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A framework for producing gbXML building geometry from Point Clouds for accurate and efficient Building Energy Modelling

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HIGHLIGHTS

- Improved Building Energy Modelling workflow proposed for existing buildings.
- Solution proposed for rapid generation of as-built geometry from Point Clouds.
- Identification of a framework for storing the building geometry in gbXML format.
- Plans for future verification of solution outlined using industrial standards.

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ABSTRACT

The industrial sector accounts for 17% of end-use energy in the United Kingdom, and 54% globally. Therefore, there is substantial scope to accurately simulate and efficiently assess potential energy retrofit options for industrial buildings to lower end use energy. Due to potentially years of facility renovation and expansion Building Energy Modelling, also called Building Energy Simulation, applied to industrial buildings poses a complex challenge; but it is an important opportunity for reducing global energy demand especially considering the increase of readily available computational power compared with a few years ago. Large and complex industrial buildings make modelling existing geometry for Building Energy Modelling difficult and time consuming which impacts analysis workflow and assessment options available within reasonable budgets. This research presents a potential framework for quickly capturing and processing as-built geometry of a factory, or other large scale buildings, to be utilised in Building Energy Modelling by storing the geometry in a green building eXtensible Mark-up Language (gbXML) format, which is compatible with most commercially available Building Energy Modelling tools. Laser scans were captured from the interior of an industrial facility to produce a Point Cloud. The existing capabilities of a Point Cloud processing software and previous research were assessed to identify the potential development opportunities to automate the conversion of Point Clouds to building geometry for Building Energy Modelling applications. This led to the novel identification of a framework for storing the building geometry in the gbXML format and plans for verification of a future Point Cloud processing solution. This resulted in a sample Point Cloud, of a portion of a building, being converted into a gbXML model that met the validation requirements of the gbXML definition schema. In conclusion, an opportunity exists for increasing the speed of 3D geometry creation of existing industrial buildings for application in BEM and subsequent thermal simulation.

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1. Introduction

In 2012 the end-use energy by industry accounted for 54% of all delivered end-use energy globally [1]; in 2015 this value was 17% for the United Kingdom (UK) [2]. This presents a substantial opportunity for the implementation of energy saving schemes within industry that could have a dramatic effect on reducing global energy use. Not only would reducing energy use aid in the extension of dwindling global fossil fuel energy resources [3], but this would also lower the overhead costs within industry, thus allowing companies to be more adaptive and competitive in manufacturing and process industries [4].

One method of achieving these energy savings is to utilise Building Energy Modelling (BEM) software such as Integrated Environmental Solutions (IES) Virtual Environment (VE) [5], EnergyPlus [6] and DesignBuilder [7] to name a few. This type of software is capable of simulating a thermal model of a building in order to establish the energy use profile. Interventions can then be proposed to reduce energy use whilst at the same time ensuring occupant comfort. Typically, these retrofit suggestions can include changes to construction materials, glazing, the Heating, Ventilation and Air Conditioning (HVAC) system, adjusting thermostat set points, changing solar and internal gains or altering occupant behaviour via education programmes. Traditionally BEM is used to simulate residential and commercial buildings. However, in recent years there are examples of the application of BEM for manufacturing facilities [8,9] in which significant energy savings were obtained. One of the drawbacks to BEM is that model geometry usually has to be remodelled from scratch that can result in long timescales and increased project costs. If building plans are incomplete, due to expansion and refurbishment, modelling can be difficult and inaccurate. Onsite measurement of geometry for manual modelling can also be cost and time prohibitive as alluded to by Ascione et al. [10].

BEM utilises a Finite Volume Model (FVM) of buildings and room envelopes in order to simulate the thermal mass of each thermal volume relative to each other and the surrounding environment of the building. The high resolution of detail required in a typical Computer Aided Design (CAD) model for building construction is not required in BEM. This means that establishing the exact wall and room geometries is not as crucial; a wall modelled out of position by a centimetre will not have a significantly detrimental effect on the room's calculated volume and thermal mass. This provides an opportunity for rapid building geometry capture, that does not require high detail resolution, for utilisation in BEM.

Point Clouds are datasets that consist of multiple points stored within a three-dimensional (3D) coordinate system; usually a Cartesian coordinate system (i.e. X, Y and Z). This type of dataset can be useful to virtually represent the surface geometry of objects within the coordinate system. These datasets can represent landscape topography, building features (e.g. floors, walls, roofs, windows and doors) and equipment. Point Clouds can be acquired through the implementation of sophisticated laser scanning equipment that can record data points in a 3D volume down to a resolution of a few millimetres. A high resolution Point Cloud of a building, for example, could have millions of data points in the dataset. Most commercial laser scanners are supplied with software allowing the 3D coordinates to be mapped into a CAD software package.

The benefits of Point Clouds for mapping real-world objects as-built are numerous. For example, the ability to inspect manufacturing or construction tolerances, rapid geometry mapping of large objects or land areas, use as-built information to inform future design decisions and further enhancements such as virtual reality plug-ins.

The ability to accurately measure and capture geometric information for the purposes of BEM is highly beneficial in order to inform effective sustainable retrofit decisions. Point Clouds offer one method to rapidly generate as-built building geometry in a VE that can include possible renovations that have taken place since the building was first constructed.

The broad aim of this research is to identify a potential solution of quickly capturing as-built geometry of large scale and complex buildings that can be applied to BEM. A review of previous related works, in Section 1.1, summarises previous attempts to achieve similar results and the research gaps that will be addressed in this work. The novelty in this paper is the outlining of a gbXML framework that will allow the generation of a valid gbXML format from a set of internal building Point Clouds.

For clarification, Building Information Modelling (BIM) is used across a range of engineering disciplines to store building data centrally however interoperability between the disciplines is a growing concern as every engineering application requires individual modelling capabilities [11–19]. This can lead BIM files to become unwieldy unless correctly planned and implemented at all levels on a project. BEM can be considered as a specific BIM application subset.

1.1. Previous related works

This work focuses on the use of BEM at an individual building level however it should be noted that some work has previously been conducted in using Point Clouds for BEM applications over larger urban areas [20,21], this differs from efforts of other researchers that have primarily used GIS data for BEM applications [22].

Volk et al. [23] conducted a review of BIM implementation within existing buildings including data capture techniques and subsequent attempts of model reconstruction. The authors concluded that a major challenge is the automation of data capture and BIM creation as the existing efforts struggle with capturing concealed structural geometry or semantic building information in challenging environmental conditions. However, the inclusion of monitored values such as energy use, resource use and maintenance costs into a BIM will provide considerable advantages in a building's lifecycle.

Cho et al. [24] reviewed state-of-the-art technology to automatically create as-built geometry and thermal models for BEM and retrofit assessments from external Point Clouds of a building shell into the green building eXtensible Mark-up Language (gbXML) format for BEM purposes [25,26]. Subsequently, Wang and Cho [27,28] introduced a method of automatic as-built BIM model creation and automated thermal zone creation to create a building zone and room zones through a case study. An external laser scan and thermography of a residential building were captured which were mapped onto each other and 2D floor plans were used to determine location and size of each thermal zone (interior rooms/features), see Fig. 1. The authors demonstrated a framework for automatic model generation of a building envelope using the gbXML [25,26] schema format from external Point Clouds and thermography.

Thomson and Boehm [29] aimed to automate generation of 3D geometry from Point Cloud data rather than a labour-intensive manual operation. The proposed method only concentrates on major room boundaries; doors, windows and similar objects are ignored. The authors concluded that there has been partial success towards the aim of fully automatic reconstruction, especially where the environment is simple and not cluttered. It was identified that clutter in the environment obscured the building features that need to be constructed.

Previtali et al. [30] presented an automated methodology to derive highly detailed 3D vector models of existing building façades starting from terrestrial laser scanning data. The final product is a semantically enriched 3D model of the building façade that can be integrated in BIM for planned maintenance. The integration between derived façade models and infrared thermography is presented for energy efficiency evaluation of buildings and detection of thermal anomalies. It is noted that the integration does not extend into a more holistic full lifecycle BEM.

Poullis [31] presented a framework for automatically modelling from Point Cloud data for large urban areas, up to 16 km^2, resulting in a set of non-overlapping, vastly simplified, watertight, polygonal 3D

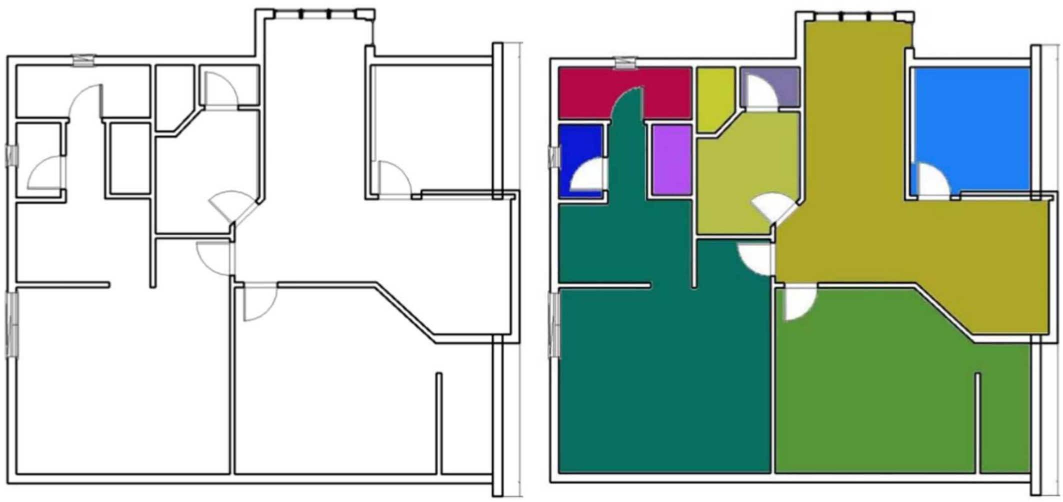

Fig. 1. (Left) Original floor plan image; (Right) Room zone segmented floor plan image [28].

models. The author produced a robust unsupervised clustering algorithm based on a hierarchical statistical analysis of the geometric properties of the data. The developed framework was tested with large Point Cloud datasets. This type of Point Cloud processing could be used to assist energy simulation of large urban areas such as the work presented by Chen et al. [32].

Armesto et al. [33] presented a multi-sensor acquisition system capable of automatically and simultaneously capturing an array of useful data for BEM. Energy evaluation was performed via a virtual navigation allowing thermal leakages to be observed. Temperature and humidity maps facilitated the detection of insulation problems in outer walls or windows, whilst the illumination map allowed evaluation of light levels for working conditions. This data could be transferred to energy evaluation software. Unfortunately, the presented technique only provides a snapshot of the building construction and use in time making it difficult to predict long term future energy performance.

De Angelis et al. [34] produced a Point Cloud, via a 3D laser scan, of the target building which was transposed into an accurate BIM model. The model was subsequently converted for BEM application via manual improvements. Through modelling and simulation, the authors recorded a maximum potential energy reduction of 37.3% however the authors provided no evidence of confirming results against real-world data by metering the building.

The methodology considered in the cited papers above generally consider geometry that has been isolated to localised external geometry, corridors (with limited clutter) or external topography. In comparison, this paper considers a full building envelope including internal room and floor layout. There are some examples of existing research where a high amount of internal detail is captured and processed and these are subsequently summarised below. However, these are not applied to industrial settings.

Ochmann et al. [35] presented an automatic approach for the reconstruction of parametric 3D building models from indoor Point Clouds. Results of the reconstruction can be exported, as an Industry Foundation Class (IFC) format [36], into BIM software. The developed algorithm was able to identify walls between adjacent rooms and reconstruct room separating wall elements, see Fig. 2. The process was demonstrated with good levels of success. The authors identified areas of future research to include (1) comparison of reconstruction results with existing, manually generated models for quantitative results, (2) a generalisation to multiple stories and (3) the usage of different capturing devices and real-time handling of streamed data. The authors note previous research does not realise reconstructed volumetric elements to which, they allude, is required for application in energy monitoring of buildings.

Xiong et al. [37] presented a method of converting raw Point Cloud data, captured from a laser scanner positioned at multiple locations in a facility, into a semantically rich building information model. They presented novel methods of clutter removal, occlusion reconstruction and opening detections for buildings from internal laser scan data. An advantage to the presented method is the use of machine learning to classify openings and planes that are occluded by internal furniture based on the assumption that opening features, such as a single window design, appears in multiple places within a building. Similar to other research the reconstruction of a building model is limited to a single building storey.

To-date the existing research has focussed on simple building geometries or features. Each of the research efforts are novel without directly expanding upon the previous research of others. This has resulted in a range of different Point Cloud processing solutions that, although have provided promising results, are still in their infancy that utilise a single specific software application, format or limited geometry. A research gap exists in that no research has been undertaken to create a generic industry accepted process or applying to more complex geometries such as those within a manufacturing environment from internal scans.

In addressing this research gap, development of such a solution would enable the technique to be applied to older and more complex industrial buildings where its value would be clearly demonstrated as building plans may not be kept up-to-date over, potentially, decades of

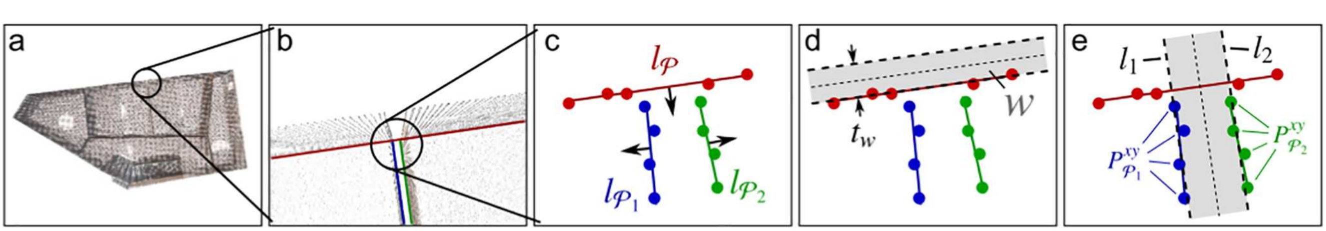

Fig. 2. The 5 steps of wall candidate generation [35].

Fig. 3. 3D visualisation of Factory 2050.

renovation. Applying this technique to existing buildings has the potential to produce the geometry quicker than manually remodelling the building geometry in BEM software thus improving the workflow for predicting energy use.

1.2. Case study – as-built building geometry

As part of the University of Sheffield's Advanced Manufacturing Campus, Factory 2050 (F2050) [38] is the UK's first fully reconfigurable manufacturing facility that enables a collaborative approach to research between industry and academia, see Fig. 3. A case study focusing on F2050 has been produced to showcase this geometry capture methodology.

In the field of BIM there are two key file schemas that are used to structure portable data depending on its application. These include IFC [36] that uses a Standard for the Exchange of Product model data (STEP) file structure and gbXML [25,26] that uses an eXtensible Markup Language (XML). Both are used for securely transferring BIM data between different software depending on the required applications such as BEM. Through development of an automated Point Cloud processing algorithm, any geometry created from laser scan data should be able to be stored in one or both of these formats as this then increases the wider application of creating 3D geometry from laser scan data. The focus of this research is on a gbXML output format as it is more suited for sustainability applications [15]. However, this does not preclude generalising the research in this paper to both formats in future research.

2. Methodology

This research presents a conceptual framework of how as-built building geometry could be successfully utilised for BEM, see Fig. 4. The research gap addressed by this paper is highlighted in bold in the framework, illustrated in Fig. 4, that aims to increase the speed of the geometry creation phase during a BEM workflow which can typically take multiple weeks. A laser scan can be performed in a few days but currently requires extensive manual post-processing.

2.1. Point cloud data capture & registration

Utilising a Laser Scanner [39], with a tripod, laser scans and photographs were captured at 86 internal positions around the F2050 building over approximately five working days. The laser scans were captured at a resolution of 12.5 mm at 10 m from the laser scanner. This generated 86 individual Point Clouds such as the one shown in Fig. 5a. All of the individual laser scans were subsequently manually registered, in a commercial Point Cloud processing software, as overlapping Point Clouds, as shown in Fig. 5b The resulting laser scans could then be exported as a single ".e57" [40] format file which is an industry recognised standard for storing Point Cloud data.

Fig. 5b illustrates a rich database of approximately 676 million points within a 3D coordinate system that represents the internal geometry of F2050. At this stage three observations were made;

A heavily glazed building such as F2050 creates a significant amount of noise during Point Cloud capture as glass refracts the radiation from the laser scanner. Time-of-flight instruments, such as the

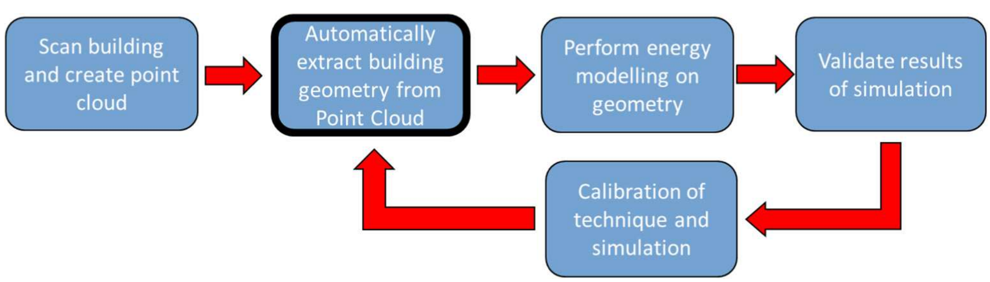

Fig. 4. Conceptual framework of capturing and using as-built geometry for BEM.

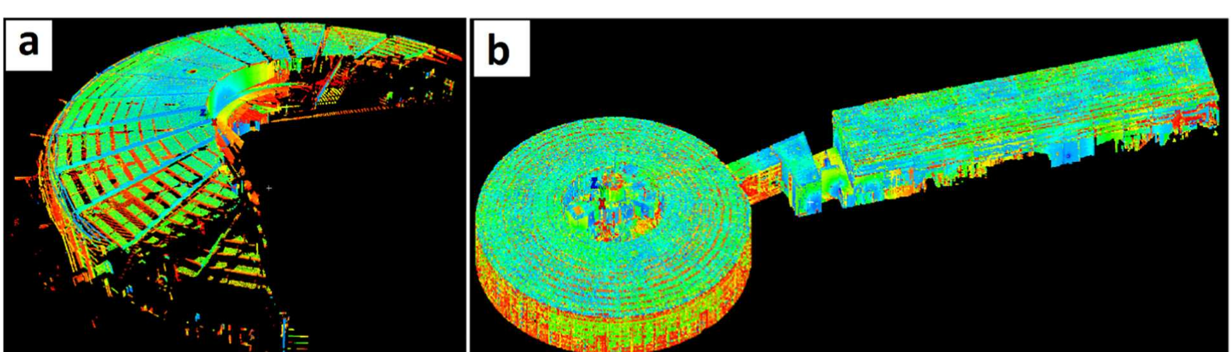

Fig. 5. (a) Point Cloud generated from a single laser scan of F2050, (b) Unified and cleaned Point Cloud of entire F2050 building.

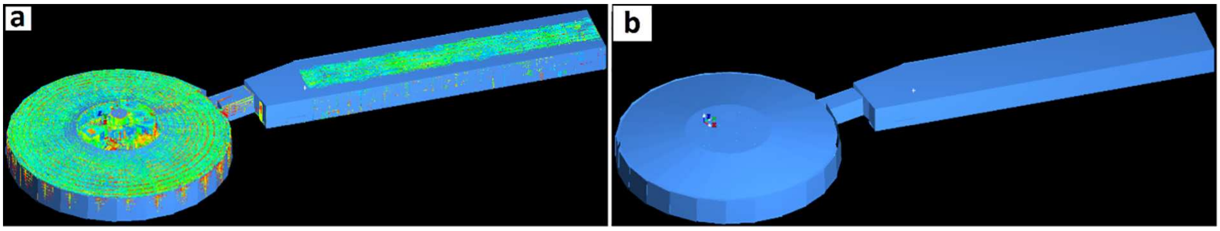

Fig. 6. (a) Unified Point Cloud with patches applied, (b) Generated patches isolated from Point Cloud.

Laser Scanner used, interpret the returned radiation from the glazing as being further away from the laser scanner than reality; this was observed by the large amount of erroneous points shown to be external of F2050, see Fig. 5a. The reflections within Point Clouds were observed to have low intensity. There are tools, within some Point Cloud processing software, that allows for removal of points in a particular intensity range however the tool operates as a blanket removal which may inadvertently remove low intensity points associated with solid surfaces. The use of multiple overlapping laser scans should militate against this risk.

The sole use of internal laser scans has meant that some geometry, not visible to the laser scanner, such as spaces above suspended ceilings on the 2nd floor has not been fully captured confirming observations by Volk et al. [23]. In addition, during the laser scanning process some internal areas such as locked rooms could not be accessed which again leaves geometry omitted from the Point Cloud. External building laser scans may improve this situation to capture the generic building envelope however access to the roof, if required, is not always practical with a static laser scanner and tripod; a drone mounted laser scanner is one possible solution that requires further research. This is likely to reduce the accuracy of a Laser Scan workflow but this is yet to be determined.

There is the potential for the incorporation of a Global Positioning System (GPS) or live streaming of captured laser scan data to improve the speed of laser scan registration during post-processing as well as enabling simple extraction of useful information such as wall thicknesses between rooms or the external shell of a building [41]. This area of research is out of the scope of this paper.

2.2. Geometry extraction from point cloud data

2.2.1. Existing software capabilities

Prior to BEM geometry extraction, some Point Cloud processing software does provide the functionality to manually clean the laser scans to remove erroneous points, such as reflections and then unify the individual clouds into a single Point Cloud. Having created a unified Point Cloud patches were applied to the geometry to investigate the built-in abilities of the software to generate walls, floors and ceilings, see the blue patches in Fig. 6a. This was a manual operation that required points on each surface to be manually selected as seed points from which each patch was automatically grown. Then adjacent patches were manually merged where applicable to form a single surface such as a wall.

Fig. 6b illustrates that following the generation of external building surface patches, that have been mapped onto the Point Cloud, the patches can be isolated from the Point Cloud. These were successfully exported as a ".coe" file which could be viewed in Revit 2017 [42] however the patches are considered to be raw data objects and unconnected which meant they could not be recognised as forming the boundaries of room/building boundaries in BEM where a FVM is most likely required.

The closed nature of commercial Point Cloud Processing software has highlighted that they may not be the best tools to develop further within this body of research and that examples from the existing research should be used to automate the Point Cloud conversion process and progress this technology application.

2.2.2. Capabilities of state-of-the art

As discussed in Section 1.1, the research conducted by Ochmann et al. [35], is able to reconstruct building geometry from a Point Cloud with good levels of success. One of the advantages of the presented method is the ability to model room separating walls; instead of two parallel planes/surfaces on either side of a wall. This simplifies the final model and enables adjacent thermal spaces to be easily identified for BEM applications. On obtaining the prototype that was produced for the DURAARK project [43] a single ".e57" laser scan for F2050 was run through the programme, the reconstruction results of which are shown in Fig. 7.

This illustrates promising results in identifying laser scan boundaries and some glazed surfaces however it is unable to handle high and sloped ceilings typical of industrial buildings. In providing a foundation it is well placed to be developed further in this research however it was unable to handle the full F2050 dataset or multiple stories. As a result, effective Point Cloud down-sampling strategies and a generalised multi-

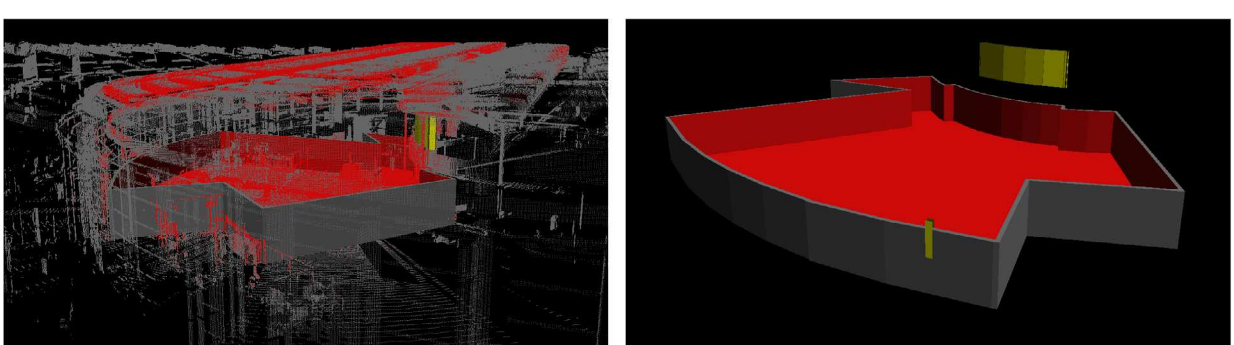

Fig. 7. (left) A single F2050 Point Cloud and the associated laser scan reconstruction, (right) the isolated reconstruction of a single F2050 laser scan.

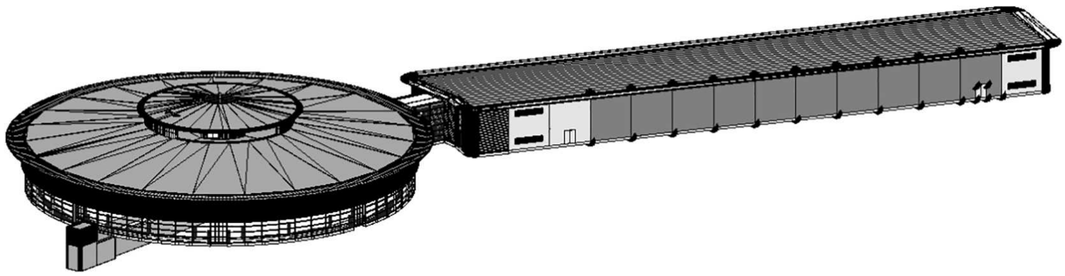

Fig. 8. F2050 BIM as viewed in Revit 2017 [42].

storey solution need to be a focus of future research.

On closer inspection of the source code, opening detection (windows, doors etc.) were assigned based on crude geometric shapes to differentiate them. In this particular area the work conducted by Xiong et al. [37] may prove useful in training the software for particular opening geometries. This is planned for future research.

2.3. BEM boundary conditions

In an effort to improve the BEM workflow any solutions developed must be compared with the more traditional BEM workflow to assess the accuracy of automated BEM geometry generation. In light of this a model of F2050 has been created in IES VE [5]. This section outlines the key assumptions and boundary conditions for the F2050 model. An IFC BIM file was provided for F2050 which contained a 3D model as well as floor plans, see Fig. 8.

The BEM model geometry can be considered of a reasonably high resolution in that it included all rooms, windows and doors within the building. In order to simplify the import process from Sketch-up [44] to IES VE [5] the annulus workshop geometry was split into multiple separate but simplified volumes resulting in 426 volumes. This aided room detection by the IES VE plug-in in Sketchup [45]. The final geometry of F2050, created manually, in IES VE is illustrated in Fig. 9.

Following geometry generation boundary conditions were applied to the model in order to run a thermal simulation of the building. These included construction material properties (Table 1), HVAC system, occupancy schedule and internal gain assumptions (Table 2). These assumptions were based on discussions with F2050 building/facility manager and industry guidance documents [46].

The final IES VE [5] boundary conditions that were defined were the location and orientation, relative to North, of F2050. This enables accurate SunCast (Solar Shading Analysis) simulations to be conducted on F2050 within IES VE, prior to a full thermal simulation, see Figs. 10–12. These results illustrate that the F2050 roofs and lower south facing walls receive the majority of solar gains throughout a year. The shading around the top of the building periphery minimises solar gains to the top of the south facing walls. This SunCast simulation also enabled the use of a localised weather file for 2016, using data sourced from the UK MET Office [47], that was applied to the model. It should be noted that the energy data used for validation is also based on 2016 measurements.

Due to the nature of how F2050 is used as a demonstrator plant with multiple, yet isolated and small manufacturing cells, it can be considered a low output industrial building; especially in comparison to typical automotive manufacturers that have very complex and high throughput production lines. As such it was deemed appropriate to not consider the use of Manufacturing Process Simulation (MPS) or its combination with BEM within this research. Rather, the equipment operated within the factory is assumed as internal gains with the appropriate value assumed for a density occupancy of general office of 16 m^2/person. This results in 12 W/m^2 internal gains as per the guidance in Table 6.1 in CIBSE Guide A [46]. The accuracy of this approach has been assessed through validation of the F2050 model described within this section. The results of the validation are presented in Section 3.

In producing a model of F2050 manually for BEM applications the disadvantages of this method were highlighted. The two primary disadvantages of manually creating models for use in BEM included (1) the complexities of having to re-create a building model from scratch, even though an existing BIM model was provided; and (2) the time taken to recreate the model took several weeks compared with a single week to laser scan a building.

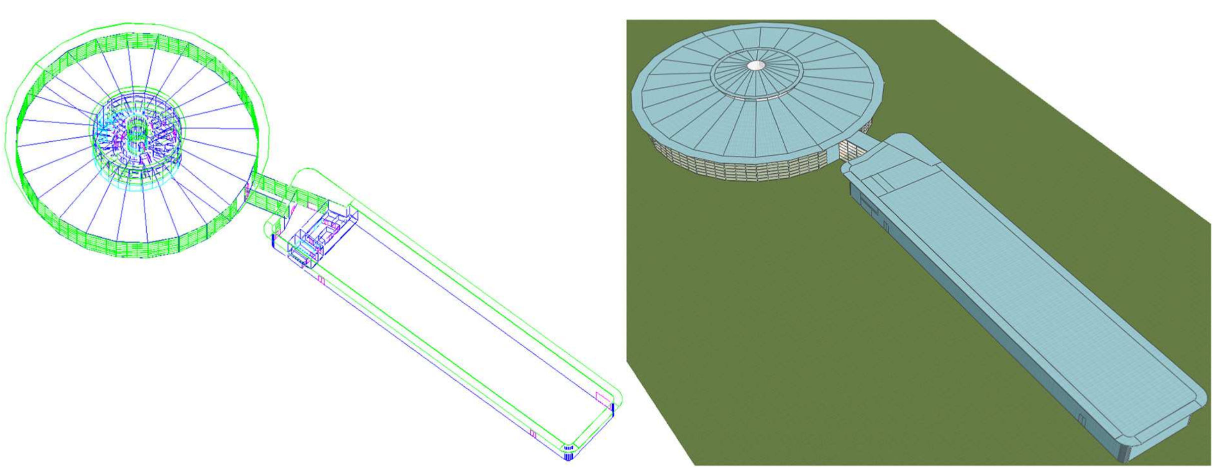

Fig. 9. Manually created IES VE Geometry of F2050.

Table 1
F2050 construction materials.

Parameters	Specification	U-value W/m^2K
External Walls	5 mm Lightweight Metallic Cladding – 70 mm Expanded Polystyrene (EPS) Slab – 1 mm Hardboard	0.453
Roof	12.7 mm Stone – 9.5 mm Felt & Membrane – 325 mm Insulation Board – 1.5 mm Steel Siding – 12.7 mm Cavity – 19.1 mm Acoustic Tile	0.121
Ground Floor	750 mm London Clay – 250 mm Brickwork – 100 mm Cast Concrete – 25 mm Dense EPS Slab – 25 mm Chipboard – 10 mm Synthetic Carpet	0.415
Window (External)	6 mm Glazing – 12 mm Cavity – 6 mm Glazing	2.86
Window (Internal)	12 mm Glazing	4.080
Window (Roof light)	8 mm Polycarbonate – 12 mm Cavity – 8 mm Polycarbonate	3.5
Doors (External)	6 mm Glazing – 12 mm Cavity – 6 mm Glazing	2.86
Doors (Internal)	6 mm Plywood (Heavyweight) – 30 mm Cavity – 6 mm Plywood (Heavyweight)	2.288
Internal Partition	12 mm Plasterboard – 50 mm Cavity – 12 mm Plasterboard	1.892
Internal Ceiling/Floor	20 mm Chipboard – 50 mm Cavity – 50 mm SCREED – 100 mm Reinforced Concrete – 50 mm Cavity – 12.5 mm Plasterboard	1.048

Table 2
F2050 boundary conditions.

Parameters	Set values
Active heating	Central heating convectorsHeat pump (electric) : ground or water source Electricity
Active cooling	Air-conditioning Electricity
HVAC setting/Set-point	21 °C
Hours of operation	On 24 h (Weekdays) On 24 h (Weekends)
Occupancy schedule	08:00–17:00 (Weekdays)
Internal gains	– 8 W/m^2 [46]
– Fluorescent Lighting	– 50 occupants, 74 W/m^2 Sensible [46], 56 W/m^2 Latent [46]
– People	
– Misc. Equipment	– 12 W/m^2 [46]
– Air Exchanges per Hour	– 0.167

3. Results and discussion

3.1. gbXML framework

The file format gbXML [25] exists for storing data describing building data for a range of sustainability purposes including BEM and can be read/imported by a variety of different BEM software such as IES VE [5] and popular BIM software (e.g. Revit 2017 [42]). This represents an opportunity for processing laser scans of a building and automatically populating gbXML building data thus reducing workflow bottlenecks and enabling quicker BEM assessments to take place.

gbXML is written in the computing language XML and is written in accordance with rules specified in the latest gbXML Schema Definition (XSD). This is a definition document that specifies all the mandatory and optional XML elements that can be contained, within a gbXML file, to describe a building. At the time of writing the latest gbXML schema is version 6.01 [26]. For the application posed in this research any gbXML

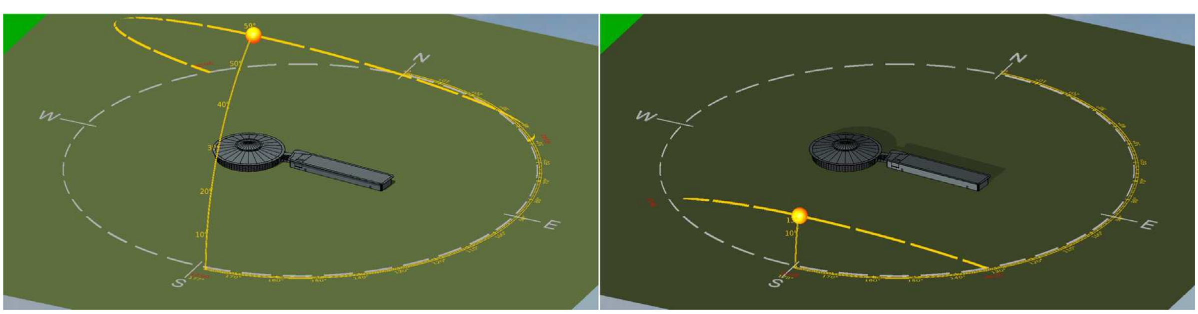

Fig. 10. (left) F2050 Summer Solstice View, (right) F2050 Winter Solstice View.

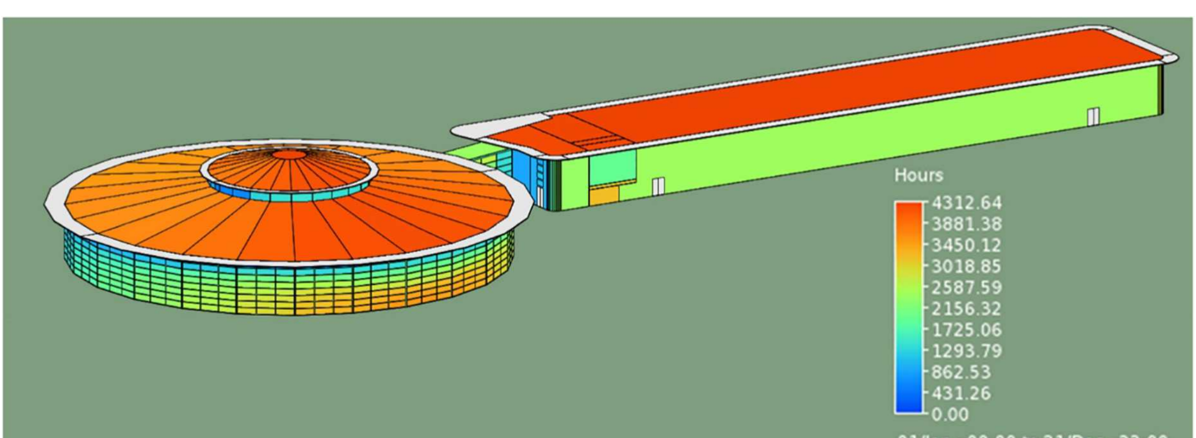

Fig. 11. Distribution of Annual Solar Exposure of F2050 (h).

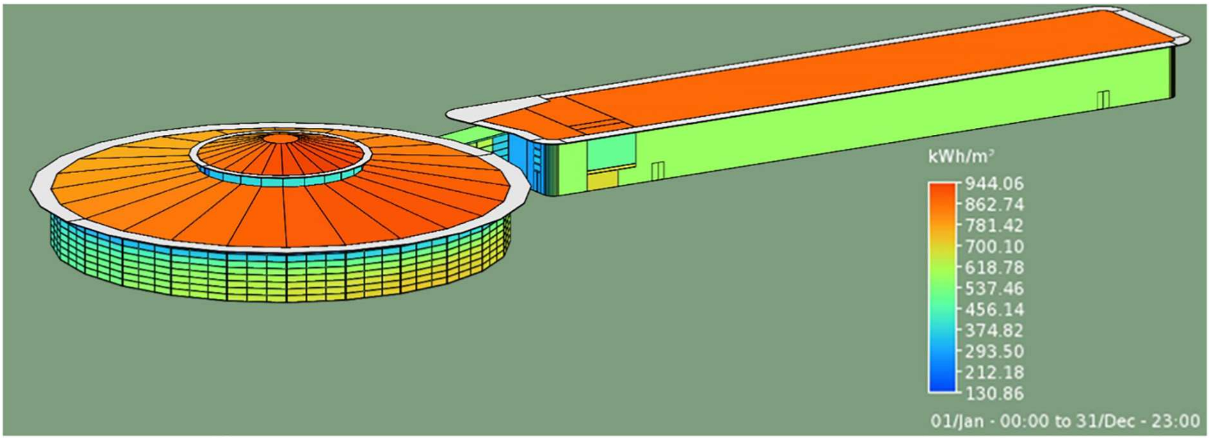

Fig. 12. Distribution of Annual Solar Exposure of F2050 (kWh/m^2).

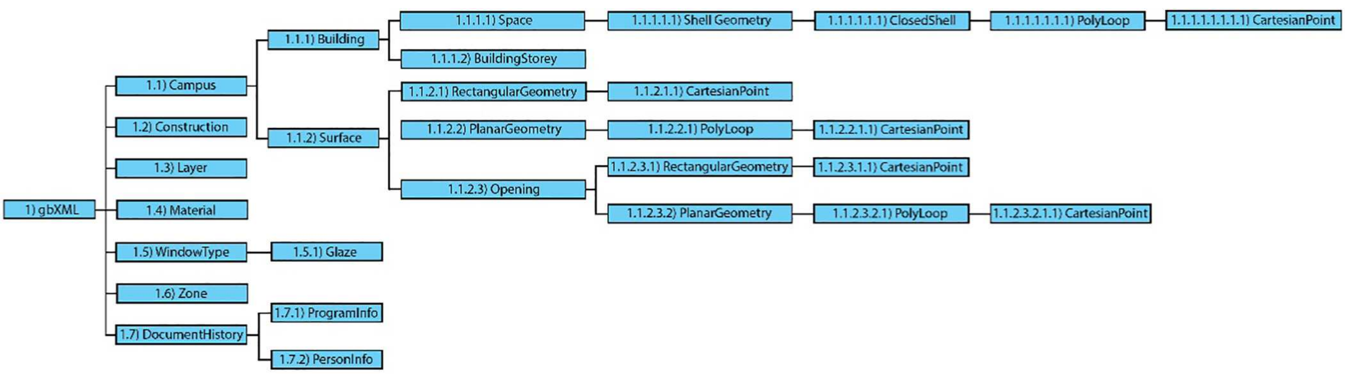

Fig. 13. Minimum Framework of gbXML elements required for geometry extraction from Point Clouds.

file created must have a specific minimum amount of information generated in order for gbXML schema validation checks to be successful. These validation checks are merely an inspection on the way the gbXML file has be written and not necessarily on the quality of the captured building geometry, however, it is extremely important for the portability of any gbXML file to be read correctly by third party software.

Building on the simple framework presented by Wang and Cho [27], the full framework of gbXML elements required to conform to gbXML validation checks, using gbXML schema version 6.01 [26], when extracting geometry from Point Clouds is illustrated in Fig. 13 and further details are tabulated in Table 3.

It should be noted that this framework illustrates the elements required as a minimum however there are a large number of other potential elements, defined in the gbXML XSD, that may be used in addition to those presented.

By incorporating the above framework onto the Point Cloud processing methodology, developed by Ochmann et al. [35], a sample gbXML file has been produced from the same ".e57" format F2050 laser scan illustrated in Fig. 7 that meets the required gbXML validation criteria [48]. This is illustrated in Fig. 14 and has been viewed in DDS-CAD Viewer [49]. The gbXML reconstruction clearly shows identified openings such as doors and windows and will be used to identify improvements to the gbXML generation in future work as well as IES VE [5].

Table 3
Terminating child elements of gbXML framework.

Number	Terminating child elements
1.1	Name
1.1.1.1	Name
	Area
	Volume
	TypeCode
1.1.1.1.1.1.1.1	Coordinate
1.1.1.2	Name
	Level
1.1.2	AdjacentSpaceId
1.1.2.1	Azimuth
	Tilt
	Height
	Width
1.1.2.1.1	Coordinate
1.1.2.2.1	Coordinate
1.1.2.3.1	Height
	Width
1.1.2.3.1.1	Coordinate
1.1.2.3.2.1.1	Coordinate

3.2. Validation

The research presented illustrates that existing Point Cloud processing software and previous research efforts have the potential to be developed further for the purposes of extracting as-built geometry that can be fed into BEM software. Existing Point Cloud processing could be automated by feeding the Point Cloud through a processing algorithm, such as those found within the literature. Such an algorithm should distinguish other features useful for BEM such as holes, windows and doors in thermal surfaces. The ability to join the patches together as intersecting surfaces will also be extremely beneficial in creating thermal volumes as part of the BEM workflow. Areas for development include the ability to handle more complex geometries, multiple stories and larger spaces as well as training the software, at run-time, for more

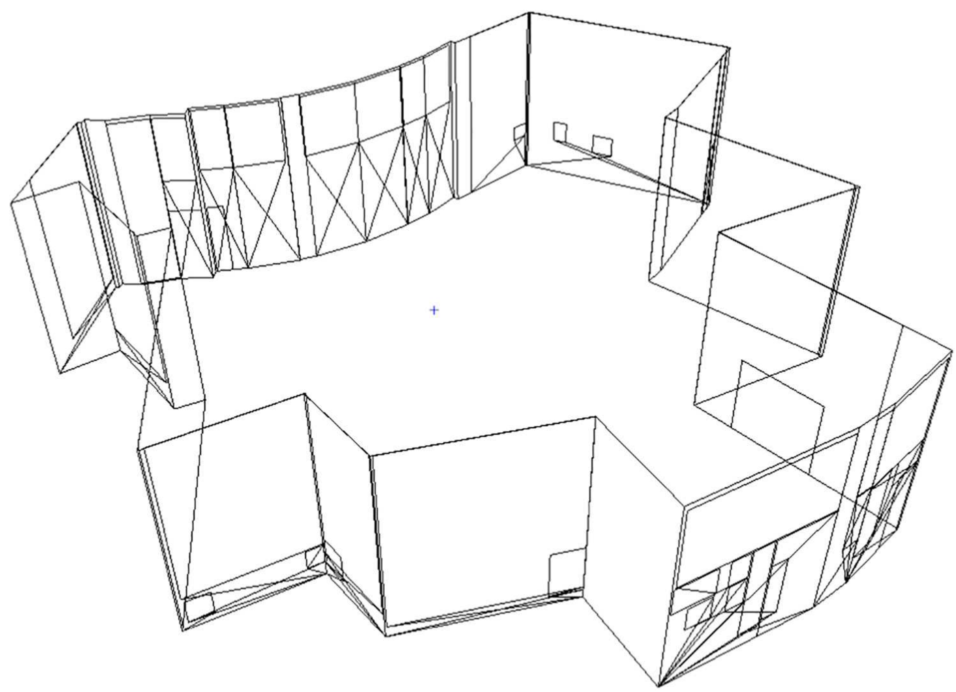

Fig. 14. Sample gbXML file generated from a single F2050 laser scan.

robust identification of occluded surface openings such as doors and windows.

If building energy model geometry generation from laser scan data can be developed further and is successful, it is important that the accuracy of the thermal simulation can be adequately guaranteed. For this purpose, in parallel with the work outlined previously, a building energy model of F2050 has been created manually as described in Section 2.3. It was noted during this process that geometry creation was the most time consuming aspect, taking several weeks, thus reinforcing the potential benefits of an automated process using Point Clouds for BEM, especially considering the novel geometry of F2050.

The appropriate boundary conditions applied to the F2050 energy model will be the same conditions applied to any thermal models generated from laser scan data for consistency. It should be noted that the results from the manual modelling method, see Fig. 15, have been validated separately.

ASHRAE Guideline 14-2002 [50] was utilised in order to validate the results illustrated in Fig. 15. This guidance calls two indices to represent how well a simulated model describes the variability in measured data. These indices include the Coefficient of Variation of the Root Mean Square Error (CVRMSE) and Normalised Mean Bias Error (NMBE) which are determined by comparing simulation-predicted data

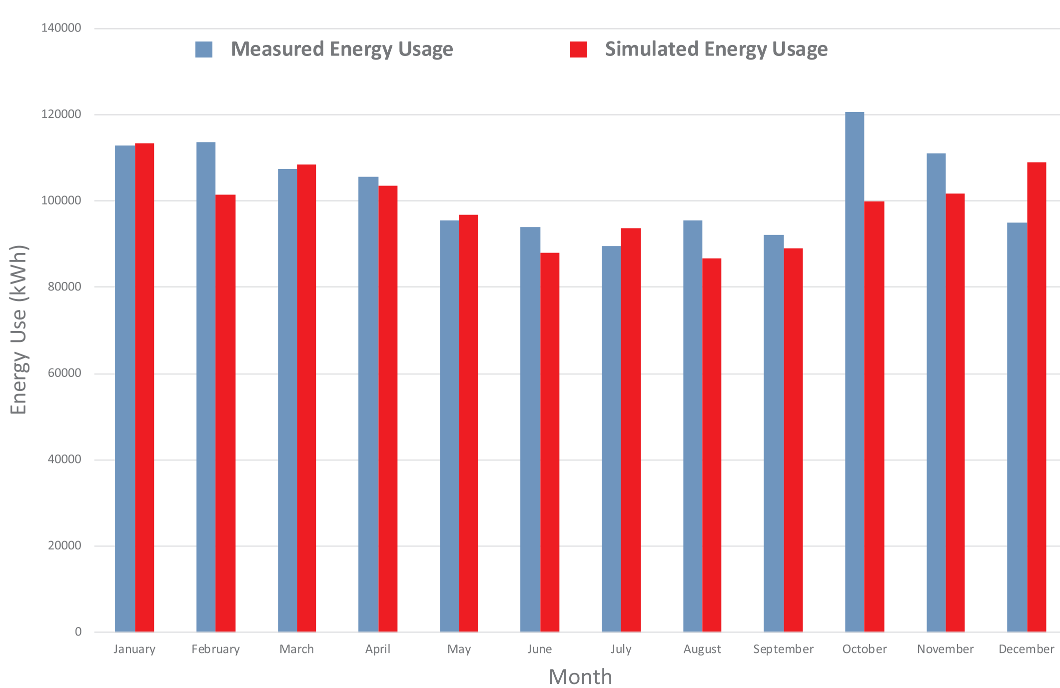

Fig. 15. Validation of the simulated total energy use (heating, cooling, lighting, equipment) in F2050 for 2016.

($\hat{y}$) to the data from energy bills for F2050 (y_i), with p, the number of parameters or terms in the baseline model, as developed by a mathematical analysis of the baseline data, set to 1. The corresponding equations for these indices are shown in Eqs. (3.1) and (3.2) respectively.

$$CVRMSE = 100 \times \frac{\left(\frac{\sum (y_i - \hat{y})^2}{(n-p)}\right)^{\frac{1}{2}}}{\hat{y}} \tag{3.1}$$

$$NMBE = 100 \times \frac{(\sum^n (y_i - \hat{y}))}{(n-p) \times \hat{y}} \tag{3.2}$$

ASHRAE Guideline 14-2002 [50] specifies limits on CVRMSE and NMBE of 15% and 5% respectively for a calibrated building model using monthly data. With respect to validation of the F2050 thermal simulation the CVRMSE and NMBE have been calculated at 12.13% and 3.66% respectively and can therefore be considered validated.

Importantly this model provides a validation benchmark against annual energy bills for a consecutive 12-month period from F2050 in 2016 to compare potential energy interventions with any BEM workflow developments.

These results, although validated, do offer insight into the relative levels of uncertainty that is accepted within the current best-practice of BEM; improving this best practice is the subject of existing research outside the scope of this paper [51–60].

The results for February, October and November, shown in Fig. 15, illustrate large discrepancies compared with other months. Although not required by the validation guidelines the difference between the measured and simulated energy use for each individual month has also been assessed. Over the 12-month period the total percentage discrepancy between measured energy use and simulated energy use was −3.3% however much larger discrepancies can be seen in the individual months. The largest negative discrepancy, where the simulated energy use was below the measured energy use occurred in October at −17.06%. Conversely the largest positive discrepancy occurred in December at +14.81%. Unfortunately, there is no specific guidance on what constitutes the maximum allowable individual discrepancies in these simulations.

The reliance on CVRSME and NMBE do allow for anomalous results to occur within a dataset to a certain degree. Coakley et al. [53] even identify that discrepancies of up to 100% have been identified between measured and simulated energy use values. There are several possible reasons for this discrepancy, as several key assumptions were made during the BEM model creation, and improvements could be made by rationalising some of the assumptions more thoroughly. However, this may not always be that easy without considerable effort and cost. It is the responsibility of the engineer, performing the BEM analysis, to determine the most appropriate level of detail required for the intended application.

For the purposes of this research, in comparing an automated reconstruction against a validated baseline, that represents an existing building, the effort in producing valid assumptions that can be repeated on the reconstruction is deemed sufficient.

The full building F2050 Point Cloud presented in this research has not been reduced in size and consists of approximately 676 million individual points. In order to improve the efficiency, of any geometry creation algorithm, research will be conducted into the optimum downsizing of a Point Cloud. This can be achieved by increasing the average spacing between individual points to reduce requirements on computing power. In addition, research needs to be undertaken on the optimum level of detail required for BEM as fine details such as light switches and power sockets are not required. For example, increasing the average point spacing, using Point Cloud processing software, to 1000 *mm* in the F2050 Point Cloud reduces the number of data points to 135,177. This has the potential to drastically reduce processing times with smaller data files but the effect on BEM accuracy is unknown.

Applying BEM to a manufacturing environment is useful, however, the incorporation of a MPS, that includes equipment energy use, would further improve the methodology through a holistic approach to energy modelling within a factory. This improvement would be achieved by considering the energy use of machines and manufacturing processes as well as building systems where appropriate. Such an approach could provide an even greater opportunity for reducing the energy demand of manufacturing facilities via retrofit projects. Garwood et al. [19] have reviewed previous attempts at combining BEM and MPS and promising opportunities have been identified for developing a holistic manufacturing energy simulation. There is the potential for the work presented in this research to be expanded into a “Laser Scan to BEM&MPS” best practice workflow and guidance.

4. Conclusions

gbXML has been identified as a promising file format candidate for interoperability between different BEM packages and this research has outlined the required gbXML framework for Point Cloud geometry extraction. Using such a framework in future research will enable generated gbXML files to meet the validation requirements of gbXML XSD V6.01 [26].

A potential solution has been identified for increasing the speed of 3D geometry creation of an existing industrial building for application in Building Energy Modelling. A suitable method of validation has also been identified by comparing the results with that of a manually created building energy model. This will enable result discrepancies to be identified to enable iterative improvements to the automated process as illustrated in Fig. 4. In addition, this comparison will highlight the advantages and disadvantages of using an automated process over the manual process. Such information can then feed into a best practice workflow and guidance for industry. This will support smarter and more cost effective decisions to be made prior to carrying out Building Energy Modelling on existing industrial facilities.

Areas for Point Cloud processing development have been identified as including the ability to handle more complex geometries, multiple stories and larger spaces as well as more robust identification of occluded surface openings such as doors and windows. The work by Ochmann et al. [35] and Xiong et al. [37] have been identified as the most promising research to build on.

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