Automation in Construction 130 (2021) 103859

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

GeoBIM for built environment condition assessment supporting asset management decision making

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ARTICLE INFO

Keywords:
BIM
GIS
GeoBIM
Asset management
Facility management
Condition assessment
Digital twin

ABSTRACT

The digital transformation in management of the built environment is more and more evident. While the benefits of location data, from Building Information Modelling or Geographical Information Systems, have been explored separately, their combination - GeoBIM - in asset management has never been explored. Data collection for condition assessment is challenging due to quantity, types, frequency and quality of data. We first describe the opportunities and challenges of GeoBIM for condition assessment. The theoretical approach is then validated developing an integrated GeoBIM model of the digital built environment, for a neighbourhood in Milan, Italy. Data are collected, linked, processed and analysed, through multiple software platforms, providing relevant information for asset management decision making. Good results are achieved in rapid massive data collection, improved visualisation, and analysis. While further testing and development is required, the case study outcomes demonstrated the innovation and the mid-term service-oriented potential of the proposed approach.

List of abbreviations

AECO	Architecture Engineering Constructions and Operations
AM	Asset Management
BE	Built Environment
BIM	Building Information Modelling
BPA	Building Performance Assessment
CA	Condition Assessment
CI&M	Condition Inspection and Monitoring
CMMS	Computerised Maintenance Management System
DB	Database
DSS	Decision Support System
EU	European Union
FM	Facility Management
GeoBIM	Integration of GIS and BIM
GIA	Gross Internal Area
GIS	Geographic Information System
ICTs	Information Communication Technologies
IT	Information Technology
JRC	Joint Research Centre
KPI	Key Performance Indicator
LCC	Life Cycle Cost
LoD	Levels of Detail
LOD	Level Of Development
MEP	Mechanical, Electrical, Plumbing
OM&R	Operations Maintenance and Repair
RM	Risk Management

1. Introduction

The Architecture, Engineering, Construction and Operation (AECO) is one of the most relevant industry sectors in the European Union (EU). In 2019, up to 9% of EU gross domestic product was provided by this sector involving 18 million direct jobs, corresponding to more than 6% of European employment [1]. However, AECO is a relatively static sector when it comes to digitisation, in particular in the use phase of theasset's life cycle [2]. Practices and processes often rely on old paradigms and approaches, hindering the enhancements resulting from the implementation of the digital tools and methods. This is – at least in part - due to the characteristic of the AECO sector in the EU, which in the past

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https://doi.org/10.1016/j.autcon.2021.103859
Received 14 November 2020; Received in revised form 22 July 2021; Accepted 26 July 2021

years has been dominated by a few large and very competitive players and alongside a large number of smaller suppliers with lower productivity [3].

Within this context, digital innovation is considered one of the strongest potential areas for improvement and could boost the productivity of the global construction sector by up to 14–15% [3]. Innovation in digital technologies is a trend that today is driving large investment both in the corporate and the academic world, thanks to the great potential of resource savings, improved sustainability and reduction of the uncertainty in information [4]. In AECO and other related economic sectors, a strong rise of digital technologies and data-driven approaches can be found [5]. The Joint Research Centre (JRC) report *Digital Transformation in Transport, Construction, Energy, Government and Public Administration* [1] summarises some main impacts of this transformation in AECO:

- the integrated adoption of technologies in every stage of the construction value chain supports better performance and increased economic margins;
- better performance promotes sector competitiveness, with effects on price reduction and increased investments in research and development;
- the adoption of digital technologies allows new business solutions to be incorporated into the traditional AECO market. This is a threat to the traditional business model, despite representing a new opportunity for IT-oriented companies.

In recent decades, a remarkable standardisation effort for the systematisation of the information management processes within the AECO sector has been undertaken. Two key approaches underpin this: Building Information Modelling (BIM) [6,7] and Geographical Information Systems (GIS). BIM represents a key example of how the digitisation can support and improve both 3D and 4D digital modelling of the physical assets and the processes in the construction and use phase. Nevertheless, given its origins in design and construction, the BIM approach tends to focus on large scale individual projects, with information relating to the construction site and engineering detail. When the management processes need to be implemented over large geographical extents (e.g. a portfolio, an infrastructure) and contexts (i.e. the space surrounding an asset, integration with information from external sources), GIS are capable of managing virtually every type of location-information.

Both BIM and GIS are location-enabled technologies – i.e. they provide information not only about ‘what’ an asset is but also ‘where’ it is located. In reality, assets rarely fit entirely into either the BIM (single project, engineering detail) or the GIS (context, infrastructure, city wide) scales – but instead span both, with Asset Management (AM) taking place at different scales depending on the scope of the specific task. However, the integration of the BIM and GIS – GeoBIM [8] - is still seldom adopted for AM.

1.1. The aim of the research

This research demonstrates how a GeoBIM approach can be used for improved digital AM. The focus is on the indoor and outdoor physical assets of a building and the surrounding neighbourhood for developing an integrated system for the Condition Assessment (CA) of the digital Built Environment (BE). This integrates BIM data, the CA data generated leveraging the power of location for the collection of the assets’ condition and GIS data for outdoor elements and spaces. The outcome of the research is the development of a GeoBIM model that supports decision making on the Operations Maintenance and Repair (OM&R) of the digital BE. The proposed approach streamlines the CA process, permits the integration of CA information (indoor and outdoor) into one data environment, supports multi-scale (depending on the purpose of the CA) assessment and informs also subsequent management stages – e.g. an in-depth specialised diagnosis of asset components (e.g. structural, systems, energy, etc.). The developed approach and system have been tested in a case study in the city of Milan, Italy.

2. State of the art

This section presents the state of the art in Condition Inspection and Monitoring, the domain in which the CA processes are implemented, BIM and GIS. enabling AM. This allows to set the boundaries of the research and to identify the knowledge gaps addressed through the development of the GeoBIM approach for CA, supporting decision making in AM.

2.1. Condition inspection and monitoring

Condition Inspection and Monitoring (CI&M) is the process of controlling and measuring performance of a product or a service and includes a set of operations to evaluate the ability to operate under in-use conditions. It is a core step of an audit process, activated in different phases of the life cycle of the asset. CI&M is a primary function in AM: according to [9], the Building Performance Assessment (BPA) provides a better knowledge of an asset enabling better and timely decisions. It also provides the knowledge base for other functions within the wider AM domain as, for instance, Facility Management (FM) [10]. In fact, the CI&M function provides relevant information to carry out evaluations and assessments at different decision-making levels. CI&M processes are mandatory in some countries, Table 1 shows some on these legislative requirements according to [11].

To ensure consistency, CI&M should be carried out according to a specific procedure and a general guideline on this function can be found in ISO 15686-3,7,10 [16–18]. A crucial process concerns the definition of the purpose and the level of detail to be adopted – e.g. should a single inspection relate to an entire room or should multiple inspections be carried out for the walls, windows, heating system and so forth. This ensures that the correct information required for measuring specific performances [10] is collected and presented via the Condition Assessment (CA), which processes the data collected during the CI&M.

Many examples of the use of digital approaches to CA have emerged in recent years. The authors in [11] present the results of research to devise the building inspection system according to a classification system for defects and a severity rating and some examples on how the CA can be improved thanks to the use of advanced Information Communication Technologies (ICTs) can be found in literature. [19] proposes a method for optimising the planning phase of the CA operations, for the improved allocation of scares resources. [20] propose an approach for integrating the BIM data in the facility CA process, enhancing the interoperability with the FM system. [21,22] propose a cross-domain Decision Support System (DSS), integrating BIM data within a data-driven procedure for allocating maintenance budget. [23] propose a

Table 1
Mandatory condition inspections and monitoring around the world.

Place	Type of mandatory condition inspection	Further references
Hong Kong	Buildings over 30 years old are inspected once every 10 years, and repairs are carried out on common parts, such as external walls, projections, and signboards.	[12]
Spain	Decree 67/2015 establishes that a technical inspection report must be drawn up for buildings older than 50 years. Further inspections must be made every 5 years after the first one.	[13]
Malaysia	The Malaysian government requires building inspections as outlined in the Total AM Manual	[13]
Italy	The Municipality of Milan requires a condition inspection for every building older than 50 years. The inspection is to be repeated periodically and guidelines are provided [14].	[15]

sensor-based anomaly detection method for driving predictive maintenance interventions based on the Digital Twin principles. [24] describe a BIM-GIS integrated method for improving the interoperability in employment of the Building Automation System (BAS) and the Computerised Maintenance Management System (CMMS), for improved FM.

2.2. Geographic information systems

In the context of built AM, every asset - no matter the scale or size - has a unique location in space and time. This information allows to differentiate it from other thousands of other similar assets in a system. Thus, location-enabled technologies – GIS and BIM – have an important role to play in digital AM. These are first considered separately to better understand where each can be applied.

Due to the evolution of Web 2.0, a massive volume of location information can now easily be created and accessed by personal devices (i.e. smartphones and laptops) through different systems and services [25]. GIS can collect, manage, analyse, and visualise any geographic information recording: where the asset is and when it is at a particular location [26]. Within a GIS, location information is stored in spatial databases enabling data modelling (i.e. storage, querying, analysis, visualisation) [27]. Spatial databases offer the advantage of central data storage and management, where data can be shared by many users no matter where they are in the world, with differing access rights. There is hence a "*single source of truth*" where any data changes are recorded for all to see. Spatial databases allow the representation of either simple geometric objects like points and lines or even more complex ones such as three-dimensional (3D) polyhedra.

Although much of the geographic information used within GIS is two-dimensional (2D), increasingly 3D data is now available in many disciplines such as in city planning and disaster response, a 3D representation can increase the insight, improve the visualisation and support the calculation of environmental impacts such as air pollution and noise [28]. Spatial databases allow the complexity in details and the large volume of 3D data to be represented in 3D models [29]. In addition, they provide the opportunity to store multiple levels of detail (granularity, aggregation) from individual features up to portfolio, city and country level. A process is known as generalisation, that preserves the model's basic semantic and structural characteristics by integrating different GIS techniques including classification, simplification and aggregation, can be used to create a less detailed model from a detailed one [30]. Multiple models can be derived from a single detailed source, with the outputs determined by user requirements.[2] The extraction of different views of the data, is allowed, for example, by the data capture tasks carried out by national mapping agencies, who are required to produce large scale (detailed) maps as well as small scale (less detailed) ones with national coverage. This is possible deriving the small scale maps from the large scale data. In 3D GIS the different levels of granularity of the model are referred to as 'Levels of Detail' (LoD) [31], with models ranging from LoD 1 (flat roof buildings) to LoD 4 (detailed internal and external information).

2.3. Building information Modelling

According to ISO 19650-1 [6] BIM is the use of a shared digital representation of a built object (including buildings, bridges, roads, process plants, etc.) to facilitate design, construction and operation processes to form a reliable basis for decisions. While a BIM model is often thought of as intelligent 3D and 4D modelling approach to construction, in fact it has as its main aim, the collaboration [32] between different stakeholders in construction, removing data silos. BIM activity can be broadly sub-divided into three categories (adapted from [33]):

- Information management - creation and long-term curation of information relating to a built asset, at all phases of its lifecycle;
- Project management - making efficient and effective use of this information to improve efficiency, reduce costs and waste during construction and operation;
- People – the complex relationships between the social and technical resources that represent the complexity, collaboration and interrelationships of today's organisations and environments.

Within BIM, there is no specific equivalent of the multi-scale 'generalisation' process seen in GIS – i.e. the process of deriving a less detailed representation from a more detailed one. In fact, the reverse process is proposed through a *level of information need* approach. According to ISO 19650-1 [6] the quality of each information deliverable should be defined in terms of its granularity to serve the purpose for which the information is required and no more. This is referred to as the level of information need and concerns both graphical and non-graphical information. The ISO standard does not give any definition of standardised levels of information as, for example, the BIMforum does for its Level of Development [34] that, despite the different name, serves the same purpose of the ISO level of information need. The American definition ranges from LOD 100, where the element may be graphically represented in the model with a symbol or other generic representation; all the way through to LOD 500 where the model element is a field verified representation in terms of size, shape, location, quantity, and orientation. Non-graphic information may also be attached to the model elements. This process reflects the construction focus for which BIM was initially created, representing the increasingly detailed model of an asset that will be generated as the construction progresses.

2.4. GeoBIM application in asset management

Given the multiple scales, granularity and detail that can be encompassed by Facilities and AM tasks, neither BIM nor GIS on their own sufficiently cover the built environment at an appropriate scale: BIM focusses on very large scale (detailed) models including engineering and structural detail, usually relating to a single site or project. GIS focusses on less detailed models and, while a single building can be modelled in some detail at LoD 4, models usually cover entire cities or even countries. GeoBIM can be broadly defined as the integration of BIM and GIS, taking advantage of similarities that include the fact that:

- both model the real world as is or as it could/will be,
- both use location information coupled with semantic information,
- both permit modelling at various scales and granularity,
- both model indoor and outdoor information [35].

Despite the similarities, integration of BIM and GIS data into one system is not as straight forwards as converting data from one format to another – challenges include:

- different approaches to geo-referencing (placing objects on a map),
- differing focus for modelling (construction/engineering, large scale, very detailed versus smaller scale, city-wide or national models, with no restrictions on the feature types that can be modelled),
- geometry modelling (parametric or constructive solid geometry in BIM, boundary representation in GIS);
- different approaches to centralised data management (spatial databases in GIS, federated file systems in BIM) [35].

Given that it is a newly emerging field of research, there is relatively little work, to date, on the application of GeoBIM in an AM context. A comprehensive review of applications in this field can be found in [36]. Work described in [37,38] focussed on the challenges of integrating

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[2] The 2D equivalent of this process is seen when a user zooms into the detail of an online map and then zooms further out, at each step seeing data that is more generalised.

asset geometry and asset identifiers within the Crossrail project, as a prerequisite to railway AM. [39] describe the integration of BIM, 2D mapping and the Internet of Things to support comfort analysis in buildings. [40] describe the integration of BIM and GIS (although not specifically termed GeoBIM) for sewer AM – with tasks including informing operational intervention, asset residual life prediction and monitoring energy consumption. [24] propose a similar integrated approach for utility tunnel maintenance, with focus on the data integration task required, although detail of the specific AM tasks that this approach could support is not provided.

Of perhaps greater relevance to the approach proposed in this article, [41] outline a multi-scale system to support construction and FM for large Mechanical, Electrical, Plumbing (MEP) systems. They note in particular that current approaches mean that any facilities manager, while being required to respond e.g. to a leak within minutes, will need to go through potentially large quantities of documentation to identify the specific valve to shut off. They propose an integrated multi-scale BIM/GIS solution with detailed multi-level data in the BIM being made available as required, and less detailed models – e.g. topological/connectivity models – being provided by GIS. FM tasks carried out include: query and visualisation of the layout of the MEP (including upstream and downstream analysis); identifying optimal routes for efficient inspection processes; linking with pedestrian flow information to ensure that the MEP system provided optimal comfort, delivered efficiently; supporting maintenance work and condition analysis. [42] also focus on FM, proposing a GeoBIM solution that divides the environment into space/floor/building units, and that can be used for tasks including room scheduling, management of joint equipment, site navigation, developing remodelling plans, fire-fighting scenarios and energy consumption analysis. The multi-scale approach is also taken by [43] who explore visualisation of electricity demand and supply across the GIS/BIM divide, linking the smaller scale feeder model (local electricity supply) with the larger scale electrical component model (the demand) and noting that the approach can scale to include larger networks.

3. The importance of location for decision making in asset management

The Institute for Asset Management's (IAM) Subject Specific Guidance 22/23/24 [44] provides an overview of the types of information needed for AM including both "location and spatial links" and "condition data". Also, given the review of the literature, it can be stated that knowing the location of an asset – and its constituent parts – at different levels of granularity is necessary as follows:

- frequently built asset portfolios cover multiple locations, and decision makers need to know which site the condition report refers to and where the asset is on that site, to ensure that funds – e.g. for equipment upgrade – are allocated to the correct site and specific asset on that site;
- in situations where multiples of the same component exist – e.g. escalators, signal boxes, it is possible to identify a specific instance by an ID plate or QR tag or similar. However, this relies on the plate/tag being present and readable, and on the database containing the corresponding ID (which in this loose-coupled situation may not be the case). The location of the asset is something fixed and two items of the same asset type cannot be in the same place at the same time. Therefore, tagging an asset by its location removes uncertainty on which asset you are referring to. This does of course require a robust positioning system;
- changes in condition (e.g., paint deterioration, clogged filters, boiler's components degradation) depend on location. Location in AM allows to timely respond to the following questions. Is the asset in a cold area of the world, close to the sea, near a busy road, in an area of the building that is highly trafficked, close to a boiler? Location is the only way to link these different sources of data - e.g. which road is closest to the building? How many storms were there here last year? Is this air conditioner in direct sunlight?
- as result of the previous factors, Cost (installation, sourcing components, decommissioning, cost of conducting the condition assessment) will depend on location, as well as the work management operations (including staffing, routing, health and safety, disruption to a network, disruption to neighbours);
- there is a need for a way to aggregate the very detailed asset components and corresponding condition surveys and resulting indicators to something at higher level. The generalisation of the location information data offers a natural approach to this aggregation - e.g.: aggregate the assets by room, by building, by site, by city, county, country.

4. Case study overview

The opportunity to apply the GeoBIM approach to AM, has arisen in the context of the university Leonardo Campus of the Politecnico di Milan, Italy. This area hosts the premises of the Politecnico and is characterised by the presence of more than 25 building, with different functions (e.g., administration, lectures, libraries, departments etc.). The functionality and, in general, the quality of this city environment can be preserved not only at the building and the related equipment level, but also considering the surrounding infrastructure and services. This leads to the need for BE level OM&R service able to address different management scales in an integrated manner.

To test the effectiveness of the GeoBIM approach a case study building (Fig. 1)located in the East Leonardo Campus has been selected. The building comprises lecture theatres and workshops. Its Gross Internal Area (GIA) is approx. 3.700 sqm and consists of 1 underground and 3 floors above the ground. The building is surrounded by a private open space at north and west, and by public open spaces at east and south. These areas have been considered as part of the development of the GeoBIM BE CA approach as considering the BE as a whole (indoor/outdoor private and public spaces) is a requirement for the development of the advanced OM&R services, ensuring a quality integrated campus environment.

5. Methods, tools and data

The overall research schema is represented in Fig. 2, although this article presents the steps highlighted in dark blue.

5.1. Service requirements

A crucial step for the development of the integrated GeoBIM CA system concerns the definition of the AM service requirements. For this research, the angle of the portfolio owner, who wants to achieve a better knowledge of the managed assets, to make better decision on OM&R, has been assumed. This leads to the definition of the CA service according to the criteria of completeness, rapidity, and relevance of collected data on critical assets. The AM service requirements, together with the definition of the digital modelling procedures determine the ways the GeoBIM model is developed and enable the processes for data production and collection (BIM modelling, CA modelling and GIS data integration) to match stakeholder needs.

Two main matter must be defined to carry out effectively the CA requirements: what to inspect and how to assess what is inspected. The identification of the relevant entities to be evaluated during the inspection campaign is a crucial phase both for driving the data collection operations and for the development of the digital assets (the elements of the indoor and outdoor BE) according to a specific level of detail, allowing a quick modelling and the effective implementation of the condition inspection campaign. Fig. 3 represents the asset breakdown structure of the BE employed. The entities modelled are those impacting the most on the technical performances of the physical assets and can be

Fig. 1. Case study location. Authors' image including a view from https://maps.polimi.it/maps/.

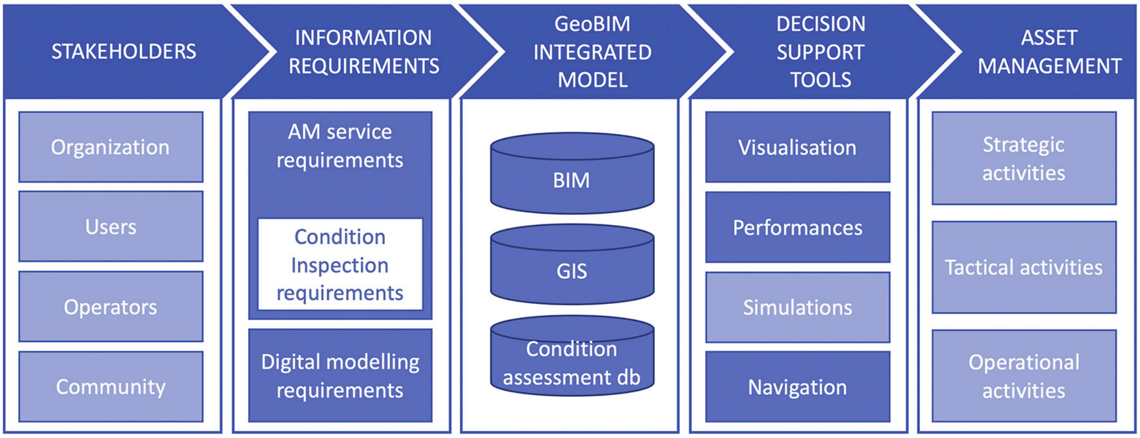


Fig. 2. Research schema.

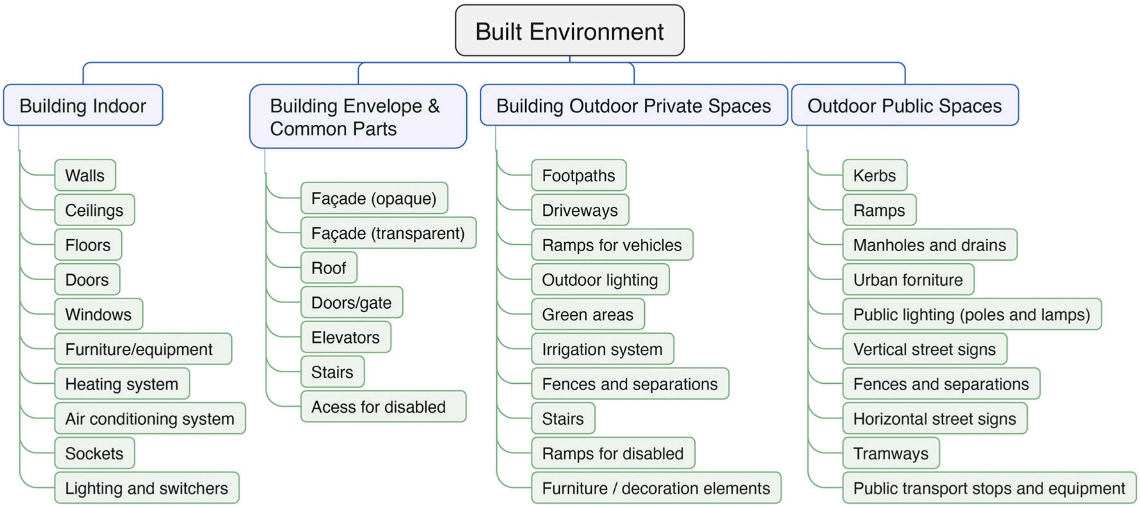


Fig. 3. Condition inspection asset breakdown structure of the built environment.

identified and assessed through a visual inspection [45].

In addition to what and how to inspect and assess, of particular interest to asset and facility managers is the definition of the optimal time to inspect the components to maximise their value [19]. Several inspection objectives need to be met during the assets' life cycle [46]. There are many studies aiming to define the best inspection schedule in building CA. The traditional periodic fixed-time inspection approaches, in fact, show low efficiency in the early assets' life cycle and may produce high risk of failure at the later stages [47]. The IfcElement (the generalisation of all components of a building or a system) can be related to the Pset_Condition, that allows to store the assessment results and the assessment date as a IfcDate defined in [48]. Although prioritising the critical building components based on previous assessments can help to optimise the frequency of inspection for re-assessment [49], defining the most effective inspection schedule is out of this research's scope.

5.2. Development of the GeoBIM integrated model

Once the object of the survey is defined (Fig. 3), the definition of the digital modelling requirements can be carried out. The BIM model of the existing building was developed adopting a low level of geometrical detail [6]. Since the aim is to support the streamlined assessment of the spaces, the MEP systems are modelled only when they are visible and accessible for the visual inspection. This allows also to reduce the times for BIM modelling.

A review of the asset breakdown structure highlighted the fact that the features representing the building outdoor private spaces and public spaces are typically those represented as geospatial information (i.e., within a GIS) and thus may be available as open data from the Municipality of Milan. Therefore, it was possible to source existing geometry models (in 2D) for most of the required asset/feature types.

Given the benefits of using a spatial database (e.g., multi-user access, central data security) a decision was made to use a PostgreSQL/PostGIS database as the integration data store. A multi-step approach was carried out to migrate the BIM and GIS data into the database, as follows:

1. Georeference the BIM and export the BIM as IFC (Industry Foundation Classes, an interoperable interchange format for BIM);
2. Convert the IFC to 3D spatial data format (a multi-patch shapefile) and visualise;
3. Import the data into the spatial database (PostGIS) where it could then be integrated with GIS data (also converted from shapefile into a spatial database);
4. Aggregate the data as necessary to match to the required schema for Condition Assessments.

For the GIS data, despite the CA process makes use of a more rapid survey approach in many cases, the effort to tag the condition of each individual streetlight, bollard, kerb element and so forth is substantial. Thus, aggregated geometry was required to enable the overall condition of each area to be mapped. Two approaches could be considered here – firstly, tagging all the manholes along a street segment as having 'condition x'. However, this might be misleading and imply a level of detail in the assessment that was not in fact present. Thus, additional aggregated feature types were also created in the GIS. Similarly for the BIM data, the object model generated by the IFC export process does not correspond directly with that required for the AM task. Thus, a further process of aggregation was required to generate the features that could then be associated with the required CA. Additionally, given the differing geometry formats between BIM and GIS, a geometry simplification task was required before features from the BIM could be visualised in a GIS viewer. s.

5.3. Capturing condition information

The CA method used is, following the best practice [45,50–52], divided into two main stages. The first stage concerns the inspection of the entire asset without employing highly specialised operators or tools. In this stage, the assessment is carried out solely based on a visual examination, helping to reduce associated costs. The second stage, depending on the findings of the first one, focuses on specific parts of the assets and adopts expert assessors' evaluation and specific instrumentation. This second stage is very specific and varies depending on the type of asset being analysed. The detailed inspection has not been adopted as method for this research, as we focus on the first stage, applicable to any type of asset.

The CA is implemented according to the method proposed by Re Cecconi et al. [53]. During data capture, the values of the attributes (the assessed elements) can vary on a *likert* scale from 1 to 5 according to their degradation level, where 1 indicates a very good condition (Table 2).

The condition of each indoor element listed in the asset breakdown structure (Fig. 3) is related to the spaces (*rooms*) of the building as an attribute of the room itself. The same approach has been adopted for collecting information on the whole building, and the surrounding private and public space ("*Building Envelope and Common Parts*" and "*Building Outdoor Private Spaces*"). All data is captured via mobile devices, timestamped and stored in the spatial database, linking it directly with the corresponding 3D asset geometry.

The subjectivity of the surveyors [54,55] may cause major issues in the assessment [56] and can lead to a 30% mean difference in maintenance cost [57]. To avoid this, a reference condition matrix has been created to harmonise the assessment of the defects of each single element. An example for the building indoor elements is given in Fig. 4.

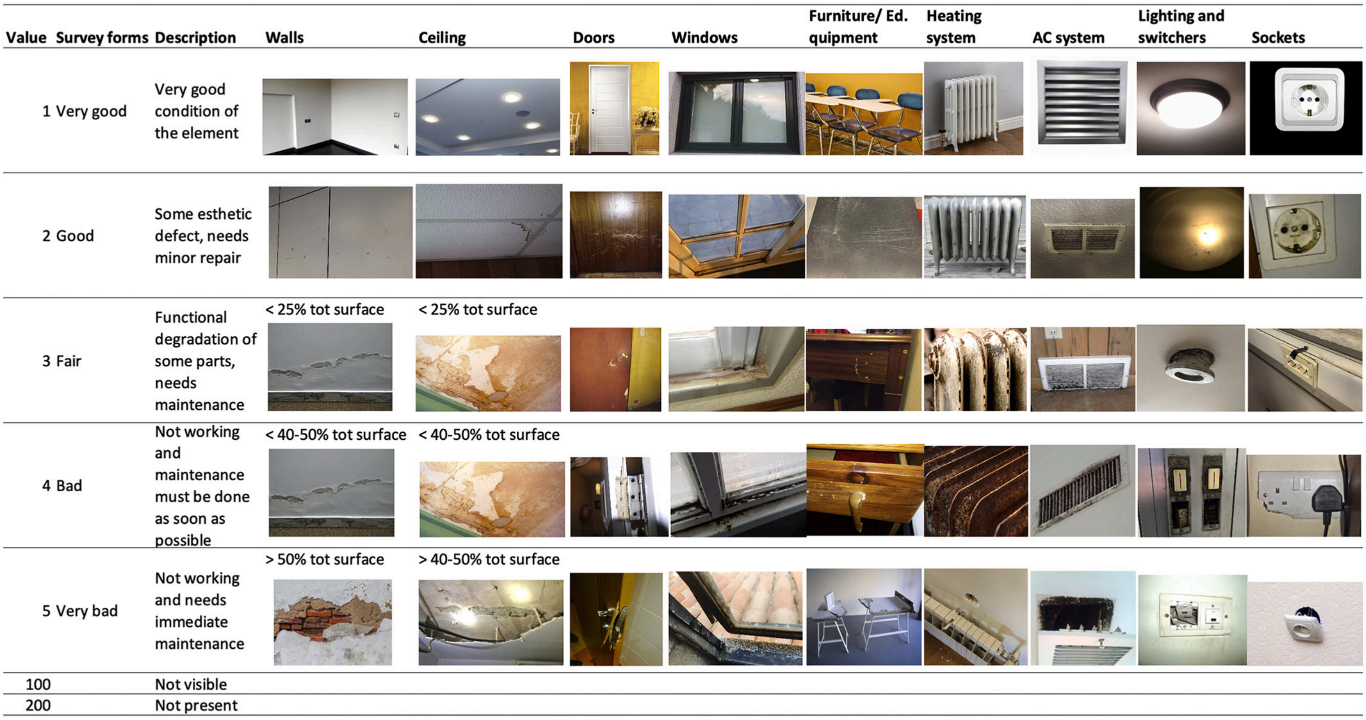
A different approach has been developed for the CA of the outdoor public spaces. In this case it was not possible to identify a single aggregated geometry that would represent the elements of the area, while also allowing sufficient granularity to cover the detail required. Similarly to the approach described for the building-related CA, the evaluation of the condition of the public space elements have been accomplished according to a 1–5 *likert* scale. In addition, while the elements in Fig. 3 are assessed according to the procedure explained in the previous paragraphs, for road/pavement condition, a different approach is required to assesses the intensity of the degradation. Therefore, every time a crack, detachment, hole etc. of the surface is found, the assessment is made on a scale 1 to 5 where 1 corresponds to an aesthetic defect and 5 is an hazardous issue for users (Table 3). The geometry and location data has being captured as necessary.

To allow the agile collection of the data, four Google Forms [58] were created:

- Indoor CA - Building indoor spaces (one per room);
- Outdoor CA - Building envelope & common parts;

Table 2
Condition levels considered for the condition assessment.

Condition	Description
1 Very good	The element is new or in very good condition
2 Good	Some aesthetic defect, needs minor repair.
3 Fair	Functional degradation of some parts, needs maintenance. In the case of surfaces (e.g. walls), the degradation affects less than 20% of the total area.
4 Bad	Not working and maintenance must be done as soon as possible. In the case of surfaces, the degradation affects 20%–40% of the total area. The functional degradation of many parts is detected.
5 Very bad	Not working and needs immediate maintenance. In the case of surfaces, the degradation affects more than 50% of the total area and there are serious issues to the functionality of the element. It is dangerous for the users
100 Not visible	
200 Not present	



Value	Survey forms	Description	Walls	Ceiling	Doors	Windows	Furniture/ Ed. quipment	Heating system	AC system	Lighting and switchers	Sockets
1	Very good	Very good condition of the element									
2	Good	Some esthetic defect, needs minor repair									
3	Fair	Functional degradation of some parts, needs maintenance	< 25% tot surface	< 25% tot surface							
4	Bad	Not working and maintenance must be done as soon as possible	< 40-50% tot surface	< 40-50% tot surface							
5	Very bad	Not working and needs immediate maintenance	> 50% tot surface	> 40-50% tot surface							
100		Not visible									
200		Not present									

Fig. 4. Condition assessment sample for indoor spaces.

Table 3
Degradation intensity considered for the CA of the surfaces in the public space.

Degradation intensity	Description
1 Very good	Some aesthetic defect, needs minor repair.
2 Good	Some degradations as micro cracks, minor detachments.
3 Fair	The defect (cracks, holes, detachments, etc.) affect the functionality of the surface.
4 Bad	Major degradations (cracks, holes, detachments, etc.) and need to be maintained.
5 Very bad	Major degradations (cracks, holes, detachments, etc.) and need to be maintained as soon as possible since it could be hazardous for users.

- Outdoor CA - Building's surroundings;
- Outdoor CA - Public areas (neighbourhood – streets, street signs, lighting etc. and the defects of the roads and pavements).

The assessors were provided with reference printed maps from which they could also note the ID values of each asset surveyed. This allowed the form data to be automatically imported into the database and linked the condition survey directly with the associated geometry. Data collected on the building and its surroundings can be directly related to the elements in the BIM model, while data collected on outdoor elements are imported in the GIS environment as geolocated data.

5.4. Decision making support tools development

A bespoke 3D interface (using CesiumJS[3]) was developed for the project to allow interactive exploration of the data, especially for users not having any GIS or database experience. Several reports and maps were included on the website to enable this, including:

- a list of all features which have not yet been surveyed,
- a count of all surveyed features by their condition status (gives a general overview of the condition of the building and its surroundings),
- a list of the work each surveyor (or group of surveyors) has completed (who is more efficient),
- what percentage of each feature type has been surveyed.

Condition levels are transformed into a score ranging from 0 to 1 according to formula (1):

$$p = \begin{cases} \dfrac{c-1}{4} \; if \; c \leq 5 \\ n/a \; if \; c > 5 \end{cases} \tag{1}$$

where
c is the condition value (Table 3)
p is the CA score.

The average condition of a room inside the building is thus computed as:

$$p_{room} = \frac{\sum_{i=1}^{n} p_i}{n} \tag{2}$$

where
p_i is the score of the element *i* of the room, i.e., the ten objects listed under Building indoor in Fig. 3;
n is the number of elements inspected, i.e., the number of elements having the score different from n/a.

Eventually, the condition score for the building indoor elements is the weighted mean of the score of each room, Formula (3). Weights are related to the importance of the room. Each room of the building is classified into one of four classes of importance considering the higher importance of the defects in a main room as a lecture theatre or a meeting room, in relation to the one in, for example, a closet.

$$p_{Building\ indoor} = \frac{\sum_{i=1}^{m} p_{room,i}}{m} \tag{3}$$

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[3] https://cesium.com/cesiumjs/ [accessed 12th May 2021].

where

$p_{room,\ i}$ is the score of the room *i* of the building;

m is the number of rooms inspected.

Accordingly, the "Building Envelope and Common Parts" and "Building Outdoor Private Spaces" condition scores are computed as the average of the scores of the elements making up the two built environment parts as listed in Fig. 3.

6. Results

An FME[4] workbench was created to convert the IFC data into GIS shapefiles (multi-patch format to retain the 3D geometry). A total of 53 different layers were created, reflecting the inclusion of 53 different (although related) classes in the IFC model. The conversion was validated using the FME Data Inspection tools. GIS data for the surrounding area was imported into PostGIS using the QGIS data management tool.

6.1. Data aggregation and schema matching

A number of additional steps were required to ensure that the imported data matched the assets breakdown structure for the CA. A *one: one* direct mapping was made from the BIM into the breakdown structure for features such as stairs, windows, doors. However, a number of individual features (*IfcWallStandardCase, IfcSlab, IfcRoof, IfcDoor, IfcWallStandardCase, IfcWindow*) needed to merged to form the shell of the building at LoD 2 (required as geometry for the Outdoor CA – Building Envelope and the Outdoor CA – Building Surroundings surveys). Thirdly, while storing the very complex geometry resulting from the conversion of *IfcFurnishingElement* (benches, desks, chairs) and *IfcFlowTerminal* (e.g. light fittings, sockets) in a spatial database does not present problems, visualisation within GIS packages of such complex data is not possible. Therefore, a generalisation process was applied and these features were represented as simple points.

6.2. Capturing the condition data

A total of 342 CAs were carried out on site, with 99 rapid assessments. The general model used in the integrated database provides a *1: many* relationship between a feature (geometry) and the CAs, as a CA may be repeated for the same feature at regular intervals. Where the geometry already exists - i.e. where it was sourced from the BIM or from existing GIS data – the CA data was associated via a join. Where the geometry did not already exist, the CA team were first required to digitise the geometry in the corresponding database layer (via QGIS, making use of the in-built feature editing tools). Once this was completed, a CA could be associated with the geometry. Table 4 summarises the geometry types used to provide location information for each of the four surveys.

Table 4
The geometry used for each of the four surveys.

Survey	Geometry used to provide location information for the asset(s)
Indoor CA – Building	IfcSpace from BIM, converted to *rooms* within the spatial database
Outdoor CA - Building envelope & common parts	3D building, created by combining different elements from the BIM
Outdoor CA - Building's surroundings	Outdoor Private Space (GIS)
Outdoor CA - Public areas (neighbourhood)	Various individual features (GIS)

6.3. Decision making

Fig. 5 shows an overview of the 3D visualisation tool, highlighting the internal room data, with Fig. 6 showing a small subset of room condition reports. The proposed approach allows to integrate indoor and outdoor CA information with the related built environment geometries and to visualise it in different software platforms. Fig. 7 shows the CA data captured both for indoor and outdoor elements and how they can be filtered for representing different condition levels ("*very poor*" CA in this case). Also, Fig. 8 shows the results of the assessment of the Lighting & Switches system on the ground floor of the building, categorised according to the CA. The different software platforms employed allow different granularity in the data visualisation. This is particularly useful when different users' categories need to access data. In this situation they may have different needs and skills in using a specific software (e.g. Revit, QGIS, CesiumJS), for a specific purpose (e.g., data analysis, visualisation, data update etc.). Hi accessibility of data and usage flexibility, allow to support better data-driven decision making in AM.

Data has been processed according to the approach described in paragraph 5.4 and the results have been summarised in Figs. 9–12. The condition of the building indoor elements presents anoverall good/fair status, with a more critical condition detected for the heating system.

The building envelope and the common parts do not show any particular criticalities, except for the accessibility system, which among the others shows the worst condition (fair/poor).

The outdoor building surroundings present a critical condition of the driveways, green areas,disabled accessibility, furniture and decoration elements. The irrigation system was not present and has assumed a null value.

Fig. 12 represent the assessment of the outdoor public spaces. The overall condition is between the good and fair, with a particular higher criticality for the vertical street signs, ramps, fences, and separations.

A further processing has been carried out for the defects of the external surfaces (i.e. roads and pavements). These have been assessed separately, evaluating the intensity of the degradation and not the overall condition of the physical element. Fig. 13 highlights that most of the observed defects were ranked at fair (57.14%) and bad (28.57%) levels.

Finally, the data has been aggregated and represented in Fig. 14, allowing to have the comprehensive view of the assessment of the BE. Therefore, the building envelope, the indoor and outdoor private and public spaces can be assessed as a whole, supporting the decision maker in the prioritisation of maintenance and refurbishment intervention. Moreover, despite being tested on a single building, the proposed approach allows an effective streamlined CA at the portfolio level, through a multi-scale approach.

7. Discussion

This paper sets out to demonstrate how an integrated GeoBIM approach can be used for improved digital AM, focussing condition inspection of the indoor and outdoor entities of a building and the surrounding neighbourhood, with a university campus and its surroundings as a case study. The approach developed demonstrates the potential of integrated location-enabled data for AM, and for managing a seamless digital environment of indoor/outdoor, large scale (high detail, small area)/small scale (lower detail, wider area) entities and spaces – as highlighted in Table 4 - that is extremely extensible to meet the needs of a campus-wide system and beyond that work at municipal, regional and national level.

Having a centralised, integrated database supports decision making in two senses. Firstly, it is possible to rapidly obtain an overview of the features that have or have not been surveyed, and for the latter then prioritise the activity of the survey teams and develop a model of trust in

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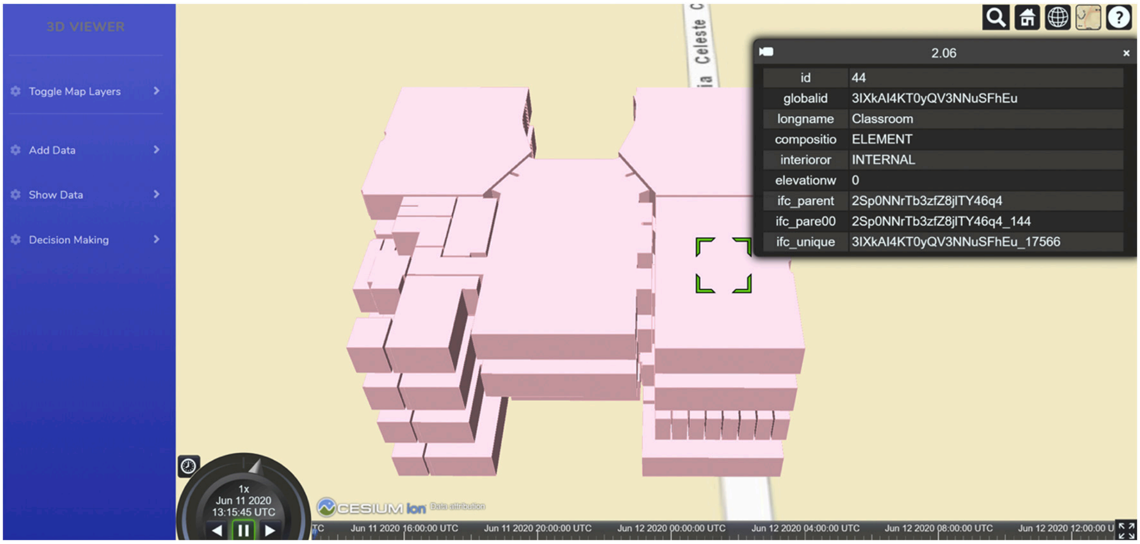
[4] FME is a geospatial data integration platform provided by Safe Software - https://www.safe.com/fme/ [Accessed 12th May 2021].



2.06

id	44
globalid	3IXkAI4KT0yQV3NNuSFhEu
longname	Classroom
compositio	ELEMENT
interioror	INTERNAL
elevationw	0
ifc_parent	2Sp0NNrTb3zfZ8jITY46q4
ifc_pare00	2Sp0NNrTb3zfZ8jITY46q4_144
ifc_unique	3IXkAI4KT0yQV3NNuSFhEu_17566

Fig. 5. Interactive 3D Visualisation showing rooms.

Show 8 entries

Search:

ID	Room ID	Building ID	Wall	Ceiling	Doors	Windows	Furniture and Equipment	Heating System	Airing System	Sockets	Lighting and Switches	Date and Time	Group
691	253		2	2	2	2		2	3	2	2	2020-10-11	611
690	252		1	1	2	1		1	6	1	2	2020-10-11	146
689	251		1	1	2	1		6	1	1	1	2020-10-11	627
681	248		2	6	5	1		4	1	2	3	2020-10-11	600
684	247		1	2	3	2		1	2	2	1	2020-10-11	289
675	244		1	1	2	3		6	4	2	1	2020-10-11	114
676	244		1	1	2	3		6	4	2	1	2020-10-11	114
677	244		1	1	2	3		6	3	2	1	2020-10-11	114

Showing 1 to 8 of 691 entries

Fig. 6. Sample room (indoor_ca) condition reports.

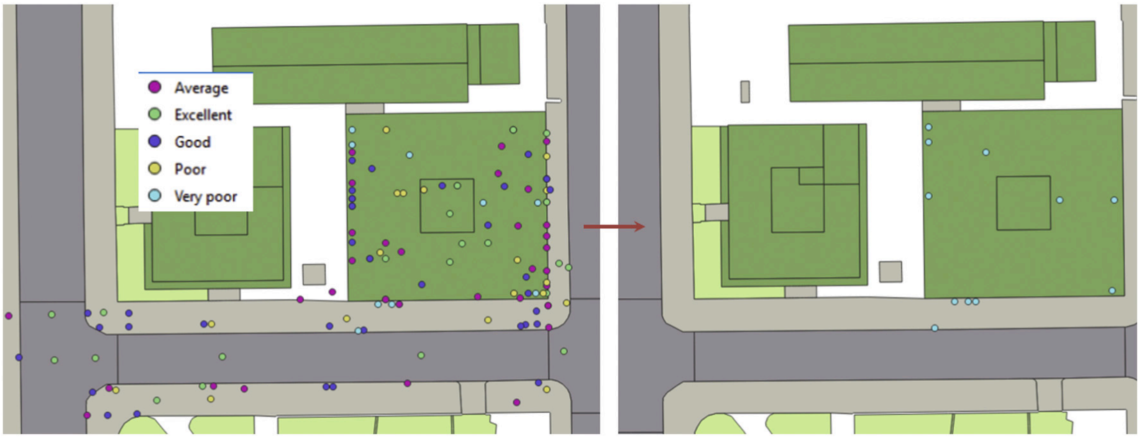


Fig. 7. BE CA data visualisation and filtering of only "Very poor" condition elements.

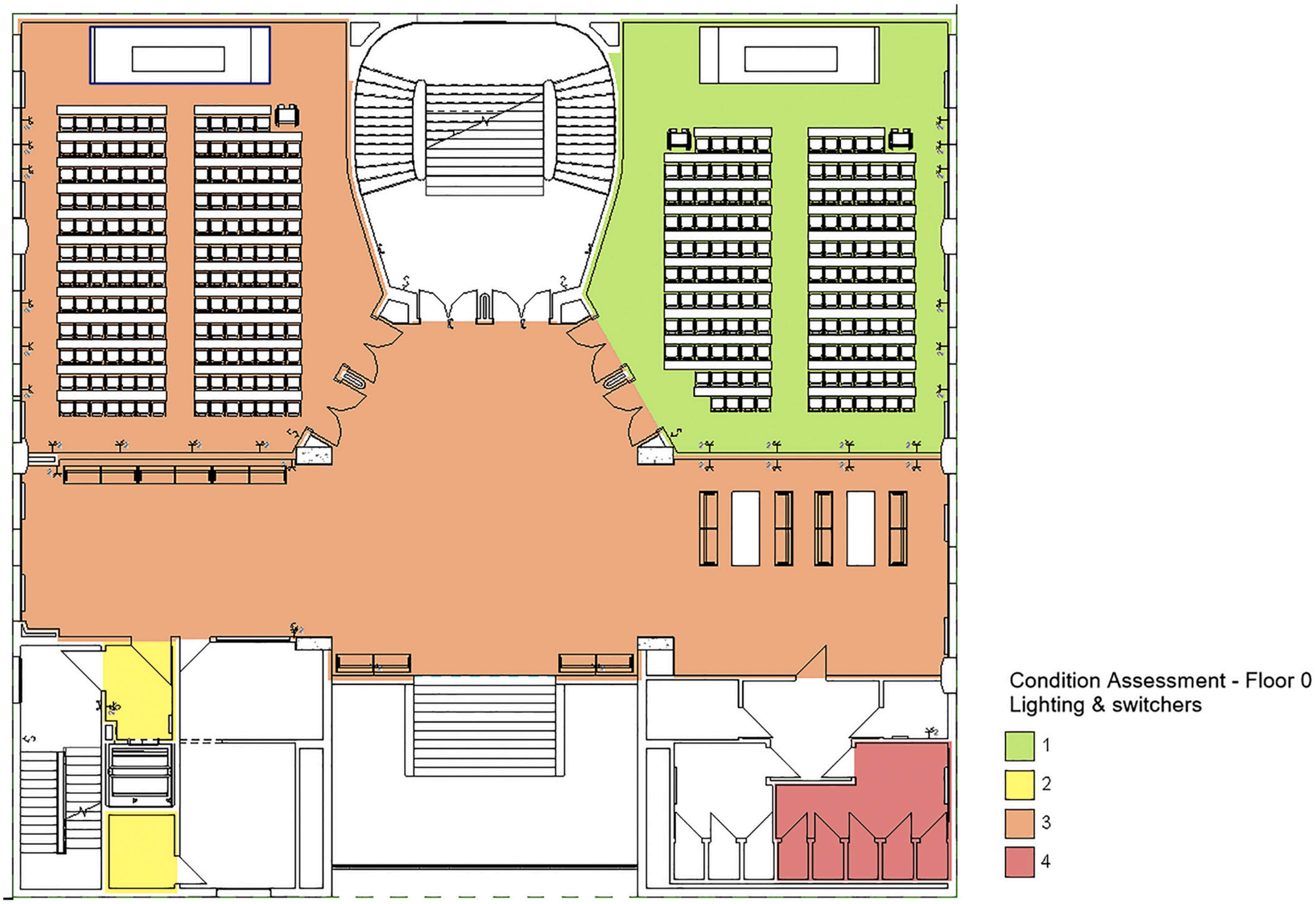


Fig. 8. Indoor CA – Building results visualised for the lighting and switchers system.

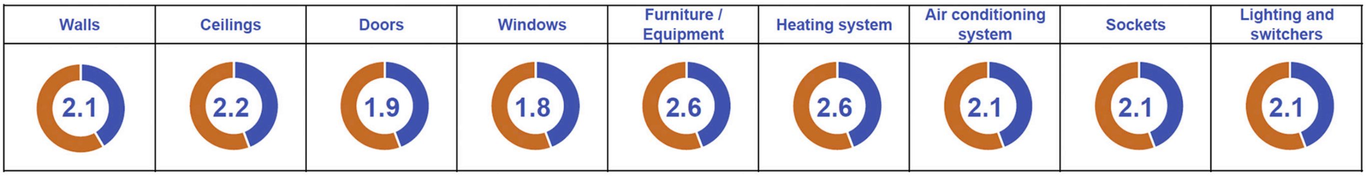


Fig. 9. Indoor CA – Building results.

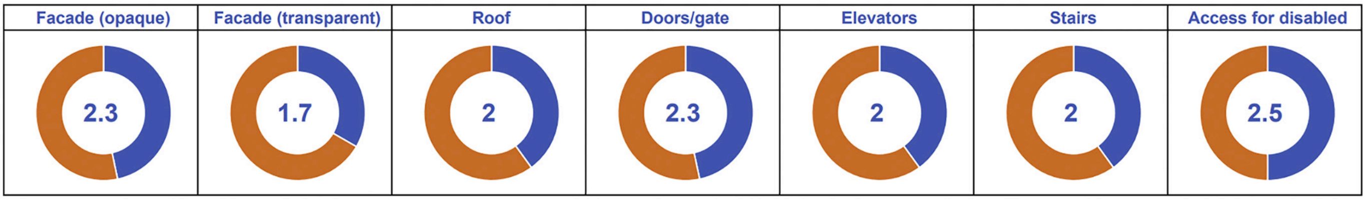


Fig. 10. Outdoor CA - Building envelope & common parts results.

the condition data – i.e., if most of the assets has not been surveyed in the last 2 years, then the value place on the resulting CA might be less. Secondly new features to be surveyed or otherwise included in the AM task can be easily added into the spatial database and visualised using the off-the-shelf GIS tools (e.g. QGIS). This is also possible through the 3D visualisation tool developed, which also demonstrated the opportunity to democratise the data – i.e., proved access for non-specialists. This is highly important in the AM field, because most of the stakeholders either need information that cannot be directly provided by BIM authoring tools and by GIS tools (synthetic reports, dashboards, Key Performance Indicators - KPIs, etc.) or do not use those tools [53].

Additionally, the approach is repeatable - it is common that condition surveys are conducted on a regular basis (with frequency depending on the criticality of an asset) and having a centralised data store allows to run time-based analysis to monitor deterioration of the facility and its surroundings. Knowing the location of the assets to be surveyed also

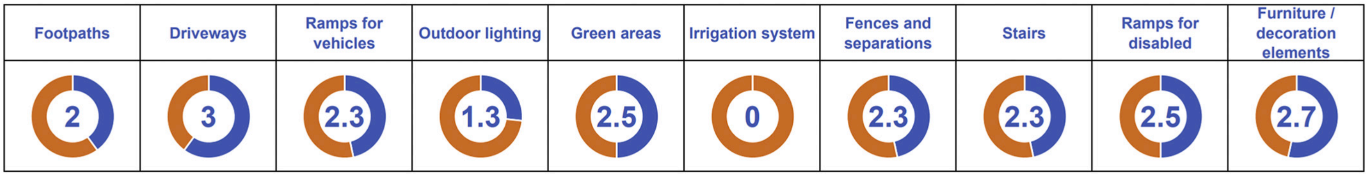


Fig. 11. Outdoor CA - Building's surroundings results.

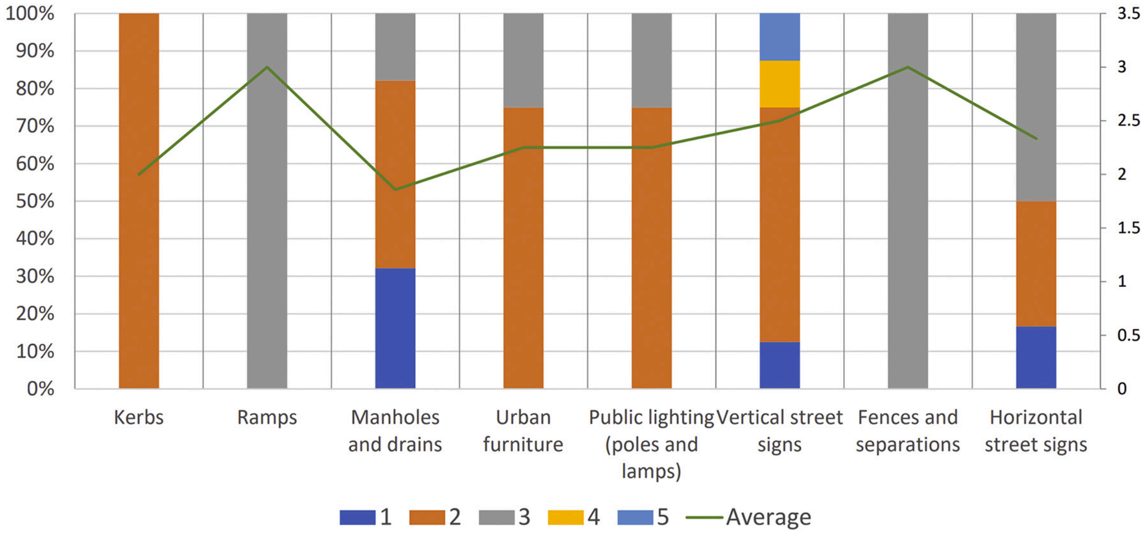


Fig. 12. Outdoor CA - Public areas (neighbourhood).

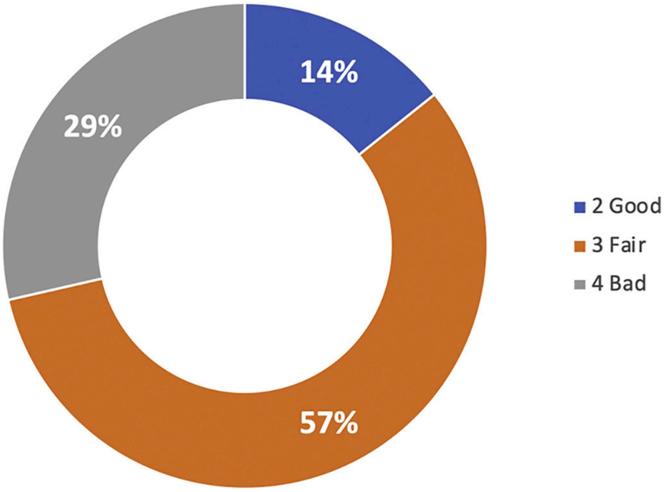


Fig. 13. Scores of the defects of the surfaces.

permits optimal deployment of the survey task itself (via a 'travelling salesman' approach which calculates the best route between multiple locations). It additionally assists in the interpretation of the CA results – visualising an asset in context, coupled with ad-hoc queries of the location data and demand data – can help to understand why, for example, one boiler is deteriorating much faster than another. Regular reports can also be automatically generated by aggregating the data.

From a technical perspective PostGIS[5] is a spatial database extender for the PostgreSQL database and was selected for this project due to the availability of 3D data storage and manipulation functionality as well as due to the ease of integration with QGIS. PostgreSQL, PostGIS and QGIS are free and open source, reducing the barriers to entry for asset managers.

In general a database has the fundamental advantage of acting as a central store for data, permitting multiple users and applications to connect and share information. A central database means that integration with other tools - e.g. maintenance personnel scheduling – is possible.

The adoption of the proposed approach allows to collect large datasets with reduced resources and saving times for inspection. This results in the development of tools for supporting decision making at the AM and OM&R levels. Moreover, data are collected both for the building, and the BE elements, allowing a continuous assessment of the city environment. This allows to assess and control the BE in an innovative way, possible thanks to the integration of the digital technologies adopted and the multi-scalar and cross-domain approach adopted.

A key challenge of the approach described here is the overall technical complexity. There is a need for a database administrator, a need to create the BIM data and convert it, a need to curate the data long term (updating the data as necessary when the built environment is modified in any way), a need for integrated geospatial and AM expertise. However as noted in Section 1 there is an increasing understanding of the power of digital data within the AECO sector and having such expertise in house will greatly facilitate the uptake of a digital approach to AM.

The process of integrating data from three sources – BIM, GIS and CA – highlighted the importance of bespoke semantic mapping which, to date, cannot be fully automated. Both BIM and GIS data, having been captured for alternative purposes, did not provide a 1:1 mapping of the features identified by the stakeholders as being required for the condition survey. Additionally, the process of conversion from BIM to spatial database resulted in extremely complex geometry which had to be generalised (converted to a point) to be visualised within a GIS.

The work described in this paper was carried out over a relatively

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[5] https://qgis.org/en/site/ [Accessed 11th June 2020].

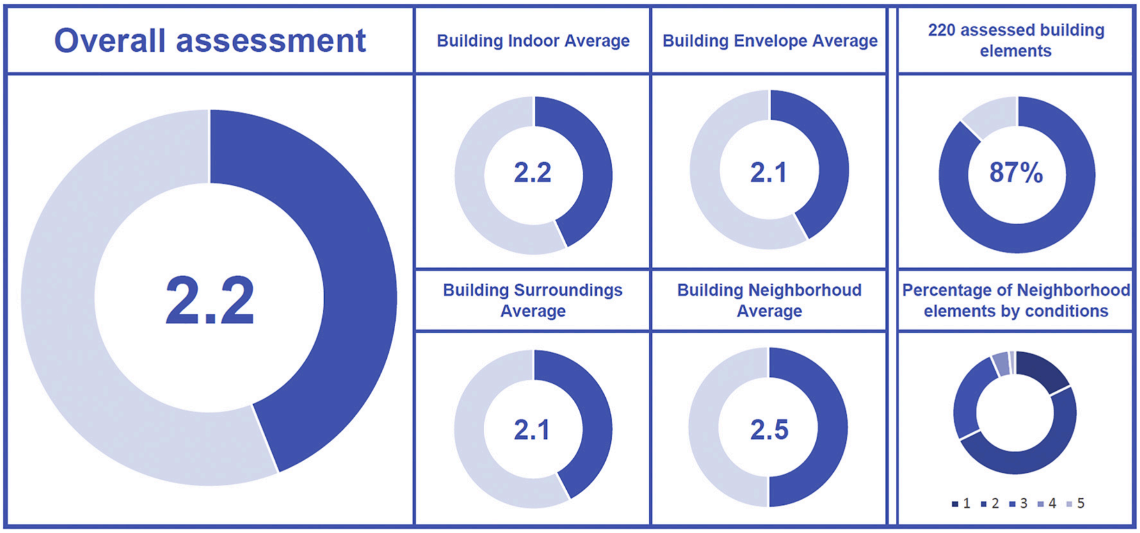

Fig. 14. Dashboard summarising the overall results of the CA.

small area in and around the campus of the Politecnico di Milano, Italy and highlighted the overall potential of this approach. However, it should be applied to further case studies, to validate its effectiveness and fine tune the processes implemented. Moreover, the following key areas have been identified, where further research work is required:

- obtaining a better understanding of the information requirements of the multiple stakeholders involved in built AM – e.g., via interviews. This would also enhance our understanding of the importance of, and potential for, location data in this context. Moreover, the exploration of further GeoBIM AM information requirements, can inform the BIM and 3D GIS modelling of the built environment;
- exploring generalisation algorithms to find a suitable representation for the complex BIM geometry within a spatial database context, supporting the AM business processes;
- exploring automation options for data capture, in particular relating to CA (e.g. via tablets directly into the database or via sensors) and monitoring changes in the BE (e.g. via regular surveys or laser scanning);
- further exploring the links between location-enabled data and AM, in particular the potentially parallel tasks of aggregation from component, to building, to portfolio and the generalisation of location data from detailed BIM through to 3D city model and 2D country level maps and the integration with other AM tools;
- exploring the long-term data curation processes required to realise full value from the initial (expensive) data capture costs and ensuring quality data along the life cycle of the physical assets.

These are future research lines, originating from the research presented in this article.

8. Conclusions

This paper demonstrated the power of integrating BIM, GIS and CA data to provide location-enabled decision making for asset managers, in particular highlighting the opportunity to use this approach to improve the efficiency of condition survey capture processes and the resulting information management and analysis tasks. The resulting system can be used by both private and public asset managers, in particular as we have used an open-source software approach for data management and visualisation. Additionally, the multi-scale approach lends itself to built AM for both small and large portfolios, and can be adapted to take advantage of existing data (e.g. if a BIM is not present a simplified 2D or 3D model of a building could suffice although the resulting location-enabled CA would not be as granular).

Once captured (and curated), centrally-stored integrated location data relating to the built environment can also be used in many other ways: to obtain a total count of chairs or desks, and hence a cost for replacement; for decisions relating to health and safe levels of social distancing/building capacity and also street capacity; for fire evacuation routes – taking occupants safely out of the building and identifying a place of safety on campus or in the neighbourhood, for general routing and navigation between buildings across a campus and its neighbourhood; for planning maintenance operations considering health and safety (does repairing an asset require working at height, is the asset near a high voltage and/or a critical system etc.).

Such a 3D digital model of the built asset also has potential to form a component of a wider digital twin of a city, and, coupled with sensor devices that report asset condition in real time, links directly to emerging smart city initiatives, providing evidence to underpin decision making at multiple scales and in multiple contexts.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to express their heartfelt thanks to MSc Eng. Héctor Ortiz for his valuable contribution in the realisation of the BIM model.

References

[1] G. Baldini, M. Barboni, F. Bono, B. Delipetrev, N. Duch Brown, E. Fernandez Macias, K. Gkoumas, E. Joossens, A. Kalpaka, D. Nepelski, M.V. Nunes de Lima, A. Pagano, G. Prettico, I. Sanchez, M. Sobolewski, J.-P. Triaille, A. Tsakalidis, M. C. Urzi Brancati, Digital Transformation in Transport, Construction, Energy, Government and Public Administration, Publications Office of the European Union, Luxembourg, 2019. https://publications.jrc.ec.europa.eu/repository/handle/JRC116179.

[2] RIBA, RIBA Plan of Work 2020 Overview, 2020, https://doi.org/10.4324/9780429346637-2.

[3] F. Barbosa, J. Woetzel, J. Mischke, M.J. Ribeirinho, M. Sridhar, M. Parsons, N. Bertram, S. Brown, Reinventing Construction: A Route to Higher Productivity. https://www.mckinsey.com/~/media/McKinsey/BusinessFunctions/Operations/Our Insights/Reinventing construction through a productivity revolution/MGI-Reinventing-Construction-Executive-summary.pdf, 2017.

[4] R. Saxon, K. Robinson, M. Winfield, Going Digital. A Guide for Construction Clients, Building Owners and Their Advisers. https://www.ukbimalliance.org/wp-content/uploads/2018/11/UKBIMA_Going-Digital_Reportl.pdf, 2018.

[5] A. Bolton, M. Enzer, J. Schooling, E. Al, The Gemini Principles. https://www.cdbb.cam.ac.uk/system/files/documents/TheGeminiPrinciples.pdf, 2018.

[6] ISO, EN ISO 19650-1:2018. Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) - Information management using building information modelling. Part 1: Concepts and principles. https://www.iso.org/committee/49180.html?fbclid=IwAR14dRLyXIH_C3jrlfzD0Uke_HimIXeR_w5_CJoFwC2gsJAL4hrOfRLFJ20, 2018.

[7] ISO, EN ISO 19650-2:2018. Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) - Information management using building information modelling. Part 2: Delivery phase of the A. https://www.iso.org/committee/49180.html?fbclid=IwAR14dRLyXIH_C3jrlfzD0Uke_HimIXeR_w5_CJoFwC2gsJAL4hrOfRLFJ20, 2018.

[8] F. Noardo, C. Ellul, L. Harrie, E. Devys, K. Arroyo Ohori, P. Olsson, J. Stoter, Eurosdr geobim project a study in europe on how to use the potentials of Bim and geo data in practice, ISPRS - international archives of the photogrammetry, Rem. Sens. Spatial Inform. Sci. XLII-4 (W15) (2019) 53–60, https://doi.org/10.5194/isprs-archives-XLII-4-W15-53-2019.

[9] R. Marmo, M. Nicolella, F. Polverino, A. Tibaut, A methodology for a performance information model to support facility management, Sustainability. 11 (2019) 7007, https://doi.org/10.3390/su11247007.

[10] S. Lavy, J.A. Garcia, M.K. Dixit, KPIs for facility's performance assessment, part I: identification and categorization of core indicators, Facilities. 32 (2014) 256–274, https://doi.org/10.1108/F-09-2012-0066.

[11] R. Bortolini, N. Forcada, Building inspection system for evaluating the technical performance of existing buildings, J. Perform. Constr. Facil. 32 (2018), 04018073, https://doi.org/10.1061/(ASCE)CF.1943-5509.0001220.

[12] Hong Kong Buildings Department, Mandatory BuildingInspection Scheme MANDATORY Window Inspection Scheme. https://www.bd.gov.hk/doc/en/resources/codes-and-references/code-and-design-manuals/GGMBISMWIS.pdf, 2010 (accessed June 9, 2020).

[13] Department of Territory and Sustainability, Decreto 67/2015, de 5 de mayo, para el fomento del deber de conservacio´n, mantenimiento y rehabilitacio´n de los edificios de viviendas mediante las inspecciones técnicas y el libro del edificio (Decree 67/2015, of 5 May, for the promotion of the duty). https://noticias.juridicas.com/base_datos/CCAA/552321-d-67-2015-de-5-may-ca-cataluna-fomento-del-deber-de-conservacion-mantenimiento.html, 2015.

[14] Comune di Milano Direzione Urbanistica, Approvazione delle linee guida di indirizzo per la verifica dell'idoneita' statica delle costruzioni presenti all'interno del territorio comunale ai sensi dell'art. 11.6 del Regolamento Edilizio (Approval of the guidelines for verifying the static suitabi). https://www.comune.milano.it/documents/20126/3813098/Approvazione+Linee+guida.pdf.pdf/e60d3427-a978-f340-6549-d707f3c51241?t=1572450198651, 2016.

[15] Comune di Milano, RE Regolamento Edilizio Comune di Milano (Milan Municipality Building Regulations), Milano, https://www.comune.milano.it/documents/20126/3813098/Regolamento+Edilizio+-++Approvato+con+deliberazione+del+Consiglio+Comunale+n.+27+del+2+Ottobre+2014+e+successive+modificazioni+ed+integrazioni.pdf/02e04741-4c68-35ca-4155-eccffd7fc6e4?t=1558544993206, 2014. (Accessed 9 June 2020).

[16] ISO, ISO 15686-3:2002 Buildings and Constructed Assets — Service Life Planning — Part 3: Performance Audits and Reviews. https://www.iso.org/standard/29430.html, 2002.

[17] ISO, ISO 15686-7:2017 Buildings and Constructed Assets — Service Life Planning — Part 7: Performance Evaluation for Feedback of Service Life Data from Practice, 2017.

[18] ISO, ISO 15686-10:2010 Buildings and Constructed Assets — Service Life Planning — Part 10: When to Assess Functional Performance Bâtiments. https://www.iso.org/standard/44859.html, 2010.

[19] M.N. Grussing, Optimized building component assessment planning using a value of information model, J. Perform. Constr. Facil. 32 (2018), 04018054, https://doi.org/10.1061/(asce)cf.1943-5509.0001198.

[20] K. Kim, J. Yu, Improvement of facility condition assessment processes using BIM Data, in: Construction Research Congress 2016: Old and New Construction Technologies Converge in Historic San Juan - Proceedings of the 2016 Construction Research Congress, CRC 2016, American Society of Civil Engineers (ASCE), 2016, pp. 2432–2442, https://doi.org/10.1061/9780784479827.242.

[21] N. Moretti, F. Re Cecconi, A cross-domain decision support system to optimize building maintenance, Buildings. 9 (2019) 161, https://doi.org/10.3390/buildings9070161.

[22] F. Re Cecconi, N. Moretti, S. Maltese, L.C. Tagliabue, A BIM-based decision support system for building maintenance, in: Advances in Informatics and Computing in Civil and Construction Engineering, Springer International Publishing, Cham, 2019, pp. 371–378, https://doi.org/10.1007/978-3-030-00220-6_44.

[23] Q. Lu, A.K. Parlikad, P. Woodall, G. Don Ranasinghe, X. Xie, Z. Liang, E. Konstantinou, J. Heaton, J. Schooling, Developing a digital twin at building and City levels: case study of West Cambridge campus, J. Manag. Eng. 36 (2020) 1–19, https://doi.org/10.1061/(ASCE)ME.1943-5479.0000763.

[24] P.C. Lee, Y. Wang, T.P. Lo, D. Long, An integrated system framework of building information modelling and geographical information system for utility tunnel maintenance management, Tunn. Undergr. Space Technol. 79 (2018) 263–273, https://doi.org/10.1016/j.tust.2018.05.010.

[25] P.A. Longley, M.F. Goodchild, D.J. Maguire, D.W. Rhind, Chap 1: Geographic Information: Science, Systems, and Society, Geographic Information: Science, Systems, and Society, 2015, pp. 1–15. ISBN: 978-1-119-03130-7.

[26] T. Blaschke, H. Merschdorf, Geographic information science as a multidisciplinary and multiparadigmatic field, Cartogr. Geogr. Inf. Sci. 41 (2014) 196–213, https://doi.org/10.1080/15230406.2014.905755.

[27] P.A. Longley, M.F. Goodchild, D.J. Maguire, D.W. Rhind, Chap 7: geographic data modeling definitions, in: Geographic Information: Science, Systems, and Society, 2015, pp. 152–172. ISBN: 978-1-119-03130-7.

[28] J. Stoter, H. Ledoux, S. Zlatanova, F. Biljecki, Towards sustainable and clean 3D Geoinformation. in: Geoinformationssysteme 2016: Beiträge zur 3. Münchner GI-Runde (pp. 100-113). VDE Verlag. ISBN: 978-3879076109.

[29] C. Ellul, J. Altenbuchner, LoD 1 vs. Lod 2 - Preliminary investigations into differences in mobile rendering performance, in: ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 2013, pp. 129–138, https://doi.org/10.5194/isprsannals-II-2-W1-129-2013.

[30] E. Muñumer Herrero, C. Ellul, J. Morley, Testing the impact of 2D generalisation on 3D MODELS-exploring analysis options with an off-the-shelf software package, in: ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci. II-2 W 1, 2018, https://doi.org/10.5194/isprs-archives-XLII-4-W10–119-2018.

[31] T.H. Kolbe, G. Gröger, L. Plümer, CityGML: Interoperable Access to 3D City Models, in: Geo-Information for Disaster Management, Springer Berlin Heidelberg, Berlin, Heidelberg, 2005, pp. 883–899, https://doi.org/10.1007/3-540-27468-5_63.

[32] J. Sharman, The NBS Guide to Collaborative Construction, NBS. https://www.thenbs.com/knowledge/the-nbs-guide-to-collaborative-construction, 2017.

[33] F.E. Jernigan, Big BIM, Little Bim: The Practical Approach to Building Information Modeling: Integrated Practice Done the Right Way!, 4site Press, 2008.

[34] J. Bedrick, W. Faia, P.E. Ikerd, J. Reinhardt, Level of Development (LOD) Specification Part I, Bim-Bep 254, 2020. www.bimforum.org/lod.

[35] C. Ellul, J. Stoter, L. Harrie, M. Shariat, A. Behan, M. Pla, Investigating the state of play of geobim across Europe, in: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, Int. Soc. Photogr. Rem. Sensing. (2018) 19–26, https://doi.org/10.5194/isprs-archives-XLII-4-W10-19-2018.

[36] M. Garramone, N. Moretti, M. Scaioni, C. Ellul, F. Re Cecconi, M.C. Dejaco, BIM and GIS integration for infrastructure asset management: a Bibliometric analysis, ISPRS annals of photogrammetry, Rem. Sens. Spatial Inform. Sci. VI-4 (W1–20) (2020) 77–84, https://doi.org/10.5194/isprs-annals-vi-4-w1-2020-77-2020.

[37] G.A. Boyes, C. Ellul, D. Irwin, Exploring BIM for operational integrated asset management - a preliminary study utilising real-world infrastructure data, ISPRS annals of the photogrammetry, Rem. Sens. Spatial Inform. Sci. 4 (2017) 49–56, https://doi.org/10.5194/isprs-annals-IV-4-W5-49-2017.

[38] C. Ellul, G. Boyes, C. Thomson, D. Backes, Towards integrating BIM and GIS—an end-to-end example from point cloud to analysis, Lecture Notes Geoinform. Cartography. (2017) 495–512, https://doi.org/10.1007/978-3-319-25691-7_28.

[39] M. Gunduz, U. Isikdag, M. Basaraner, Integration of BIM, WEB MAPS and IOT for supporting comfort analysis, ISPRS annals of the photogrammetry, Rem. Sens. Spatial Inform. Sci. 4 (2017) 221–227, https://doi.org/10.5194/isprs-annals-IV-4-W4-221-2017.

[40] V. Edmondson, M. Cerny, M. Lim, B. Gledson, S. Lockley, J. Woodward, A smart sewer asset information model to enable an 'internet of things' for operational wastewater management, Autom. Constr. 91 (2018) 193–205, https://doi.org/10.1016/j.autcon.2018.03.003.

[41] Z.Z. Hu, J.P. Zhang, F.Q. Yu, P.L. Tian, X.S. Xiang, Construction and facility management of large MEP projects using a multi-scale building information model, Adv. Eng. Softw. 100 (2016) 215–230, https://doi.org/10.1016/j.advengsoft.2016.07.006.

[42] J.-E. Kim, C.-H. Hong, A study on facility management application scenario of BIM/GIS modeling data, Int. J. Eng. Sci. Invention. 6 (2017) 40–45. http://www.ijesi.org/papers/Vol(6)11/Version-1/I0611014045.pdf.

[43] T. Gilbert, S. Barr, P. James, J. Morley, Q. Ji, Software systems approach to multi-scale GIS-BIM utility infrastructure network integration and resource flow simulation, ISPRS Int. J. Geo Inf. 7 (2018) 310, https://doi.org/10.3390/ijgi7080310.

[44] J. Schwarzenbac, D. Anderson, B. Beal, T. Burgess, D. Crowley-Sweet, T. Fynn, J. Harrison, J. Holdsworth, A. Odunsi, M. Osborne, A. Putley, J. Rennie, T. Taylor, A. Walkley, C. Waring, M. Winterburn, Subject Specific Guidance 22, 23 and 25 - Asset Information, Strategy and Data Standards, Institute of Asset Management, 2015. https://theiam.org/shop/products/20659.

[45] ASTM, Guideline for Condition Assessment of the Building Envelope, American Society of Civil Engineers, Reston, VA, 2014, https://doi.org/10.1061/9780784413258.

[46] D.R. Uzarski, M.N. Grussing, J.B. Clayton, Knowledge-based condition survey inspection concepts, J. Infrastruct. Syst. 13 (2007) 72–79, https://doi.org/10.1061/(ASCE)1076-0342(2007)13:1(72).

[47] Q. Ai, Y. Yuan, S.L. Shen, H. Wang, X. Huang, Investigation on inspection scheduling for the maintenance of tunnel with different degradation modes, Tunn. Undergr. Space Technol. 106 (2020) 103589, https://doi.org/10.1016/J.TUST.2020.103589.

[48] ISO, ISO 16739-1:2018 - Industry Foundation Classes (IFC) for Data Sharing in the Construction and Facility Management Industries — Part 1: Data Schema. https://www.iso.org/standard/70303.html, 2018 (accessed March 22, 2021).

[49] F. Faqih, T. Zayed, A comparative review of building component rating systems, J. Build. Eng. 33 (2021) 101588, https://doi.org/10.1016/j.jobe.2020.101588.

[50] G. Sá, J. Sá, J. De Brito, B. Amaro, Statistical survey on inspection, diagnosis and repair of wall renderings, J. Civ. Eng. Manag. 21 (2015) 623–636, https://doi.org/10.3846/13923730.2014.890666.

[51] A.J. Prieto, A. Silva, Service life prediction and environmental exposure conditions of timber claddings in South Chile, Build. Res. Inf. 48 (2020) 191–206, https://doi.org/10.1080/09613218.2019.1631143.

[52] C. Ornelas, J. Miranda Guedes, F. Sousa, I. Breda-Vázquez, Supporting residential built heritage rehabilitation through an integrated assessment, Int. J. Architect. Heritage (2020), https://doi.org/10.1080/15583058.2020.1712496.

[53] F. Re Cecconi, S. Maltese, M.C. Dejaco, Leveraging BIM for digital built environment asset management, Innov. Infrastr. Solut. 2 (2017) 14, https://doi.org/10.1007/s41062-017-0061-z.

[54] E. Ogbeifun, C. Mbohwa, J.H.C. Pretorius, Developing an effective renovation plan: the influence of data collection tools, Int. J. Build. Pathol. Adapt. 36 (2018) 63–76, https://doi.org/10.1108/IJBPA-09-2017-0035.

[55] G. Mayo, P. Karanja, Building condition assessments – methods and metrics, J. Facility Manag. Educ. Res. 2 (2018) 1–11, https://doi.org/10.22361/jfmer/91666.

[56] A. Straub, Using a condition-dependent approach to maintenance to control costs and performances, J. Facil. Manag. 1 (2002) 380–395, https://doi.org/10.1108/14725960310808079.

[57] Q.L. Kiang, Brite Euram 4213: Condition Assessment and Maintenance Strategies for Buildings and Building Components, 2006, p. 4213. http://www.recc.com.sg/download/be, 4213 project summary.pdf (accessed June 9, 2020).

[58] Google, Google Forms – create and analyse surveys, for free. https://www.google.com/intl/en-GB/forms/about/, 2020 (accessed May 8, 2020).