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Topologic

Tools to explore Architectural Topology

Abstract

Buildings enclose and partition space and are built from assemblies of connected components. The many different forms of spatial and material partitioning and connectedness found within buildings can be represented by topology. This paper introduces the 'Topologic' software library which integrates a number of architecturally relevant topological concepts into a unified application toolkit.

The goal of the Topologic toolkit is to support the creation of the lightest, most understandable conceptual models of architectural topology. The formal language of topology is well-matched to the data input requirements for applications such as energy simulation and structural analysis. In addition, the ease with which these lightweight topological models can be modified encourages design exploration and performance simulation at the conceptual design phase.

A challenging and equally interesting question is how can the formal language of topology be used to represent architectural concepts of space which have previously been described in rather speculative and subjective terms?

Keywords Non-manifold Topology, Idealised model, Material model.

1 Introduction

This paper focusses on the conceptual issues surrounding the use of topology in architecture. It builds on previous research and proof of concept studies (Aish and Pratap 2013; Jabi 2014; Jabi et al. 2017). Other concurrently published papers describe in greater detail the implementation of the Topologic toolkit and specific applications of Topologic in building analysis and simulation (Jabi et al. 2018; Chatzivasileiadi, Lannon, et al. 2018; Wardhana et al. 2018).

Topology and in particular non-manifold topology are vast subjects that span algebra, geometry and set theory. It is beyond the scope of this paper to delve into the mathematical constructs and proofs that precisely define non-manifold topology. Topology has applications in biology, medicine, computer science, physics and robotics among others. Since the motivation for this research is to address the needs of architects and engineers, this research focusses on a specific application of non-manifold topology in the representation of significant spatial relationships in the design of buildings using computer-aided three-dimensional geometric processing.

We can contrast this approach with more conventional representations of buildings as a collection of physical building components, typically modelled as manifold solids, as demonstrated by Building Information Modelling (BIM) applications. While BIM can be used to model the physical structure of the building, architecture is usually conceived in terms of an overall form and a series of related spatial enclosures (Curtis 1996). This spatial conceptualization is a key aspect of architectural design because it directly anticipates how the resulting building will be experienced. However, there are no practical design tools which support the creation of this spatial representation of architecture. Non-manifold topology is ideally suited to create a lightweight representation of a building as an external envelope and the subdivision of the enclosed space into separate spaces such as rooms, building storeys, cores, atria, etc. This lightweight representation also matches the input data requirements for important analysis and simulation applications, such as energy analysis, (Ellis, Torcellini, and Crawley 2008).

Conventional BIM applications, in contrast, do not explicitly model the enclosure of space. Although it might be possible to indirectly infer the enclosed spaces from the position of the physical building components, the fidelity of this representation depends on the precise connectivity of the bounding physical components, which cannot be relied upon. Even if this approach was viable, the level of detail of BIM models is often too complex for this type of analysis (Maile et al. 2013). Detailed BIM models are also cumbersome to change which may inhibit design exploration at the conceptual design stage.

One option might be to explore spatial modelling with existing solid modelling applications. However most of these applications are based on conventional manifold modelling techniques and do not support non-manifold topology. Indeed, many regular manifold modelling applications treat non-manifold topology as an error condition.

The objective of this research is to develop design tools based on precise topological principles but presented in ways which are understandable by architectural users who may have little previous experience of topology. The intention is that Topologic can be an effective intermediary between the abstract world of topology and the practical world of architecture and building engineering.

2 Background

2.1 The distinction between manifold and non-manifold Topology

In a previous paper (Aish and Pratap 2013) the following distinctions were made between manifold and non-manifold topology:

> "A 3D manifold body has a boundary that separates the enclosed solid from the external void. The boundary is composed of faces, which have (interior) solid material on one side and the (exterior) void on the other. In practical terms, a manifold body without internal voids can be machined out of a single block of material."

> "A non-manifold body also has a boundary [composed of faces] that separates the enclosed solid from the external void. Faces are either external [separating the interior (enclosed space) from the exterior (void)] or internal [separating one enclosed space (or cell) from another]. Furthermore, a non-manifold solid can have edges where more than two faces meet."

2.2 The distinction between an idealized and a material model

One of the key themes which runs through this research is the distinction between an 'idealised' model (of a building) and a 'material' model of the physical building components. An early demonstration of this principle was made in 1997 (Aish 1997) and further developed (Hensen and Lamberts 2012).

Typically, idealised models are far less detailed than material models, therefore lighter and more easily edited. In addition, the different topological components of the idealised model (faces, edges, vertices) can be used as the 'supports' for related building components in the material model. The connectivity of the components in the material model need not be directly modelled. Instead this connectivity can be represented through the topology of the idealised model.

2.3 Previous research

The case for non-manifold topology as well as its data structures and operators for geometric modelling were comprehensively set out by (Weiler 1986). In his introduction, Weiler explains why non-manifold topology is needed:

> "A unified representation for combined wireframe, surface, and solid modelling by necessity requires a non-manifold representation, and is desirable since it makes it easy to use the most appropriate modelling form (or combination of forms) in a given application without requiring representation conversion as more information is added to the model."

Non-manifold topology allows an expansion of the regular Boolean operations of union, difference, and intersection. This expanded set includes operators such as merge, impose, and imprint. For a full description of non-manifold operators, please consult (Masuda 1993).

Representing space and its boundary was the focus of early research into BIM (Björk 1992; Chang and Woodbury 1997) and into 'product modelling' (PDES/STEP) (Eastman and Siabiris 1995) and was proposed as an approach to the representation of geometry definition for input to Building Performance Simulation in the early design stages (Hui and Floriani 2007; Jabi 2016). However, this has not been emphasised in modern BIM software which has focussed more heavily on representing the building fabric through manifold geometry and advocated the derivation of energy models from them.

Separately, non-manifold topology has been successfully used in the medical field to model complex organic structures with multiple internal zones (Nguyen 2011; Bronson, Levine, and Whitaker 2014).

Our focus is to create a schema which separates abstract topological concepts from domain specific and pragmatic concerns of architecture, engineering and construction. We maintain this separation, but we also illustrate the important connections between the two: how buildings can be represented by topology and how a topological representation can potentially assist architectural users in the conceptualisation and analysis of new buildings. Therefore, our focus is not to create new non-manifold data structures, but rather to harness existing geometry and topology kernels in an innovative way; indeed, it is completely feasible that the Topologic schema could be implemented with different data structures or with different kernels.

A comprehensive and systematic survey of topological modelling kernels, which support non-manifold topology, was carried out by the authors and published elsewhere (Chatzivasileiadi, Wardhana, et al. 2018). Features and capabilities of kernels were compared in order to make an informed decision regarding what underlying kernel to use. Popular geometric kernels, such as CGAL, were discounted due to their inability to represent higher dimensional entities such as *CellComplexes* and for their more limited set of irregular Boolean operations.

3 The Topologic toolkit

The core Topologic software is developed in C++ using Open Cascade (https://www.opencascade.com/) with specific C++/CLI variants developed for different visual data flow programming environments (Wardhana et al. 2018). Topologic integrates a number of architecturally relevant topological concepts into a unified application toolkit.

The features and applications of Topologic are summarised in Fig. 1 and Fig. 2.

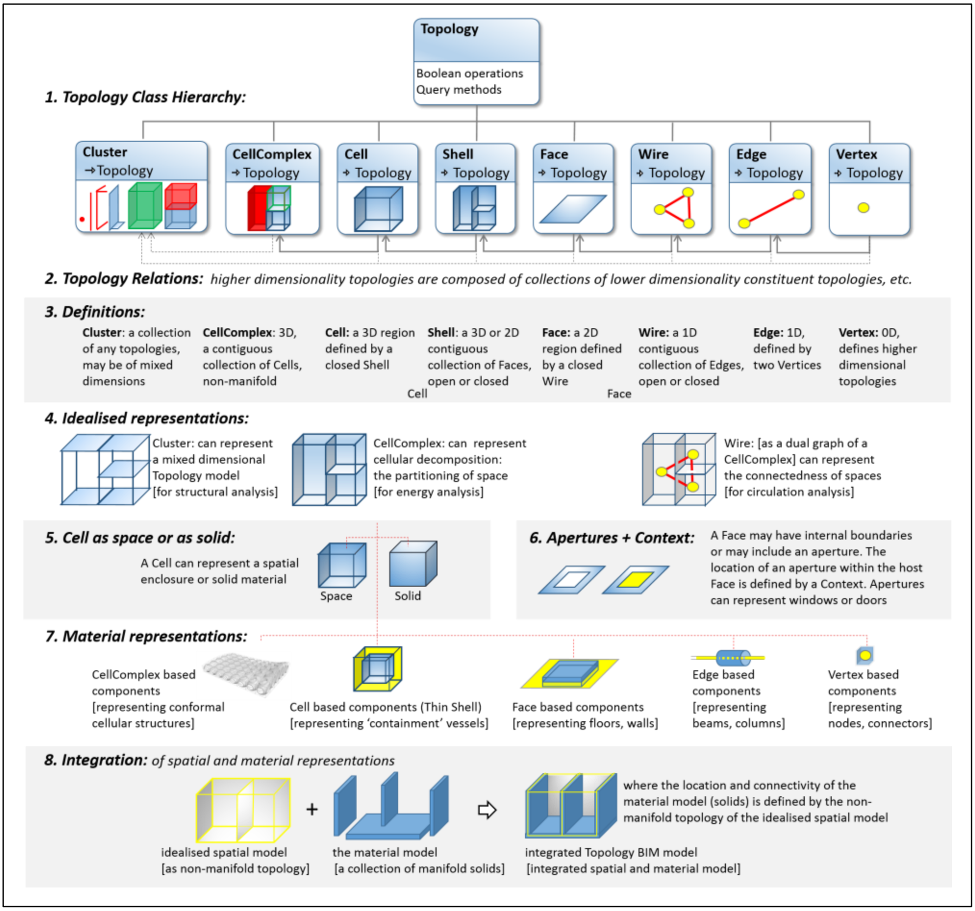
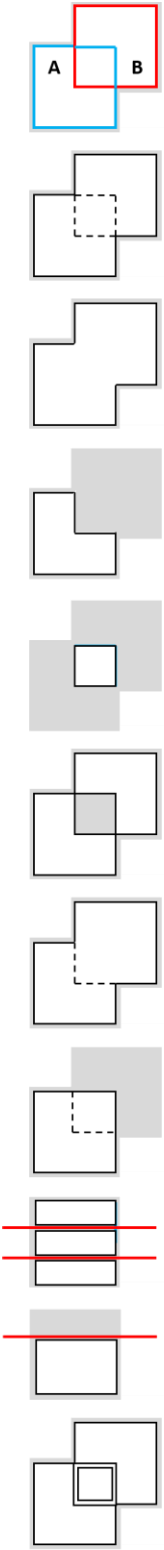


Fig. 1 The Topologic application toolkit summarised in eight key points.



Input: Starting configuration where A and B intersect.

Merge: All parts of A are intersected with all parts of B. The parts of A are split at the intersection with B and the parts of B are split at the intersections with A to form the merge result. The result is non-manifold.

Union: All parts of A which are within the region of B and all parts of B which are within the region of A are removed.

Difference: [A difference B] All parts of B which are not within A are removed.

Intersect: All parts of A which are not within the region of B and all parts of B which are not within the region of A are removed

XOR: Only those parts of A which are not within the region of B and those parts of B which are not within the region of A are retained.

Impose: [A Impose B] All parts of A which are within the region of B are removed. The result is non-manifold.

Imprint: [A Imprint with B] All parts of B that are not within A are removed. The result is non-manifold.

Slice: [A slice with B] A is a higher dimensional and B is typically a collection of topological entities of lower dimensionality. The result is non-manifold.

Trim: A is a topological entity of higher dimensionality and B is typically a topological entities of lower dimensionality, returns the part of A on a specified side of B

Unmerge: [which is the converse of a Boolean operation] returns a Cluster of unconnected manifold entities by duplicating those entities which were previously shared within the input topology.

Fig. 2 Boolean Operations implemented in Topologic.

3.1 Class Hierarchy

The Topologic class hierarchy is designed to provide the architectural end-user with a conceptual understanding of topology. It also functions as an "end-user programmers' interface" (EDPI). This user-oriented class hierarchy is distinct to the implementation-oriented class hierarchy within the Topologic core.

The Topologic superclass [Fig. 1, section 1] is abstract and implements constructors, properties and methods including a set of Boolean operators. These operators can be used with both manifold and non-manifold topology [Fig. 2]. Topologic implements the expected concepts such as: *Vertex*, *Edge*, *Wire*, *Face*, *Shell*, and *Cell*. The interesting additional topological concepts are:

CellComplex which is a contiguous collection of *Cells* and is non-manifold.

Cluster which is a universal construct and allows any combination of topologies, including other 'nested' *Clusters*, to be represented. A *Cluster* may represent non-contiguous, unrelated topologies of different dimensionalities.

3.2 Topological relationships

Topologic supports the building and querying of three different types of topological relationships [Fig. 1, section 2]

Hierarchical relationships: between topological entities of different dimensionality. These relationships are created when a higher dimensional topology construct is composed from a collection of lower dimensional topologies. Subsequently the compositional relationships may be queried:

```
cellComplexes = vertex.Edges.Wires.Faces.Shells.Cells.CellComplexes;
```

Conversely, the decompositional relationships may also be queried, for example from higher dimensional topologies down to the constituent collections of lower dimensional topologies:

```
vertices = cellComplex.Vertices;
```
or
```
vertices =
 cellComplex.Cells[n].Shells[n].Faces[n].Wires[n].Edges[n].Vertices;
```

Lateral relationships: these occur within a topological construct when the constituents share common topologies of a lower dimensionality.

```
adjacentCells = cellComplex.Cells[n].AdjacentCells;
adjacentFaces = shell.Faces[n].AdjacentFaces;
```

Connectivity: The path between two topologies can be queried.

```
path = topology.PathTo(otherTopology);
```

3.3 Idealised representations

Three different idealized models are considered [Fig. 1, section 4]

Energy Analysis: a *CellComplex*: can represent the partitioning and adjacency of spaces and thermal zones.

Structural Analysis: a *Cluster* can be used to represent a mixed-dimensional model, with *Faces* representing structural slabs, blade columns and shear walls, *Edges* representing structural columns and *Cells* representing building cores.

Digital Fabrication Analysis: a *CellComplex* can represent the design envelope where topology can inform the shape and interface between deposited material (Jabi et al. 2017).

Circulation Analysis: a dual graph of a *CellComplex* can represent the connectedness of spaces.

3.4 *Cell* as a Space or as a Solid

A *Cell* is defined as a closed collection of faces, bounding a 3D region. However, this same topology can represent two distinctly different application concepts: a Solid and a Space [Fig. 1, section 5]. A Solid is interpreted as a single homogeneous region of material and its boundary defines where the material ends and the void begins. This is the interpretation of the *Cell* as used in 'Solid Modelling' and BIM applications.

A Space is a more abstract concept and may include an implied conceptual distinction between the material which is 'contained' (represented by the enclosed 3D region of the *Cell*) and the 'container' (represented by the *Faces* of the *Cell*). A *Face* may represent a boundary which is intended to be materialized with a defined thickness or may represent a 'virtual' (e.g. adiabatic) barrier which is not intended to be materialized.

Solids and Spaces have exactly the same *Cell* topology, but the domain specific semantics and expected behaviour of this topology may be different. Consider a boolean 'difference' operation representing a hole drilled into a *Cell* [as a solid]. A new part of the *Cell* boundary would be created, but the result would still be a *Cell*.

What result would the user expect if the same *Cell* represented a Space? Would the boolean 'difference' only apply to a specific Face [as part of the Space's boundary]? Would the user expect the boolean operation to create an internal boundary within the selected Face? Would the user expect this operation to destroy the integrity of the enclosure, changing the *Cell* into an open *Shell*?

This example helps to explain the difference between a material model (the *Cell* as a Solid) and an idealised model (the *Cell* as a Space). More generally this example demonstrates the need for the architectural users to customise the application of abstract topological concepts with the domain semantics which suits their purpose.

This relationship between application semantics and abstract concepts works both ways. Sometimes more generally applicable concepts emerge by abstracting ideas from other specialist domains. For example, the concept of a topological *Cell* may have originated as an abstracted analogy of a biological cell, with similarities in terms of the homogeneity and continuity of the contained 3D region and the role of the cell wall as a closed container with selective permeability [Fig. 3].

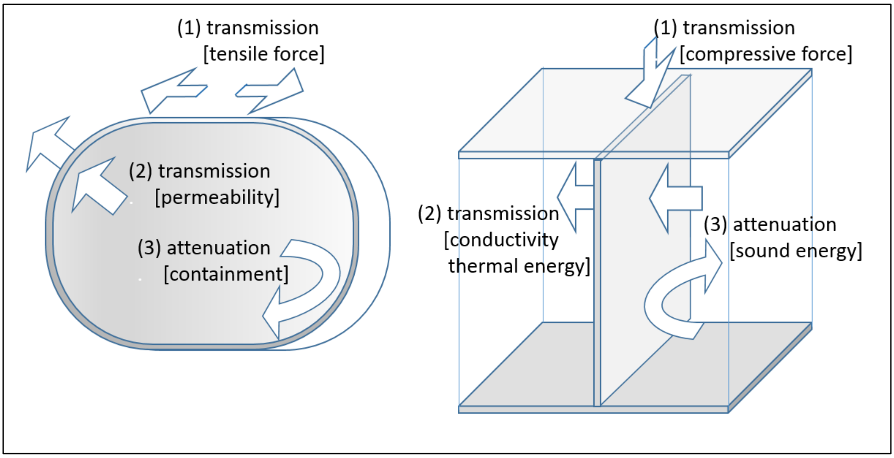


Fig. 3 The cell wall as a separator and as a connector, in biology and in architecture (with acknowledgement to Wix, 1994).

3.5 Apertures and Contexts

A *Face* may have internal boundaries which may represent an aperture. The location of an aperture within the host *Face* is defined by a Context. Apertures can represent windows or doors. [Fig. 1, section 6] (The representation of Apertures is discussed in more detail in section 4.4 'Regional Topology')

3.6 Material representations

While all *Cells* have a common topology [a closed 3D region bounded by *Faces*] different configurations of *Cells* may be generated from different types of foundational topologies using different geometric operations [Fig. 1, section 7], for example:

Point location connector components: may be based on *Vertices*.

Linear components such as columns or beams: may be based on *Edges (or Wires)* using operations where a cross section *Wire* is extruded along a path.

Area based components such as slabs, floors, walls may be based on *Faces*: using offset operations with a specified thickness and direction.

Volume based components such as a containment vessel may be based on *Cells* using thin-shell operations and a specified wall thickness.

Conformal cellular structures, used in 3D printing, may be based on *CellComplexes*.

Complex sub-assemblies of material components can be modelled as *Clusters*.

3.7 Integration of idealized and material models

The integrated BIM model uses the idealized non-manifold spatial model to define the location and connectivity of the material model. [Fig.1, section 8]. The defining centre lines or centre faces of walls and floors of the material model may be offset from the edges and faces of the idealized model. We can now appreciate the difficulty of attempting to reverse the direction of the arrow to recover an idealized spatial model from a material model.

In traditional BIM, the 3D material representation is the defining model while the drawings are the derived models. With architectural topology the idealized non-manifold topological representation becomes the defining model and the 3D material representation is now a derived model.

The idealised non-manifold spatial model acts as a useful conceptual and practical intermediary between the user and the material model [Fig 4]. In this workflow the user is not manually placing specific material components on specific *Faces* or *Edges* of the idealised model. If such a workflow had been adopted, then any change in the idealised topology might have removed these specific *Face* or *Edge* and orphaned [or potentially deleted] the material components. Also such a change to the idealised topology might have created new *Faces* and *Edges* which the user would be required to populate with material components.

Instead, the populating of the idealised topology is rule-based using the Visual Data Flow programming tools available in the host application. The rule-based generation of the material model allows alternative building configurations to be easily explored via the manipulation of the idealised spatial model as previously suggested (Aish and Pratap 2013).

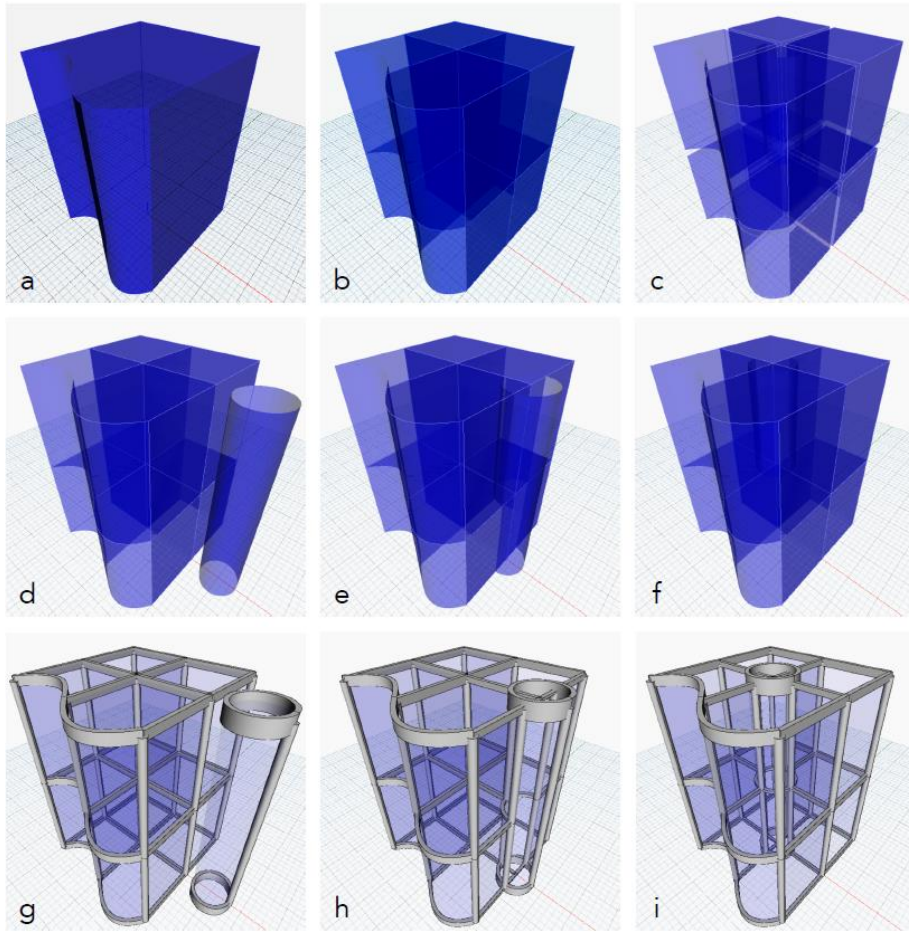


Fig. 4 An idealised spatial model built with non-manifold topology can be used as a convenient intermediate representation to manipulate a material model, involving:

a) creating a cell from a lofted solid

b) dividing the cell using several faces, resulting is a CellComplex

c) the individual cells can be derived from the CellComplex

d) introduce a cylinder outside the CellComplex

e) move the cylinder into and imposed on the CellComplex: new cells are created.

f) move the cylinder further into the centre: the cells update accordingly.

g,h,i) corresponding material models are derived from the NMT models in d,e,f.

The workflow includes detecting vertical and non-vertical edges, sweeping a circle along vertical edges to create cylindrical columns and a rectangle along non-vertical edges to create rectangular beams. The depth of the beams are parametrically computed according to their length. For visualisation purposes, the surfaces are thickened slightly into solids and made translucent.

4 Using non-manifold topology to represent relevant architectural concepts

Non-manifold topology embraces five concepts with architectural relevance:

4.1 Non-manifold *Cell*

A *non-manifold Cell* may contain internal *Faces* which are not part of the external *Cell* boundary. Both sides of such internal *Faces* point to the same enclosed region. The concept of a non-manifold *Cell* is required to model internal 'semi-partitions' of architectural spaces which do not fully divide the cell. [Fig. 5]

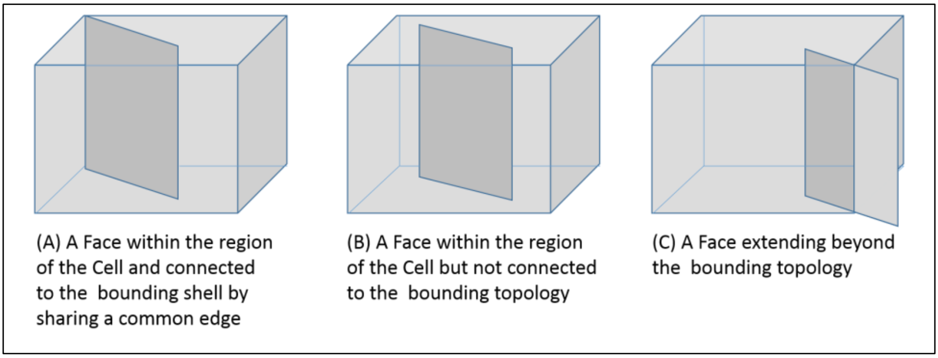


Fig. 5 Different configurations of non-manifold Cells.

4.2 Cellular Topology

Cellular Topology is implemented as a *CellComplex*, where some *Faces* of the *Cell* are also the external boundary, while other *Faces* form the boundary between adjacent *Cells*. Cellular Topology can be used to model a building which is partitioned into different architectural spaces [Fig. 6].

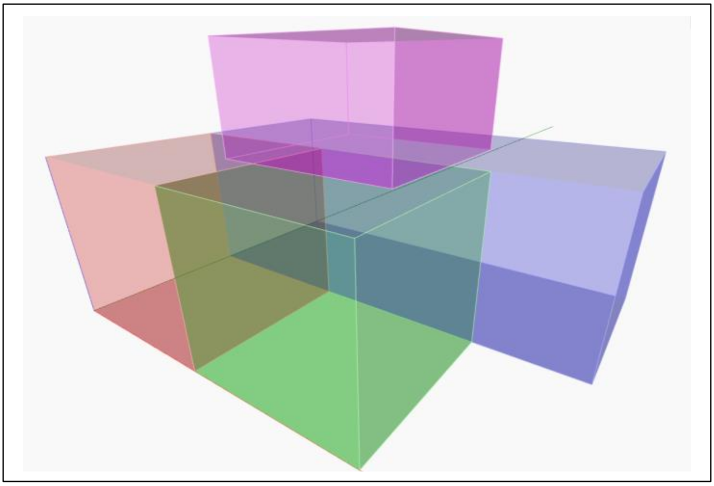


Fig. 6 Cellular Topology modelled as a CellComplex.

4.2 Mixed dimensionality Topological models

In non-manifold topology it is possible to construct a single topological model composed of entities of different types and dimensionality. The concept of a mixed dimensionality topology is implemented as a *Cluster* and can be used to create an idealized model of the structure of a building [Fig. 7].

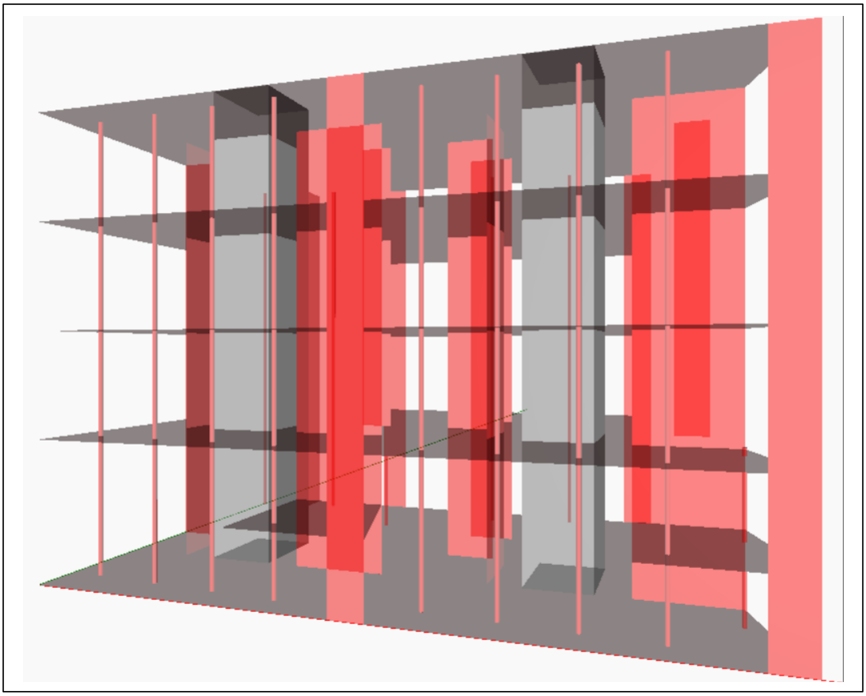


Fig. 7 A mixed dimensional model with Edges representing the column centre lines and Faces representing floor slabs, blade columns and shear walls. Cells are used to represent the building cores.

4.4 Regional Topology

In conventional topological modelling, higher dimensional topological entities are constructed from lower dimensional ones. Higher dimensional topological entities are connected because they share common lower dimensional entities. For example, adjacent *Cells* within a *CellComplex* may share a common *Face*.

However, in the domain of architecture there are other forms of connectedness which cannot be directly expressed in this way. For example, a column can be idealised as an *Edge*. A floor or ceiling can be idealised as a *Face*. We intuitively understand that a column [*Edge*] may connect a floor [*Face*] to a ceiling [*Face*], but how can this be described if the column is in the middle of the floor and when there is no topology within the definition of the floor and ceiling *Faces* which is shared with the *Vertices* defining the column's *Edge*? [Fig. 8].

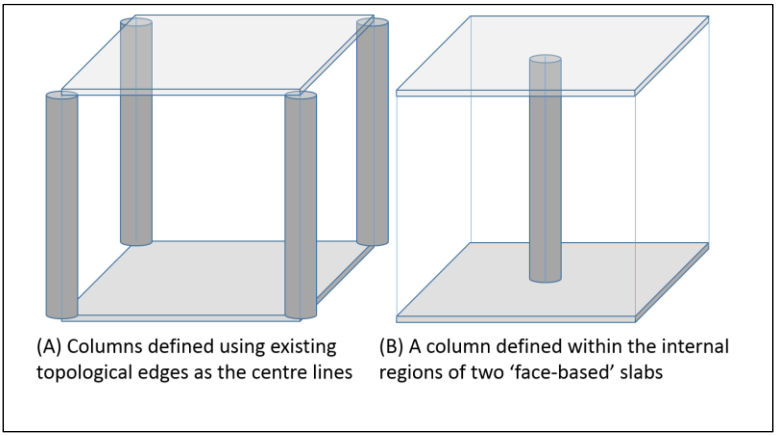


Fig. 8 Defining the 'Context' to describe the connectedness of two topologies where one entity exists within the region of the other entity and when the two entities do not share any common constituent topology.

Similar issues arise when we consider an internal boundary within a *Face*. For example the *Face* may represent a wall and the internal boundary may define an Aperture such as a window or a door. We intuitively understand that the Aperture [as a single 2D region] is contained within the 2D region of the *Face*, with no shared topology.

To address these issues, Topologic introduces the concept of a *context* to represent the connectivity between two topological entities which do not otherwise share common topology. In this example, the Aperture is the *subject* (representing a window) and is defined *within the region* (or *context*) of the *host Face* (representing the wall). The user may optionally specify that the *context* defines a locational 'link' between the *subject* and the *host*. Here the vertices of the subject are defined in the parameter space of the host and are now dependent on any changes which are applied to the host. [Fig. 9].

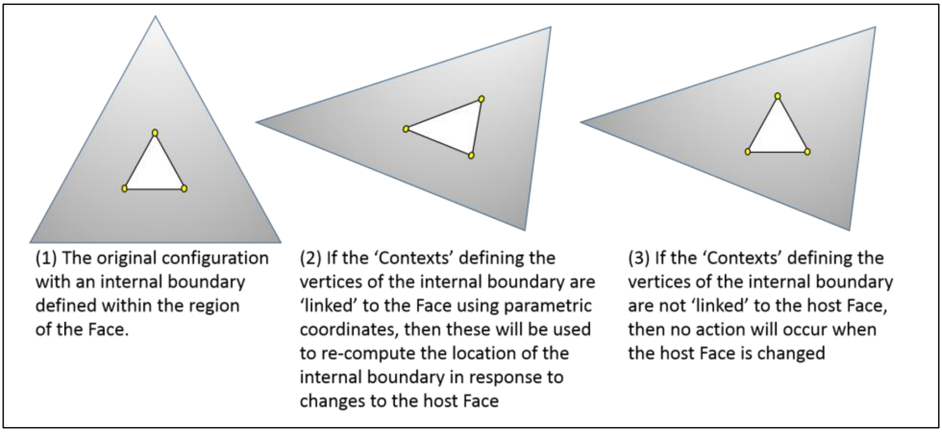


Fig. 9 The option to 'link' the *subject* topology to the *host* topology.

The *context* with parametric coordinates is only used when there is no shared topology connecting the two entities [Fig. 10].

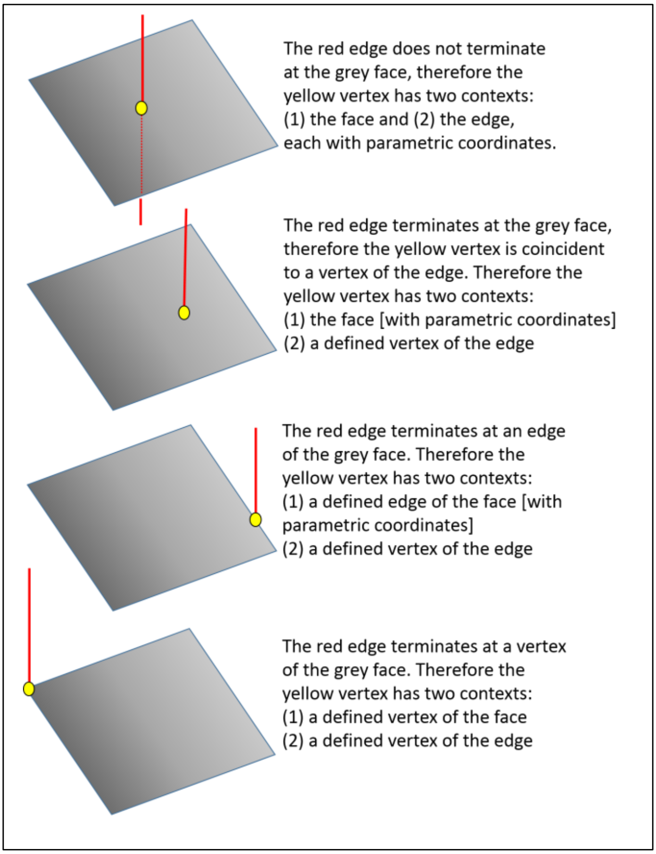


Fig. 10 Given the intersection of an Edge [red] and a Face [grey] in different configurations, then the concept of the *context* [with parametric coordinates] is used when the resulting Vertex occurs within a region of the intersecting topologies.

4.5 Variable Topology

In architecture, spatial divisions may be 'hardcoded' as distinct rooms separated by physical walls. While buildings appear to be solid, one of the central tenets of architecture is that the use of space within a building is or should be flexible. We think of multi-use or reconfigurable spaces.

There appears to be no established architectural methodology which prescribes how the topology of a building emerges. In fact, the architectural design process is quite imprecise. It may start with an occupancy model and a description of the anticipated activities of the occupants. Activities may vary in time and space. Activities may overlap. Alexander (1965) noted that neither activities nor space could be adequately described by a simple hierarchical decomposition. The process by which activities get translated into specific spatial enclosures and the choice as to which boundaries of these enclosures are actually materialised as walls or are left as purely virtual, is often a matter of contention [Fig. 11].

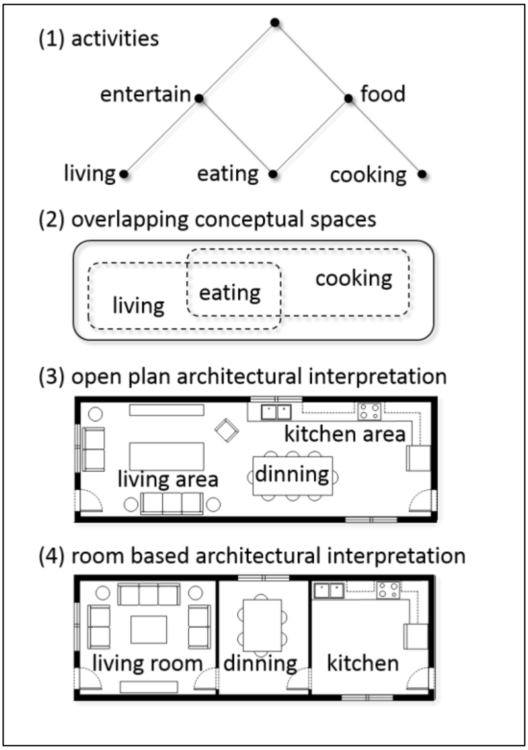


Fig. 11 The choice of spatial configuration often starts with identifying underlying activities of the occupants (1). These activities and their spatial requirements may overlap. It may be inappropriate to describe these as a simple hierarchical decomposition (with acknowledgement to Alexander, 1965). The process by which activities are translated into defined conceptual spaces (2) and are further translated into recognisable enclosures (3) or into specific rooms (4) often reflects architectural intuition rather than a defined methodology.

Virtual partitions may also be used in the topological representation of other building sub-systems. For example, an atrium may be considered as a single continuous space, or it may be considered to be subdivided into different air conditioning zones without physical partitions. Depending on the simulation parameters, virtual *Faces* could be inserted and can be represented in the analytical model either as adiabatic or diathermic.

More generally, architecture is often characterized by degrees of spatial partitioning and connectedness. How can these different and sometimes ambiguous architectural concepts of space be represented with topology? Topology provides a formal way to represent connectedness, but when applied to architecture, it requires the user to choose what is being connected.

If two adjacent regions have exactly the same contents with the same behaviour and are so intimately connected that there is no effective barrier between them, then perhaps they should be considered as a single region. So, the ultimate form of connectedness is the unification of two adjacent regions into a single region or *Cell*. Therefore, a *Cell* is more than just a continuous 3D region. It also implies that what is contained represents a level of homogeneity, which has appropriate meaning within the application domain.

If *Cells* represent spaces and *Faces* represent walls (or partitions) then operations which add or remove the *Faces* of *Cells* within a *CellComplex* can radically change the topology. The result of a modelling operation to an existing topological construct may change the 'type' of that construct. The advantage of Topology is that it tells the architectural users exactly what has been modelled in terms of partitioning and connectedness and the type of the result [Fig. 12].

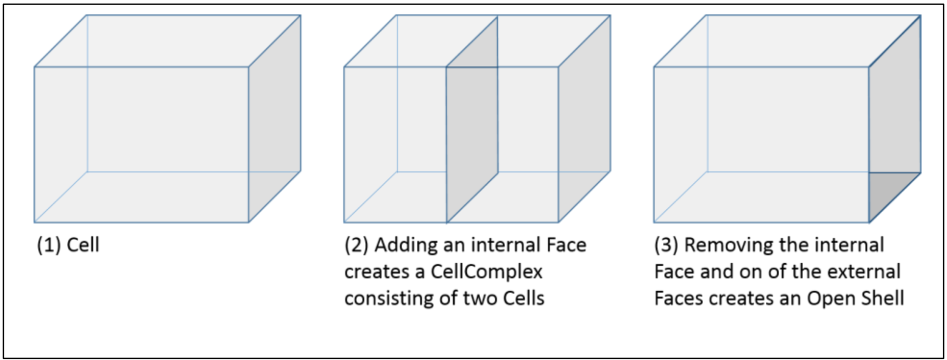


Fig. 12 Editing operations to add or remove topological components can have a radical affect, including changing the type of topological construct.

The general conclusion is that, where possible, the user should define a single canonical non-manifold topology model describing the maximal partitioning of space. Different subdivisions may be combined to represent the spaces required for different activities. Different dual graphs can be constructed as required by different analysis and simulation applications [Fig. 13].

5 Applying topology in Analysis, Simulation and Fabrication

Vitruvius distinguished between the practical aspects of the architecture (*fabrica*) and its rational and theoretical foundation (*ratiocination*) (Pont 2005). Establishing topological relationships was found to be an essential component of the setting out of the conceptual principles of a design project (Jabi et al. 2017). Non-manifold topology was also found to be a consistent representation of entities that can be thought of as loci, axes, spaces, voids, or containers of other material.

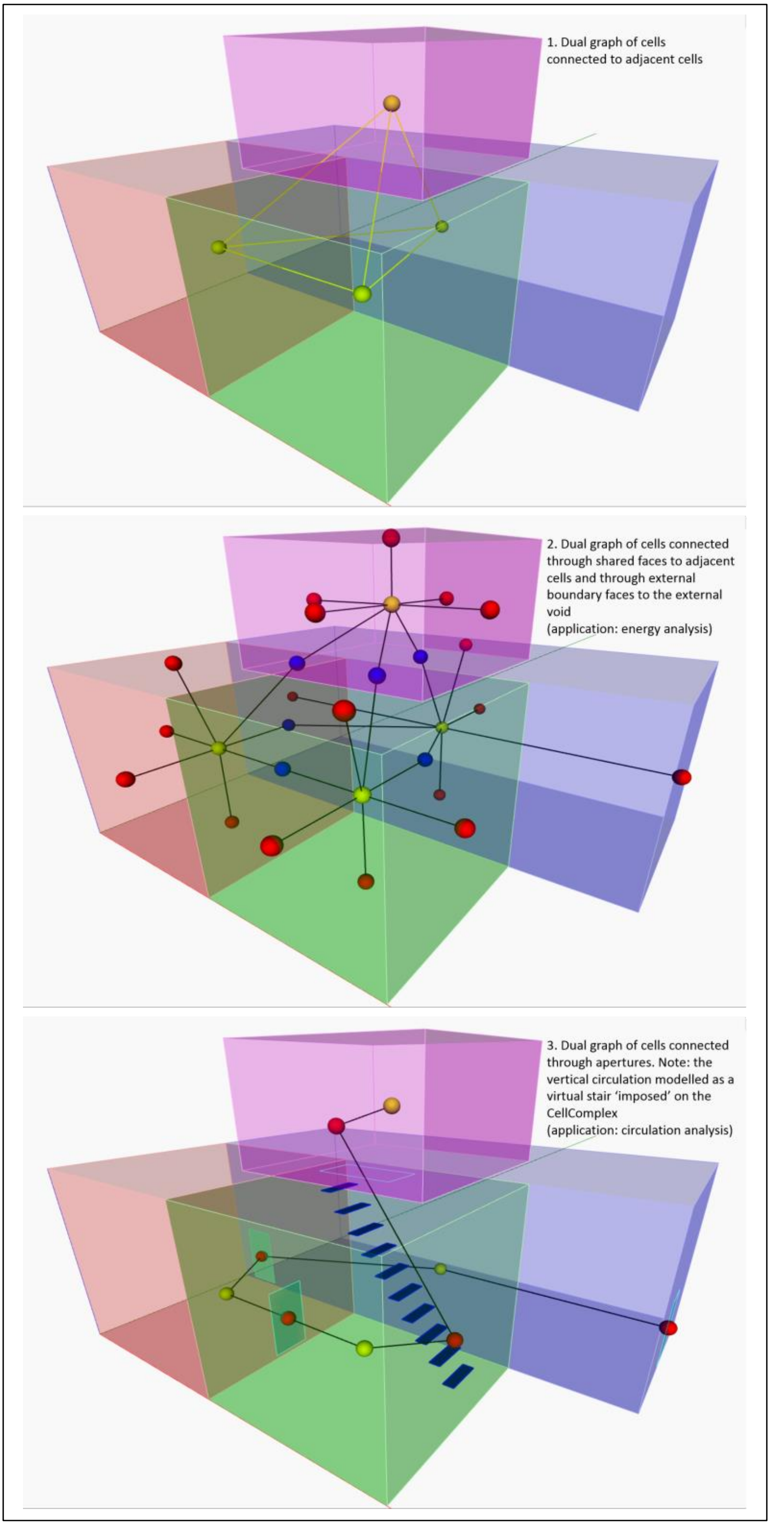


Fig. 13 Dual graphs can be constructed which describe alternative connectivity of the Cells representing architectural spaces and used as different analytical models.

This concept was previously explored by the authors in the context of energy analysis, façade design, and additive manufacturing of conformal cellular structures (Jabi 2016; Fagerström, Verboon, and Aish 2014; Jabi et al. 2017).

5.1 Energy Analysis

A proof of concept implementation of non-manifold topology for energy analysis allowed the user to create simple regular manifold polyhedral geometries and then segment them with planes and other geometries to create a non-manifold *CellComplex* (Chatzivasileiadi, Lannon, et al. 2018; Wardhana et al. 2018). The tool can create complex geometry that produces outputs that are highly compatible with the input requirements for energy analysis software. *Cells* within the *CellComplex* are converted to spaces with surfaces, and bespoke glazing sub-surfaces, and set to their own thermal zones.

5.2 Digital Fabrication

A proof of concept implementation of non-manifold topology for digital fabrication allowed a *CellComplex* to be conformed to a NURBS-based design envelope (Jabi et al. 2017).The resulting model used topological and geometric queries amongst adjacent *Cells* to create rules for depositing material. These query results were used to identify boundary conditions and to deposit material only where needed. This improved the material efficiency and resulted in a higher mechanical and structural profile for the 3D printed model.

6 Conclusions

New design technologies often emerge in response to the limitations of existing technologies and have the potential to benefit the architectural design process. Understandably, the founding concepts and terminology may be unfamiliar to architectural practitioners which may inhibit adoption of these technologies.

The challenge in developing Topologic has been to maintain the theoretically consistent use of topological concepts and terminology, yet relate these to the more ambiguous concepts of space and ‘connectedness’ found in architecture. The application of topology as a direct link between architectural conceptual modelling and relevant analysis applications is becoming established. A more challenging task is to explore how topology can contribute to the way in which architecture as the ‘enclosure of space’ can be conceptualised.

7 Acknowledgments

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