

EXPLORING BIM FOR OPERATIONAL INTEGRATED ASSET MANAGEMENT– A PRELIMINARY STUDY UTILISING REAL-WORLD INFRASTRUCTURE DATA

G. A. Boyes^{a*}, C. Ellul^a, D. Irwin^b

^a Dept. of Civil, Environmental & Geomatic Engineering, UCL, Gower Street, London, WC1E 6BT, UK

^b Crossrail Ltd. Floor 28, 25 Canada Square, Canary Wharf, London, E14 5LQ, UK

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ABSTRACT:

The use of 3D information models within collaborative working environments and the practice of Building Information Modelling (BIM) are becoming more commonplace within infrastructure projects. Currently used predominantly during the design and construction phase, the use of BIM is capable in theory of providing the information at handover that will satisfy the Asset Information Requirements (AIRs) of the future Infrastructure Manager (IM). One particular challenge is establishing a link between existing construction-centric information and the asset-centric information needed for future operations. Crossrail, a project to build a new high-frequency railway underneath London, is handling many such challenges as they prepare to handover their digital information to the future operator, in particular the need to provide a two-way link between a federated 3D CAD model and an object-relational Asset Information Management System (AIMS). This paper focusses on the potential for improved Asset Management (AM) by integrating BIM and GIS systems and practices, and makes a preliminary report on how 3D spatial queries can be used to establish a two-way relational link between two information systems (3D geometry and asset lists), as well as the challenges being overcome to transform the data to be suitable for AM.

1. INTRODUCTION

Over the past decade, Architectural, Engineering and Construction (AEC) sectors in many countries have seen an accelerated uptake in the use of Building Information Modelling (BIM). The philosophy of BIM is that it provides a collaborative working environment to share intelligent, structured information attached to a 3D information model (BIM Task Group, 2014). The driving force behind the adoption of BIM is the eager expectation that digital technologies will foster more efficient collaboration between project stakeholders. For example, in 2015 the UK government made a saving of £840m within its construction projects, of which a significant proportion is attributed to the adoption of BIM (HM Government, 2015).

As well as the savings being delivered during the design and construction phase (referred to as the CAPEX phase), the AEC industry is also anticipating that these efficiencies can be passed on to the Owner/Operator for their additional benefit throughout the operational life of the constructed asset (the OPEX phase). The reasoning behind this is that collaboration between parties leads to a better design which delivers lifelong savings in running costs. Savings are also achieved from the handover of design information to the Owner/Operator that enables them to make wiser decisions with regards to maintenance, modification and disposal.

Crossrail is a complex infrastructure project tasked with designing, building and commissioning a high-frequency railway to run across central London. The project includes the construction of 42 km of tunnels and 10 new underground stations that will connect into the existing underground railway network. Once complete, Crossrail will hand over the track and station infrastructure to Network Rail and Transport for London (TfL), who will take on the legal responsibility of Infrastructure Manager (IM).

The project, approved back in 2007, is not mandated to comply with more recently published BIM specifications. Nevertheless, Crossrail has a vision to lead the way in creating and maintaining data for constructing, operating and maintaining railway infrastructure and hand over a digital information model that meets the Asset Information Requirements (AIRs) of the future IM. The implementation of these AIRs into the IM Enterprise Asset Management System (EAMS) is in accordance with their Asset Management (AM) strategy. AM is used to ensure that assets contribute towards an organisation's objectives while taking into account cost and risk (ISO, 2014). AM covers activities such as procurement, replacement and amortisation of assets but also includes the management of planned maintenance and defect repair.

Tracking the location of assets is an essential function of AM and Facility Management (FM)¹ (Solihin, et al., 2016). It is here that the intelligent geometric information found in BIM (usually stored as Computer Aided Design (CAD) data) has great potential. Geographic Information System (GIS) provide many analytical tools which can be used to complement the design and editing functions of BIM/CAD applications. During the design phase, asset geometries are modelled as CAD objects, in parallel to asset information being collated in a separate system. The transformation of CAD data into a GIS would allow asset managers to directly query spatial information from an EAMS as the object-relational architecture of GIS provides methods for linking asset information and geometry.

This would offer functionality such as “is this asset in the correct space”, or “what other spatial information (e.g. environmental data) exists at this location”. However, before BIM and asset information can be combined in a GIS, it is necessary to export and transform the information and overcome any semantic, schematic and syntactic interoperability issues (Bishr, 1998).

¹ FM has similar information requirements to AM, but differs as it concerns assets and activities related to maintaining the working environment required for the core business activities (ISO, 2017).

*Corresponding author - gareth.boyes.13@ucl.ac.uk

Approach	Level	Description	Example
Schema-based	Data	Resolving syntactic, schematic and semantic heterogeneities between systems.	Mapping CityGML and IFC schema for automatic conversion (Isikdag and Zlatanova, 2009)
			Utilities ADE within CityGML for IFC data (Hijazi, et al., 2012)
			Unified Building Model from which both CityGML and IFC can be extracted (El-Mekawy, et al., 2012)
Service-based	Process	Researching 3D WFS for IFC	Visualisation of multi-source info in web browser (Lapierre and Cote, 2007)
Ontology-based	Process	Ontological services to bridge semantic gap	Query-based method to address the challenge of semantic interoperability (Peachavanish, et al., 2006)
Process-based	—	Standardised documentation of use cases for IFD and MVD	Documenting processes related to precast concrete design (Eastman, et al., 2010)
System-based	Application	Building systems to support applications	Prototyping SDW system for using GIS as a portal for IFC viewer (Kang and Hong, 2015)

Table 1. Five research approaches and three levels of BIM/GIS integration (Kang and Hong, 2015; Amirebrahimi, et al., 2015)

The Crossrail technical information team are trialling the exchange of BIM information from a CAD platform to a GIS platform. This is being done to demonstrate additional ways of using the information through the closer integration of BIM and GIS. This paper will describe some of the challenges in preparing information for hand over from the construction to operation phases and how spatial analysis tools available in GIS applications can be used to provide preliminary solutions to these challenges.

2. UK BIM MANDATE - ASSET MANAGEMENT

In 2011, the UK Government took the decision to advance the implementation of BIM in the UK (Cabinet Office, 2011) and directed the creation of a UK BIM Task Group drawing together stakeholders from industry and government. At the same time, the government set a mandate that all central government procurement contracts are to include a provision for “the employment and handover of a fully collaborative 3D Building Information Model with all project and asset information, documentation and data being electronic as a minimum by 2016”.

As well as providing greater efficiency during the design and construction phase, the UK Government expects the collaborative environment to provide a foundation for asset management during the operational phase (Cabinet Office, 2011). To achieve this aim, the UK BIM Task Group has overseen the publication of a standards documentation that sets out the contractually required level of BIM. Included in this documentation is PAS 1192-3 (BSI, 2014), a Publicly Available Specification (PAS) that publishes a “specification for information management for the operational phase of assets using building information modelling”.

Organisations that implement PAS 1192-3 are required to maintain an Information Management Process (IMP) covering the life-cycle of their managed assets. The aim of the IMP is to maintain the integrity of asset information in support of the organisation’s asset management activities. To do this, the AIRs that support an organisation’s asset management activities are set. These AIRs are achieved through the use of an Asset Information Model (AIM) by which all operational information or data is contained or referenced. PAS 1192-3 provides typical examples of information requirements that an organisation may need, however, the AIRs are ultimately driven by the organisational needs. One particular AIR listed in PAS 1192-3 is asset location, and the PAS suggests the use of spatial referencing or a GIS to achieve this.

PAS 1192-3 states that the AIM shall exist as a federated model, i.e. a model linking distinct component models including a 3D object-based model describing the environment and location of the asset. The AIM may also be linked to other existing enterprise systems, such as EAMS, GIS and spatial analysis toolkits. The PAS specifically states that any interface between the AIM and another system shall be implemented by two-way linking.

Two-way linking provides synchronisation and avoids the creation of duplicated, and potentially conflicting, information between two systems. Establishing a link between the non-spatial EAMS and the spatial CAD model bestows geometric representation upon information within EAMS. Geometric representation enables assets to be distinguished from their neighbours and provides visualisation and spatial analysis of assets in the context of their surrounding environment.

3. LITERATURE REVIEW

3.1 Current research conducted into BIM/GIS integration

There have been many papers published in the field of BIM / GIS integration (Fosu, et al., 2015) covering a diverse range of understanding of how system integration should be achieved. Kang and Hong (2015) classified research in the field of BIM/GIS integration into five approaches: schema-based service-based, ontology-based, process-based and system-based. In a similar manner, Amirebrahimi, et al. (2015) identified three levels of BIM/GIS integration: data level, process level and application level. These classifications are summarised with example literature in Table 1.

3.2 BIM and GIS in Asset Management

Zhang, et al. (2009) consider the use of BIM and GIS applications for data collection and management, data analysis and visualisation in AM. BIM applications provide a valuable source of information, but it is GIS applications that provide the tools that are needed to perform spatial analysis. The ability to use information in disparate systems is conditional upon their interoperability and level of integration (Zhang, et al., 2009).

Thabet, et al. (2016) published a case study documenting the experience from the perspective of facility managers during the handover of a large educational institution. One of the challenges that they identified is the poor quality information relating to asset location and the locations served by assets. They propose a

System	Software	Object	Identified by	Spatial Information	Description
EIMS	Bentley eB	Structured data & Documents e.g. Asset tech data sheets in PDF	Document No. e.g. CRL1-XRL-AA-AAA-CR001-00001	No geometry Maybe textual reference in document	Asset documentation tagged by Asset No.
AIMS	Bentley eB	Asset e.g. Escalator	Asset No. (Site code + Function code + unique no.) e.g. CR101-AAA-00001	Ref. to Space ID with no geometry. Optional (x,y,z) coord.	
CAD	ProjectWise/ MicroStation	Geometrical CAD Element e.g. Surface, Solid	Filename & Element ID	Geo-referenced 3D geometry	Federated model aggregating multiple reference files
Fire Plan	MicroStation	Space e.g. Ticket Hall SID code LIS-1-22	Space ID	2D line drawing Not geo-referenced	2D plan for required by emergency services in which every space is identified
2D/3D GIS	Oracle Spatial/ ArcSDE	Point, line & polygon features Multipatch	Object ID	Oracle Spatial SDO_GEOMETRY Multipatch BLOB	Crossrail Maps data & Land management information Trial 3D GIS via web-based portal.

Table 2. Crossrail Information Systems

workflow supporting the handover of asset information that emphasises the importance of stipulating information requirements at the earliest opportunity.

Kang and Hong (2015) propose a system providing facility managers with access to BIM information from a GIS portal. BIM object information is extracted, transformed and loaded to a Spatial Data Warehouse (SDW) for visualisation in a GIS using a star schema data structure to link between the BIM model and the SDW model. The geometry of the BIM objects stored in the SDW exists in different levels of detail to support fast visualisation in the GIS. Selecting objects in the GIS portal allows the BIM information and geometry to be viewed in a BIM viewer.

Solihin, et al. (2016) considered how the use of federated models had implications on spatial containment which they consider to be a very essential feature of operational BIM. From their investigation, they propose changes to the Industry Foundation Classes (IFC) file format to enable deferred references that enable resilient object relationships between files.

A consistent theme in the literature is that the handover of BIM information to asset and facility managers is a challenging and expensive process (Thabet, et al., 2016; Solihin, et al., 2016). It is also apparent that BIM and GIS applications need to work together to make better use of the information (Kang and Hong, 2015; Zhang, et al., 2009).

4. CROSSRAIL INFORMATION SYSTEMS

The Crossrail information model is implemented via four separate systems (Table 2). Bentley Enterprise Bridge (eB) runs the **Electronic Information Management System (EIMS)** which manages access to all documentation and their supported workflows related to the project. The **Asset Information Management System (AIMS)** is managed as a subsystem within EIMS enabling documentation to be linked to over a million assets.

The **BIM/Computer Aided Design (CAD) System** exists as a federated model as required by BS1192:2007 (BSI, 2007). This

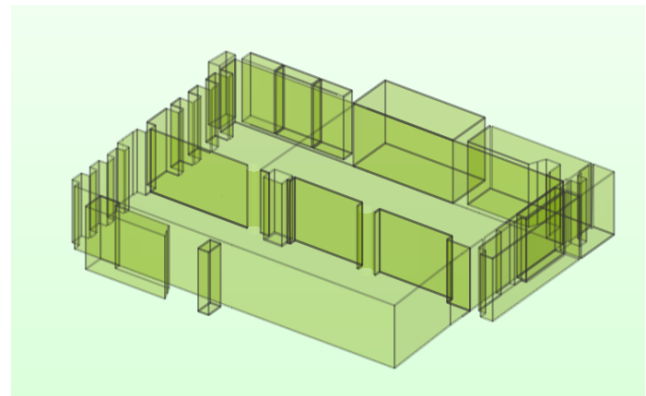


Figure 1. Fire Plan spaces - Station ticket hall

geometric information is stored in the Bentley MicroStation V8 (Select Series 2) format with controlled access managed by Bentley ProjectWise. BIM extensions (i.e Bentley Architecture, Bentley Structural Modeller, Bentley Electrical Systems, etc.) provide BIM authoring tools for creating intelligent BIM objects.

A **Geographic Information System (GIS)** also exists to support the design, construction and ultimate delivery of the project. These GIS systems are used to disseminate and visualise project information as well as providing administrative and analytical functions. GIS information is stored as SDO_GEOMETRY in Oracle Spatial with the exception of ESRI multipatch features which are stored as a Binary Large Object (BLOB). Multipatch is the feature type used for storing 3D solid or surface features in ESRI systems.

The CAD system contains station **fire plans** which are 2D line drawings annotated with floor plan information. These are manually converted into polygons which can be extruded using flooring and ceiling information to provide 2.5D volumetric representation in a 3D GIS Figure 1. Every space in the fire plan has a unique ID which is used by AIMS to specify the asset location.

In contrast to the requirements of PAS 1192-3 in Section 2 which require objects to be linked to geometry (but which was pub-

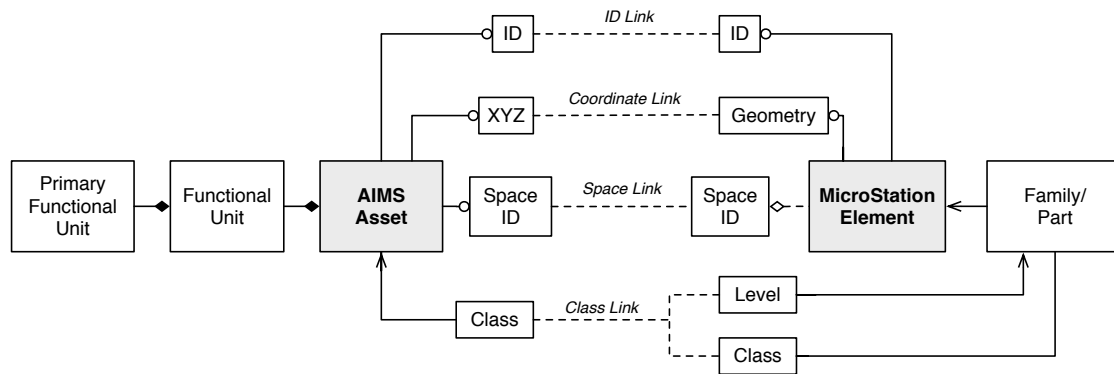


Figure 2. Direct, Spatial and Semantic methods of linking AIMS and CAD objects

lished after the Crossrail system was configured) the Crossrail system holds all information components separately. In addition to the lack of link between AIMS and BIM, the objects within the CAD were created by different sub-contractors in support of design and construction work at an early stage (before the Asset Management Strategy was fully developed), whereas AIMS information is coordinated by a central asset management team.

The CAD objects, created to meet different requirements, have a different scheme of classification to assets in the AIMS. Hence, the correlation of asset classes and CAD classes exists as a complex $m:n$ relationship. A single AIMS asset (e.g. a wall) might be represented in MicroStation as multiple architectural elements (e.g. wall panels). Furthermore, the hierarchy of how objects are aggregated in the CAD model does not always correlate with the hierarchy in AIMS. Overcoming this challenge (the $m:n$ link between asset information and geometry) is fundamental to enabling the potential of operational BIM.

5. STEP 1 - EXAMINING OPTION FOR LINKING

To satisfy the requirements of PAS 1192-3, as well as to offer the potential for an integrated Asset Management System to the IM, the Crossrail technical information team identified four methods for linking asset items in AIMS with geometry elements (Figure 2). The suitability of each method was considered in terms of the time required to input links into the system, the link quality, and potential for implementation.

ID Link — This method implements an explicit link between the Identifiers (IDs) of AIMS assets and MicroStation elements. The work-hours required to input a defined link for every AIMS asset is prohibitively expensive, given that there are millions of assets. Crossrail had requested the software provider to develop a customised application to facilitate this work but technical and commercial issues related to linking groups of elements across different files prevented its development. Additionally, such a link does not possess referential integrity and is susceptible to be broken should the element ID change.

Coordinate Link — This method would provide an explicit spatial relationship between a fixed point on the asset and the geometry of the related MicroStation element, and involves tagging each asset in AIMS with an (x,y,z) coordinate to its approximate location in London Survey Grid as it is commissioned/inspected. The inputting of point coordinates representing each asset was trialled by the Crossrail technical team but was abandoned due to the unacceptably slow speed of entry. It was also found to be unreliable due to the introduction of human errors during the input

process and the trial of this method was discontinued in preference for the next method of linking.

Space Link — The third method is an inferred spatial relationship based upon the identity of the space attributed to the asset and the space(s) enclosing the CAD element. However, a long element (e.g. a pipe) may pass through multiple spaces, creating a $1:M$ relationship between asset and space. This $1:M$ relationship will need to be catered for if this method is to remain effective. Populating the AIMS using this method while surveying or commissioning the assets is faster because it is simpler for data inputters to enter the identity of the space according to its name rather than coordinates. As part of the task of creating a 2D fire plan, every space in the infrastructure is allocated a unique ID.

Class Link — The final method is an inferred semantic relationship based on schemes of classification. As mentioned in Table 2, the two systems use slightly different schemes of classification between CAD model and the AIMS and so a method of mapping schema needs to be established. By itself, this method is impractical due to the voluminous return of potential links when performing a query. However, used in conjunction with the Space linking method, (i.e. the method described above), it is hoped to reduce the number of unsolved links to a sufficiently manageable task for a human asset manager to perform manually. By **matching the asset descriptions** between the two systems as far as possible given their slight differences, and combining this with **matching by identifying assets located in the space** a better overall match rate will be achieved.

In support of this task of establishing relational links, it is proposed to use 3D GIS analysis tools to perform a spatial query on each CAD object to determine the named space in which it is located. The first step towards this is to extract, transform and load the data from CAD into GIS, and the remainder of this paper will investigate suitable methods for achieving this.

6. STEP 2 - VALIDATING THE SELECTED LINKING OPTION

Given the millions of elements to be exported from thousands of files, the linking workflow needs to be automated and capable of batch running, and it should also be able to export not only the geometry of each asset, but also any associated information and the spaces in which the assets exist. It is also fundamental that the resulting data should be topologically correct — i.e. an enclosed space should in fact be enclosed, to allow the space in which an asset is located to be identified using a *contains* query.

Given that, as noted above, the Crossrail information system was commissioned in 2009 and uses Bentley MicroStation V8 (Select Series 2), which was released in July 2010, export formats were limited to what was available in this software and it was also necessary to explore a number of different export options before one was found that did not result in loss of required information.

Thus, the geometric information was exported from MicroStation in the native .DGN format, via Autodesk .DWG format, via the buildingSMART .IFC format, and via Trimble SketchUp .SKP format. In order to permit subsequent validation of the workflow, a MicroStation Visual Basic Application (MVBA) script was written to count MicroStation elements in the source file and output element information such as ID, layer and bounding box dimensions to a CSV file.

Once the geometry was exported, FME was used to transform into multipatch features for writing to an ESRI geodatabase to be read into ESRI ArcScene to check the quality of the transformation. The quality of the transformation was assessed by counting the number of features lost, by a visual comparison, by checking that each transformed element could still be identified by its original MicroStation Element and then finally by testing whether the features were topologically closed. The ArcScene *Inside3D* tool was used to validate that a spatial query could be performed to find the 3D space where an object existed. These were created by extruding 2D polygon spaces extracted from floor plans with height data.

7. RESULTS

7.1 Selecting an export option

The ticket hall of the new Liverpool Street station was chosen to compare the export of geometry from MicroStation. The station was chosen because 2.5D polygon spaces had been already been extracted from the 2D CAD fire plans. The geometry was saved in files created from two of the Bentley BIM extensions, Structural Modeller and Electrical Services. The exported geometry contained a variety of geometry shapes including straight-sided blocks, blocks with cut-aways and openings, extruded sections and complex curved geometry.

7.1.1 Reading MicroStation DGN in FME Reading files direct from the native MicroStation DGN format is not a viable as FME Workbench is unable to read Surface type elements in this format (Safe Software, 2017). and the majority of elements created using the MicroStation BIM extensions belong to this type.

7.1.2 Reading Autodesk DWG in FME FME Workbench is capable of reading surfaces in Autodesk's DWG format which MicroStation is capable of exporting in. However, MicroStation Element IDs are not retained during the export which precludes the ability to trace objects back to the source file. Furthermore, the SmartSolid and SmartSurface element types, used to aggregate component elements, are broken down during export, thus multiplying the number of elements being handled. On completion of the transformation, a test was carried out on the surfaces to determine their topological correctness. This revealed that over half of the surfaces were not closed, or were found to have other topological defects, such as inverted faces. The work required to heal the geometry was considered to be too great, and research shifted to exploring the IFC format.

7.1.3 Reading Industry Foundation Classes in FME The IFC format is an neutral open source format for BIM information exchange overseen by buildingSMART International. However, attempts to use FME to read models created using Bentley Structural Modeller but then exported as IFC was fraught with difficulty as the application would hang whilst attempting to read the geometry. No such problems were experienced opening the same IFC file in Autodesk Revit or Solibri Model Viewer. IFC files exported from models created using Bentley Electrical Services did not suffer any issues. In all cases, the IFC file can still be read by FME provided only the Bounding Box representation of each element is read instead of the full geometry. This functionality provides the ability to read the semantic information contained within the IFC file.

Attempting to understand the problem, a script was written in Python to use the IfcOpenShell toolbox to parse the IFC file and save each element in its own IFC file. These standalone files were then read in a batch so as to skip the unreadable files. Overall 13 percent of the IFC geometry was found to be unreadable. The geometry elements rejected by FME Workbench were inspected in Solibri Model Viewer (Solibri, 2017). Looking closely at the geometry reveals polyhedral slivers extending out from the element surface (Figure 3). It seems that attempting to transform these slivers into a 3D GIS format is causing FME to hang. The effect on the model can be observed in Figure 5 which shows gaps in the ceiling of the ticket hall.

7.1.4 Reading Trimble SketchUp in FME This export function saves the model as a single object in the file (which can be deaggregated in FME). This means the model components are not exported with any reference to the source Element ID needed for a two-way link. However, it is a feature of the SketchUp export function that geometry is tagged with the source file level name and this functionality can be exploited to provide a workaround solution. An MVBA script was written to move each element to a new level named according to the element ID which could be now read in FME.

This geometry-tagging workaround was not always successful, but it is also possible to perform a spatial join on the feature centrepoinets with the centrepoinets calculated from the bounding boxes read by the MVBA script and written to a CSV file. In the end, 2.1% of the elements exported from Structural Modeller files required human assistance to assign a MicroStation ID. The manual tagging is also needed to handle incidents where the SketchUp exporter splits an element into two parts.

7.2 Merging in FME Workbench

The extracted SketchUp geometry was then merged with the semantic information exported via the IFC format and written as

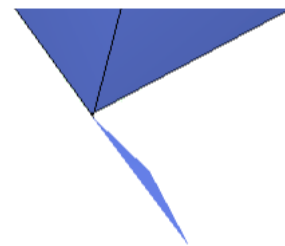


Figure 3. Polyhedral sliver created from IFC defined CSG

	MicroStation Elements		IFC Elements		SketchUp Elements			Total
	(Unfiltered)	(Filtered)	(Total)	(Valid)	(Total)	(Manual)	(Split)	
Structural BIM Files								
Tunnels	642	368	403	395	260	0	0	260
Ceiling	199	160	162	113	163	10	3	163
Corridor	306	269	280	234	180	0	0	180
Ticket Hall	133	118	116	96	119	6	1	119
Basement	48	46	42	38	46	0	0	46
Electrical BIM Files								
Ticket Hall	477	471	471	471	611	—	—	471 (IFC)
Street Level	372	371	370	370	547	—	—	370 (IFC)

Table 3. Export, transformation and loading of MicroStation Elements via IFC and SketchUp to GIS

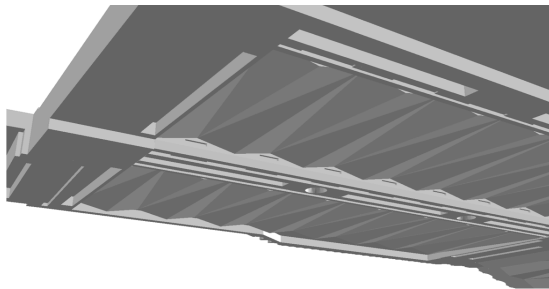


Figure 4. Ticket hall ceiling - intended geometry

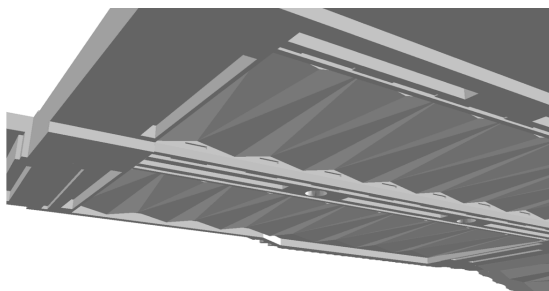


Figure 5. Ticket hall ceiling- elements lost in transformation

3D multipatch features to an ESRI geodatabase. Each feature was identified with a MicroStation Element ID which, together with the source filename, enables the object to be traced back to the originating element in the source file.

The success of the geometry extraction is recorded in Table 3 for five files exported from Structural Modeller and two files exported from Electrical Services extension. The second column is the elements counted in MicroStation using the MVBA script including features used for marking out and textual annotations. The third column is the elements after filtering to remove text, construction lines, etc. The fourth is elements exported via IFC using the bounding box representation together with the number of elements that could be read by FME. The sixth is the number of elements exported by SketchUp accompanied by the number elements of that required manual tagging. The eighth column is the number of elements that the SketchUp exporter split. The final column is the number of multipatch features outputted.

The number of exported features is identical to the number of elements counted by the MVBA script taking into account the splits. This is with the exception of the tunnels file where there are 108 elements unaccounted for. These elements were searched for by their Element ID in MicroStation and they were found to be invisible in the original model. With regard to elements created using the Electrical Services extension, the IFC exporter performs

admirably. Consequently, the workaround described here is only required with respect to the Structural Modeller files.

7.3 Validating in ArcScene

The transformed elements were checked using the *IsClosed* tool in the ESRI 3D Analyst toolbox. This tool checks whether the topology of the multipatch feature is closed, thus satisfying the principal test for solidness. Although a small percentage of features were not closed, it was possible to heal them using the *Enclose Multipatch* tool in the 3D Analyst toolbox.

The majority of steps in the workflow were automated using a batch script. However, a small number of exceptions, such as the invisible tunnel elements detailed above, require human input to determine a reason why they were not handled by the FME workspace. The need for manual resolution prevents a fully automatic workflow which would otherwise decrease the time taken to extract, transform and load geometry and decrease the chance for human error.

Figure 6 depicts a 3D model of an underground station ticket hall as viewed in ArcScene. As a final test, the usefulness of transforming the geometry and loading it into ArcScene was proven through the use of the *Inside3D* tool. A 2D floor plan with height information was extruded and converted into a multipatch solid. The *Inside3D* tool was then successfully used to identify the names of spaces that the transformed features are located within.

8. DISCUSSION AND FURTHER WORK

Crossrail is trialling the use of 3D GIS to permit the operational management of asset information, thus yielding further benefits of implementing BIM within the Crossrail project. The work described here demonstrates the potential of GIS and associated spatial analysis tools to overcome the problems identified in Section 4, i.e. the lack of a link between asset information and location. This works towards establishing a two-way link between the federated CAD and the non-geospatial AIMS and thus meet the requirement specified in PAS 1192-3 described in Section 2.

It also demonstrates a key difference between theoretical approaches or those that have been trialled on smaller construction programmes to the challenges faced by large civil engineering projects which run over a decade or more. The results show that, given the challenges of the latter and the fact that the information system was put in place prior to the UK BIM mandate, there is the potential for the Crossrail BIM to be used for operational purposes in the context of AM. Conceptually, the research undertaken in this paper is best described as system-based research, using the classifications used by Kang and Hong (2015) performing integration at the application level (Amirebrahimi, et al., 2015).

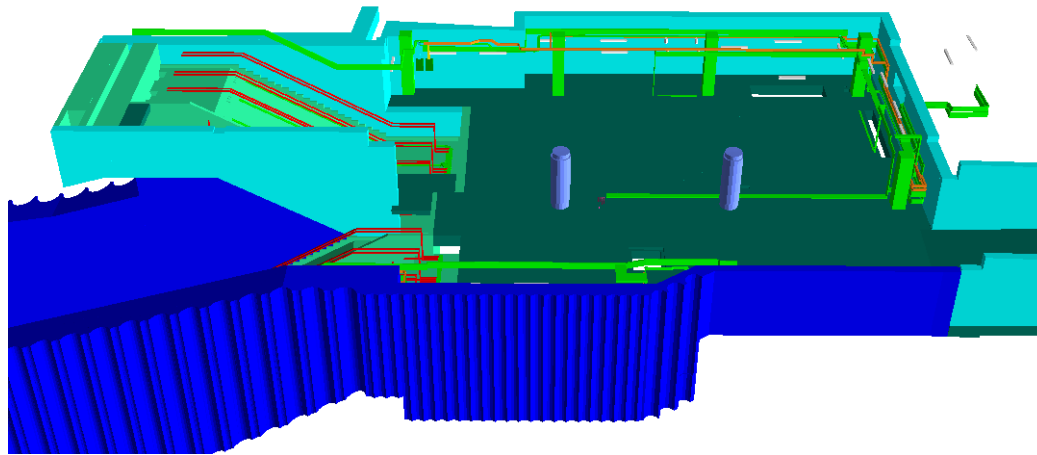


Figure 6. Station ticket hall showing structural, architectural and MEP objects in ESRI ArcScene

The issues described reflect previous work in this field – indeed, the woes of BIM interchange and interoperability are well documented with problems (Pazlar and Turk, 2008; Delfosse, et al., 2012) and exporting data from BIM application to GIS has proved to be complex despite the existence of standard exchange formats such as IFC. In the case of Crossrail, the inability to export geometric and semantic information in a single file capable of being loaded into a GIS has required a significant amount of resources in terms of time. Workarounds provide a temporary solution but a large project requires processes that are fully automated. The methods described above go a long way towards achieving this in the context of the Crossrail system, although further extensive testing is required to validate this preliminary approach.

8.1 Examining the Sources of the Conversion Problems

Exporting geometry from CAD into a GIS format requires the conversion of the geometry into Boundary Representation (B-Rep). Straight-sided objects, e.g. a vertical wall, can be identically represented, but curved surfaces, e.g. a tunnel casing, must be discretised and substituted with planar faces. This permanent loss of detail can never be recovered from the transformed geometry. By keeping a reference to the source geometry in the original file, the object can be re-transformed at any time with smaller stroke tolerance (i.e. a higher quality discretisation). However, high fidelity transformation of large objects, such as a tunnel, will be limited by the memory and processing power available.

The reason for FME failing to read IFC geometry can be attributed to geometry errors created converting Constructive Solid Geometry (CSG) to B-Rep. CSG elements in MicroStation are retained within the IFC file during export to this format and their conversion to B-Rep is performed in FME. But when the file is exported as a SketchUp file, the CSG is converted to B-Rep within MicroStation. The B-Rep converted by MicroStation does not contain geometry errors and can thus be handled by FME.

The CSG conversion engine in FME Workbench is attempting to convert a degraded geometry following export from its native source. It appears that floating point rounding errors are causing a thin polyhedral sliver to be created which is causing the conversion to fail. The CSG conversion engine used in MicroStation to export SketchUp files is not affected, either because it is processing source data, or it has built-in resilience to remove the sliver.

The modelling process has created a latent defect that is undetectable in the native application but is apparent on export. This

issue could be resolved either by training CAD modellers to avoid error-prone geometry, or developing the application so that the CSG to B-Rep conversion is always performed in the native software. As the IFC schema supports multiple geometry representations, the option should exist to include B-Rep geometry when exporting IFC from Bentley MicroStation. In the meantime exporting geometry via the SketchUp format and merging information in FME Workbench provides a workable solution.

8.2 Asset Management and Spaces

The final step of this experiment demonstrated the ESRI 3D Analyst toolbox can be used to identify the location of geometric objects by reference to a named space. This supports the requirement for matching geometric objects with assets in AIMS as described in Section 5. The ability to identify features by location in this way also provides the capability to filter a visualisation by reference to spaces, thus enabling the user to remove peripheral features that may be cluttering the visualisation. Also in terms of visualisation, features might be classified using colours related to the space where they belong. This space information can be coupled with asset space information and used to narrow down the potential asset information for each geometry.

The use of a spatial query to determine the space (or spaces) that an object is located may not lead to a match with the same asset that has been located by human interpretation. For instance, if an asset passes through more than one space (e.g. a pipe), the person responsible for marking down the name of the space where that asset is located may decide to use the space where the pipe is predominantly located, or where the pipe starts or ends. This will need to be considered when trying to match assets and objects using an automated method. If the name of only one space is used, then the names may differ. If all the spaces that the asset is located are used, then the problem may become unmanageable.

Objects and assets may fail to match because the spatial query is dependent upon the quality of the representation of the space. The spatial queries carried out in Section 7 were performed using extruded 2.5D floor plans. The geometry of these extruded features presumes that the floor and ceiling are level and the walls are vertical without any deviation for architectural features such as sloped floors or rounded tunnel casings. Future work will include research to generate spaces that are more representative of complex geometry. Spaces that are more faithfully represented may return more meaningful results when used in spatial queries.

Spaces that are accurately represented may be useful for other applications. For example the use of topological spaces in indoor navigation (Zlatanova, et al., 2016). Perhaps, as also proposed by Kang and Hong (2015) generalisation algorithms can be used on space geometry to provide a framework for supporting simplified visualisation of the indoor environments, thus reducing memory and processor specifications. More accurately defined spaces might also be used in conjunction with point cloud surveys to detect changes between *as-designed* and *as-built* models.

8.3 Further challenges

The potential exists to export the geometry and asset information into a GIS and exploit the spatial analysis options identified by Zhang, et al. (2009) including measuring area and volume, measuring the length of cable runs, and situational awareness of assets. Federated models used in a project Common Data Environment (CDE) are difficult for finding the right information due to their folder structure. Transporting the information into a 3D GIS provides a portal to find information in federated models using the architecture proposed by Kang and Hong (2015).

The work described in this paper has mainly focussed on the practical aspects of exporting and transforming geometry. Although the geometry extracted from the CAD is now loaded inside a GIS, there has been no integration with regard to semantics. The next stage in this research project will be to investigate semantic-based and ontological-based approaches as described in Section 3.1.

9. CONCLUSION

The work carried out in this paper adds to the system-based research into BIM/GIS integration. It has highlighted the difficulties of exporting BIM geometry from a live project into 3D GIS, identifying issues with CSG-based IFC geometry. Workaround methods have been validated for extracting, transforming and loading CAD/BIM geometry into a GIS where it provides an environment to exploit spatial analysis tools (Zhang, et al., 2009). Further research will continue to investigate whether extruded plans are a suitable representation of the complex spaces of an underground railway. Further research can then be carried out to develop the effectiveness of matching CAD elements and AIMS assets. If this can be accomplished, then the integration of BIM and GIS can be achieved meeting the requirements for a two-way link between systems in PAS 1192-3.

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References

- Amirebrahimi, S., Rajabifard, A., Mendis, P., and Ngo, T., 2015. A Data Model for Integrating GIS and BIM for Assessment and 3D Visualisation of Flood Damage to Building, In *CEUR Workshop Proceedings Research@Locate'15, Brisbane, Australia, 10-12 March 2015*, pp. 78-89.
- BIM Task Group, 2014. BIM Task Group FAQs, <http://www.bimtaskgroup.org/bim-faqs/> (25 July 2014).
- Bishr, Y., 1998. Overcoming the semantic and other barriers to GIS interoperability, *Int J Geogr Inf Sci* 12(4), pp. 299-314.
- BSI, 2007. BS 1192:2007 Collaborative production of architectural, engineering and construction information, BSI.
- BSI, 2014. PAS 1192-3:2014 : Specification for information management for the operational phase of assets using building information modelling, British Standards Institution, London.
- Cabinet Office, 2011 Govt. Construction Strategy, UK Cabinet.
- Delfosse, V., Schrayen, J., Juchmes, R., and Leclercq, P., 2012. Some advice for migrating to IFC, In T. Fischer, K. De Biswas, J.J. Ham, R. Naka, & W.X. Huang, eds., *The 17th International Conference on Computer-Aided Architectural Design Research in Asia*, pp. 265-274.
- Eastman, C.M., Jeong, Y.S., Sacks, R., and Kaner, I., 2010. Exchange Model and Exchange Object Concepts for Implementation of National BIM Standards, *J Comput Civil Eng* 24(1), pp. 25-34.
- El-Mekawy, M., Östman, A., and Hijazi, I., 2012. A Unified Building Model for 3D Urban GIS, *ISPRS Int Geo-Inf* 1(3), pp. 120-145.
- Fosu, R., Suprabhas, K., Rathore, Z., and Cory, C., 2015. Integration of Building Information Modeling (BIM) and Geographic Information Systems (GIS) – a literature review and future needs, In *Proc. of the 32nd CIB W78 Conference 2015, 27th-29th October 2015, Eindhoven, The Netherlands*, pp. 196-204.
- Hijazi, I.H., Ehlers, M., and Zlatanova, S., 2012. NIBU: a new approach to representing and analysing interior utility networks within 3D geo-information systems, *Int J Digit Earth* 5(1), pp. 22-42.
- HM Government, 2015 Digital Built Britain – Level 3 Strategy.
- Isikdag, U. and Zlatanova, S., 2009. Towards Defining a Framework for Automatic Generation of Buildings in CityGML Using Building Information Models, In *3D Geo-Information Sciences*, Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 79-96.
- ISO, 2014. BS ISO 55000:2014 Asset management: Overview, principles and terminology.
- ISO, 2017. ISO 41011:2017 Facility management - Vocabulary, International Standards Organisation.
- Kang, T.W. and Hong, C.H., 2015. A study on software architecture for effective BIM/GIS-based facility management data integration, *Automation in Construction* 54, pp. 25-38.
- Lapierre, A. and Cote, P., 2007. Using Open Web Services for urban data management: A testbed resulting from an OGC initiative for offering standard CAD/GIS/BIM services, In *Urban and Regional Data Management: UDMS 2007 Annual*, CRC Press, Boca Raton, Fla.; London.
- Pazlar, T. and Turk, Z., 2008. Interoperability in practice: geometric data exchange using the IFC standard, *IJ of Information Management* 13, pp. 362-380.
- Peachavanish, R., Karimi, H.A., Akinci, B., and Boukamp, F., 2006. An ontological engineering approach for integrating CAD and GIS in support of infrastructure management, *Adv Eng Inform* 20(1), pp. 71-88.
- Safe Software, 2017. MicroStation Design Quick Facts, https://docs.safe.com/fme/html/FME_Desktop_Documentation/FME_ReadersWriters/igds/quick.facts.igds.htm (27 Apr 17).
- Solibri, 2017. Solibri Model Viewer - Solibri, <https://www.solibri.com/products/solibri-model-viewer/> (27 April 2017).
- Solihin, W., Eastman, C., and Lee, Y.-C., 2016. A framework for fully integrated building information models in a federated environment, *Adv Eng Inform* 30(2), pp. 168-189.
- Thabet, W., Lucas, J., and Johnston, S., 2016. A Case Study for Improving BIM-FM Handover for a Large Educational Institution, In *Construction Research Congress 2016 May 31–June 2, 2016, San Juan, Puerto Rico*, pp. 2177-2186.
- Zhang, X., Arayici, Y., Wu, S.-W., Abbot, C., and Aouad, G., 2009. Integrating BIM and GIS for large scale (building) asset management: a critical review, In *The 12th International Conference on Civil, Structural and Environmental Engineering Computing, 1-4 Sep 2009, Funchal, Madeira, Portugal*.
- Zlatanova, S., Oosterom, P.J.M.V., Lee, J., Li, K.J., and Lemmen, C.H.J., 2016. LADM and IndoorGML for Support of Indoor Space Identification, *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci.* IV-2-W1, pp. 257-263.