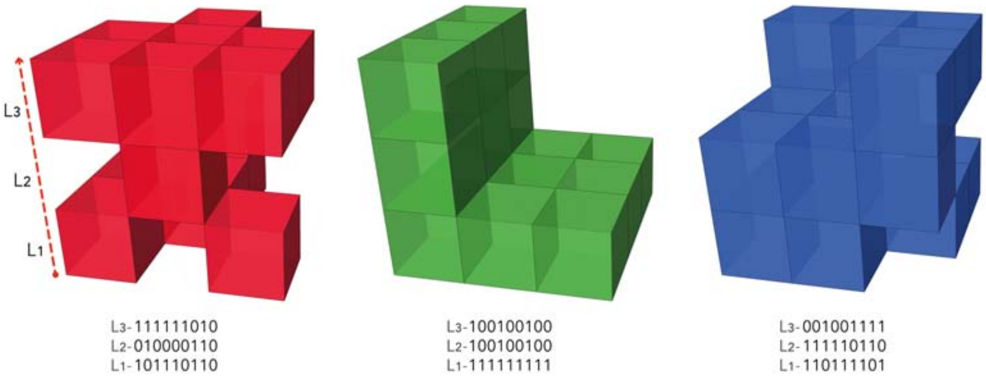

Figure 7
Voxel models with the binary occupancy representation

tial relationships early on the conceptual design geometry. As the project progresses, the spatial network would evolve along with the increasing granularity and allow changes to be updated accordingly.

The advantage of this approach is expected to be the flexibility and scalability associated with the spatial topological network, with which designers are relieved from providing precise information at an early conceptual design phase. Our intention is that by procedurally building up the information using such a spatial topological network, various needs at different design phases could be ultimately accommodated in a true automatic fashion. In addition, the capability of capturing no-conventional rectangular spaces via voxels also provides designers a better computational vehicle to explore different designs.

As the development is still at its infancy stage, more examples would be sought to validate and improve the voxelisation procedure. In particular, one of the future applications would aim to investigate a smooth transition from conceptual design geometry to simulation-ready configuration for energy performance analyses. This is to tackle long-lasting interoperability issues on conceptual modelling and energy modelling. In addition, a conceptual meta-graph representation would be provided to facilitate better understanding of the building information models, leading to automatic diagnostics at an early design stage for pre-construction planning in a more effective and efficient fashion. For instance, through reasoning spatial connectivity between spaces, simulation could be conducted to investigate fire escape planning.

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REFERENCES

Bazjanac, V 2009 'Implementation of Semi-automated Energy Performance Simulation: Building Geometry', *CIB-W78 26th International Conference on Information Technology in Construction*, Istanbul, pp. 595-602

Biswas, T, Wang, T-H and Krishnamurti, R 2013, 'From Design to Pre-Certification Using Building Information Modeling', *Journal of Green Building*, 8(1), pp. 151-176

Borrmann, A and Rank, E 2009, 'Topological Analysis of 3d Building Models Using a Spatial Query Language', *Advanced Engineering Informatics*, 23, pp. 370-385

Chen, M, Kaufman, A and Yagel, R (eds) 2001, *Volume Graphics*, Spring-Verlag, New York

Eastman, C 1999, *Building Product Models: Computer Environments, Supporting Design and Construction*, CRC Press, New York

Goldstein, R, Breslav, S and Khan, A 2014 'Towards Voxel-Based Algorithms for Building Performance Simulation', *eSim 2014 Conference Proceedings: IBPSA-Canada eSim Conference*, Ottawa, p. 1B.1

Hitchcock, R and Wong, J 2011 'Transforming Ifc Architectural View Bims for Energy Simulation', *Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association*, Sydney, pp. 1089-1095

Jones, N, McCrone, C, Walter, B, Pratt, K and Greenberg, D 2013 'Automated Translation and Thermal Zoning of Digital Building Models for Energy Analysis', *Proceedings of 13th International Conference of the International Building Performance Simulation Association*, pp. 202-209

Maile, T, O, J, Bazjanac, V and Rose, C 2013 'BIM-Geometry Modelling Guidelines for Building Energy Performance Simulation', *Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association*, Chambéry, France, pp. 3243-3249

[1] http://www.buildingsmart-tech.org/specifications/ifc-overview

[2] http://www.buildingsmart-tech.org/specifications/ifc-releases/summary

[3] http://www.buildingsmart-tech.org/implementation