

# Spatial Information Modeling of Buildings using Non-Manifold Topology with ASM and DesignScript

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**Abstract.** *Much of the discourse in architectural geometry has focused on the geometric design and physical optimisation of the material ‘Building Model’, specifically the building structure and envelope, and the digital fabrication of facades. In this paper we want to “go behind the façade” and consider architecture not so much as a physical building model, but at a more abstract level, as the ‘enclosure of space’. The intent is to explore related geometric and topological concepts which can be the foundation of appropriate computational design tools. The objective of these tools is to support the design of a ‘spatial’ architecture and the use of the spatial analysis of building models in related engineering design processes. To achieve this we are using the concept of non-manifold topology implemented in ASM (the Autodesk Shape Manager), but in a novel way. In this approach the interior of what would normally be referred to as a ‘solid body’ is not thought of as being composed of solid material, but rather as an enclosed void that can be used in an architectural sense to represent the ‘enclosure of space’.*

## 1 Introduction

Architecture has been described as the ‘enclosure of space’. Indeed most buildings are conceived in two ways:

- as a 3D geometric envelope (that separates the outside from the inside)
- *and* the partitioning of the enclosed space into constituent spaces (or rooms)

We might call this a ‘spatial’ or idealized model of the building. Most conventional ‘Building Information Modeling’ applications adopt a different approach, by providing design tools which support the placement and editing of components (such as walls, floors, columns and beams, etc.) that represent the material aspects of the building. We might call this a material or physical model of the building.

It is of course recognized that at the end of an architectural design process the design, engineering and construction teams should have produced a complete unambiguous ‘building information model’.

However during an exploratory design process it is important that the architects and engineers can build the lightest possible model using the least effort that gives the most accurate feedback about their design and engineering concepts.

Our contention is that a modeling process that combines spatial modeling (via non-manifold topology) and associative parametric modeling (via scripting) can facilitate this “light weight – least effort – maximum feedback” design methodology.

It is envisage that the resulting spatial information model (and associated topological queries) can be used for:

- early structural analysis, using such tools as Robot Structural Analysis
- early design energy analysis using tools such as Green Building Studio
- fire analysis (using CFD)
- egress analysis

as well as the topological and geometric support model for the material model of the building (see Fig. 1 (left)).

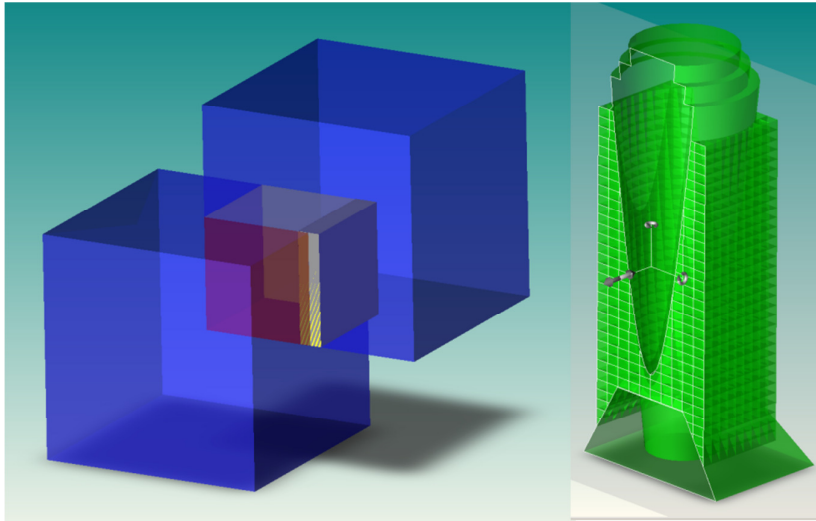


Figure 1(left): A single non-manifold solid, consisting of three cells constructed by the non-regular union of two (blue) cubes. One of the faces of the inner (red) cell has been used as the supporting geometry for a wall component (yellow).

Figure 1(right): A spatial information model built with ASM. This is a cut-away model and illustrates a number of non-regular modeling operations that are unique to non-manifold topology. The initial solid was ‘sliced’ horizontally with floor planes and then vertically (with wall planes in X and Y). Finally a conical solid representing the atrium was ‘imposed’. The resulting cellular topology structure can be interrogated with topological query functions.

To realise this concept, we have implemented a set of special non-regular Boolean operations to create non-manifold bodies and a series of topological classes to allow the designer to access the topology of the resulting spatial models. Topological query functions are provided to allow the designer to make a traversal of the spatial model of the building.

For a given building we can distinguish between the spatial model, different analytical models and the material model of the building:

- The spatial model of the building is the partitioning of the building envelope into discrete cells representing the interior spaces or rooms.
- The material model of the building is the collection of physical components that will make up the constructed, tangible building. The material model might use the topology of the spatial model (for example, the cells, faces, edges and vertices) as supporting geometry for the individual solid models presenting these typical physical building components.
- There can be a number of different analytical models of the building (for example, for structure or for building performance).

Our proposal is that the different analytical models can be derived by attributing the spatial model and without the need to build a material building model. Indeed the material model should only be built after the analytical models have served their purpose in the design process.

In this process the topological and geometric modelling functionality is combined with the DesignScript associative modelling language. Spatial Information Modeling and parametric/associative modeling work well together and allow the designer to experiment with 'what-if' scenarios. Changes to the spatial model can automatically update any downstream engineering analysis (such as Green Building Studio) and the dependent material model.

## 2 Manifold and Non-manifold solids

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 a 3D manifold body each edge represents the meeting of exactly two faces, so that everywhere where faces join there is always solid material on one side of the boundary and a void on the other side.

The boundary of a body does not have to be connected - a body can have several disjoint pieces of boundary, as long as each connected piece of the boundary is closed. This means a single body can contain disjoint volumes of material, and a single volume can have one or more interior voids, where each is defined by a closed boundary with material on one side and an interior 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.

### 3 Regular and Non-regular Boolean Operations

One way to construct non-manifold bodies is by using non-regular Boolean operations. When Boolean operations are used to create a new body from a number of input bodies, these inputs are often configured so that all or part of one input body intersects with the other input body, see Figure 1(a).

Generally with *regular boolean operations*, external faces of the input bodies that are within the resulting body are removed.

Generally with *non-regular boolean operations*, external faces of the input bodies that are within the resulting body are retained

	union	intersection	difference	impose	imprint	slice
regular inputs						
regular operations				N/A		
non-regular operations		N/A	N/A			

Figure 2: The result of different regular or non-regular operations with manifold inputs. Note: some operations (union and intersection) are symmetric, while other operations (difference, impose) are asymmetric. With asymmetric operation there is the convention that one input is referred to as the ‘part’ (A), the other input is referred to as the ‘tool’ (B).

We can compare:

- *Regular union* operation (where all external faces of the input bodies within the output body are removed)
- *Non-regular union* operation (where all external faces of the input bodies within the output body are retained [for example, in Figure 1 (left), generating three cells])
- *Non-regular impose* operation (literally ‘impose the tool on the part’), so that the internal faces within the output body that are derived from the ‘tool’ input remain, but the internal faces within the output body that are derived from the ‘part’ are removed [in this example, generating two cells])

Note:

- There is no regular *impose* operation, because all regular operations remove the external faces of the tool from the interior of the resulting body.
- There are no non-regular *intersection* or *difference* operations, because with these operations there are no external faces of the input (tool) body within the interior of the resulting body.

Figure 1(right) showed a practical example of applying multiple non-regular Boolean operations. In this example there were multiple ‘slice’ operations using planes in different X, Y and Z directions, followed by an ‘impose’ operation. This illustrates that even if the modeling process starts with manifold bodies, the results (after the first non-regular operation) will be a non-manifold body.

Therefore, subsequent non-regular operations will use non-manifold bodies as input, as follows:

	union	intersection	difference	impose	imprint	slice
non-regular inputs						
regular operations				N/A		
non-regular operations		N/A	N/A			

Figure 3: The result of regular or non-regular Boolean operations with non-manifold inputs

## 4 Topology Classes Implemented

The following classes have been implemented:

- Shell: A connected set of Faces in a manifold solid. A solid with a hollow void inside it has two Shells, one external Shell and another internal Shell.
- Cell: A closed, continuous volume enclosing a spatial partition in a non-manifold solid.
- Face: A face can be an interior-exterior face with material on one side and a void on the other, or it can be a double-sided interior face or a double-sided exterior face.
- Edge: There can be internal edges in a non-manifold model.
- Vertex: There can be internal vertices in a non-manifold model.

With the range of manifold and non-manifold classes and the range of regular and non-regular Boolean operations, the designer is able to create manifold and non-manifold solid models. By exposing the properties of geometry and topology classes to the designer, he is able to make his own topological queries. These queries can be used to build a number of different spatial information models.

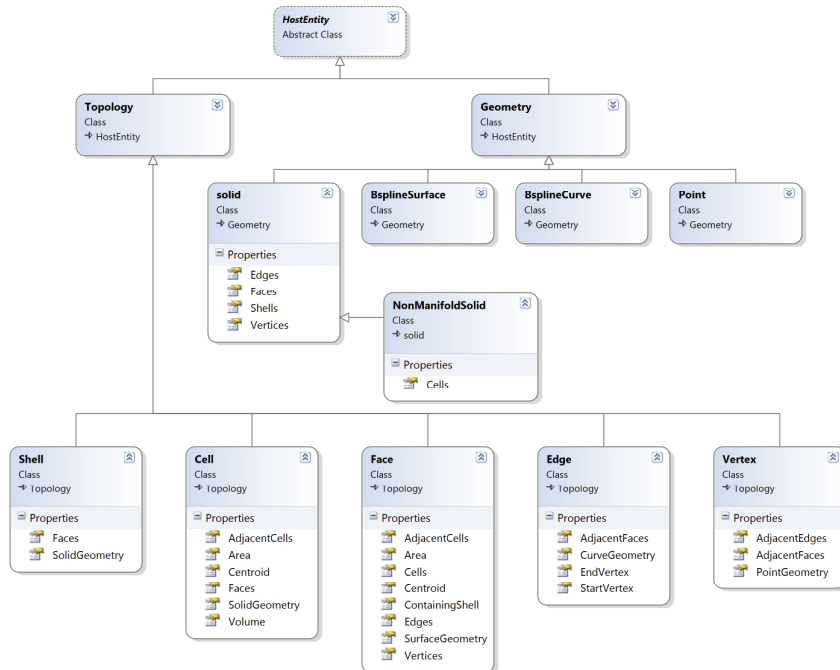


Figure 4: The DesignScript geometry and topology classes, with their properties

## 5 Using a non-manifold spatial model to create alternative analytical and material building models

The spatial model of a building and the analytical or material models of the building are interrelated. The spatial model consists of cells, faces and edges:

- Cells can represent the enclosed spaces or rooms of the building
- Faces can be used as the supporting geometry for “area” based material components (walls, floors, roofs, etc.)
- Edges can be used as the supporting geometry for “curvilinear” based material components, for example structural members (columns, beams)
- Vertices can be used as the location of “point” based connectors

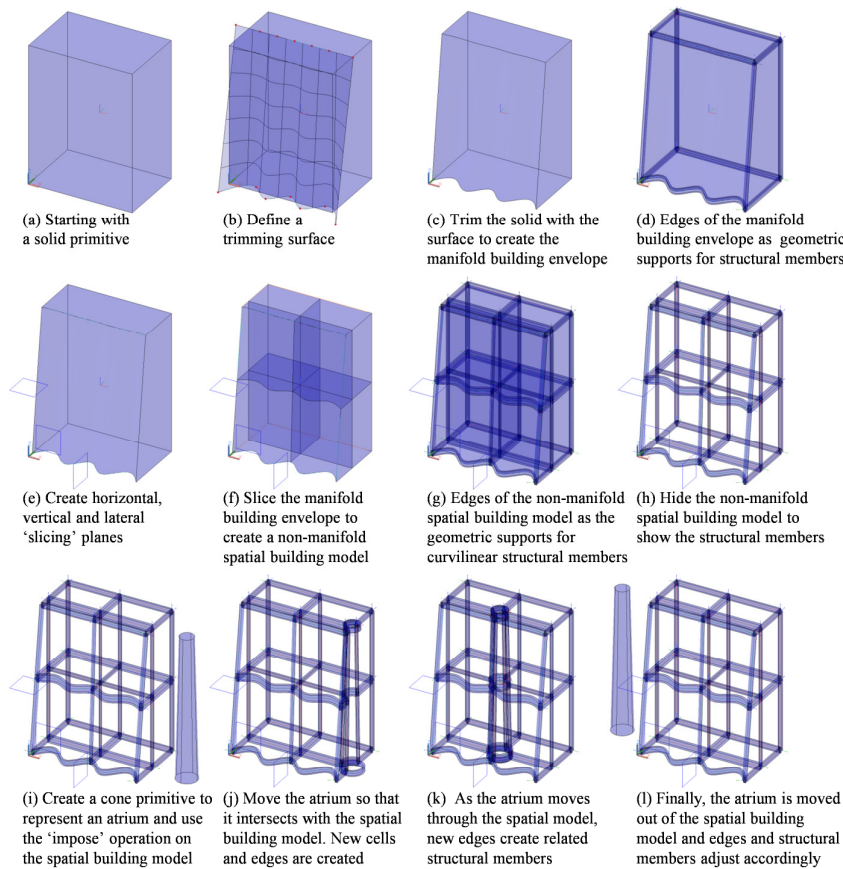


Figure 5: The modelling sequence to construct a non-manifold spatial model of a building and the use of the edges of this model to construct a structural model.

### 5.1 Building a structural model from a non-manifold spatial model

A spatial non-manifold model of the building can be used to:

- extract horizontal edges to define beams
- extract vertical edges to define columns
- extract exterior faces to define roof elements
- extract interior horizontal faces to define floors (slabs)
- extract exterior vertical faces to define exterior walls and facades
- extract interior vertical faces to define interior walls and partitions

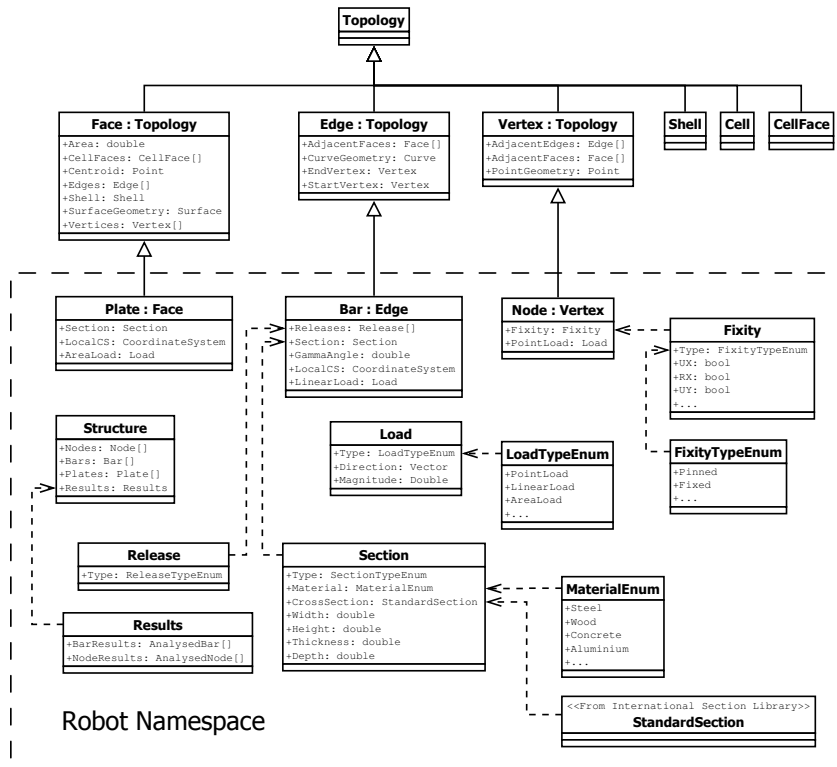


Figure 6: Class hierarchy showing the use of topological super classes (face, edge and vertex) in relation to the sub classes (Plate, Bar and Node) within the Robot namespace.

By using the number and type of faces associated with each edge it is possible to determine the position of each edge within the spatial model and to populate different types of edges with an appropriate type of structural component.



The following rules may be applied [and have been encoded in DesignScript]:

- an edge defined only by external faces implies that the edge is at an external position, typically at a corner of the building
- an edge defined by a combination of external and internal faces, typically implies an edge at an external mid-facade position
- edges defined by internal faces implies an edge within an internal region

## 5.2 The use of the spatial information model for energy analysis

Here the key topological elements are the cell and the faces that bound each cell. In this application each topological element is given additional attributes to provide a complete data model for an energy analysis (see the Green Building Studio namespace, Figure 7). Here the space class can be derived from the topological cell class and a surface class can be derived from a topological face class.

The topological analysis defines which faces are external or are internal and between cells, and therefore which cells are adjacent. In terms of energy modelling this enables the different conditions in adjacent spaces and the resultant energy flows through common surfaces to be directly modelled.

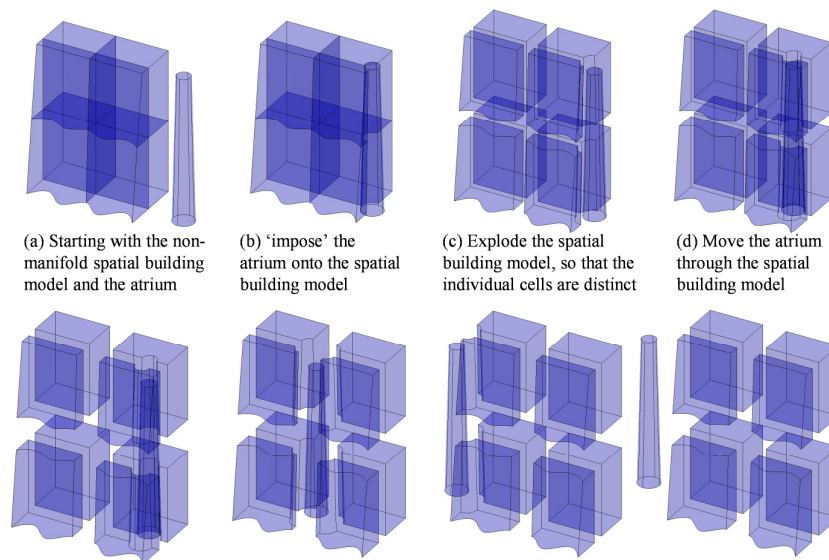


Figure 7: The modelling sequence to construct a non-manifold spatial model of a building. The cells within this model can be used to construct volumetric and spatial adjacency data suitable for input into energy analysis applications.

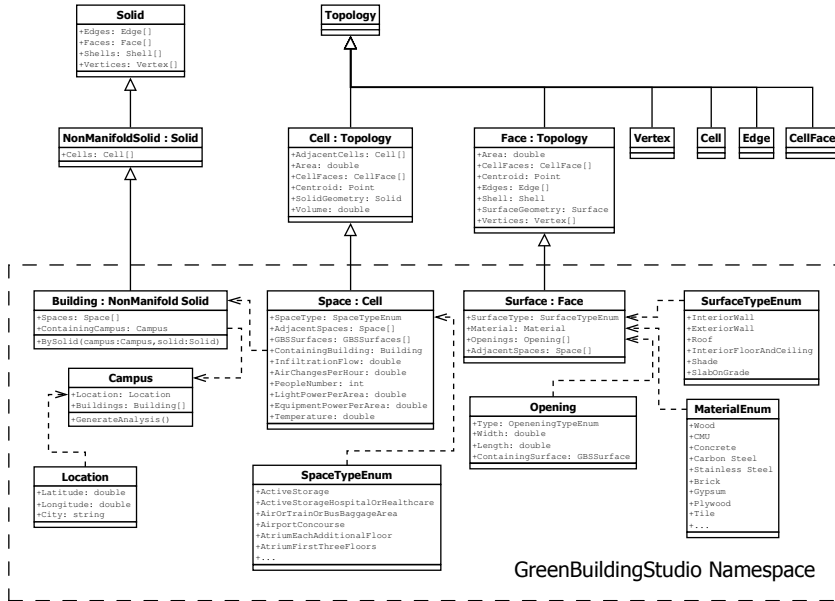


Figure 8: Class hierarchy showing the use of topological super classes (cell and face) in relation to the sub classes (space and surface) within the Green Building studio namespace.

Additionally it is possible to use the topological relations to traverse the spatial building model. Starting in one space, it is possible to inspect the constituent surfaces property, and for each surface inspect its adjacent spaces property. Such a traversal would ignore spaces and faces previously visited.

The notional thickness of the faces multiplied by the face area can be used to factor the cell volume, to arrive at a reasonably accurate volumetric data without the need for a precise building model. Certainly this volumetric data will be within an acceptable tolerance when compared with the accuracy of the other data involved.

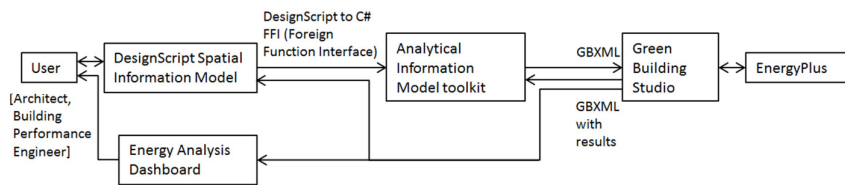


Figure 9: Using the AIM (analytical information modeling) toolkit, this cellular and face data can be exported as GBXML to Green Building Studio, with the resulting energy analysis either returned for display within DesignScript or via other energy analysis dashboards.

## 6 Integration with DesignScript:

In this research, we are exploring the combination of non-manifold topology and scripted parametric design tools and related work flows.

We see possibilities for designing that may not have existed before in which a single spatial and topological model can be used to drive multiple analytical models, and then a unified material model (Figure 10).

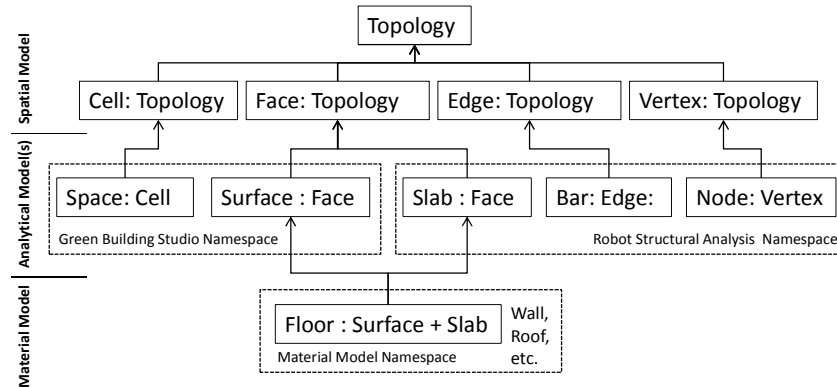


Figure 10: The three level modelling approach:

- (1) a spatial model using topology
- (2) a number of different (discipline specific) analytical models
- (3) a unified material model, where some material components (for example, a floor) are essentially multi-functional and combine information and behaviour for multiple analytical models. Multi-functional components can be implemented in DesignScript via multiple inheritance.

One of the characteristics of the modelling process presented here is that a minor change to the modeling of the initial building volumetric geometry can have a profound effect on the resulting topological model. Cells (and the cells' faces and edges) can appear, disappear and reappear. Additionally faces and edges may be split or combined.

It is difficult to see how a modeling tool that relied on the user manually building an analytical or material model could work. Each time a change is made to the volumetric model, a new topology would be created and previous analytical and material models would be completely out of date.

A better way to connect the topology of the spatial model to the analytical and material models is through a rule based script. This can provide a robust connection which can appropriately respond to the appearance, disappearance and reappearance of topology and its related geometry.

Additionally, DesignScript supports the use of multiple inheritance to directly represent the essential multi-functional behaviour of components in the material model: in this example, representing both structural and building performance.

Overall, this approach combines and unifies topology and geometry, with different analysis and simulation tools, and with scripting tools which supports advanced features such as associative and imperative programming and multiple-inheritance. It is anticipated that this unified toolset can provide the necessary infrastructure for multi-criteria design optimisation<sup>2</sup>.

## Conclusions

This paper presents a novel application of non-manifold topology together with parametric and associative scripting to model the spatial organization of a building and to use this information to create different analytical and material models of a building.

The core of the DesignScript system is a set of unified geometry and topology classes that can be driven through a number of different programming paradigms. Without the ability to manipulate such spatial models parametrically and programatically it is doubtful whether a user could “handcraft” such complex geometry using interactive direct manipulation techniques or could systematically explore alternative configurations and options. This supports our contention that a modeling process that combines spatial modeling (via non-manifold topology) and associative parametric modelling (via end-user scripting) can facilitate a “light weight – least effort – maximum feedback” design methodology.

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