Towards Integrating BIM and GIS—An End-to-End Example from Point Cloud to Analysis

Claire Ellul, Gareth Boyes, Charles Thomson and Dietmar Backes

Abstract Building Information Modelling (BIM) is becoming increasingly important within the UK, not least because of a UK Government directive that mandates Level 2 BIM for companies tendering for Government work, with the aim of reducing the cost of construction of public assets by 20–30 %. While this is aimed at new construction, it can be foreseen that a wider introduction of BIM could also result in savings during large refurbishment projects, which form a significant part of construction work in the UK, as well as during the occupancy phase of the building. However, unlike new projects, where the model for the BIM can be obtained from CAD drawings, deriving a detailed BIM for pre-existing structures requires some form of scan-to-BIM operation using laser scanning. To contribute to sustainability in construction, an underlying driver for BIM, the BIM must also be integrated with other data sources. Therefore, once the scan is complete, the resulting point cloud must be converted into geometry objects and geo-referenced for integration with Geographical data such as air quality or noise information. This paper presents an end-to-end example of this process, focusing in particular on the challenges of integrating BIM and GIS into one framework, and highlighting preliminary steps to be carried out during BIM creation in order to enable this to take place.

Keywords BIM · 3D GIS · Integration · Environmental data · Spatial databases

1 Introduction

A sustainable built environment should minimise whole-life carbon and material costs through efficient use of resources (energy, waste, water), contribute to the physical and mental health of its users, enhance productivity and be adaptable for future uses (Sustainable Development Commission 2011). Building Information Models

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(BIM) aim to improve sustainability by giving architects and engineers access to a wealth of detail and digital information about a projects construction and maintenance through its life-cycle, providing an improved, collaborative, efficient way of working. They are of great interest to major Civil Engineering and other construction projects in the United Kingdom (UK), not least because of the UK Governments requirement for "fully collaborative 3D [three dimensional] BIM (with all project information and data being electronic) as a minimum by 2016" (Cabinet Office 2011).

While much focus has been given to questions relating to the definition of BIM (see Sect. 2.1), and to the creation of BIM for new projects, to date, less research has been targeted at creating BIM for existing buildings (either for facilities management or as part of a retro-fit process). Additionally, a major challenge that currently prevents BIM from achieving its full potential for improving sustainability (and reducing cost) in construction is the lack of integration of data held within BIM with other sources of data about the wider context of the built environment for example details about the urban landscape, traffic congestion, air quality, noise, flooding, population demographics, maintenance and staffing schedules, infrastructure such as water pipes, drains, fibre-optic cables. These types of information are commonly held in a Geographical Information System (GIS) and integration with BIM could answer questions such as "Where is the nearest supplier of concrete (GIS), when and how much should I order (BIM)?", " How do I route plasterboard to my site (GIS) and where do I need to store it on site for maximum convenience (BIM)?", "Is the current capacity of the drainage system (GIS) sufficient for this new construction (BIM)?", "What is the flood risk in this underground station (GIS) and what internal wiring will be damaged in different flooding scenarios (BIM)?"

Integration between BIM and GIS is required if BIM is to meet its goal to support a sustainable built environment. Indeed, "BIM is about infrastructure, and therefore GIS is critical to its delivery" (Kemp 2011) and predicted savings of $15.8 billion per year could be made from integrated processes (Kemp 2011). However, there is currently no clear path to interoperability or integration between GIS and BIM. This is in part a technical challenge (e.g. incompatible data formats) but is also a conceptual challenge as the gap between two approaches to modelling the world must be bridged.

A number of case studies (Sebastian et al. 2013; Irizarry et al. 2013; Zhang et al. 2009) illustrate the potential of the integration of these two sources of information and (El Meouche et al. 2013) have reviewed software based approaches to this problem. However, to date it is difficult to find a case study relating to the creation of a BIM of an existing building and its subsequent integration with GIS data. A first example of this end to end process is presented in this paper. We describe the creation of a BIM for the Chadwick Building (home of the Department of Civil, Environmental and Geomatic Engineering—CEGE—at University College London) and the subsequent integration of this BIM with noise and air quality data collected via GPS-enabled sensor devices as part of the EveryAware Citizen Science research project (Loreto 2012). The result shows the potential of such integration for an investigation into noise and air quality distribution around the building, and importantly also highlights some integration challenges that could be overcome by providing appropriate BIM capture guidelines early on.

The remainder of this paper is structured as follows—Sect. 2 provides background information on BIM and GIS integration. Section 3 describes the data used in the project, and Sect. 4 presents the process used to integrate the disparate data sources. Section 5 provides a discussion of some of the issues encountered, leading to recommendations for BIM capture in future projects.

2 Background

2.1 Building Information Modelling

Building Information Modelling (BIM) is a comprehensive process that enables parties in the Architecture Engineering and Construction industries to collaborate on a project. The UK BIM Task Group defines BIM as value creating collaboration through the entire life-cycle of an asset, underpinned by the creation, collation and exchange of shared 3D models and the intelligent, structured data attached to them (Building Information Modelling Task Group 2013). In general, the aim of BIM is to improve the performance of infrastructure, reduce waste, increase resource efficiency, reduce risk, increase resilience and increase integration (Kemp 2011).

The acronym BIM has acquired different meanings in different contexts. In one sense it is the corporate attitude needed to ensure that collaboration succeeds and the management of information and the complex relationships between social and technical resources that represent the complexity, collaboration, and interrelationships (Jernigan 2008). The second sense of the acronym BIM refers to the server network and software tools that store, construct and visualise the 3D model. The 3D model is then the final sense of the BIM acronym, and the focus of this research. This model is built up from parametric objects representing building components in object-orientated software. These parametric objects may be geometric or non-geometric and are attributed with functional, semantic or topologic information (Volk et al. 2014).

The development of BIM can be graphically represented by the BIM wedge in Fig. 1 with the different maturity levels being summarised in Table 1 (Building Information Modelling Task Group 2013). The UK Government has mandated that all government construction contracts must incorporate fully collaborative Level 2 BIM (with all project and asset information, documentation and 3D data being held electronically) as a minimum by 2016 (Cabinet Office, 2011). In the UK, 39 % of 1350 participants at the National Building Specification survey between December 2012 and February 2013 responded that they were using BIM and 71 % agreed that BIM represents the future of project information (Zeiss 2013).

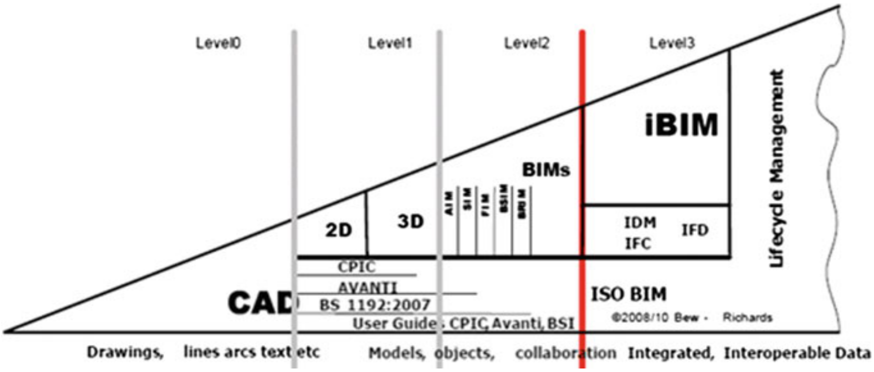

Fig. 1 Levels of building information modelling, (Building Information Modelling Task Group 2013)

Table 1 BIM levels

Maturity level	Description
Level 0	Unmanaged 2D CAD
	Paper or electronic paper
Level 1	Managed 2D/3D CAD
	Collaboration tools provide a common data environment
Level 2	Proprietary BIM (pBIM)
	Managed 3D BIM data held in BIM software (e.g. Revit)
	Integration on the basis of proprietary interfaces
Level 3	Integrated BIM (iBIM)
	3D BIM in IFC format enabled by web services
	Managed through a collaborative model server

2.2 *Comparing BIM and GIS*

BIM has been stated to be "a modelling technology that combines the design and visualisation capabilities of CAD with the rich parametric object and attribute modelling of GIS" and unlike Computer Aided Design (CAD) entities are meaningful (Casey and Vankadara 2010)—i.e. walls and windows are modelled as such. This broad definition, at first glance, is similar to that for a GIS, which models both attributes and geometry. Both can model the built environment in 3D and both can model both indoor and outdoor features within this environment. Additionally, both BIM and GIS data can be managed in a Database Management System (although for BIM this is usually just done for storage purposes rather than offering direct query capabilities). They both provide efficient methods for the documenting, editing, managing and visualising spatial and non-spatial information, and both can represent the world 'as is' and also model historic data and future planning and modelling outcomes, and model data at varying scales. BIM has been stated to be "a modelling technology that combines the design and visualisation capabilities of CAD with the rich parametric object and attribute modelling of GIS" and unlike Computer Aided Design (CAD) entities are meaningful (Casey and Vankadara 2010)—i.e. walls and windows are modelled as such. This broad definition, at first glance, is similar to that for a GIS, which models both attributes and geometry. As can be seen by comparing the descriptions of IFC (in Sect. 2.4) and CityGML in Kolbe et al. (2005) Level of Detail 4, both can model the built environment in 3D and both can model both indoor and outdoor features within this environment. Additionally, both BIM and GIS data can be managed in a Database Management System (although for BIM this is usually just done for storage purposes rather than offering direct query capabilities). They both provide efficient methods for the documenting, editing, managing and visualising spatial and non-spatial information, and both can represent the world 'as is' and also model historic data and future planning and modelling outcomes, and model data at varying scales.

However, a number of key differences exist which present a challenge to interoperability, in part due to their different origins. Interoperability is defined as "the ability of two or more information systems to share data, information or processing capabilities" Worboys and Duckham (2004). Bishr (1998) identifies three types of interoperability:

1. **Semantic**—looks at the interaction of two or more systems without a pre-defined or agreed upon interface, assuming that the meaning of the objects is embedded in the objects themselves—a fact can have more than one description, for example a road can also be called a street
2. **Schematic** —the same object in the real world is represented using different concepts in the database i.e. it is an object in one database and a property in another—for example the publisher of a book can be a property of the book, but also a separate entity
3. **Syntactic** —the databases use different paradigms e.g. relational or object-oriented models or rasters versus vectors

While initially it may appear that issues preventing BIM and GIS integration relate primarily to syntactic interoperability, and in particular to data exchange formats, schematic issues and semantic issues are of great relevance, in particular given the diverse origins of the two domains. BIM modelling developed within the Computer Aided Design (CAD) world as a specialised process for designing infrastructure and buildings for construction. GIS on the other hand developed from the need to record and manage information already in existence, and models not only the built environment but also demographics, transportation, natural resources, disease spread and many other areas. It addresses the who, what when why how and also what exists at a particular location, what has changed over time, what spatial patterns exist buffering, proximity analysis, spatial modelling tools (Casey and Vankadara 2010) and is particularly strong when integrating spatial and non-spatial data.

Authors including (Pu and Zlatanova 2006; Kemp 2011; Casey and Vankadara 2010; Cowen 1988; Zhang et al. 2009 and Zlatanova and Prosperi 2006) list the following key differences:

For BIM the visual representation of an engineering project provides the primary source of information with semantic information, such as construction material, represented by patterns and hatching. Building elements modelled include railings, plates, ramps, slabs, stairs and walls. Extensive, detailed, 3D models including wall thicknesses and other structural details can be visualised. BIM models are standalone (single project) with no link to their real-world location. Additionally, for pre-existing buildings or infrastructure, geometry is often generated by laser-scanning, which can cause issues with completeness.

In contrast, for GIS, very rich semantic information (attributes) can be stored alongside geometric representations of features as spatial data. In many cases, such data is stored in a spatially-enabled relational database facilitating interoperability with other data via queries. Information is located within both local and global spatial reference frameworks, making it easy to interrogate the data based on location (e.g. what buildings are within 100 m of this point?, what is under this road?). However, detailed 3D geometry is not well modelled e.g. a wall is represented as a line, no matter its thickness or construction material.

2.3 Previous Attempts at BIM/GIS Integration

A number of authors describe work towards BIM and GIS integration, with particular focus on transforming Industry Foundation Class data (IFC) to CityGML (Kolbe et al. 2005). While much of this is uni-directional (e.g. El-Mekawy et al. 2011; Hijazi et al. 2011; Tobiáš 2015), bi-directional integration has also been attempted, with (El-Mekawy et al. 2011) presenting an intermediate 'neutral' model that acts as a staging point between the two. Semantic interoperability (Casey and Vankadara 2010; El-Mekawy et al. 2012), is a core focus of these efforts, which create a number of domain ontologies to identify the important objects and classes on either side of the integration.

Implementing this theoretical approach at a more practical level, (El Meouche et al. 2013) examine syntactic interoperability, providing a review of potential software packages for data interchange between the various systems. Application-based case studies include (Sebastian et al. 2013) who describe the process of migrating IFC data into CityGML Level 4 to support noise and disturbance modelling in the construction and maintenance of bridges. An application domain extension (ADE) to CityGML is developed for this purpose, and two case studies (in Spain and The Netherlands) are presented. Integration permits a detailed focus on worker and resident safety, noise and traffic disruptions. A second example transforms utility network information (inside a building) from IFC to CityGML, again creating an ADE for the purpose. A 1:1 mapping between IFC and ADE is achieved in the majority of the cases (Hijazi et al. 2011). Additional research into utilising BIM and GIS for flood damage investigation is presented by Amirebrahimi et al. (2015).

2.4 Industry Foundation Classes

The IFC (industry foundation classes) exchange format was developed by the International Alliance for Interoperability (now known as building SMART) and provides a formalized representation of typical building components e.g. wall, door, and their attributes e.g. type, function, geometric description, relationships. It also supports topological information ("connected to") and abstract concepts such as schedules, activities and construction costs (Casey and Vankadara 2010). Unlike CAD, objects are grouped into logical entities (classes, with properties such as name, materials, relationships, constraints)—i.e. a wall is an object with attributes rather than just a collection of lines (much like standard GIS modelling). Product information is grouped according to construction trade—such as HVAC, building controls, electrical, plumbing, fire protection, structural elements (Casey and Vankadara 2010). Full details of the IFC standard can be found on the Building Smart website (Building Smart 2015a).

3 Data

3.1 Preparing the BIM

The data being used in this project is a BIM of University College London's Chadwick Building (Fig. 2). The full process of creating the BIM is described in Backes et al. (2012, 2014).

The Chadwick is a Grade I listed building and as such is subject to stringent policies and planning procedures regarding building works and the model was constructed via terrestrial laser scanning. Terrestrial laser scanners generally make use of a beam of laser light that is either pulsed or phase modulated and by calculating the time delay between the out and return in the former or the phase shift in the latter. Each scan creates a volume of 3D point measurements called a pointcloud that can also be coloured if imagery is captured as part of the capture process. For the Chadwick BIM, multiple scans were required to capture areas within the building by moving the instrument to mitigate shadows from obstacles in the line-of-sight of the scanner. To bring the pointclouds from different setups together, a registration process is required. This identified common features in the scenes and made use of strategically placed targets to align the scans.

The scanning project was carried out over the course of ten weeks with the help of four engineering undergraduates and the majority of the scans were captured to

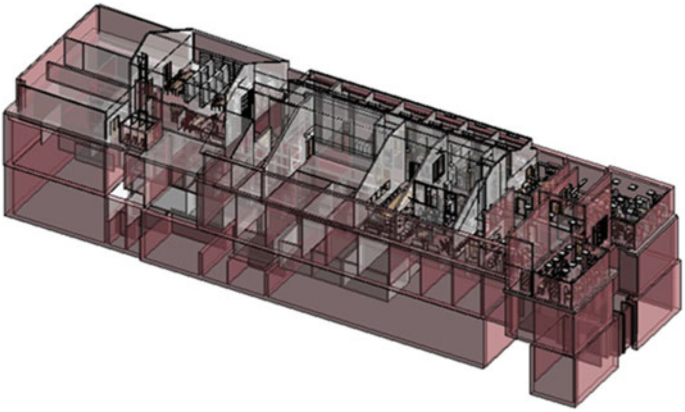

Fig. 2 Chadwick BIM

provide at least 8 mm sampling density (Backes et al. 2014). A typical scan contained about 27 million points and about 250 MB in size (Backes et al. 2014). The resulting point clouds were stitched together and were used as a guide to create the geometric elements of the model, within Autodesk's Revit Software. For the first floor test area (which is the focus of the integration study described in this paper), the resulting geometry was created with a relatively low level of detail—i.e. detail such as sockets and so forth was omitted and only walls, floors and ceilings modelled. Walls were assumed to be the blank space between scans of adjacent rooms and the scans were supplemented with an internal survey of the building. Figure 2 shows the resulting BIM.

3.2 Capturing the Noise and Air Quality Data

The noise and air quality data forming part of this study were captured as part of a separate project evaluating the potential of low-cost sensors for crowd sourcing of such data. The EveryAware project (Loreto 2012) designed and developed an App—Widenoise—to enable mobile phone users to measure sound levels, annotate them and then upload these to a central map. Each noise measurement is 30 s in duration, and the measuring process is manually triggered by the user. An air-quality sensor box that can be coupled to a mobile phone App via blue tooth was developed to allow continual monitoring of the environment (i.e. no user intervention required). Details of Widenoise can be found in Loreto (2013) and of the AirProbe system in Chap. 1 in Loreto (2014). Noise data was captured over a 2-day period at various locations around the Chadwick Building, with air quality data captured by leaving the sensor boxes in fixed locations for 24 h intervals. In both cases, given that the sensors were designed for outdoor use, the data was tagged to ensure that it's indoor capture location could be identified during post-processing. Within the Chadwick Building, a total of 420 noise points and 4161 air quality points were captured.

4 Integrating the Data

4.1 Geo-Locating the BIM

Figure 3 shows the first floor of the Chadwick building, with the ceilings removed. As noted above, the BIM coordinate system maintains a local reference and the geometry must therefore be geo-located prior to integration—in this case, into British National Grid. This can be performed within AutoDesk Revit (Autodesk 2015a) by identifying a number of coordinate points at the base of the building by using 1:1250 topographic mapping provided by the UK National Mapping Agency, the Ordnance Survey. Within Revit, the "Specify Coordinate at a Point" option can be used to transform the points. It is also important to change the units within Revit—as noted in Section Table 2 one of the key differences between BIM and GIS is the scale. Units can be changed from millimeters to meters via the "Project Units" option in Revit.

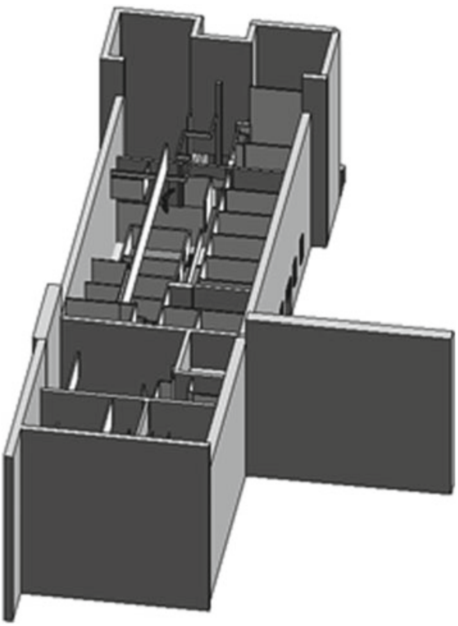

Fig. 3 CEGE BIM—first floor

Table 2 BIM versus GIS

BIM	GIS
Describes buildings and facilities very detailed, mm measurement units	Describes buildings, entire sites, regions or countries, meter measurement units
Initiated during procurement phase of facility lifecycle, focussed on built environment	Wide-ranging focus
Used to organise information to specific contractual deliverables	Used to organise multiple types of information, and to integrate spatial and non-spatial information
Very sophisticated 3D geometry can be modelled—B-Rep, NURBS, Splines and CSG	Less sophisticated geometrically, mostly 2D, B-Rep for 3D
Focus on geometry, primarily on construction materials	Focus on generic geometry, attributes and sophisticated spatial analysis
No ability to model networks	Models networks and connectivity
Basic database integration	Sophisticated database integration
Local coordinate systems generally used	Regional, National or Global Coordinate Systems

4.2 Converting the BIM to GIS

Once the data is appropriately positioned and units set, the Autodesk Revit suite (Autodesk 2015a) offers the option to export data into the neutral IFC format described in Sect. 2.4. To minimise export time the "Export Base Quantities" box should be unchecked and the "Split Walls and Columns by Story" checked. The IFC file can then be imported into a GIS using the SafeSoft FME suite (Safe Software (n.d)) which permits a direct translation of an IFC file into a spatial database. Given it's more advanced 3D spatial query functionality, Oracle Spatial (Oracle 2013) was used in this case. The resulting data is automatically divided into a number of layers that correspond to the IFC Elements provided by the schema, such as IFCWall, IFCSlab_solid, IFC_Stair, IFCWallStandardCase. A summary of the key resulting layers is given in Table 3.

A total of 65 layers and tables were created by the conversion process, with 47 of these having no associated geometry. These are used to store additional information such as the relationships between objects, additional descriptors for objects (e.g. door panel or lining properties) and project related information (ownership and organisation details).

4.3 Geo-Locating the Noise and Air Quality Data

As can be expected, the use of GPS to capture positional information for the noise and air quality data proved problematic indoors. However, the EveryAware Apps

Table 3 GIS layers from the Chadwick BIM

Number of objects	Layer description
118	IFCBuildingElementProxy used to model monitors and notice boards
1	IFCColumn used to model a supporting column
16	IFCCovering ceiling elements
52	IFCDoor
282	IFCFurnishingElements for chairs, wall units, desks and shelving
78	IFCOpeningElements
15	IFCPlates used to model internal glass walls
2	IFCSlabs
1	IFCStair
16	IFCWall
309	IFCWallStandardCase
33	IFCWindow

provided for each measurement device also permitted each sample to be tagged. A map was created sub-dividing the internal space on the first floor of the Chadwick building into grids and each measurement tagged to allow geo-referencing. All data was imported into QGIS and edited to translate it into the correct location manually.

Figure 4 shows the resulting integrated data, with additional points outside the building being related to other EveryAware sensing activities carried out on the

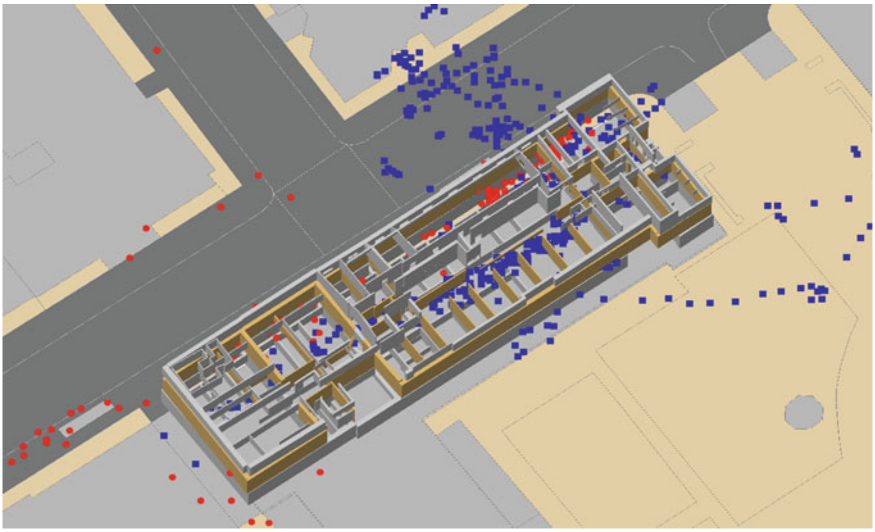

Fig. 4 Integrated data (noise data in *blue*, air quality data in *red*). (Topographic mapping data Ordnance Survey Crown Copyright)

street. The data was also assigned a height value to ensure that it was geo-located to the correct floor in the building.

4.4 Querying the Integrated Data

The original aim of the study was to use SQL to query the integrated dataset to find out, for example, the average, minimum and maximum noise level in each tested room in the building at different times of day and days during the week. However, although this was theoretically possible, two issues initially prevented this final level of querying. Firstly, the export process to convert the BIM into an appropriate format for use in GIS (via IFC) did not create enclosed spaces on which topological queries (contains) could be applied to identify the noise and air quality points within a specific room. Although a number of these elements could have been constructed by combining wall, floor, door, window and ceiling geometry these were not tagged appropriately in the BIM. Figure 5 highlights the different tagging of similar objects within the BIM—internal walls are tagged as 'WallStandardCase' (in grey) and 'Wall' (in burgundy).

Secondly, parallel research calibrating the noise and air quality sensing devices, carried out within the EveryAware (Loreto 2012) project, highlighted issues with the quality of the noise and air quality data which meant that while it was possible to determine whether noise was at a low, medium or high level it would not be possible to extract accurate values from the data. Figure 6 highlights the calibration results

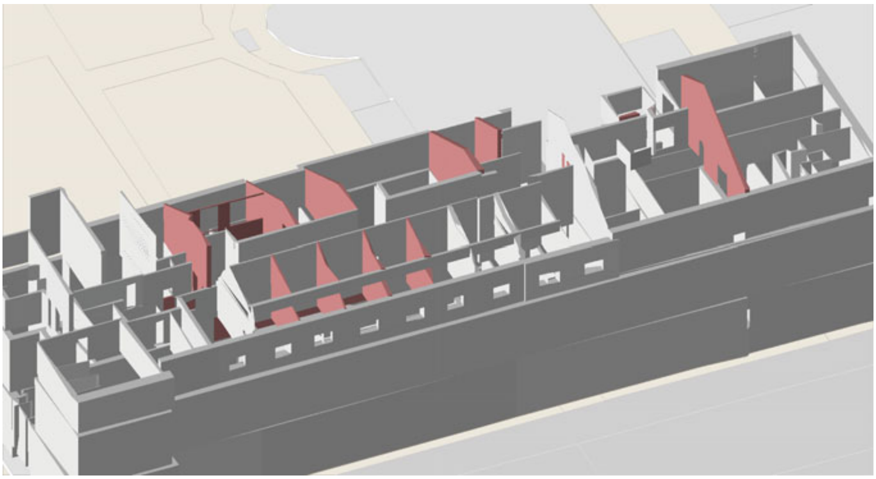

Fig. 5 BIM data in GIS, highlighting internal walls tagged differently in the BIM—burgundy shows IFCWall and *grey* shows IFCWallStandardCase (Topographic mapping data Ordnance Survey Crown Copyright)

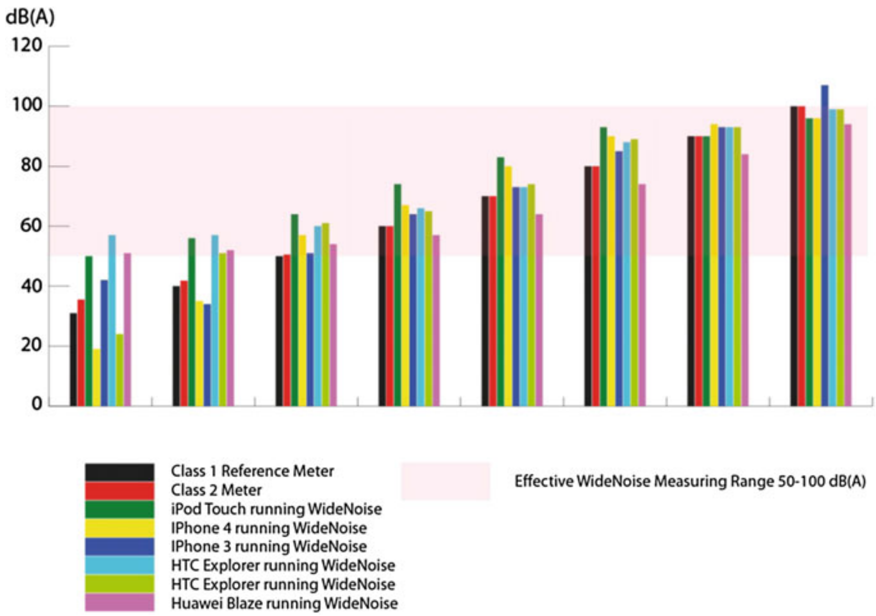

Fig. 6 Results of calibration activities in an anechoic chamber, noise sensing on mobile phones

for the noise dataset, showing differences even between phones from the same manufacturer. Further details of the calibration process for noise can be found in Sect. 4 in Loreto (2010) and for air quality in Sect. 2 in Loreto (2010).

4.5 *Utilising IFC Spaces for Room Geometry*

An alternative approach to reconstructing a room from its component geometry (walls, doors, floors and so forth) is to make use of the IFCSpace and the IFCRelSpaceBoundary elements. An IFCSpace "represents an area or volume bounded actually or theoretically. Spaces are areas or volumes that provide for certain functions within a building" and is hierarchical in nature (Building Smart 2015b). The IFCRelSpaceBoundary represents contiguous space, whether physical (based on wall centres) or virtual and permits adjacency relationships between spaces to be defined. It is geometrically described as a collection of planar polygon faces, with each face relating to a particular building element that is stored as a boundary attribute, and in this represents Boundary Representation geometry commonly used to model 3D GIS. A second iteration of the export process from Revit to IFC was therefore carried out to ensure that spaces were created—the result of this is shown in Fig. 7. This data was imported in to Oracle Spatial (version 12.1.0.2.0—Enterprise Edition) using FME. As this resulted in multi-surface polygons, Oracle's

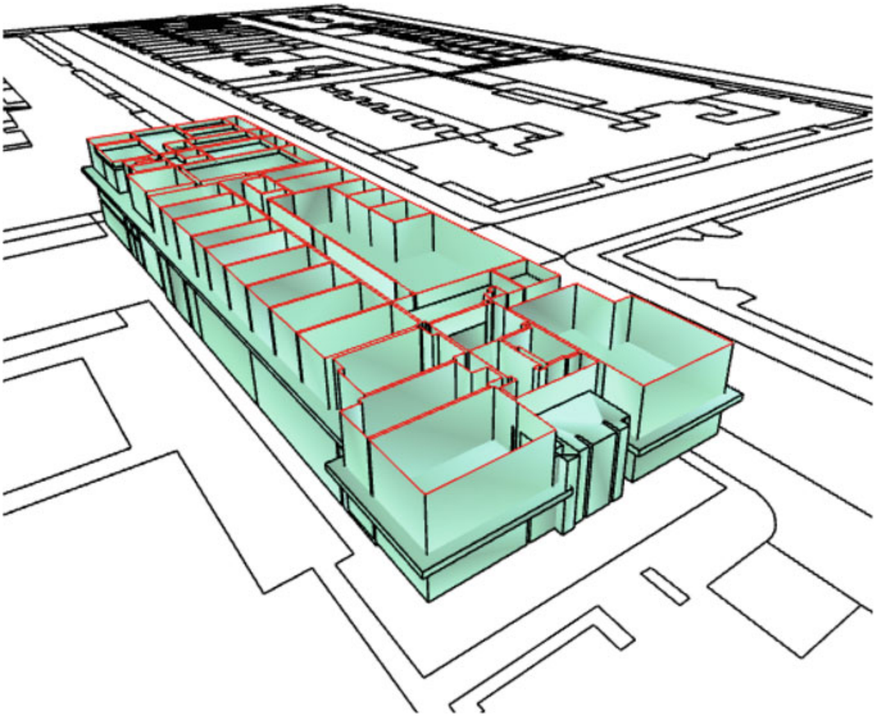

Fig. 7 Rooms in the chadwick building created using IFC spaces (Topographic mapping data Ordnance Survey Crown Copyright)

Table 4 Noise values in the Chadwick building

Room number	Number of noise points	Minimum dB	Average dB	Maximum dB
102	4	50.82	51.2	51.7
103	11	31.51	48.48	56.23
120	2	41.09	41.27	41.44
1M00A	2	51.42	54.54	57.65
1M01	2	38.76	45.85	52.95

CONVERT3007TO3008 utility was used to create the required volumes representing each room, resulting in a total of 112 rows, each representing a room in the building. To illustrate the potential of the approach on a small subset of data, Oracle SQLnqueries were then used to identify the minimum, average and maximum noise values for 5 rooms in the building—the results are given in Table 4. An example of the SQL statements used is shown here:

```
SELECT ROUND(MIN(A.DATA_AVERAGE),2) AS MIN, B.NAME
    FROM 3D_NOISE_DATA A, CHADWICK_IFCSPACE_SOLID B
```

```
WHERE SDO_INSIDE(A.GEOM, B.GEOM) = 'TRUE'
GROUP BY B.NAME
ORDER BY MIN ASC;
```

5 Discussion and Conclusion

The results obtained demonstrate the potential of spatially integrating BIM and GIS data to investigate sustainability-related issues in a building that is currently in use. Using the techniques described, it is possible to use laser scanning to create a detailed 3D model of the building, geo-reference it and integrate tagged sensor data to obtain room-by-room measurements. As noted above, these sensor values are subject to calibration issues, and indeed in most cases only one or two points were captured per room. However, utilising the same approach and SQL queries similar to that given above, along with higher quality equipment could provide a good understanding of the spatio-temporal distribution of air quality and noise within the building.

Although not specifically required for the Chadwick Building, this information could potentially be provided in real time if a live sensor feed were available, as appropriate triggers could be written to update average values every minute in the database and a dashboard used to display results to a building manager. As the data is geo-referenced, the results obtained could also be correlated with traffic counts on the street outside the building, as well as with swipe security access data showing when the building is occupied. Information from the BIM—such as construction material of the internal walls—could be used to identify where retrofitting could ameliorate a noisy environment, or where extractor fans may improve air quality.

The processes described above also highlights the relative complexity of creating a detailed BIM for an existing building in an appropriate format for use with GIS. This complexity relates in particular to the time and effort required to perform the scans and convert them into usable geometry, but also to ensuring that the resulting BIM is structured and tagged appropriately.

Section 2.2 highlighted the different approaches to geometry modelling in BIM and GIS. However, in this case study this syntactic difference did not prove to be a problem, with Oracle Spatial able to model the converted data in 3D (further tests are required to identify whether geometric detail was lost in the conversion). The number of layers created by the conversion process did, however, confirm that gaps between the approaches to schematic modelling in BIM and GIS will need to be addressed going forward, as currently the objects of interest to GIS (e.g. rooms), represented as single objects, need to be constructed from component windows, doors, walls, floors and ceilings. Semantically, an IFCSpace is also not directly equivalent to a GIS "room".

The IFC-spaces based approach means that resulting data is held in 'spaghetti' format in the GIS (in Oracle Spatial), which gives in duplication of the walls between rooms as each room is modelled as a separate solid, and results in the loss of topological information—e.g. connectivity—contained in the IFC file (see Sect. 2.4). Further manipulation would be required to extract this information and create a topological structure (e.g. without duplication of walls) which would in turn be useful for applications such as indoor navigation. The resulting output also lacks the door and window geometry associated with any room, although these can also be separately extracted from the IFC data.

5.1 Suggested Guidelines for BIM Creation

Based on the initial work described in this paper, we make the following suggestions towards addressing technical aspects of the BIM/GIS integration challenges described in Sect. 2.2.

1. **Geo-reference the BIM from the outset**. The process described above, where the BIM was geo-referenced by identifying corresponding locations on a 2D Map, lacks the accuracy that could be obtained by geo-referencing the BIM using survey techniques on site.
2. **Ensure measurement units are set appropriately**. While construction engineering works in mm, GIS works in m.
3. **Select the appropriate level of detail for scanning**. The scans used to create the Chadwick BIM provided at least 8 mm sampling density, which was not required for the GIS analysis proposed by this project and caused issues in terms of capture time. A very high sampling density and resulting detailed scans means that the resulting geometry can be utilised for multiple purposes, with only relevant geometry being retained in each model, there is an overhead in terms of storage and geometry capture time.
4. **Ensure consistent tagging of the geometry**. On successful conversion from BIM to GIS queries to, for example, find the thickness of the glazing of individual windows in rooms identified as 'cold' by their occupants are possible. However, this depends on appropriate tagging of individual objects within the BIM creation process. As shown in Fig. 5, this tagging also needs to be consistent to allow algorithms for room reconstruction to be run within the GIS environment.
5. **Capture IFCSpace Objects**. The work described above highlights the benefits of utilising IFC Spaces to convert data between BIM and GIS. However, to achieve this both the spaces and the space boundaries must be correctly modelled in Revit prior to conversion into GIS format. They must also be recognised by the conversion software (IFCSpace recognition was introduced in FME 2014 and in Revit 2015 spaces can also be automatically created (Autodesk 2015b) but this still requires the capture of fully enclosed spaces as part of the BIM creation process.

5.2 Further Work

The example in this paper highlighted the potential of combining data captured via a BIM process with other GIS data sources, to address real-world sustainability issues relating to air quality and noise, as well as producing a first list of guidelines for BIM creation that will facilitate integration. We fully acknowledge that this is a very preliminary list, and plan to add to it in the future, ideally with contributions from others working in this field.

Further work will involve working with a more detailed BIM, perhaps including information relating to HVAC systems, and developing an additional facilities-management case study. Correct tagging of objects within a BIM is also important, and automated tools may be required to validate consistency as the size and scope of many BIM is beyond the capabilities of manual checking.

A final, longer term goal involves more direct integration—the current approach to migration (export to IFC then import into a spatial database) means that changes to the BIM are not propagated through, which may cause issues of inconsistency. Developing similar case studies will contribute towards a more in-depth investigation into the question of which features (both geometry and attributes) should be shared between a very detailed BIM and the GIS or vice versa.

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