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Linking design and simulation using non-manifold topology

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ABSTRACT
The aim of this paper is to propose a different method to design buildings by using and enhancing a representational technique called non-manifold topology (NMT). The methodology already exists but is ignored by current building information modelling (BIM) software in favour of a component-based approach. While the topological information embedded within NMT has many uses in the spatial representation of architecture, including building occupancy analysis and structural analysis, the focus in this paper is on the efficacy of NMT in linking design and building performance simulation (BPS). The proposed approach avoids the process of simplifying models produced by BIM software to conduct BPS. In particular, NMT allows for a clear segmentation of a building, unambiguous space boundaries, and perfectly matched surfaces and glazing sub-surfaces. The NMT approach was tested through a software prototype that integrates 3D modelling software and an energy simulation engine.

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Early design stage; 3D modelling; non-manifold topology; building performance simulation

Introduction

Traditionally, building information modelling (BIM) systems used in architectural design only represent the physical or material aspects of buildings as 'domain specific' assemblies such as walls, floors and columns. These entities can have associated properties such as weight and cost. Solid models are the most prevalent representation of the three-dimensional aspects of buildings (Attia et al. 2011). Most solid models use manifold topology to represent boundaries that separate the external void and the internal enclosed volume. Systems that use manifold topologies struggle with the notion of space in architecture as a void that exists in-between and is enclosed by the aforementioned solids (Maile et al. 2013). Early research into BIM included abstract notions of space (Chang and Woodbury 1997) as well as 'product modelling' (PDES/STEP) (Eastman and Siabiris 1995) and boundary representations of space (Björk 1992). This 'enclosure of space' is the unique and defining property of architecture. Architects and critics often discuss the hierarchy, organization and qualities of space within a building (Curtis 1996). Yet, modern BIM systems are largely unable to describe precisely the spatial enclosure and organization of a building as a series of hierarchically connected or divided spaces. With BIM systems, architects can only evaluate the spaces within the building after they have gone to considerable effort to model the complete building fabric as an assembly of physical components (Ellis, Torcellini, and Crawley 2008).

Building geometry for building performance simulation

Engineers are becoming increasingly reliant on the use of BIM to extract the needed information for their simulations (Bazjanac 2008). Many architects are adopting BIM as a central database and workflow for documenting and sharing the geometry of the design project among other attributes and almost 50% of the industry is now using BIM (Young et al. 2009). While BIM provides many well-documented advantages, it tends to create complexity and errors. BIM models created by architects may fit an architect's view of the project, but are not necessarily structured for building performance simulation (BPS) (Maile et al. 2013). Energy BPS software such as EnergyPlus requires an abstracted and simplified 3D input model consisting of zero-thickness boundaries that represent walls or partitions between thermal zones. In contrast, BIM models strive to include as much detail as possible; most of it might not be relevant to BPS and in worst cases might be misinterpreted and misused by BPS software rather than ignored. These extraneous details would need to be stripped away and the model simplified and re-configured to fit the input requirements of energy analysis software.

Software, such as ECOTECT® (Roberts, Andrew, and Marsh 2001) and DesignBuilder® (Wasilowski and Reinhart 2009), combine energy modelling with simple architectural modelling for use by architects. They rely on a dual approach to creating geometry definitions for BPS: (1) the import of data using standard formats such as industry foundation classes (IFC) and gbxml and (2) user delineation and modification of thermal zones and geometry based on the underlying CAD drawings and models. Ellis, Torcellini, and Crawley (2008) state that it is difficult to convert traditional CAD and BIM models to thermal ones. It is considered difficult to derive an energy model from a fully detailed BIM model due to a lack of time and skill resources while automatic derivation of the data faces challenges in identifying and simplifying important geometry. Their alternative approach is to develop both the architectural model and the energy model simultaneously with every geometric element explicitly assigned to either

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of the two models or shared by them if appropriate. However, their software uses the modelling capabilities of SketchUp® that rely on traditional polyhedral manifold modelling that can be susceptible to user error in aligning spaces and matching surfaces. Jakubiec and Reinhart (2011) report that these issues have divided the building simulation community because while BIM strives for a single model, there are advantages for a hybrid approach that combines several models for several types of analyses. Their DIVA software uses the manifold polyhedral and non-uniform rational basis splines (NURBS) based modelling capabilities of the Rhino software to build detailed models for daylight analysis. For energy analysis, however, DIVA requires users to "construct a simple perimeter one-zone volume for energy analysis based on the existing detailed architectural geometry." The limitations of this approach are similar to that of Ellis et al. in that users are asked to simplify a detailed model after the fact using methods that could lead to errors in modelling and thus to inaccuracies in simulation results.

None of the above approaches asks the user to think topologically about their design because they assume the design has already been decided and the methods for creating it are fixed. Pratt et al. (2012) attempt to address this issue by specifying modelling protocols that designers should follow to ensure that CAD models can be easily translated into thermal ones. Their approach, however, caters to the lowest-common denominator in CAD software. They only require modelling software to support "surface geometry that can be described with vertices defined by spatial coordinates." Their protocol identifies the correct needs (e.g. surfaces that bound a space must create a complete polyhedron), but they place that responsibility on the user if the translation software cannot detect and automatically cap incomplete polyhedral geometry.

An interesting approach is proposed by Smith, Bernhardt, and Jezyk (2011) whereby a simple BIM model is sliced into floors by the designer. The thermal zones, glazing and surface assignments are created automatically by the software with a limited ability to over-ride the default material assignments while the thermal zones do not appear to be modifiable. The authors claim, but do not provide evidence, that the BIM model and the energy model are kept in sync as the design evolves, but it is unclear how a more complex BIM model would continue to be correctly and automatically simplified by the software into an energy model. This approach views the energy model as a derivative of the process rather than as a topological foundation that underpins the design and its spatial organization.

Granadeiro et al. (2013) propose the use of a radically different method of design based on shape grammars to create rule-based compositions that are then integrated with energy analysis software. Similar to Pratt et al., Granadeiro et al. propose that architects follow new protocols for design that integrate design creativity and BPS requirements. However, while the use of shape grammars and rule-based systems for BPS is novel from a theoretical point of view, their use for geometry creation is cumbersome and overly restricts the creativity of designers in the early stages (Fleisher 1992). Additionally, the authors acknowledge that shape grammars' downside is the complexity of computer implementations. A more rigorous and realistic approach based on IFC is proposed by Bazjanac (2008). He advocates the use of IFC because it is the only international standard that is robust, mature, open, "intelligent" (object-oriented) and extensible. Yet, he acknowledges that populating a BIM-IFC model is not trivial and can only be done "through software". The process he puts forward

> ... starts with the population of the BIM; this is followed by model and data checks, correction of faulty information, addition of missing data, rule-based data transformation to meet data formatting needs of the simulation engine, continuous additional model and data checks, execution of simulation, and analysis of results.

Again we see a difficult process that seems to correct errors rather than propose an approach that would avoid introducing them into the process in the first place.

BPS in the early design stages

It is generally agreed that energy analysis is currently carried out too late in the design process (Ellis, Torcellini, and Crawley 2008; Attia et al. 2011; Weytjens, Macris, and Verbeeck 2012). Traditionally, engineers use simulation as a tool for code compliance and equipment sizing after the building design and form have been finalized. Many architects and clients would welcome a performance analysis of their project earlier in the design process if it were feasible, cost effective and useful so that they can discover and avoid problems earlier and create a more considered design solution (Brahme et al. 2001). In the early design stages, architects usually create representations that are distilled to include only the information necessary to progress the design. While architects often argue that these schematic designs are tentative, fluid and subject to change, there is evidence that early design decisions carry over almost intact to the final project (Eastman 2009). Thus, greater feedback needs to be given to the designer at this stage since early decisions can radically affect the performance of the final built project. Unfortunately, conducting performance analysis in the early design stages remains problematic due to several factors:

(1) The information and representations in these stages may be incomplete and insufficient to conduct a meaningful analysis.
(2) The analysis may be resource intensive (time consuming, requires high-end computing, requires expert staff) and thus expenditure and effort to provide these resources may not be justifiable at that stage.
(3) To conduct the analysis, models may need to be exported from the main design software into the analysis software and that may lead to lost information and complexity.
(4) The complexity and obscurity of the analysis engine itself may reduce its trustworthiness and use.
(5) The outputs from analysis engines may be complex, verbose, numeric and difficult to interpret by visually oriented users.
(6) Architects may decide that they have the necessary intuition or experience about the design and thus feel that performance analysis at an early stage is not necessary.

Research needs

The literature as summarized here points directly to a persistent problem and indirectly to a possible solution that has yet to be reached. Mainly, the initial creators of 3D data (architects and designers) are building 3D models using various approaches that fit their particular needs, but not those of BPS software. Additionally, the use of BPS by architects in the early design stages faces challenges and thus needs to be more fully integrated with their design process.

The literature consistently argues for the use of BPS in the early design stages pointing to its possible benefits. In these pre-BIM stages, architects generally use simple models that are more compatible with the input requirements of energy analysis (Granadeiro et al. 2013). They also strive to exert the least amount of effort and spend the least amount of time to build the simplest possible models that yield the largest insight into the project (Aish and Pratap 2013). Finally, architects assemble their design project out of simple spaces that are in proportion to each other and bounded by thin walls that do not yet have thickness while architectural detailing is usually represented in later stages (Jabi 1998) (Figure 1). It is these characteristics of architectural design in the early stages and research pointing to the importance of early decisions in later stages that prompts researchers to advocate the use of BPS in the early design stages. Based on this premise, it is then an important research need to integrate BPS in the creative design workflow. More specifically, there is a need to define an appropriate approach for creating 3D geometry that is compatible with both the designer's view of the building and the input requirements for BPS software.

Architects need a new modelling approach supported by an expanded set of tools that allow them to think more topologically about their buildings and create models that are consistent, flexible and extensible to help them meet the input requirements of various BPS engines while maintaining their design creativity and desired spatial complexity.

The remainder of the paper argues that many of the pitfalls and shortcomings of current approaches can be avoided by helping designers think topologically about their designs. A novel paradigm in 3D modelling of buildings based on non-manifold topology (NMT) is put forward as an approach to the representation of geometry definition for input to BPS in the early design stages (Hui and De Floriani 2007; Nguyen 2011; Aish and Pratap 2013). NMT is not usually used in architectural design, but has been successfully used in the medical field to model complex organic structures with multiple internal zones (Nguyen 2011; Bronson, Levine, and Whitaker 2014). Yet, its application to architecture is not far-fetched. It is possible to compare complex organic structures with multiple internal zones to complex buildings with similar multiple internal zones. This approach provides topological clarity of complex structures that has the potential to allow designers better design and simulate the performance of their buildings.

Definition of NMT

Non-manifold geometric models can be defined as combination of vertices, edges, surfaces and volumes. While this may sound similar to traditional solid geometry boundary representation, NMT allows for and consistently represents any combination of these elements while traditional boundary representation struggles with representations that combine, for example, an isolated vertex, edge, and a solid in one representation (Figure 2).

Mathematically, NMT is defined as cell-complexes that are subsets of Euclidean Space (Masuda 1993). Elements in an NMT structure are hierarchically inter-connected (Figure 3). The bottom-most element is a *vertex* (point). Vertices can exist in isolation or they can be the end-points of an *edge* (line). The similarity with traditional surface boundary representation ends here because isolated and inter-connected vertices and edges can form open and closed *loops*. Loops combine to create a *face* (surface). Faces, in turn, can combine to create *shells*, but those can also contain isolated vertices, edges and faces. Next, the concept of a *volume* is introduced which can be made out of a series

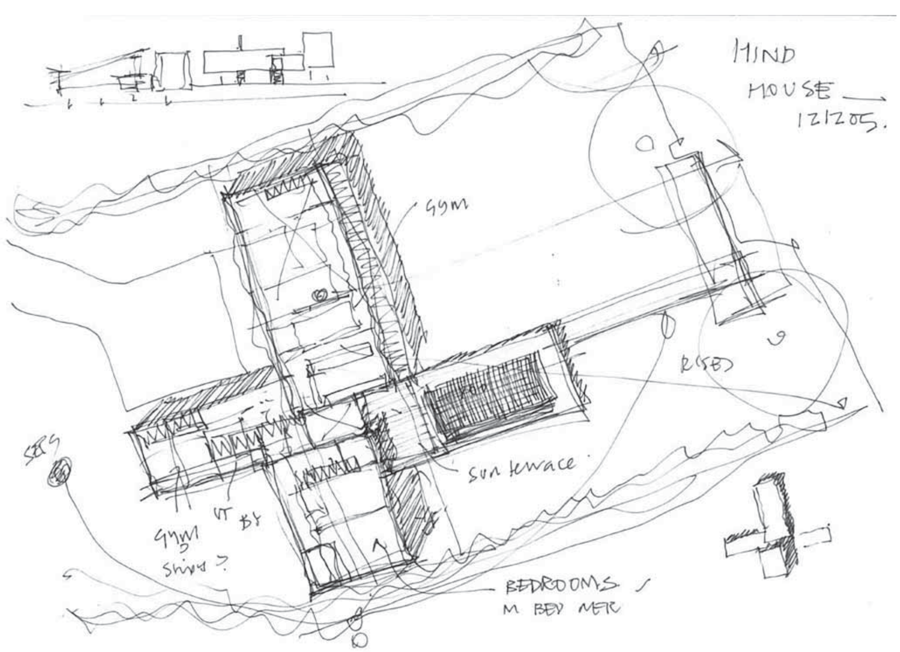

Figure 1. Hind House, sketch plan (Image courtesy of John Pardey Architects).

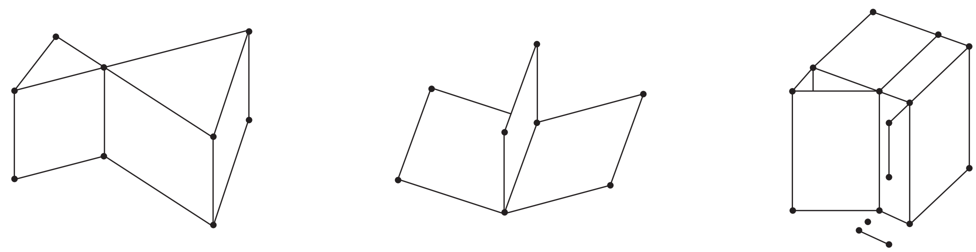

Figure 2. Examples of NMT objects.

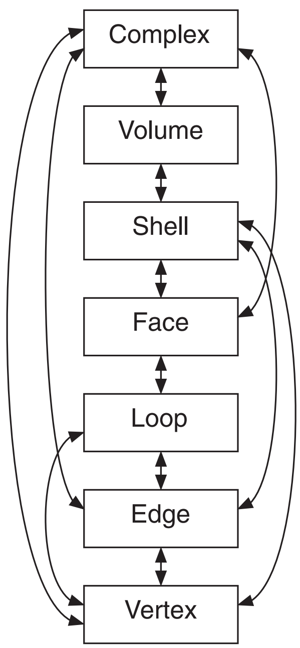

Figure 3. Hierarchical structure of non-manifold topological elements – after (Masuda 1993).

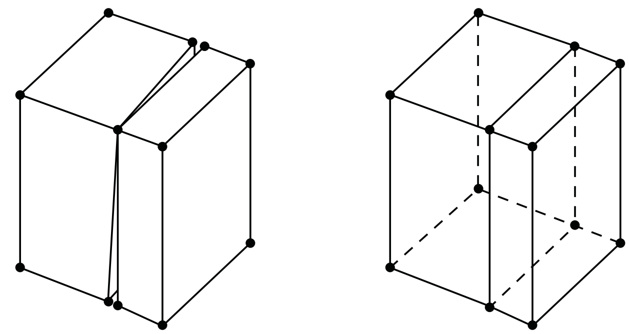

Figure 4. Illustration of possible errors in surface matching of component-based polyhedral objects vs. NMT objects.

of connected shells. Finally, the top-most element is named a *complex*. Complexes can be made out of any combination of volumes, faces, edges and vertices. These expanded data structures and topological relationships allow for a richer representation of loci, centrelines, elements, surfaces, volumes and hierarchical structures that are usually found in architectural compositions.

NMT allows for a redefined set of Boolean operations (i.e. union, subtraction and intersection) that includes the notion of *merging* and *extraction*. In traditional Boolean operations, the original operands disappear and are replaced with the resultant shape based on the chosen operation. In NMT, however, the two shapes are merged and can overlap and consistently share vertices, edges, surfaces and volumes without redundancy (Aish and Pratap 2013). In addition, because the data structure maintains all sub-objects, simple algorithms can be implemented that extract the smallest volumetric units. In the case of the implementation in this paper, an algorithm was deployed to extract the cells/spaces within an NMT object to define independent thermal zones.

One of the sources of errors in simplifying polyhedral BIM models for BPS is surface matching. In the case of adjacent spaces that share a partitioning surface, each space will have their own set of surfaces that could have been the result of an independent modelling operation. The software would then be required to reason that these two surfaces are in fact one and the same and try to match them. This is not always accurate and can lead to errors. The consistency of an NMT object means that adjacent spaces that shared a partition create surfaces that are perfectly matched (Figure 4).

Methodology

Following a critical literature review that identified knowledge gaps and research needs, the methodology followed in this paper focuses on the use of software prototyping to test the potential of NMT as an approach to modelling architectural buildings for BPS. The main methodological steps consist of: (1) Investigating appropriate software platforms and libraries, (2) Delineating design criteria for the prototype based on the literature review, (3) Building and testing the software prototype and (4) Conducting a case study to analyse the results, discover the approach's potential and limitations, and identify future work.

The use of NMT for energy analysis

This paper extends earlier work on the use of NMT for building representation (Aish and Pratap 2013; Jabi 2014). In summary, geometry with NMT represents a 3D object as a set of enclosed cells with interior partitions or exterior surfaces. Unlike regular manifold topology, a single edge can be shared by more than two surfaces and a single surface can either be a boundary between the interior of the object and the exterior world or between two cells within the object. Additionally, the topology allows cells, surface, edges and vertices to be queried as to their adjacencies. For example, a user can query the software what cell shares a surface with or sits directly above another cell because

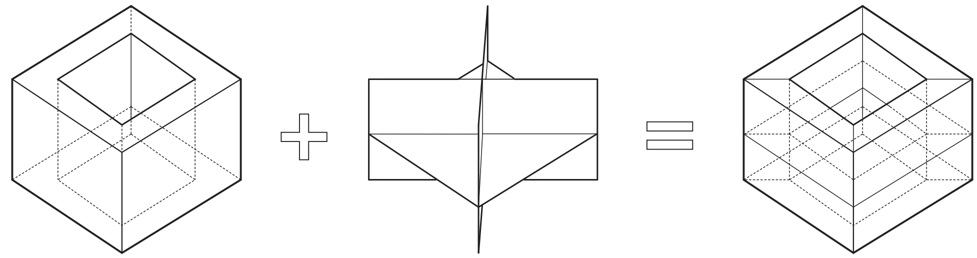

Figure 5. When a regular polyhedral geometry (left) is intersected by a series of planes (middle), a geometric shape with a NMT is created (right).

the topology establishes these types of connections. The implementation of NMT, as described below, allows the user to begin the process by creating simple massing geometries (using regular manifold polyhedral geometry) and then segments them with planes and other geometries to create a set of surface-bound cells (Figure 5). It is important to note here that the resulting geometry is not a set of separate polyhedral objects with duplicate and overlapping surfaces, but a single NMT geometry in which cells (volumes) share the same surface, edge or vertex. The custom software developed for this paper can then query and derive polyhedral cells, edges, surfaces or vertices on-demand from the NMT structure. Traditionally, this type of structure is considered a modelling mistake in most 3D CAD software because the created geometry is not a regular manifold polyhedral one, but in this case, a user can create geometry that matches well with the input requirements for energy analysis software. In such a scenario, cells are ultimately converted to spaces with heating and cooling loads, equipment, and glazing ratios and set to their own thermal zones.

3DSTEP: energy analysis for architects

3DSTEP, which is an acronym for 3ds Max® To EnergyPlus, is software that resides within a parametric 3D design software environment (Autodesk® 3ds Max®) and integrates with an industry-standard whole-building energy simulation engine (EnergyPlus) using the OpenStudio® software development kit (SDK) and the DSOS SDK (Figure 6).

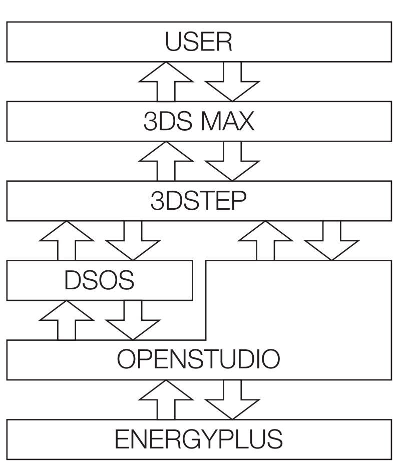

Figure 6. 3DSTEP software architecture.

Autodesk® 3ds Max® is a powerful parametric 3D modelling, rendering and animation software popular amongst architects. 3ds Max® also includes tools for daylight and artificial light simulation and analysis which makes it ideal for parametric 3D form finding and simulation in the early design phases. Using these tools, users can analyse proposed designs through qualitative photo-accurate renderings, and quantitative methods such as numeric Lux values and daylight factors (Reinhart and Breton 2009). In addition, 3ds Max® allows the extension of its capability using a scripting language, a SDK, and imported dynamically linked software libraries.

EnergyPlus is an industry-standard whole-building energy simulation programme, developed by the US Department of Energy (DOE) that allows its users to analyse the performance of a simulated building (Crawley et al. 2000).

OpenStudio® is a set of stand-alone software tools, a plugin for SketchUp®, and an open-source SDK developed by the US National Renewable Energy Laboratory (NREL) (Guglielmetti, Macumber, and Long 2011). In this paper, OpenStudio® refers mainly to the NREL's SDK that allows software developers to interface with EnergyPlus from their own software.

DSOS is a SDK that interfaces with OpenStudio® developed at the Welsh School of Architecture, Cardiff University (Jabi 2014). DSOS exposes many of the services in the OpenStudio® SDK and handles the process of constructing a building model according to the specifications of OpenStudio®. DSOS was used successfully to integrate Autodesk® DesignScript® (now Dynamo®) with EnergyPlus. This paper extends this earlier work and uses the powerful 3D modelling, rendering and animation environment found in 3ds Max® with its comprehensive and mature scripting language for both input and output.

Thus, with the addition of 3DSTEP, architects and designers can use 3ds Max® in the early design stages to model, render and animate their building in 3D, simulate its spatial and material properties, conduct lighting studies and analyse its thermal and energy use performance all within their native and familiar design software environment.

Design criteria

The development process of the 3DSTEP software included three fundamental design criteria derived from the literature review:

Compatibility with typical representations found in the early design stages

Can the designer use simple 3D massing representations and avoid over-specifying the design with information not usually available during the early design stages? This criterion was analysed based on previous published work on the types of artefacts produced by architects in the initial design stages and possible counterparts within a 3D modelling environment (Jabi 1998). In particular, this paper continues the exploration of NMT as an appropriate spatial model for energy analysis in the early design stages (Aish and Pratap 2013; Jabi 2014).

Clarity and depth of output

Can the designer easily and quickly understand the meaning of the visual output without distraction from the design process? Can the designer get more detailed and quantitative information if needed? The literature points that architects react more favourably to visual indicators rather than to numeric output from BPS software (Attia et al. 2011). This criterion was assessed through prototype software testing and various methods of presenting analysis information as discussed later in this paper.

Reasonable resource requirements

Can performance indicators be computed in a reasonable amount of time? Common sense dictates that the longer a simulation takes the less often it will be used in the design process. This criterion was measured through software instrumentation on a typical workstation. Energy use and thermal simulations are resource and time intensive and cannot be conducted in real time on a typical modern workstation. Thus, a version of the software was extended to use cloud-based high-performance computing (HPC) with the anticipation that cloud computing will be the preferred method of analysis once networks are more robust and the workflow is more streamlined.

3DSTEP workflow

Using 3DSTEP, a user specifies the location of a series of templates and files that include the building's geographic location (using a standard EnergyPlus weather file), its architectural use (e.g. standard medium-sized office building), a set of default parameters regarding its construction and material, and the desired number and configuration of thermal zones per floor. These defaults can be modified at any time to suit the building being analysed. The user starts the process by simply selecting the massing model of the building from the scene within 3ds Max®. Optionally, the user can also select a series of objects and surfaces to act as shading surfaces. The user then inserts the number of floors and an overall glazing ratio. 3DSTEP uses this information to intersect the polyhedral mass with a series of planes to create geometry with a NMT. Once the NMT is created, it is queried to retrieve its cells that are then converted into spaces (e.g. offices). Each cell is then queried for its surfaces and based on their orientation and neighbouring cells, they are categorized into one of the following types: Exterior roof, ground surface, interior ceiling partition, interior wall partition or exterior wall. This is easily accomplished due to the hierarchical character and consistency of non-manifold topologies. Additionally, glazing sub-surfaces (i.e. windows) are applied only to exterior walls. The parent surface determines the location and shape of the glazing sub-surface while the glazing ratio determines its surface area. 3DSTEP had to overcome two limitations of the OpenStudio® SDK and EnergyPlus regarding glazing sub-surfaces. The OpenStudio® SDK would usually automatically add windows to satisfy the glazing ratio. However, the SDK does not add a glazing sub-surface to any surface that is not perfectly vertical. However, since walls are not always necessarily vertical, 3DSTEP was modified to add glazing surfaces to any exterior surface that is not horizontal rather than rely on the OpenStudio® SDK for that functionality. Additionally, EnergyPlus does not allow four-sided windows to be any shape other than a perfect rectangle. That is, any non-rectangular (e.g. trapezoidal) window would cause errors. However, EnergyPlus does accept triangular windows and thus the solution was to modify the software to triangulate all window surfaces so that no window is composed of more than three points.

Once the user has completed the modelling of the building and initiated the simulation, the 3DSTEP software communicates with the OpenStudio® SDK and the DSOS SDK to build the OpenStudio® Model, and analyse it using EnergyPlus. An important feature of 3DSTEP is that it leverages the object-oriented capabilities of 3ds Max® to store the results of the analysis directly in each 3D cell as a set of custom numeric attributes. The user can select any space in the 3D scene and examine the numeric analysis results for that specific space. In addition, each 3D space is displayed with a specific colour based on the analysis results. The user can modify the lower and upper limits of the colour scale and the scene updates in real-time to reflect the new colour range. Given the animation capabilities of 3ds Max, the assigned colours as well as the numeric custom attributes can both be animated.

The requested results are retrieved from the EnergyPlus database using a standard SQL database query and displayed back in the 3ds Max® design environment automatically. The software can be configured to allow the user to specify what result to display and to visualize either a single simulation result, multiple design alternatives dynamically using the software's built-in animation capabilities, or a matrix of simultaneous alternatives for comparative analysis. For example, the user can request to visualize a single simulation of the calculated design cooling loads for thermal zones of a building with a specific glazing ratio. Alternatively, the user can ask the software to assemble a dynamically changing colour-coded animation of the same cooling loads that change due to a change in the building's glazing ratio or to a change in the building's form or location on the site. Finally, the user can configure the software to run multiple simulations and display the results in a matrix within the 3D scene for comparison. This process provides a complete generate and test cycle without the need for any data format conversions or file-based export and import and leverages the advanced 3D capabilities of the host environment for a richer and more interactive analysis of the results.

Finally, 3DSTEP maintains a time-stamped copy of the OpenStudio® Model file (.OSM) and all the EnergyPlus input and output files. The .OSM file can be opened in SketchUp® for visual verification (Figure 7). Additionally, it can also be opened in the OpenStudio® stand-alone software for further input of additional information if needed (Figure 8). The EnergyPlus input files (.idf) and the output files (.html and .sql) can also be useful for reading the information using other software.

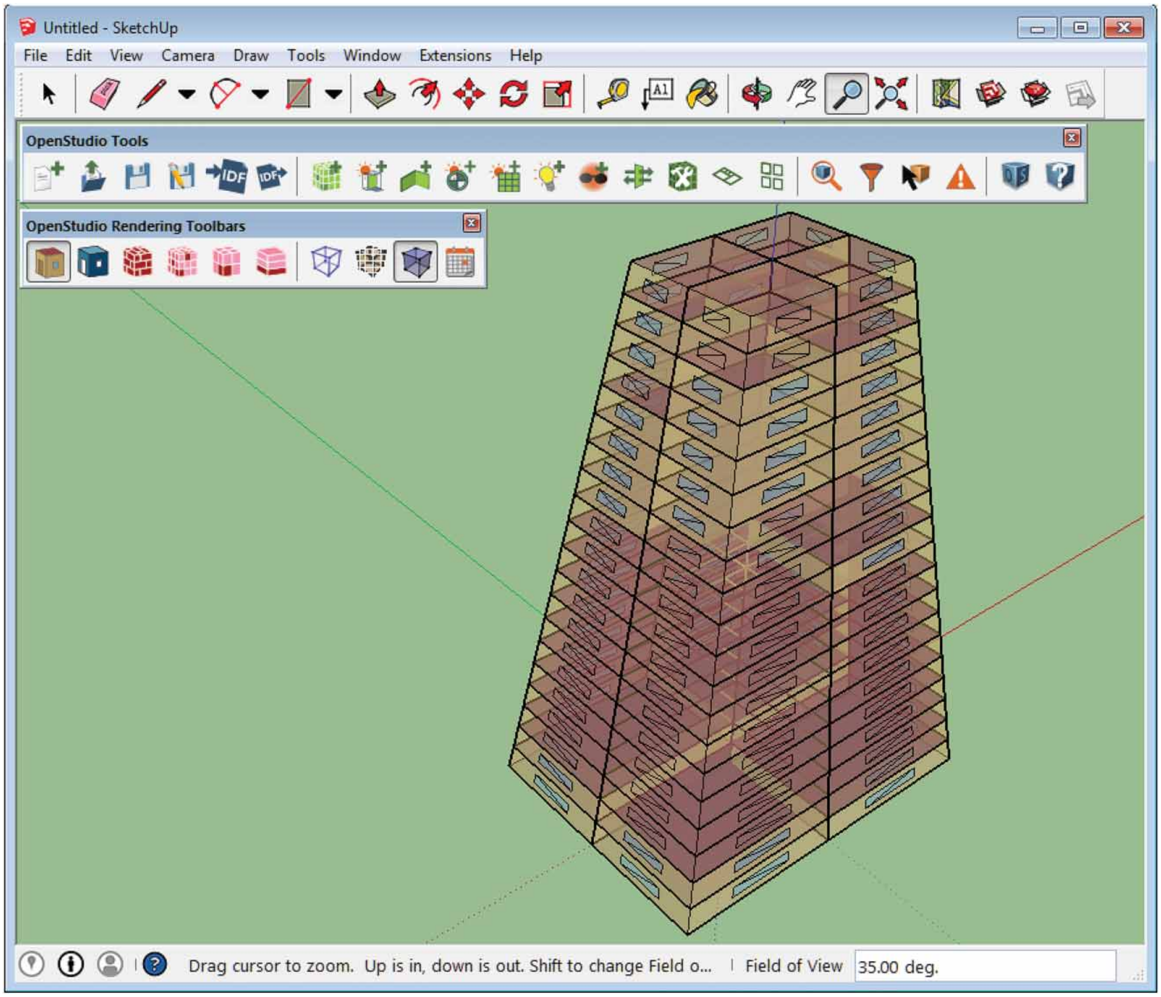

Figure 7. 3DSTEP Model displayed in SketchUp® using the OpenStudio® plugin.

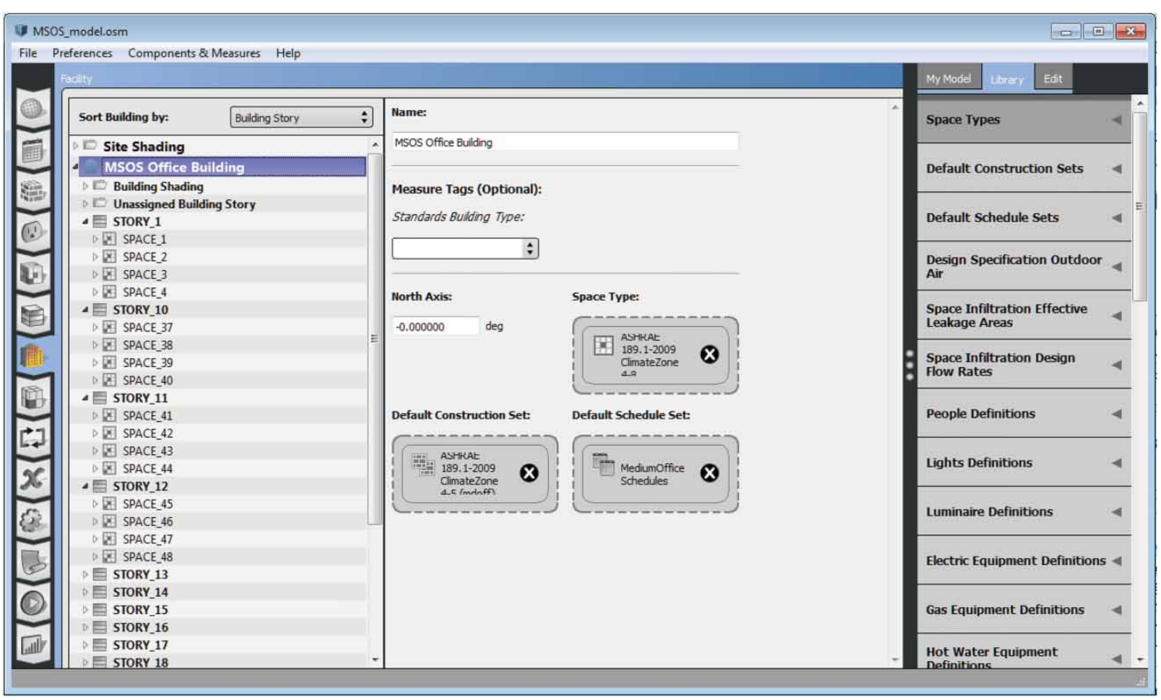

Figure 8. 3DSTEP Model displayed in the OpenStudio® stand-alone software.

Test case

In order to test the software, a simulation was run on an Apple® MacBook® Pro 13-inch laptop with a 2.5GHz Intel® Core i5 processor with 8GB of memory and an Intel® HD 4000 Graphics card with 1GB of memory. The software was run using the Parallels® emulation software (Figure 9).

A simple massing model of a tall office building was created in 3ds Max®. At its base, the building has a length of 40 m, a width of 30 m and a height of 60 m. It tapers inward to a length of 20 m and a width of 15 m at its apex (Figure 10). The office building is to be segmented into 20 floors with 4 thermal zones on each floor. The glazing ratio is specified as 0.4 (40% of the exterior wall surfaces). The office building is located in the general London area in the UK and uses the weather data file for Gatwick airport. However, any geographic location and weather file can be substituted to simulate energy performance in different parts of the world. As we will see below, the software also allows the addition of adjacent structures that can affect energy results. The building, in this case, is oriented along the four cardinal directions (A 3D arrow in the figures below points in the north direction).

Several horizontal cutting planes and two vertical planes were used to slice the basic model and convert it automatically into a single geometry with an NMT (Figure 11). The segmentation of the model to automatically create the thermal zones is user-defined and could have been done in a different manner by modifying the number, location and orientation of the cutting planes in relation to the basic model. While it was an easy and quick method to slice a massing model to create the NMT using the limited toolset in 3ds Max®, it is important to note

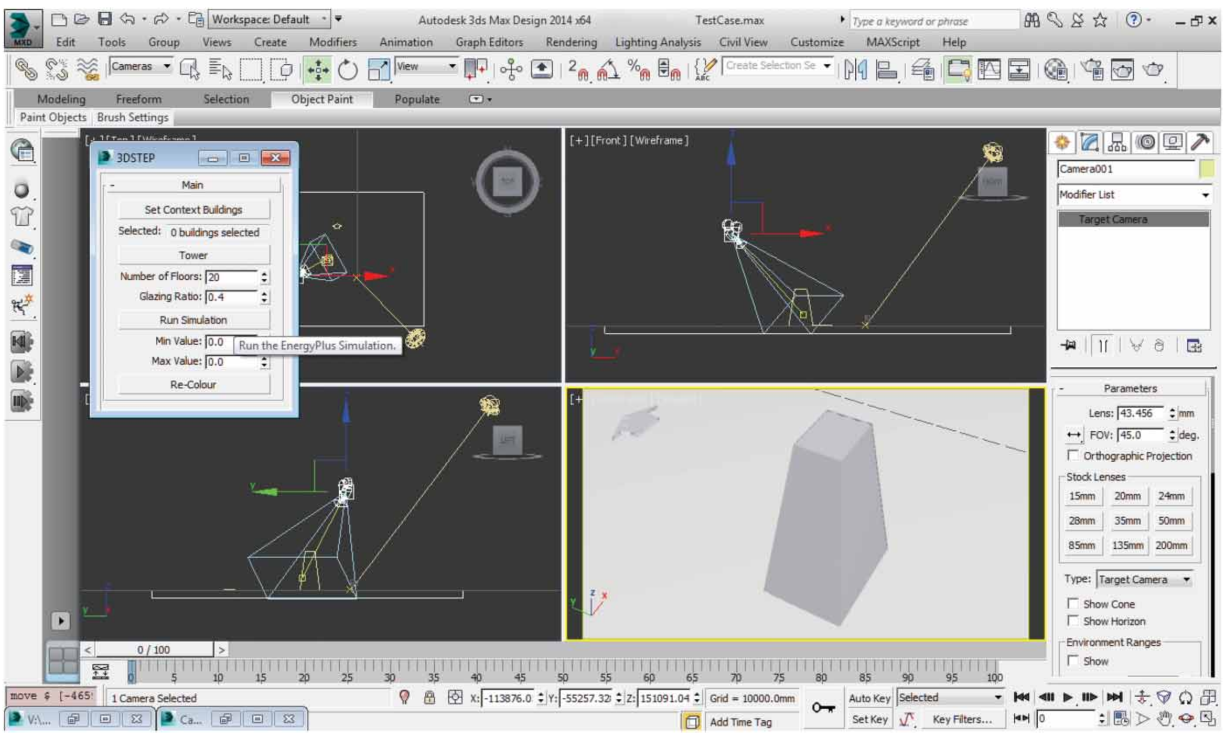

Figure 9. 3DSTEP general user interface within Autodesk® 3ds Max®.

Figure 10. 3D representation of the basic massing model of an office tower.

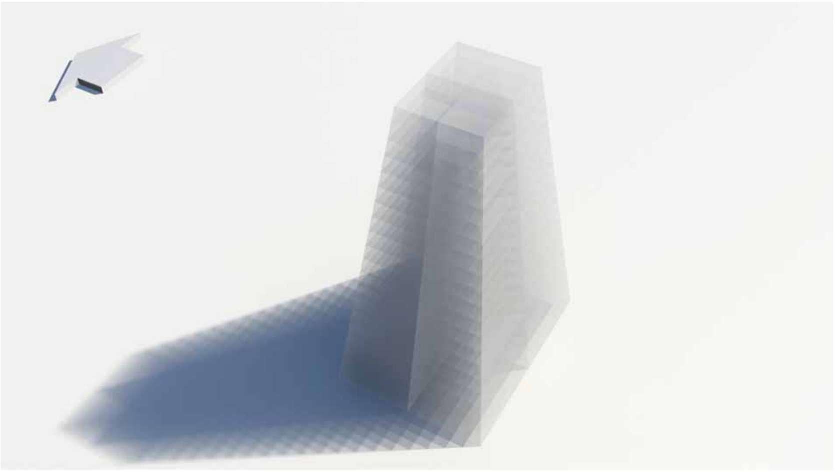

Figure 11. 3D representation of the NMT.

that this would not be the only creation method in the future. A comprehensive NMT editor should allow a rich set of tools for the creation of NMT objects. An OpenStudio® model is initialized with a template that contains all weather data, default constructions, building use, default heating and cooling loads, a thermostat set to heat at 20°C and cool at 25°C, and default air flow. All defaults are based on the ASHRAE 189.1-2009 standard for the design of high-performance green buildings. Next, each cell in the NMT is converted into an office space and assigned default people, equipment and loads. The walls of these cells are assigned a default construction set for medium office buildings. Glazing is applied to the exterior walls by copying the parent surface, scaling it down to the correct surface area, and triangulated. A default exterior fixed window construction is applied. While engineers might wish to specify all these details as they might affect the accuracy of the simulation, architects in the early design stages are far less concerned with numeric accuracy and are more interested in parametric investigations (What/If analysis) and general performance trends represented through visual indicators (Attia et al. 2011).

The difference in the modification dates of the .IDF input file (19:00:23) and the .SQL output file (19:04:57) indicates that the simulation in EnergyPlus consumed 4 min and 35 s. In that time, it simulated an office building with 20 storeys and 80 thermal zones with 320 glazing sub-surfaces. The calculated design cooling loads varied from 2211.37 W for the smallest north-facing space at the apex of the building with an area of 82.69 m^2, resulting in a calculated cooling load of 26.74 W/m^2, to 8671.66 W for the largest southwest-facing space at the base of the building with a floor area of 300 m^2, resulting in a calculated cooling load of 28.91 W/m^2 (Figure 12).

In order to test the effect of shading surfaces, two blocks representing adjacent buildings were placed on the southeast corner of the building and a new simulation was conducted.

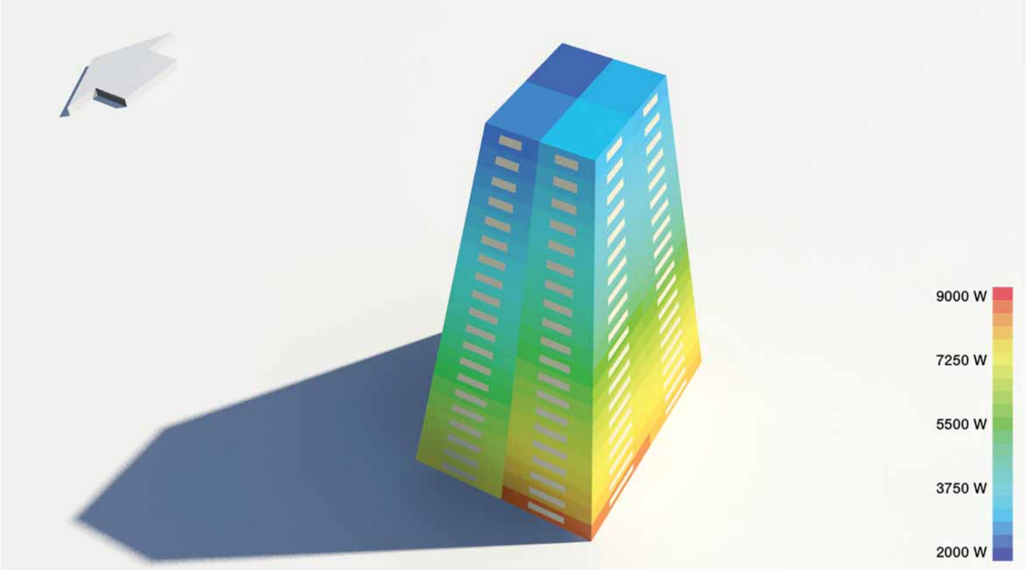

Figure 12. 3D representation of analysis results for calculated design cooling loads in Watts. Glazing ratio is 0.4.
Notes: Greyscale images might not show salient differences in values. For a more accurate rendering of the data, please consult the colour images included in the online version of this paper. In this figure, the lower (blue) values on the scale occur at the top of the building, and the higher (red) values at the bottom.

The visual effects are clearly visible in the lower southeast corner of the building where the cooling loads were reduced due to overshading (Figure 13). Without overshading, the space on the southeast corner of the ground floor (SPACE_4) had a cooling load of 8189.31 W (27.30 W/m^2). With overshading, the same space's cooling load was reduced by 12.5% to 7165.17 W (23.88 W/m^2). For visual clarity, the shading surfaces in the figure below were prevented from casting shadows. It is important to note that the inclusion and omission of shadows in all figures is purely for visual clarity and has no effect on the energy simulation itself. Yet, this points to an interesting potential: Because 3ds Max® is capable of accurate and realistic simulations of daylight and materials, one can imagine that the addition of 3DSTEP can allow a multivariate study of light and thermal performance using an integrated and multi-faceted representation. This type of presentation of analysis results could help designers better understand the inter-related issues when analysing building performance (Jakubiec and Reinhart 2011).

Finally, the software prototype allows the user to automatically run and collate several EnergyPlus simulations into an interactive and animated model. In the example below, an animation was automatically created where the glazing ratio was varied from 0 to 0.8 (Obviously, a zero or a very low-glazing ratio may not be a logical solution, but this range was chosen purely for illustrative reasons). The colour scale range was set between 1000 and 20,000 W. The 3ds Max® interface allows the user to interactively scrub (move back and forth) between the frames with colours and numbers updating in real-time. Renderings of six frames were captured for presentation here (Figure 14). In addition to the fact that cooling loads increase as the glazing ratio increases, the study illustrates that with a low-glazing ratio, the main difference in cooling loads is between south facing

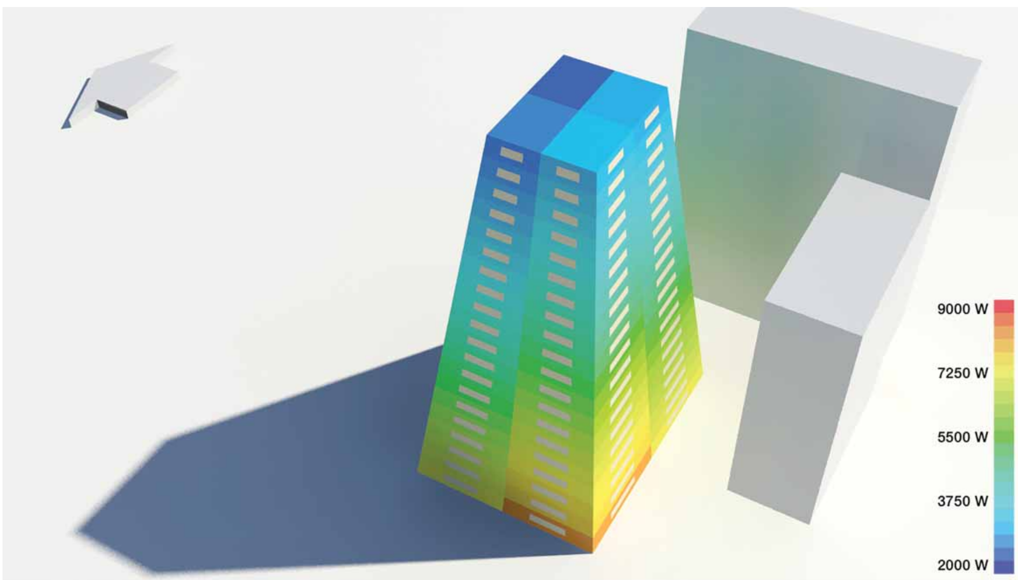

Figure 13. 3D representation of analysis results for calculated design cooling loads in Watts with overshading from neighbouring surfaces. Glazing ratio is 0.4.
Notes: Greyscale images might not show salient differences in values. For a more accurate rendering of the data, please consult the colour images included in the online version of this paper. In this figure, the lower (blue) values on the scale occur at the top of the building, and the higher (red) values at the bottom.

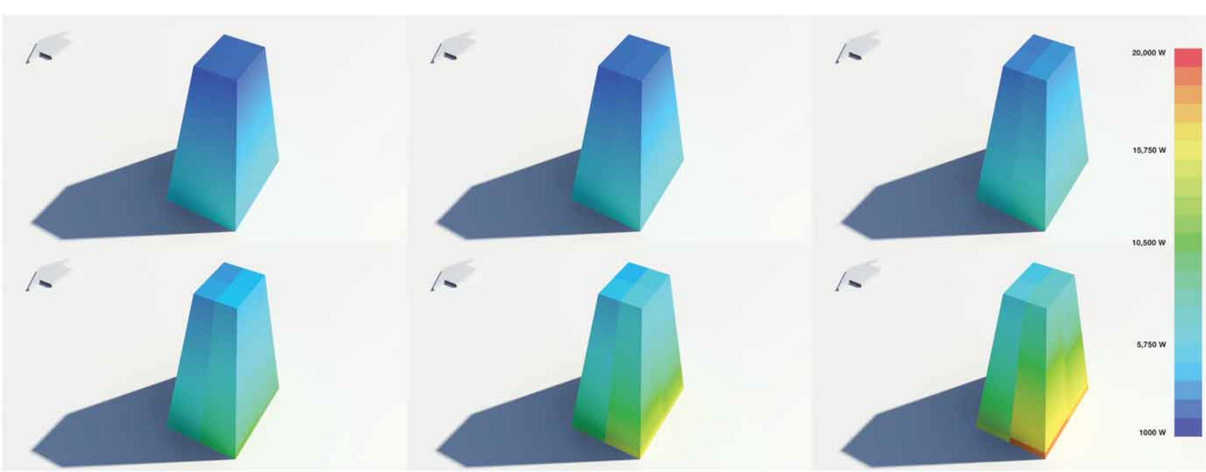

Figure 14. Six frames of an animation illustrating the effect of increasing the glazing ratio from 0 (upper left corner) to 0.8 (lower right corner) on the calculated design cooling loads.
Notes: Greyscale images might not show salient differences in values. For a more accurate rendering of the data, please consult the colour images included in the online version of this paper. In this figure, the lower (blue) values on the scale occur at the top of the building, and the higher (red) values at the bottom.

and north-facing thermal zones. As the glazing ratio increases, the differences between east facing and west facing zones and between different floors become more pronounced.

Conclusion

The current implementation uses Autodesk® 3ds Max®, OpenStudio® and EnergyPlus due to their popularity within the architectural field for 3D modelling and BPS, respectively. Other software such as Rhino® and SketchUp® do not expose any NMT functionality to the user so they could not be used. While NMT's ability to represent very complex structures in other fields has been proved, the robustness of the implemented algorithms within 3ds Max® limits the complexity of what can be modelled at present. In addition, EnergyPlus itself has limitations in the allowed complexity of the input geometry. We are currently exploring, in detail, these limitations through a Master of Architectural Science dissertation conducted by a student at the Welsh School of Architecture, Cardiff University and will publish the results in the future.

The energy performance of a building is heavily influenced by the design of its glazing surfaces. A limitation of the current implementation is that it derives the glazing sub-surfaces based solely on a desired glazing ratio and the geometry of exterior surfaces. We are currently improving the software to allow the user to design bespoke glazing sub-surfaces. The new implementation, under testing, tracks the total area of glazing sub-surfaces and updates, within the user interface, the numeric value of the glazing ratio.

While it could not be described in detail in this paper due to space limitations, a version of the 3DSTEP software has been integrated with a cloud-based version of EnergyPlus installed on a distributed HPC platform provided at the host university. Initial unpublished results indicate that this solution would be effective for conducting several simulations and for retrieving the results for later visualization in a batch process. Another option for cloud-based simulation is NREL's new initiative to offer OpenStudio® as server software on Amazon's servers and Autodesk's beta version of EnergyPlus in the cloud. Cloud-based solutions could speed up the generate/analyse cycle for larger datasets. However, the possible disadvantage in these offerings is that the workflow may depend on creating input files, uploading them, waiting for them to download, and re-importing them into the software. Any gains in speed due to high-performance computing could be lost due to a slow workflow that relies on file exchange over the network.

3DSTEP strives to be platform-agnostic. An earlier version was created for Autodesk® DesignScript® (now Dynamo®) that took advantage of that platform's ability to represent NMT. Unfortunately, the current version of Dynamo® has removed that capability, but current discussions with the development team aims to bring that functionality back. In the meantime, we are continuing our investigation into other platforms including open-source ones.

The combination of NMT and a versatile 3D software environment has the potential to provide a flexible and comprehensive solution for architects to think more topologically about their designs and investigate building performance using simple 3D massing models in the early design stages while maintaining design creativity and flexibility. The results point to the strong potential of NMT as a suitable representation that is highly compatible with the input requirements of BPS engines. The avoidance of file exchange allows for a fluid and rapid generate-analyse cycle using a graphical user interface and a visual 3D environment rather than an offline batch process and an exclusively numeric data presentation. The fact that some 3D software such as 3ds Max® can also analyse daylighting offers an opportunity to simulate and analyse a design proposal using a multivariate approach.

It is important to note here that an introduction of NMT as a unifying representation of architectural constructs has greater implications for the future of BIM than the current energy simulation application described here. NMT can provide a rich alternative to component-based modelling that allows architects to think topologically, hierarchically and spatially. It is not a second, alternative or derived representation, but a foundational one that can support and define the characteristics of and relationships between higher order locational, axial, laminal and spatial constructs. The use of a novel approach to the topological modelling of a building and its integration with an advanced 3D modelling and visualization platform for the input and display of data has made it clear that there is a need to further investigate and conduct user-testing of innovative methods for creating, displaying and interacting with geometric, topologic, and BPS data using advanced interfaces and information theory.

Disclosure statement

No potential conflict of interest was reported by the author.

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