Built environment data modelling: a review of current approaches and standards supporting Asset Management

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Abstract: Information Management is crucial in the Asset Management domain. Well-structured information management processes allow to access the needed data, in the right format, and enables the development of cross-domain Asset Management services. Several studies can be found in literature, on the capabilities and applications of digital tools in Architecture Constructions and Operations (AECO), demonstrating how digitisation has changed the traditional processes. Moreover, many data modelling approaches and standards can be used to support digital Asset Management applications. Due to the advancement of Digital Twin related research, the interest for the ontological and data modelling approaches have increased in recent years. This article aims at organising the body of knowledge on data modelling in AECO, through a critical review of existing approaches and standards. The literature is studied and the main trends are highlighted. The most relevant articles are selected and a contents analysis is carried out. The study shows that digital Asset Management applications require interdisciplinarity and data access across different domain; two main approaches for the development of intermediate data models can be identified in literature and a unique data model able to represent multiple scales and domains cannot be found. Thus, some future research works are proposed as a conclusion of the literature review.

Keywords: Data Modelling, Information Management, Asset Management, AECO, built environment, digital twin.

1. INTRODUCTION

The Architecture Engineering Construction and Operations (AECO) is an idle sector, relying on outdated procedures hindering the collaboration and the efficient employment of resources (Pärn, Edwards, and Sing 2017). AECO, in Europe, has been historically characterised by the presence of few large enterprises, able to provide high performances in delivering digital-based products and services and many Small and Medium Enterprises (SME), adopting labour intensive processes (Baldini et al. 2019). However, this trend is likely to change in the next years due to increasing investments in newcos adopting and developing new technologies in AECO (Baldini et al. 2019). Even small improvements could lead to big savings and the full-scale digitisation in the next decade could lead in non-residential sector large savings: €0.62T to €1.06T (13% to 21%) in Engineering and Construction and €0.26T to €0.44 T (10% to 17%) in Maintenance and Operations (Gerbert et al. 2016). This trend pushed many organisations towards the business processes re-engineering, to develop better and digital-based services (Saxon, Robinson, and Winfield 2018). This dynamic is also possible thanks to the standardisation efforts (for instance, within the context of the ISO series 19650), supporting the development of digital processes and the adoption of digital tools (ISO 2018). A further leading force, boosting the industry digitisation, is the advancement of the Digital Twin (DT) concept. A DT is generally conceived as a modular dynamic system connecting and using heterogeneous data sources, for improved operations and decision making (Boje et al. 2020). BuildingSMART International (2020) identify three main themes to be addressed in digital twinning:

- the lack of a widely accepted approach for integrating the data coming from different domains, for supporting information management across the life cycle of the assets, removing the barriers of the data silos and promoting collaborative approaches;
- the needs for standards on data integration, connecting the realm of data management and integration, giving priority to approaches focusing on semantic precision to facilitate the establishment of a resilient ecosystem of DTs;
- the need for a security minded approach for data hosting ownership and privacy.

Addressing these issues, this paper aims at providing a review on the open and most used data modelling approaches in AECO, at different scales, with a specific focus on supporting operations in the use stage. The research is carried out considering the management of the built environment, in the perspective of the development of a distributed built environment city-level DT. Therefore, data modelling methods in different domains and their applications are analysed according to their capability to support information management in digital assets' life cycle.

2. METHODS AND TOOLS

The main steps of the literature review are represented in Figure 1. The Scopus database is queried for collecting the relevant references. The first step corresponds with the identification of the keywords, defining the boundaries of the field of knowledge. The bibliometric and contents analyses allow to scope the literature production and to identify main trends and dynamics. A selection of a reduced sample of references describing the data modelling approaches in the AECO sector, is carried out. The data models are categorised according to their use and domain (buildings, infrastructures, precincts/city, land/territory) and the capability of addressing specific domain applications. Two main sets are identified: comprehensive domain-specific data models and intermediate models, used for handling data for cross-domain AM applications. Through the literature review some insights on the most used protocols and their potential use in the development of a city-level DT are obtained.

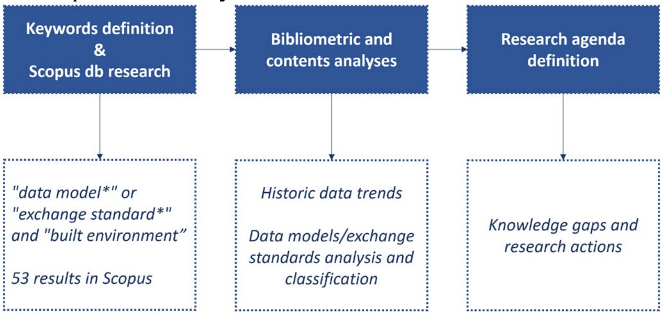

Figure 1: Research schema

The last step of the research concerns the identification of the knowledge gaps and the definition of a set of mid-term research actions.

3. DATA MODELLING IN THE AECO

The following keywords were used *"title, abstract and keywords" fields: "data model*" or "exchange standard*" and "built environment"* to query the Scopus database in January 2022. Articles in non-relevant fields for the research have been removed (e.g., medicine, material sciences, arts and humanities, chemistry), achieving a number of 53 results. The general descriptive information on the sample is represented in Table 1.

Table 1: Main information on the sample.

Description	**Results**
Period	2004:2021
Documents	53
Average citations per documents	18.45
Article	32
Conference paper	21
Authors	147
Single-authored documents	12
Documents per Author	0.361
Co-Authors per Documents	3.06

The research field is rather dynamic and shows a high average citation index per document in the period 2004-2021. Moreover, Figure 2 indicates an overall increase of the literature produced over the years (more stable after the peak in 2017). Two main peaks can be identified in 2013 and 2017. Many factors could have contributed, though they correspond to some milestones in the development of the Industry Foundation Classes (IFC) schema: IFC 4 (2013) in its first version (ISO 2013) and IFC4 ADD2 TC1 (2017). In fact, many articles analysed, address the IFC as a data model employed for different purposes. After 2017, the rising number of publications on data modelling, can be due to the increasing interest for Building Information Modelling (BIM) and Geographic Information Systems (GIS) integrated research (Ellul et al. 2018). The next sub-sections present some of the most relevant data modelling and exchange approaches, highlighting their purpose and the main information management problems addressed. In this part of the literature review, only the most relevant articles, out of the 53 identified, have been considered (also due to space limitations).

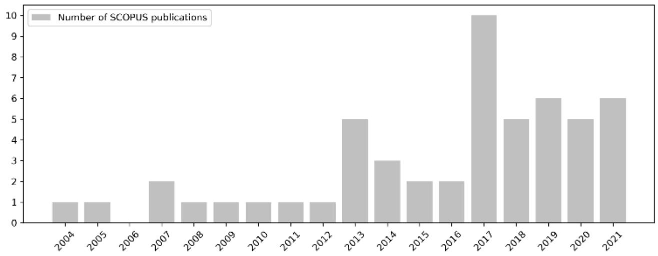

Figure 2: Annual scientific production.

3.1 Semantic enrichment and cross-domain modelling

The semantic enrichment approach is proposed in some selected articles, to handle the full complexity of advanced analytics in management of the built environment. Knoth et al. (2018) aim at creating a core cross-domain model extracting the essential classes and information from four main intermediate models: the Unified Building Model (UBM), the BIM Oriented Indoor data Model (BO-IDM), the Indoor Emergency Spatial Model (IESM) and the BIM-GIS integration model for Flood Damage Assessment (FDA model). This approach is intended as a baseline in the integration of the IFC and City Geography Markup Language (CityGML). The authors implement a method for analysing the four middle models and identifying the main relations and overlappings among them, based on Unified Modelling Language (UML) conceptual modelling. The defined cross-domain model allows domain-specific expansions. They test the method in two use-cases: Production Environment/Maintenance and 3D Digital Cadastre.

Lee *et al.* (2020) investigate the possibility to implement a domain-specific model in IFC, by means of the Information Delivery Manuals (IDM) for achieving a Model View Definition (MVD) of a structural part of the building (cast/pre-cast operations). This is allowed by the use of mvdXML format for querying the model. Moreover, they suggest ifcDoc (in mvdXML) for creating domain-specific MVDs, reusing existing models. An entity-based framework for reusing existing Exchange Requirements (ER) is finally proposed. After mapping similar classes in the 3 MVDs (PCI, ACI and AISC), they employ the XQuery language for retrieving relevant information and track classes' co-occurrence across MVDs. This allows to leverage pre-existing MVDs, enriching the existing models with further information, therefore avoiding the creation of new MVDs.

3.2 Real time data modelling

Another critical issue is the real time data modelling and integration with contextual data. Tang et al. (2020) propose to facilitate data exchange between BIM and Building Automation Systems (BAS) through IFC and the BACnet protocols. IFC is intended as an intermediate model allowing data exchange among different domains. ifcDoc is used for developing the MVD, after defining the IDM through the IDM templates (buildingSMART International 2020). The Automation and Control Networks (BACnet) objects can be modelled as visual instances in BIM. The authors map the BACnet protocol and IFC, defining a BACnet MVD.

Scheffer et al. (2018) suggest to use the *ifcSensor*, *ifcSensorType* and *ifcSensorTypeEnum* for handling the sensor data and suggest the integration with BACnet or OPC for enabling the building automation control. They also develop the sensor infrastructure and connect the data to the IFC data model. However, real-time integration is not in place yet.

Hernández et al. (2018) propose a framework for real-time data integration in a BIM-centred platform called "extended BIM" (xBIM). The xBIM approach combines static and dynamic data under the same format: IFC. They link static and dynamic data through a GlobalUID in IFC and other data sources.

Wills and Diaz (2017) propose an approach for BIM, Computer Aided Facility Management (CAFM) ad real time data integration. The sensors' infrastructure can be connected via the CAFM-Connect protocol, a subset of IFC.

Dembski et al. (2020) propose a domain-specific application for smart cities and simulations, based on a DT concept, comprehending: a 3D model of the built environment; a mathematical street network based on the theory and method of space syntax; an urban mobility simulation with SUMO; an air-flow simulation with OpenFOAM; a pollution simulation using empirical quantitative data from a sensor network; a tool for capturing the perception of urban places and photos of these places. The DT is embedded in COVISE: a collaborative visualisation and simulation environment.

3.3 Multi-scale data exchange

Many references address the problem of multi-scale data exchange and interoperability. Kardinal Jusuf et al. (2017) develop an Extract Transform Load (ETL) approach for geometric elements, from IFC to CityGML. The workflow is based on the following steps: import, create meshes, rotate, create attributes, extrude, set Coordinate Reference System (CRS), write CityGML. The output model is imported in a City Application and Visualization Interface (CAVI), to simulate energy consumption. This approach is applied to multiple buildings and provides a useful practical approach for energy analysis at the city level.

Sani and Rahman (2018) review data, service and process GIS/BIM data integrations, where the data level shows the highest level of complexity and it is the basis for implementing the service and process integration. On the data level integration, the authors make an insight on two standard data models: CityGML and IFC. The first is the data model defining the main attributes, entities and relations of the city, which is essential for city modelling. It allows the definition of different Level of Details (LoD). The second is developed in EXPRESS information schema, according to the Object Oriented (OO) concept. It provides hundreds of objects and allows the detailed representation of the building's parts. The authors summarise the main problem of the integration:

- different coordinate systems (GCS) in GIS and Local Coordinate System (LCS) in BIM;
- the different representation of the objects (e.g., b-rep, Sweep Solid – SS and Constrictive Solid Geometry - CSG);
- no exact correspondence between granularity in the representation in the two domains;
- the classes in IFC are much more specific that in CityGML and cannot be easily mapped. Despite some software solutions becoming available (e.g.: Feature Manipulation Engine - FME, BIMServer and Data Interoperability - DI an IFCExplorer), all of these can hardly maintain semantics in the conversion.

Jetlund, Onstein, and Huang (2020) propose a pattern to convert the IFC EXPRESS to UML models according to the ISO/TC 211, This approach allows to support the implementation of applications belonging to both the domain of BIM and GIS. It also provides useful insights on the IFC-UML model that is implemented by BuildingSMART and a mapping between the ISO/TC 211 standards and the IFC.

Aleksandrov et al. (2019) propose a layered system architecture for integrating and managing data coming from BIM, 3D GIS, and sensors allowing to visualise and manipulate it through a front-end layer. A UML conceptual model that allows connecting different data sources. The model is called Precinct Information Model (PIM). The authors use simplified BIMs at Level Of Detail 1 (LOD1) of 6 buildings, managing the geometries mainly at the building level. The BIM model is handled through a PostGIS database. Data can be visualised in Cesium, allowing the geospatial integration with GIS data, and through QGIS. The sensor data are integrated as historical series in the database.

Eicker et al. (2020) discuss the software architecture and data modelling for developing an urban platform (Service Oriented Architecture - SOA), aimed at improving the energy (SimStadt) and waste/wastewater issues. The model is geographically extended and involves domains such as food and goods consumptions. The model is developed starting from the 3D CityGML geometry. The authors refer to the European Innovation Partnership on Smart Cities and Communities (EIP SCC) for the reference architecture of an Open Urban Platform (OUP) and related Application Programming Interface (API). At the basis of the development of the urban model, there is the PostgreSQL database, handling the data streams. For the integration of the Internet of Things (IoT), the Open Geospatial Consortium (OGC) SensorThings API framework is used.

4. DISCUSSION

The contents analysis allows to identify the most used open data models, supporting the operations of the built environement (Table 2). The models are conceived to address specific domains of applications and aim at providing comprehensive and exaustive definitions of the objects, attributes and relationships within the specific domain.

Table 2: Domain-specific data models for built environment AM.

Institution	Data model and encoding	Domain
BuildingSMART	IFC (EXPRESS, XML, OWL)	Buildings
Onuma, Inc.	BIMXML (XML)	Buildings
BuildingSMART/ OGC	LandInfra (XML, InfraGML)	Infra.
Land XML consortium	LandXML (XML)	Civil eng. Design/survey
CEN/TC 278	TN-ITS spec. (XML, XSD, WADL)	Road network
OGC	CityGML (XML, GML)	City/land
EU	INSPIRE (XML/GML)	Land cover
ISO/TC 211	Land Administration Domain Model (LADM)	Land admin.

However, the built environment data interoperability is known to be a critical issue for improved asset information management (Noardo et al. 2020). To support the business processes, data needs to be exchanges within and outside the organisations. In fact, the OGC and buildingSMART collaborated for studying the capabilities of three of the most prominent data models in the BE: IFC, CityGML and LandInfra. They provide a comprehensive review, highlighting the main features, capabilities and issues in the integration process (Gilbert et al. 2020). They finally propose some action for better models' interoperability:

- the development of illustrative cases specifying software applications, input requirements and internal representations;
- make publicly available dictionaries, definitions used in the standards and shared resources for identifying synonyms;
- the development of a best practice on 3D georeferencing with appropriate level of precision and accuracy, considering also data provenance;
- create a system of common unique identifiers of the real-world entities' to be used during the entities' life cycle;
- agree on a shared method for harmonisation of the conceptual representation at the thematic level.

However, the actions mainly address the multi-scale data exchange and does not consider the digital AM applications angle, requiring inter-disciplinarity and data access across different domains. The initiatives above are even more relevant, within CDBB Information Management Framework (IMF), attempting at providing a common ground for ontological modelling in the DT domain (Hetherington and West, 2020). However, the framework does not provide a concrete toolbox for data modelling. Therefore, this remains an open research field. The main findings of the literature review are summarised below.

Digital AM applications require inter-disciplinarity and data access across different domain (e.g. Operations and Maintenance, energy management, space management etc.). Most of the models in Table 2 support the encoding in Extended Markup Language (XML). This is an advantage in the DT developments, that can be enabled through domain-specific data models interrelation, enhancing the representation and data access capabilities. For conceptualising this, the UML technique can be employed, supporting the mapping and modelling process. UML is used also in several intermediate models (Table 3), developed when the domain-specific models are not suitable and need to be extended or customised to hold specific information.

- Table 3: Intermediate models for supporting application-specific data exchange.

Intermediate models	Original standard
Unified Building Model (UBM)	IFC/CityGML
BIM Oriented Indoor data Model (BO-IDM)	IFC
Indoor Emergency Spatial Model (IESM)	IFC
BIM-GIS integration model for Flood Damage Assessment (FDA model)	GML/CityGML//IFC
IndoorGML	GML/XML
INSPIRE BU	INSPIRE/ XML
GreenBuildingXML (gbXML)	XML
COBie	IFC
CAFM-Connect - IFC based	IFC

The intermediate models address, for instance, the energy simulation, facility management and emergency response. As expected, IFC and GML (CityGML) are used as core schemas. **Two main approaches for the development of intermediate models** emerged. Many articles propose using domain-specific data models, as a starting point to address the calssification and data exchange. However, these are often not enough to respond to complex digital AM services requirements. Two approaches are identified in literature: the first is the data model extension approach, aimed at increasing the capabilities of domain-specific models. This results in the development of new cross-domain (extended) schemes used in specific applications (Knoth et al. 2018; Hernández et al. 2018; Eicker et al. 2020). The second concerns the mapping of existing models to identify the information requirements, used in specific applications (Tang et al. 2020; Lee et al. 2020; Wills and Diaz 2017). This approach is conceptually similar to the procedure adopted for the development of Model View Definitions (MVDs) according to the BIM approach (ISO 2013) and is aimed at reducing the complexity of the original data model, using only the needed parts.

A unique data model able to represent multiple scales and domains cannot be found in literature (Figure 4).

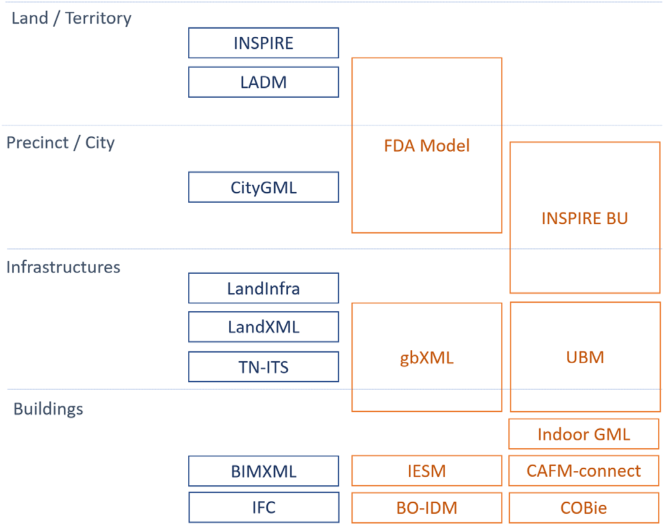

Figure 3: Main data models organised according to four scales. In blue domain-specific models, in orange the intermediate models.

Digital AM applications need a semantic enrichment of the existing models, to enable contextual data integration and appropriate support for data-driven methods (Xie et al. 2021). The intermediate models (represented in amber in Figure 3) attempt to address this matter. These models address both the need for a cross-domain and multi-scale approach for information exchange.

5. CONCLUSIONS

The review presented in this paper allowed to identify and study the most used data modelling approaches for supporting the data exchange in the management of the built environment. Data models have been classified and studied, selecting the most relevant in AECO. A clear need has emerged, reviewing the AM-related applications: a single data model able to represent the whole complexity of the built environment does not exist; neither it is convenient. The UML is a useful technique for ontology conceptualisation and, therefore, for guiding the joint use of several data models. Exploiting the most effective data models in their own domain is a good strategy allowing to better organise domain-specific data, relationships and hierarchies. However, this is not always sufficient. The initiatives aimed at developing intermediate application-specific data models provide evidence of the need for better coverage across domains and scales, when developing AM services in the built environment. The need for the interconnection of different data models, able to describe and manage the digital BE information, at different levels of granularity and cross different domain is a central issue and is an enabler for digital AM applications development. This is a new research direction, compared to the approached described in this review and can enable more flexible and modular DT applications.

An effective approach enabling data interoperability and modularity is the Linked Data approach. According to this method, information from different knowledge domains can be represented and combined through a flexible and generic language (Resource Description Framework - RDF), organised in directed labelled graphs (Pauwels and Terkaj 2016). Potential in linking cross-domain data has been documented in collaborative information management, product manufacturing data, building performance analysis, regulation compliance checking and geographical and infrastructure data (Pauwels, Zhang, and Lee 2017). Nevertheless, an agreed approach able to connect data both in the building and BE domains cannot be found in the literature and represents another research opportunity that will be investigated.

The real time data integration is crucial in digital AM applications, aligned with the DT paradigm. In literature, different approaches are documented. It is possible, for instance, to employ the IDM approach to model the data exchanges, supporting the connection between static data and IoT networks. The RDF data model can offer good support to address this problem, allowing to generate a flexible and rich meta-data ecosystem, useful for dynamic data integration. Altogether, for developing a federated data modelling approach, underpinning BE AM applications, future research works will be done for enhancing the scalability and building, BE, infrastructural and AM data exchange. This could reduce losses in the building-to-built environment transition, through the definition of robust information requirements both for static and real time data integration. Accordingly, interoperability and the delivery of advanced digital AM services, based on a connected system of data models, are being investigated.

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