# Addressing pathways to energy modelling through non-manifold topology

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**ABSTRACT**

This paper presents a comparison of different pathways for the energy modelling of complex building geometry. We have identified three key modelling questions: first, how can the spatial organisation of the building be appropriately represented for energy analysis? Second, how can curved building geometry be post-rationalized as planar elements given the planar constraints associated with energy simulation tools? And third, how can an exploratory design process be supported using a 'top-down' rather than a 'bottom-up' modelling approach?

Using a standard office building test case and EnergyPlus, the following three pathways were explored: (a) OpenStudio using a non-manifold topology (NMT) system based on an open-source geometry library, (b) OpenStudio using the SketchUp 3D modelling tool and (c) through the DesignBuilder graphical interface. The efficacy of the software used in these pathways in addressing the three modelling questions was evaluated. The comparison of the pathways' capabilities has led to the evaluation of the efficacy of NMT compared to other existing approaches. It is concluded that NMT positively addresses the three key modelling issues.

**Author Keywords**

3D modelling; non-manifold topology; energy analysis; building performance simulation; parametric design.

**ACM Classification Keywords**

I.6.4 SIMULATION AND MODELING (Model Validation and Analysis).

## 1 INTRODUCTION

Considering the adverse impacts of climate change, there is increased interest in assessing the energy performance of buildings from the earliest possible stages in design to inform design decisions and achieve increased energy efficiency. Architects and designers traditionally use building information modelling (BIM) systems to represent their buildings in order to then extract the necessary information for building energy performance simulations (BPS). While BIM models provide several advantages, they are usually prone to errors and inconsistency due to the need to model the building fabric at a higher level of detail required for construction rather than as an idealized spatial model. In addition, while BIM models created by architects might reflect an architect's view of the project, they are not necessarily structured for BPS [13]. Energy simulation programmes, such as EnergyPlus, require idealized models as inputs for the analysis, consisting of zero thickness walls or partitions between thermal zones.

The need to convert a detailed construction-oriented BIM model back to an idealized spatial model presents some unfortunate challenges to the user. First, the poor interoperability between BIM tools, such as Autodesk Revit and ArchiCAD, and BPS software, such as EnergyPlus and TRNSYS, [20] can hinder an integrated design process, and subsequently intermediate tools might need to be used. In addition, the simplification might result in a misinterpretation of the model under investigation and in unexpected discrepancies, which will require further effort to remedy and complete. This comes with the expense of time, cost, and accuracy of results. The discrepancies, which can often be significant [12, 18, 21], can undermine confidence in model predictions, contributing to the energy performance gap between modelled and monitored buildings [23]. Lastly, complex geometries consisting of curved surfaces are sometimes difficult if not impossible to translate into a suitable analytical model for BPS due to planarity constraints posed by BPS software.

To address these limitations, a novel geometry data structure, called non-manifold topology (NMT), is used to evaluate a conceptual model in terms of its efficacy in BPS. NMT is well-suited for the early design stages as it can provide idealized spatial models, which are compatible with the requirements for BPS. It allows for a clear segmentation of a building, unambiguous space boundaries, and perfectly matched surfaces and glazing sub-surfaces. The NMT

SimAUD 2018 June 05-07 Delft, the Netherlands

concept aligns therefore with the philosophy that architects and designers should “exert the least amount of effort and time to build the simplest possible models that yield the largest insight into the project” [1].

This paper extends earlier work on the use of non-manifold topology for building representation [1, 7, 8, 10] and is split into four sections. Section 2 gives a brief overview of manifold and non-manifold topology, as well as of the inputs and constraints for BPS. Section 3 presents four test cases addressing different modelling pathways for a building with complex geometry including curved surfaces and then assessed in terms of its energy performance. Section 4 includes the results of the pathway exploration and the energy analysis; Section 5 includes a discussion of the results that is followed by some conclusions in Section 6.

## 2 BACKGROUND

### 2.1 Traditional manifold approach

In a traditional 3D modelling environment, solid objects are said to have a manifold boundary, consisting of surfaces, edges and vertices. Each surface separates the interior solid condition of the object from the exterior world. Each edge is shared by exactly two surfaces of the solid and all surfaces form the outer boundary of it such that it is said to be watertight. These guaranteed attributes allow 3D software to easily operate on such geometry [7], for example to perform regular Boolean operations, such as union, difference and intersection. In the traditional manifold instance, the original operands disappear and are replaced with the resultant shape based on the chosen operation. A manifold model without internal voids can be fabricated out of a single block of material [1] and examples include the surface of a torus, a sphere, or a prism. Manifold topology is efficient in modelling physical components, e.g. building components. A BIM model can be thought of as the representation of an assembly of manifold physical components. However, the spatial arrangement of a building, which is a central concern for energy analysis, cannot be adequately represented by manifold topology. Examples of manifold and non-manifold geometry are shown in Figure 1.

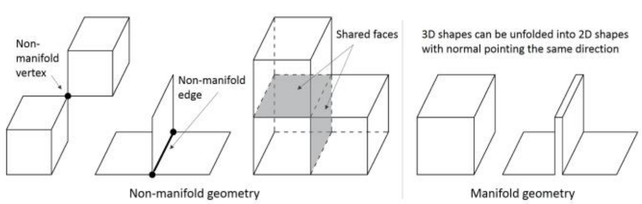


**Figure 1.** Examples of manifold and non-manifold geometry

### 2.2 Non-manifold topology

Non-manifold geometry is also made of surfaces, edges, and vertices. However, such models allow multiple faces to meet at an edge or multiple edges to meet at a vertex, and also allow coincident edges and vertices. Furthermore, surfaces can either be a boundary between the solid interior of the object and the exterior world or between two spatial cells within the object. Practically, in non-manifold models any combination of vertices, edges, surfaces and volumes is allowed in a single logical body [9]. Moreover, contrary to the manifold models, NMT models have a configuration that cannot be unfolded into a continuous flat surface and are thus non-manufacturable and not physically realizable [2].

Topological elements of non-manifold objects are hierarchically interrelated. A lower-dimensional element is used as the boundary of each of several higher dimensional ones [24] (Figure 2) and more detailed information can be found in [10]. These expanded data structures and topological relationships allow for a richer representation of loci, centrelines, elements, surfaces, volumes, and hierarchical groupings, providing model consistency and improved accuracy.

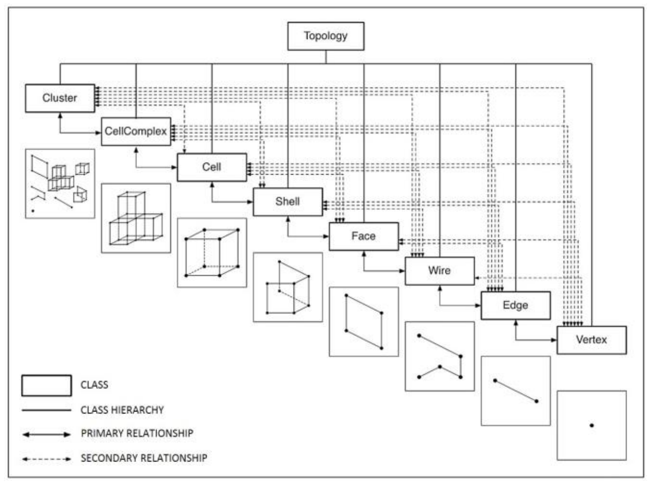


**Figure 2.** Non-manifold topology class hierarchy [10]

When Boolean operations are applied in an NMT modelling environment, the two shapes are merged and can overlap and consistently share vertices, edges, surfaces, and volumes without redundancy. Contrary to the regular operations, with non-regular (i.e. non-manifold) operations the interior surfaces, that would have been otherwise lost, are maintained [1]. Additionally, the topology allows cells, surface, edges, and vertices to be queried as to their adjacencies. For example, a user can query the model what cell shares a surface with or sits directly above another cell because the topology establishes these types of connections [9].

### 2.3 Building energy modelling input characteristics

BIM models are currently widely used by architects and designers as the geometry representation of the energy simulation model. However, in a BIM model consisting of an assembly of the detailed physical building components it is not guaranteed that the components surrounding a notional space actually touch so as to form a complete enclosure. Therefore the recognition of spatial enclosures from the physical BIM model is fraught with potential errors. Second, even if the first condition was satisfied, the resulting model of the spatial enclosure would be the literal reflection all the detailed geometry of the surrounding physical building components and would contain so much detail, so as to overwhelm any analysis or simulation program. Necessary information could thus be lost due to the abstraction and simplification performed in the translation process. Even larger hurdles are presented to designers in the transformation of the spatial geometry into thermal geometry if their models include complex representations. Only the absolutely necessary number of surfaces should ideally be created for BPS. While curved geometry needs to be segmented into planar surfaces, the relationship between the number of segmentations and accuracy of results needs further study. This segmentation may require further repair, which is labour intensive, time intensive and thus economically ineffective. It should be noted that sometimes very complex geometries are impossible to be translated into a suitable analytical model.

Moreover, a BPS tool simulates a number of geometrical and topological relationships, which operate under various constraints. This section, therefore, presents the geometrical and topological requirements for heat transfer between thermal zones through surfaces, as well as the geometrical and topological constraints posed by the energy analysis engine. EnergyPlus [25] is used in this study, as it holds the biggest utilisation share among major simulation programs for building performance simulation [15].

The requirements for heat transfer associated with spaces (or rooms) in energy simulation tools and specifically EnergyPlus are presented in Table 1. These are classified into geometrical and topological ones and other requirements as adapted from [13].

| **Heat transfer requirements in EnergyPlus** | | |
|---|---|---|
| **Geometrical requirements** | **Topological requirements** | **Other** |
| • Surface area<br>• Surface normal | • Relationship between surfaces and spaces<br>• Relationship between materials and surfaces<br>• Relationship between two opposite surfaces<br>• Surface type | • Material properties |

**Table 1.** Heat transfer requirements in EnergyPlus (adapted from [13])

Regarding the geometrical requirements, the area of the surfaces (whether analytical surfaces, such as walls, floors, ceilings, roofs or openings, such as windows, doors, holes, skylights) and their normal vectors determining the direction of the heat transfer are needed. The topological requirements include relationships and adjacencies aspects in order to calculate the heat gains and losses for each space. The three relationships include the one between surfaces and spaces, the one between materials (and their properties) and the surface, as well as the relationship between two opposite surfaces for internal heat transfer. The adjacencies requirement includes the indication of the surface type, such as internal, external or adjacent to the ground. Other requirements relate to the construction including material properties.

Additional inputs include the site specification, such as the location and the weather data for the model; building information, such as the building type, its orientation, the internal loads and their assigned operation schedules (occupancy, lighting and equipment); as well as information regarding the heating, ventilation and air-conditioning (HVAC) services of the building. The building should also consist of one or more thermal zones (i.e. spaces), depending on its size and complexity, in which temperature is controlled by a thermostat at a desired set point. Defining the above information in conjunction with the aspects presented in Table 1 is essential for an integrated building energy performance analysis which can be used to inform the building design [14].

### 2.4 Geometrical and topological constraints posed by energy analysis software

The energy analysis software and specifically EnergyPlus pose geometrical and topological constraints that need to be met in the modelling process. The identification of these constraints also helps to interpret the results derived by EnergyPlus. The constraints, as identified and synthesised from the literature, are presented in Table 2.

| **Geometrical constraints** | | **Ref** |
|---|---|---|
| G1 | Walls should not contain holes. | [5] |
| G2 | Openings should be modelled as additional geometry. | [5] |
| G3 | Openings must be rectangles or triangles. | [3, 5] |
| G4 | Zones, i.e. spaces, not just space surfaces, should ideally be convex. | [5, 17] |
| G5 | Curves should be avoided, otherwise the segment count should be as low as possible. | [17] |
| G6 | The direction of the outward facing normal for the roof overhangs should be downwards. | [22] |
| **Topological constraints** | | |
| T1 | Openings should relate to walls. | [5] |
| T2 | Openings should be co-planar. | [5] |
| T3 | Openings must not "touch" each other. | [3,5,17] |
| T4 | Openings must not share 2 edges with walls or floors or roof. | [5, 16, 17] |
| T5 | There cannot be a wall that is only a window. | [16] |
| T6 | A subsurface (window or door) should not be placed inside another subsurface. | [17] |
| T7 | Surfaces of adjacent zones must not overlap. | [17] |
| T8 | EnergyPlus does not compute heat transfer between zones if they do not share a surface. | [17] |

**Table 2.** Geometrical and topological constraints

Some clarifications are added regarding geometrical constraint G4 and topological constraint T3. G4 addresses the interior solar distribution calculation and how a concave zone or surface can affect the accuracy of the individual surface temperatures of the zone, but not its heating and cooling loads. This is why it is advised that concave elements are divided into smaller convex ones. In addition, it should be noted that, although T3 has been stated in the literature, some implementations such as [7] have overcome it, so it is likely to have been generally suggested, as it might be specific to certain cases.

## 3 MODELLING PATHWAYS

The City Hall in London, designed by Foster and Partners, (Figure 3) inspired a simple exemplary massing model of a relatively complex curved office building. It is important to note that, while the digital model is to the same general dimensions of the real building, the idealized model geometry does not represent the detailed geometry of the real building and the assigned material properties in the energy model do not correspond to the material used in the real building. Thus, any simulation results reported in this paper have no relationship to the performance of the actual built work.

The idealized 3D model comprises 9 vertically-stacked thermal zones, according to the number of floors of the real building. Each thermal zone is bounded by 20 wall panels consisting of 2 triangular windows each, as well as a floor and a ceiling. The model's orientation is consistent with that of the real building.

**Figure 3.** The City Hall in London designed by Foster and Partners [6]

Four test cases using different modelling pathways for building performance simulation were explored. The first test case was modelled in a visual data flow programming application (VDFP) using NMT and the model was then exported to OpenStudio (OS) within the host application through the DSOS plugin developed by one of the authors and presented in detail in [7, 9]. It should be noted that in this paper an improved and more efficient implementation was used. The second test case was modelled in SketchUp using the OS plugin for SketchUp, with the aim to perform the energy simulation in EnergyPlus through OS. The third test case was modelled in DesignBuilder (DB) and simulated in EnergyPlus. In the fourth test case the VDFP/NMT model was imported to DB through gbXML file format and was then simulated in EnergyPlus. Honeybee modelling workflows using automated zone and surface splitting of complex geometry exist; however, this option was not reviewed in this paper. The software architecture representing the pathways in the four test cases is presented in Figure 4.

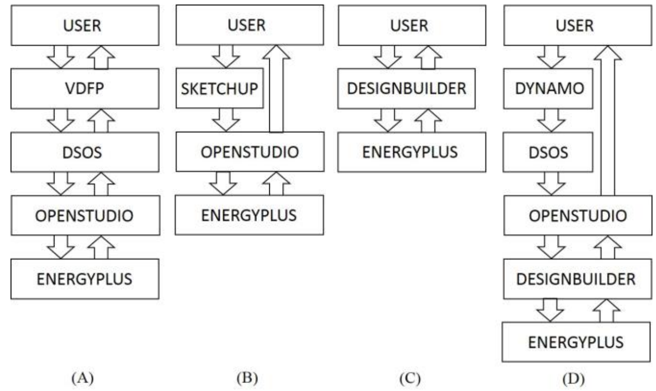


**Figure 4.** Software architecture for the four test cases. (A) VDFP/NMT to OS through DSOS, (B) SketchUp to OS, (C) DB to EnergyPlus, (D) VDFP/NMT to DB and EnergyPlus through gbXML.

### 3.1 Test cases

The images of the four models built to explore the different modelling pathways are presented in Figure 5 followed by the description of the modelling process.

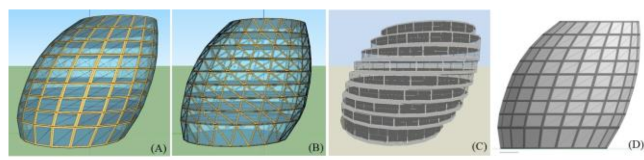


**Figure 5.** Surface and subsurface geometry of the four test cases. (A) The NMT model built in Dynamo and visualized in SketchUp, (B) The SketchUp/OS model, (C) The DB model, (D) The imported VDFP/NMT model to DB from OS through gbXML.

*VDFP/NMT building model (A)*

The first test case used parametric modelling and specifically Dynamo version 1.3.2 and an open-source geometry library providing NMT capabilities to build the model. A top-down approach was used and four steps were involved in the design process: the creation of a smooth curved wall, the creation of its EnergyPlus-compliant planar quad-mesh counterpart, its segmentation into a multi-storey building, and designing the windows.

To create the curved wall, sample points were defined on the edges of each floor as well as the roof, at the opposite sides of the wall. Every pair of points at the same height on the opposite sides of the building was used create a circle, representing the floor. By performing the lofting technique through all the constructed circles, the curved wall was formed.

The quad-mesh was created by firstly segmenting the wall's UV-space into a grid, consisting of 20 panels horizontally and 9 panels vertically. The vertical segmentation was done so that the above sample points would lie at the panel boundaries, to create the floors separating the storeys in the next step. After this grid was mapped to the actual curved wall, it was found that the resulting panel faces were approximately planar, thus no further planarization was applied. If non-planar faces were encountered, planarity constraint as discussed in Deuss et al. [4] could have been applied. The roof and the ground floor were added by closing the holes at the top and the bottom of the wall, respectively, thus creating a cell.

The final step involved performing the non-regular slice operation on the cell using 8 horizontal planes at the horizontal boundaries of the panels. This process created a non-manifold CellComplex, containing 9 Cells representing the spaces and subsequently the thermal zones in every storey. This resulting building was passed to the DSOS library [7] to create its EnergyPlus model, which includes triangulated windows according to the given window-to-wall ratio.

*SketchUp/OS model (B)*

The second test case used SketchUp Make version 17.2.2555 and OS version 2.3.0 to create the model. A bottom-up approach was used here and the model was built from bottom to top, floor by floor. The design of the first thermal zone included the creation of a 20-sided polygon to represent the floor, its extrusion by the zone height in order for the ceiling and 20 wall surfaces to be created and the horizontal scaling of the ceiling surface that was attached to the walls in order to achieve the suitable slope. Then the ceiling surface was copied and included in the next thermal zone and the above process was repeated. The same process was followed until all nine thermal zones were created. Lastly, the windows needed to be placed so that the glazing ratio is 0.7. However, as OS is not capable of applying glazing ratio to sloped surfaces, the multi face offset SketchUp plugin was applied to each zone separately and used accordingly in order to achieve the desired glazing ratio.

This modelling pathway presented several shortcomings including distorted geometry and stability issues. For example, although the sloped wall surfaces were initially modelled and visualised as rectangles, they were arbitrarily triangulated in SketchUp during the modelling process, affecting the geometry of the model and increasing its complexity. In addition, although the geometry appeared correct in SketchUp, when the same file was opened in the OS standalone application, the geometry was distorted. Stability issues were also encountered when the multi-face SketchUp plugin or the SketchUp undo button was used, causing the application to freeze and needing rebooting. When rebooted, the created geometry in the saved file disappeared, which instigated a one-off geometry creation without saving the file in order to avoid any synchronisation issues between the SketchUp model and the OS model. But even then, the geometry was distorted when opened in the OS standalone application and the surfaces could not be properly matched or intersected in order to create the required analytical model for energy analysis. Overall this modelling pathway was regarded as a cumbersome process and proved to be non-practical for such a complex building model. As the EnergyPlus compliant model of the building could not be created, this model unfortunately did not proceed to the energy performance simulation due to the geometry and stability issues that posed a significant limitation in using this pathway. This pathway could have been simplified in its modelling approach until the run is successful; however the resulting model, which would be free from curved and sloped surfaces due to the simplification, would have been similar to the DB case (model C). Therefore, to avoid replication of results, no model simplification was pursued in this modelling pathway.

*DesignBuilder model (C)*

The third test case used DB version 5.0.3.007 to create the model. A simplified model was created, as DB does not currently provide the possibility of modelling accurately such complex geometry, for example applying the required variety in the sloping of the walls in each of the zones in the specific model. Therefore, a bottom-up approach was used. First, all zones were modelled according to the diameter of the circle circumscribing the 20-sided polygon and the height of each zone. Due to DB's limitation in modelling the required variant slopes on the wall surfaces, vertical walls had to be used instead. The same glazing ratio of 0.7 was also applied, as were all relevant attributes taken from the OS medium office template.

*OS/DesignBuilder imported gbXML model (D)*

The fourth test case used again DesignBuilder (version 5.0.3.007), but instead of modelling the building using its built-in tools, we leveraged DB's capability to import gbXML files. The NMT/OS model was exported in gbXML format through the OS standalone application and imported to DB. The default settings for import were used, including the import of the thermal properties. The imported geometry to DB was correct and the model was visualised correctly. However, although the construction names and material layers were imported correctly, the thermal attributes needed to be set individually. In addition, even when they were set individually and appearing correct in the DB interface, the results in the EnergyPlus report showed differently. It should be noted that the thermal attributes as stated in the gbXML file are correct, so the mis-computation of the thermal attributes might have occurred due to a software bug in DB. This requires further investigation.

### 3.2 Common input variables

Although the models were created differently in the four test cases, some input variables were commonly shared in the two test cases that proceeded to the energy simulation in EnergyPlus. The ASHRAE 189.1 template for medium office was used in both test cases, applying default settings for construction (materials), temperature set points, occupancy and lighting loads, occupancy and lighting schedules and air flow. A glazing ratio of 0.7 was assigned. The overall height, floor area and volume of the model, as well as the height, floor area, ceiling area and volume of each thermal zone, was kept the same as much as possible. It is noted that small differences in the range of 0.5% were incurred in the volume and the floor area due to the geometrical complexity of the model and the constraints posed by the design software. The idealized City Hall models were simulated annually.

The geometrical and topological constraints presented in Table 2 and Table 3 were taken into consideration, apart from G6 and T3, as no roof overhangs were modelled and as previous studies [7] showed that adjacent windows can be operational.

## 4 RESULTS

### 4.1 Modelling outputs comparison

The different models were compared in terms of geometrical accuracy, correct material properties and number of building elements. The EnergyPlus reports were used to compare all outputs. The automated creation of the EnergyPlus geometry (Table 3) was investigated in models (A), (C) and (D). It largely depended on the input geometry in the two host applications and geometry in the host application and EnergyPlus were overall the same in terms of surface types' area in all models, apart from some negligible rounding that occurred in some instances. Although the wall/floor/roof and glazing areas were accurate in the VDFP/NMT model, its volume presented a small increase of 1.15% in the automated EnergyPlus report and this needs further exploration. This might be attributed to the complex shape of the model and possible adjustments made by EnergyPlus, but this did not affect the energy analysis calculations as these use the surface areas. An interesting point was that the volume was accurate in the imported gbXML model to DB (D), which proves the consistency of the NMT model. The model elements, i.e. the number of walls, floors, roofs/ceilings and windows were accurate in the VDFP/NMT model and the subsequent exported gbXML format, as were in the imported gbXML file to DB. They all amounted to 180 wall elements, 9 floors, 9 roof elements and 360 windows. The test case in which the model was built from scratch in DB, the geometry is accurate but simplified due to the software's limitations to represent accurately complex geometry. Moreover, the number of the wall and window elements is correct, but the number of the floor elements and roof/ceiling elements were increased to a total of 82 and 96 respectively. This possibly happened due to the concave exposed floor and roof surfaces and EnergyPlus's requirement for convex surfaces, so there was an automatic adjustment within EnergyPlus to convert the concave floor/roof area to smaller convex ones. The material properties were outputted correctly in the VDFP/NMT model and the exported gbXML file, as well as the DB model, while the imported gbXML file to DB presented discrepancies particularly in the thermal properties of the wall surfaces. Unfortunately, the SketchUp/OS model was not capable of representing accurately the geometry, so the material properties and the model elements cannot be discussed. It is assumed though that the same level of geometry as in DB is achievable in SketchUp/OS and therefore partial capability in terms of geometric accuracy is assigned to the SketchUp/OS pathway. In terms of modelling time, the VDFP/NMT model took more time to design (approximately 3-5 hours for a medium experienced user) than the DB model (2-4 hours). Regarding simulation time, the VDFP/NMT model required the most time, possibly due to the increased number of glazing surfaces, then followed the DB model and lastly the imported gbXML to DB. The results are summarised in Table 4.

| | VDFP/NMT (A), (D) | | | DB (C) | |
|---|---|---|---|---|---|
| | Host | EPlus | EPlus/gbXML | Host | EPlus |
| Total volume | 51578.3 | 52172.4 | 51578.3 | 52423.7 | 52423.7 |
| Total gross wall area | 5485.7 | 5485.7 | 5485.7 | 5037.9 | 5037.9 |
| Glazing ratio | 70 | 70 | 70 | 70 | 70 |
| Total glazing area | 3839.9 | 3840.0 | 3832.6 | 3409.9 | 3409.9 |
| Total floor area | 12353.6 | 12353.6 | 12353.6 | 12413.1 | 12413.1 |
| Ground floor area | 1103.3 | 1103.3 | 1103.3 | 1108.6 | 1108.6 |
| Total external floor/ceiling area | 617.9 | 617.9 | 617.9 | 2480.6 | 2480.7 |

**Table 3.** Comparison of geometrical inputs and automated EnergyPlus geometry

| | Geometry | Material properties | Model elements | Simulation time |
|---|---|---|---|---|
| Dynamo/NMT | ● | ● | ● | 2min 38.95sec |
| SketchUp/OS | ◐ | N/A | N/A | N/A |
| DB | ◐ | ● | ◐ | 2min 0.80sec |
| Exported gbXML from Dynamo/NMT | ● | ● | ● | 1min 45.76sec |
| Imported gbXML to DB | ● | ○ | ● | |

● Full capability ○ No capability ◐ Partial capability

**Table 4.** Comparison of models' capabilities and required times

### 4.2 Energy analysis results

As two of the attempted pathways were not able to proceed to the energy simulation due to limitations presented in the host applications, only two models, the VDFP/NMT and the DB ones were used for energy analysis. The VDFP/NMT results through the DSOS plugin were compared with the energy results from the OS standalone application and the OS SketchUp plugin and were found to be the same. This demonstrates the consistency of the model and of this pathway's suitability to energy analysis. The derived results regarding the normalised cooling and heating loads per zone are provided in Figure 6.

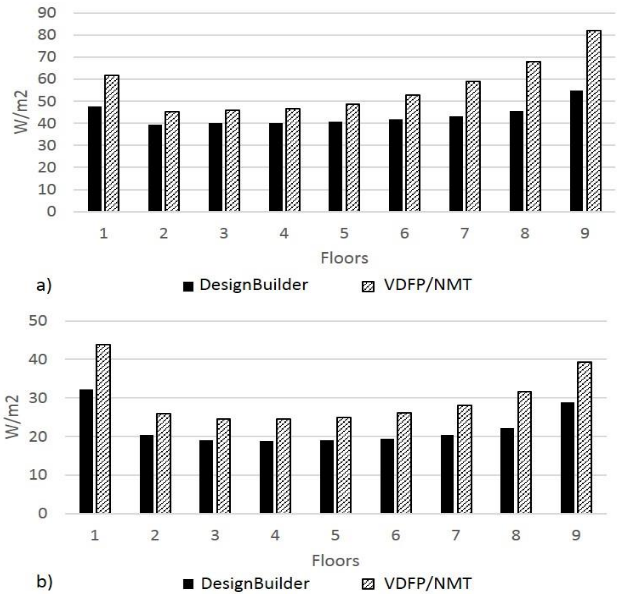


**Figure 6.** Normalized a) cooling and b) heating loads

## 5 DISCUSSION

The exploration above assessed different pathways for modelling complex building geometry in order to fit to the energy analysis process in the early design stages. Established software for energy analysis, such as DB and OS through the SketchUp interface, is widely used for simulating relatively simple geometric models providing reliable results [11, 19]. However, when it comes to complex geometric forms they either struggle to model it accurately, as in the case of SketchUp/OS or the user is urged to use a considerably simplified form, as in the case of DB. This can present geometry inconsistencies and thus questionable results. Furthermore, in the simplified DB model, EnergyPlus needed to divide the concave exposed floor or roofs of the zones into many smaller convex surfaces. The increase in the number of model elements would have an adverse impact on the computational time, and this would be unfavourable especially in larger models.

Moreover, although DB currently presents limitations in creating such complex geometry accurately, it is capable of importing it, representing and visualising it correctly, provided the imported model is correct. This was demonstrated by the import of the accurate gbXML model created in VDFP/NMT and exported through OS, proving the interoperability among the applications used. In addition, although the imported gbXML file was correct in terms of material properties, DB struggled to compute the U-values and the user needed to set them manually. Even when they were set manually and appeared correct in the DB interface, the output material properties in the output EnergyPlus file do not agree. These issues might be able to be solved through debugging of the internal communication of DB and EnergyPlus.

Overall the VDFP/NMT pathway provided the most reliable process for energy performance simulation of such complex building forms. An aspect that is inherent only to the VDFP/NMT model is the set of benefits it leverages from NMT. The consistent energy analysis results derived from the comparison through the different OS routes demonstrate its accuracy while maintaining its consistency throughout this pathway to energy analysis; yet it took slightly more time to simulate than DB, which was probably due to the higher number of glazing elements. The energy analysis results between the VDFP/NMT and the DB models as shown in Figure 6 follow the same trend across all zones, but present discrepancies, which was expected. This is likely to be attributed to the different geometry inputted to EnergyPlus in the two test cases, such as differences in the wall and the glazing area, as well as the presence of exterior floor and roof areas in DB (as seen in Table 3), and also due to EnergyPlus's micro-adjustments. As it is difficult to attribute the discrepancies to explicit geometric inconsistencies, this comparison identified the need for further exploration including a sensitivity analysis in order to investigate geometrical aspects individually. It can be however assumed that the VDFP/NMT results are more reliable compared to the DB baseline ones (but not more true to the actual building, as this was an idealized design) due to the more accurate representation of the building.

Any 'bottom-up' modelling strategy which requires the user to explicitly model individual floors or individual wall panels is extremely arduous to subsequently edit. The editing difficulty and effort required may become a negative incentive and is likely to inhibit future design exploration. By contrast, a top down modelling approach might involve a change to the form of the exterior envelope of the building or in the number of floors. In this case, the floors and idealised wall faces are automatically derived from higher level modelling procedures (such as the 'slice' operation) and offer a higher level of 'ease of use'. In fact all the user has to do is to change the 'number of floors' parameter. The ease of top-down modelling as supported by NMT is a positive encouragement for design exploration.

## 6 CONCLUSIONS

This paper presented four pathways to the energy modelling of a building with relatively complex geometry including curved surfaces. From the four pathways explored, the VDFP/NMT pathway was able to model and handle complex geometry and produce reliable results, while benefitting from the advantages of NMT. Moreover, while established software are capable of representing accurately and simulating simple geometric models providing reliable results, they either struggle with modelling complex geometric forms accurately, as shown in the case of SketchUp/OS or the user is urged to use a much more simplified design, as in the case of DB. Although this latter pathway would work, it can present geometry inconsistencies due to the required model simplification and thus produce questionable energy simulation results. Another pathway that was explored and proved possible in terms of accurate representation was to import the

VDFP/NMT model to DB through OS's gbXML format, maintaining the complex geometry. This also demonstrated the VDFP/NMT model's consistency and interoperability with other established energy modelling software. However, although DB was able to accurately visualise the imported complex model, limitations in the application of thermal properties due to possible software bugs prevented a reliable energy simulation.

This research used a single idealised model of an existing building and could be reasonably described as a 'retrospective' study. However it may be even more important to consider how this type of modelling and simulation process might be translated into practice where the form of the building is still being decided within an exploratory design process. In this context, it is not the ease with which a model is created 'one time', but the ease with which the model can be changed and re-analysed so that the performance of different configurations can be explored. Our conclusion is that NMT provides a more appropriate spatial representation of a building and more suitable idealisation of curved geometry for energy simulation. Further research could investigate how different levels of geometry complexity and thus model accuracy would affect the accuracy of energy analysis results and computation time. Additionally NMT supports a top-down modelling process which makes it substantially easier to explore design changes and thus facilitate design exploration.

## ACKNOWLEDGMENTS

This research is funded by a Leverhulme Trust Research Project Grant (Grant No. RPG-2016-016).

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