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BIM Data Model Requirements for Asset Monitoring and the Circular Economy

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BIM Data Model Requirements for Asset Monitoring and the Circular Economy

Abstract

Purpose. The purpose is to review and provide recommendations to extend the current open standard data models for describing monitoring systems and circular economy precepts for built assets. Open standard data models enable robust and efficient data exchange which underpins the successful implementation of a circular economy. One of the largest opportunities to reduce the total life cycle cost of a built asset is to employ the Building Information Modelling (BIM) approach during the operational phase because it represents the largest share of the entire cost. BIM models that represent the actual conditions and performance of constructed assets can boost the benefits of the installed monitoring systems and reduce maintenance and operational costs.

Approach. The paper presents a horizontal investigation of current BIM data models and their use for describing circular economy principles and performance monitoring of built assets. Based on the investigation, an extension to the Industry Foundation Classes (IFC) specification, recommendations and guidelines are presented, which enables to describe circular economy principles and asset monitoring using IFC.

Findings. Current open BIM data models are not sufficiently mature yet. This limits the interoperability of the BIM approach and the implementation of circular economy principles. An overarching approach should extend the current standards is necessary, which considers not only aspects related to modelling the monitoring system but for data management and analysis as well.

Originality and Value. This is the first study that identifies requirements for data model standards in the context of a circular economy. The results of this study set the basis for the extension of current standards required to apply the circular economy precepts.

Keywords: Data Modelling Standards, Circular Economy, Monitoring Systems, IFC, BIM.

Article Type: Conceptual paper

1. Introduction

The current linear economic model of making, using and disposing of is growing unsustainably far beyond the finite limits of planet Earth. This linear model prescribes the extraction of millions of tons of natural resources every year to turn them into materials and products for consumption. At the end-of-life of the products, they are discarded. In a circular economy, products at the end of their lives are still considered as resources and are reintroduced into the economic circuit. Goods are reused, refurbished and recycled in a continuous circle. The construction industry uses large amounts of materials. In Europe, it consumes between 1.2 and 1.8 Mt of construction materials annually (Herczeg et al., 2014). It is also an important economic sector, contributing on average between 5% and 13% to the total gross added value (Eurostat, 2019a). Construction and demolition activities have been responsible for up to one-third of all the waste generated in Europe (Eurostat, 2019b).

Circular economy research for the built environment has been largely focused on the beginning and the end of the built assets' life cycle. It has focused on reducing (Osmani et al., 2006) and recycling construction and demolition waste (Yuan and Shen, 2011). Increasing the efficiency of materials, using new design approaches such as Design for Deconstruction (DfD) has been explored as well (Kanters, 2018; Kibert, 2003). However, built assets have various stages during its life cycle ranging from design, and construction to operation, renovation, and decommission. The operational phase is the largest share of the total life cycle cost. Applying circular economy principles to this phase will contribute the most to the reductions of the total cost and materials used during operations.

The operational phase deals with the management of assets, maintenance, anomaly and damage detection, and renovations and alterations. Constant monitoring of the actual conditions and performance of the built asset is required to carry out these tasks effectively and efficiently. Monitoring systems have been employed primarily for critical infrastructure assets, and more recently for buildings as well, in which additional investments are justified to prevent failures and breakdowns. Moreover, these systems could also provide the necessary data to devise methods for reducing operational and maintenance costs, improving performance and quality, and informing and validating future design solutions. Due to advancements and the achieved level of maturity of sensing technologies, it is now easier to justify these investments, which are increasingly employed for several types of projects in the construction industry.

Building Information Modelling (BIM) is an Information Technology approach used to digitise all the information related to built assets to improve quality and reduce costs (Eastman et al., 2011). However, the BIM approach still lacks the provisions to include monitoring data directly into BIM models (Davila Delgado et al., 2015; Gerrish et al., 2015; Smarsly and Tauscher, 2015), which seriously hinders the full implementation of the BIM approach for the operational phase. More importantly, Circular Economy principles and BIM have been addressed only from the design perspective (Aguiar et al., 2019).

This article seeks to advance the inclusion of Circular Economy principles into the BIM approach for the operational phase of a built asset's life cycle. This paper presents an investigation into the data model requirements to describe the monitoring of the structural performance of built assets, and the underlying requirements to develop robust BIM data models that ensure full interoperability that is required to implement circular economy principles. This paper examines the capabilities of existing open standard data models to describe structural monitoring systems and circular economy principles and presents recommendations and guidelines for potential extensions.

2. Methodology

This paper presents a horizontal investigation into two themes (1) research on BIM data models and the circular economy, and (2) research on BIM data models for asset monitoring. For the first theme, it was investigated in literature how the circular economy principles can be applied to different aspects of the built assets life cycle, and the extent of research carried out in this area, presented in Section 3. For the second theme, it was investigated in literature the advances on BIM data models for asset monitoring; including the organisations that develop the standards, the standard schemas, and specific capabilities, presented in Section 4. Then, using the obtained information from both investigations, an extension to the Industry Foundation Classes (IFC) specification (a BIM data model) was proposed, which enables to describe circular economy principles and asset monitoring using IFC. An adapted version of the method to develop an extension to BIM data models, presented by Hietanen (2006), was used for the proposed extension. The method was exemplified for extending IFC for asset monitoring as there is more literature about that topic. In the case of the circular economy principles, a new set of IFC data modelling entities to enable the inclusion of circular economy principles were proposed as well.

3. BIM Data Models and the Circular Economy

Standardisation is the process of developing norms and requirements based on the consensus of different parties. Standardisation contributes to increased quality, safety and compatibility. Standard data models set the norms of how information should be organised and exchanged in between parties so that no information is lost or misrepresented. Many parties are usually involved in the construction industry, which are responsible for varied tasks. It is a highly fragmented industry, in which many factors inhibit the exchange of information and knowledge (Alashwal et al., 2011). This represents a significant obstacle to the implementation of circular economy principles. A circular economy cannot be implemented by addressing a single construction company or stakeholder. A circular economy is possible if the interconnecting companies that form the entire construction sector come together to apply circular economy principles.

The precepts that underlie the circular economy are a compilation of various decades of research about sustainability. Four main circular economy principles can be listed (Tebbatt et al., 2017) :

I. Doing more with fewer materials or energy, e.g. (Hawken et al., 2013; Stahel, 2010; Womack et al., 1991).

II. Eliminating waste by incorporating it into closed material loops: waste as food, e.g. (EMF, 2015; McDonough and Braungart, 2010).

III. Maintain or increase the value of materials, e.g. (EMF, 2015; von Weizsäcker et al., 2014).

IV. Development of closed-loop systems, e.g. (Meadows, 2008; Pauli, 2010).

Each of these principles can be achieved by implementing different aspects. Circular economy aspects that concern the different life cycle stages of built assets are presented in Table 1. It is evident that for many of these aspects, various parties, with different interests, need to be involved. For example, to implement closed-loop recycling at the decommissioning stage, all the various material suppliers (brick, concrete, steel, wood, glass, etc.) need to agree on a specific process for reconstruction, quantification, processing, transportation, etc. Because built assets are substantially more varied and complex than other consumer goods, this task is also considerably more difficult and complicated. Standard data models have been employed to make more efficient the activities between parties and reduce costs during construction (Barak et al., 2009). However, circular economy aspects have not been considered in the existing standard data models for the construction industry. As the success of a circular economy requires that an entire sector adopts its principles, the development of standard data models that facilitates the seamless collaboration in between parties is essential.

Table 1. Circular economy aspect used during different life cycle stages of built assets.

Built asset life cycle stage	**Circular economy aspects**
Design	Design for Deconstruction (DfD) Design for adaptability and flexibility Design for standardisation Design out waste Design in modularity Specify reclaimed materials Specify recycled materials
Construction	Minimise waste Procure reused materials Procure recycled materials Off-site construction
Operation & Renovation	Minimise waste Minimal maintenance Easy repair and upgrade Adaptability Flexibility
Decommission	Deconstruction Selective demolition Reuse of products and components Closed-loop recycling Open-loop recycling
Adapted from Tebbatt et al. (2017).	

3.1 Research on BIM and the Circular Economy

Despite the vast potential of BIM to contribute to advancing the adoption of circular economy principles in the construction industry, only a few research efforts have addressed this subject, e.g. Akinade *et al.* (2019). A way to visualise the few research efforts that address BIM and circular economy together is by plotting the co-occurrence of both terms (i.e. BIM and circular economy) in a graph, as shown in Figure 1. The co-occurrence map shown in Figure 1 was generated using the software called VOS Viewer (van Eck and Waltman, 2010), and it provides an indication of how related are the research efforts among BIM and the circular economy. The source data for the co-occurrence map are 2000 journal and conference papers listed in SCOPUS that include the terms BIM and circular economy in their titles, abstracts and keywords published since the year 2000. The selected papers are the most relevant papers given both search terms according to SCOPUS relevance ordering algorithm. Papers were excluded from the following research areas chemistry, physics, mathematics, pharma, health, and arts.

In Figure 1, the terms are located based on the co-occurrences in the titles, abstracts and keywords using the so-called visualisation of similarities (VOS) mapping technique (van Eck et al., 2010). The higher the number of co-occurrences, the closest they are located on the map. The size of the circle indicates the number of occurrences of each term in the title, abstract and keywords of the article. The terms are grouped into clusters of closely related terms using a clustering technique presented by Waltman et al., (2010). Four main clusters of similar terms are identified in Figure 1: (1) BIM, (2) Circular Economy, (3) Construction, and (4) Project Management. The two most prominent clusters are BIM and circular economy. A close relationship between BIM, construction, and project management is indicated in the mapping, in which the circular economy is separated significantly from the other clusters.

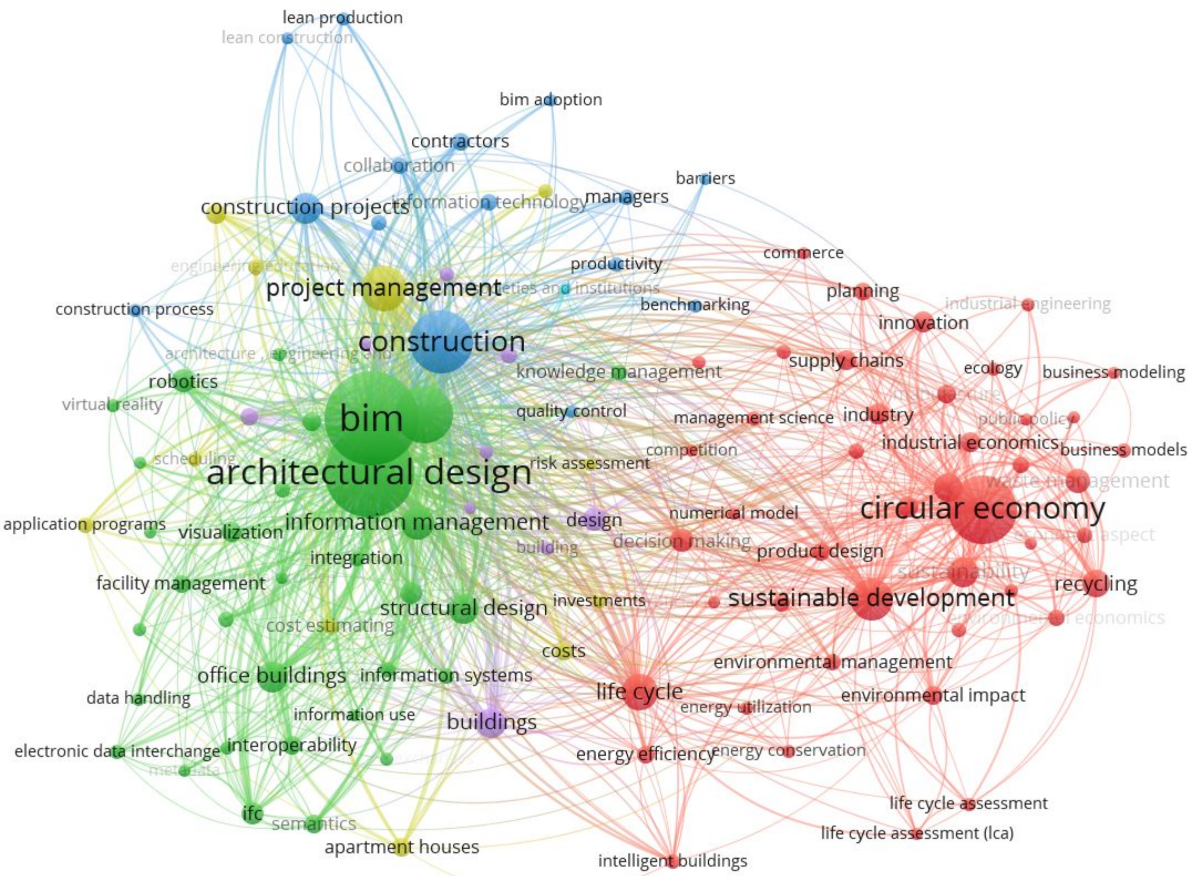

Figure 1. Co-occurrence mapping of the terms BIM and circular economy.

Figure 2 highlights only the co-occurrences of the term circular economy. It can be seen that there are weak relationships, i.e. the terms are far apart, among circular economy and BIM, architectural and structural design, construction, project management, information systems, among others. While there are strong relationships between circular economy, sustainable development, recycling, and industrial economics, among others. Given this gap in research, this paper will provide a basis to address the lack of capabilities of current data models and information management to include circular economy principles.

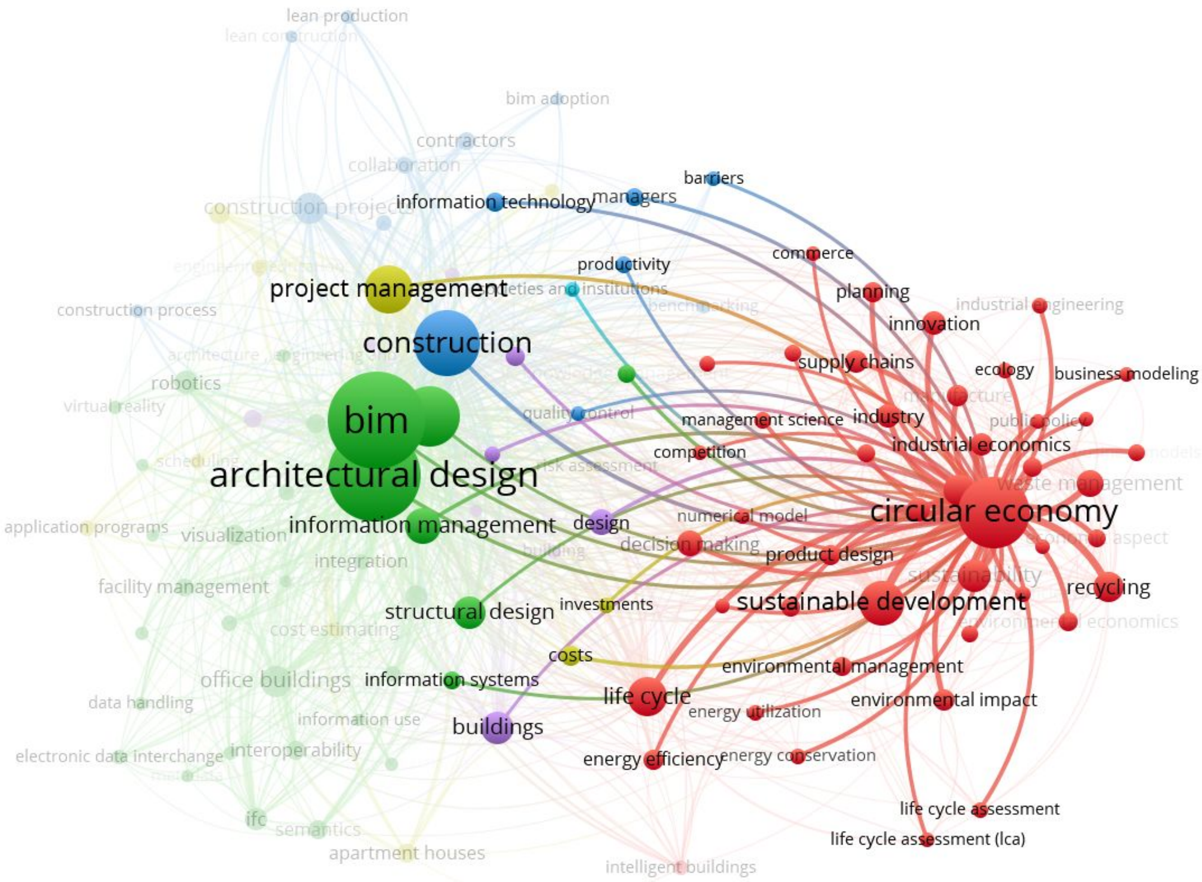

Figure 2. Co-occurrence mapping highlighting the circular economy co-occurrence terms.

4. Standard Data Models for Asset Monitoring

Given the fragmented and diverse nature of the construction industry (Alashwal et al., 2011), one of the biggest challenges to the adoption of the BIM approach is to ensure an efficient and robust exchange of information. Standard data models ensure interoperability among parties in a particular industry by prescribing principles to organise and define relationships between data. Non-proprietary or "open" standard data models are publicly available. This facilitates interoperability because any authoring tool or software solution, proprietary or otherwise, can use the same data model; therefore, they ensure the exchange of information without any data loss. Open standard data models are necessary to employ the BIM approach to its full potential for tasks related to structural performance monitoring. These data models must be able to sufficiently describe the built assets, the monitoring systems, and to manage and visualise the acquired data in a way that facilitates decision making.

BuildingSmart and the Open Geospatial Consortium (OGC) are the two leading organisations that develop open standard data models for the Architecture, Engineering and Construction (AEC) area. The Industry Foundation Classes (IFC) (Liebich et al., 2013), developed by BuildingSmart is the most used specification and intends to provide capabilities to describe all data related to all phases of the life cycle of built assets. Currently, it is able to fully describe data related to buildings primarily during the design and construction phases. IFC is written using the data modelling language EXPRESS and its exchange files are mostly encoded using the "STEP physical file" format. An IfcXML specification is also provided that generates XML 1.0 files created from the IFC-EXPRESS source. The IFC specification is in constant development to increase its capabilities. For example, extensions to the specification for describing infrastructure assets (e.g. IFC Bridge and IFC Road) are under development. These extensions are not yet official parts of the specification or supported by authoring tools, so its application is very limited.

The standards developed by the OGC are mainly focused on facility planning, emergency and asset management, and navigation. OGC has developed the Geography Markup Language (GML), an adaptation of XML (eXtensible Markup Language) to describe geographical features. Various standards that employ GML have been developed, e.g. CityGML for 3D modelling of cities; IndoorGML for indoor navigation; WaterML, for describing data form water observations; and SensorML for describing generic monitoring systems and processes.

LandXML.org has developed LandXML, which is another standard to specify civil engineering and surveying data for land development and transportation. LandXML is supported by many of the most used authoring tools. Lastly, InfraGML is being developed by the OGC. It will be a subset of LandXML, but implemented with GML.

4.1 Current capabilities

OGC supports the Sensor Web Enablement (SWE) initiative that provides web services and communication protocols for accessing online repositories of sensor data. As part of the initiative, SensorML (Botts and Robin, 2014) has been developed, which is capable of describing devices and processes related to sophisticated monitoring systems (Robin and Botts, 2006). It is a generic process model that represents physical and non-physical processes defined by inputs, parameters, and outputs. It is defined from the dataflow perspective to enable automatic processing of sensor data by generic software. Besides monitoring systems, it can also describe simulations, planning processes, alert systems, and storage and archiving systems. The main entities of SensorML are *component*, a physical process that transforms data from one form to another; *system*, an aggregation of components; *process model*, a non-physical process; *process chain*, a set of process models; *detector*, a type of component that responds given a stimulus; and *sensor*, a collection of all the mentioned entities that represent an entire sensor, e.g. an airborne laser scanner. The main limitation of SensorML, –for built asset applications, is that the object being monitored cannot be represented. Note that an ontology to describe sensor networks, the Semantic Sensor Network (SSN) (Compton et al., 2012), has been developed by the World Wide Web Consortium (W3C). The SSN ontology can be considered as a light-weight subset of SensorML, which only considers sensor-specific entities and is compatible with other OGC specifications.

SensorML has been used to describe an executable process model (Chen et al., 2012); its purpose is to facilitate real-time collaboration between web-based sensor devices in complex monitoring tasks. In this case, to determine in real-time a vegetation index, which segments water bodies, green areas, and bare soil using satellite imagery. The architecture of a network of sensors has been developed using SensorML as well (Aloisio et al., 2006). A network of various spatially distributed devices equipped with sensors has been modelled in an architecture that addresses: (i) different data formats of the different types of sensors, (ii) ownership of the devices by different parties, and (iii) a large amount of data that was recorded continuously. It was tested in a small network of sonic detection and ranging devices.

Regarding IFC, a platform that provides energy efficiency and management services is reported (Valmaseda et al., 2013). The system could, for example, monitor temperature in buildings and perform simulations and calculations to optimise operations. The IFC specification has been used only for information related to the geometric, topological, and relational data of the building, e.g. which sensor is located in which room and in which zone, etc. Data related to operations, occupancy density, weather stations, etc. are handled separately. A web service framework that links BIM models with sensor data has been reported as well (Wang et al., 2013). The authors note that the IFC specification is able to describe all the necessary elements, including the occupants (*IfcOccupant*) and thermal zones (*IfcSpatialZone*), but it cannot represent live sensor readings. Another example is a framework to combine a building management system with a BIM model for energy efficiency (O'Sullivan et al., 2004). The authors note the difficulty to assign performance data to elements and the impossibility to exchange rich data sets with HVAC content when using the current specification at that time.

5. Extending the IFC Specification

The development and extension of standards is a challenging effort. It has taken researchers and industry specialists of the AEC area many years to come up with an agreed method to develop sufficient and reliable standards (Eastman et al., 2010). The currently adopted method is the so-called use-case approach (Hietanen, 2006), which defines workflows used in practice and identifies activities, in which an exchange of information occurs. The standard data models are developed and extended based on the objectives and the content of the identified information exchanges.

The IFC specification considers incremental extensions of its capabilities. There have been proposed extensions, e.g., to include: estimating and scheduling data of construction projects (Froese et al., 1999); structural analysis data (Weise et al., 2003); data for cost estimation and tendering (Zhiliang et al., 2011); and data to describe Radio Frequency Identification (RFID) systems (Motamedi et al., 2016). Three methods exist to extend the capabilities of the IFC specification (Weise et al., 2009): (i) make use of proxy elements, and user-defined property sets, e.g. (Rio et al., 2013); (ii) references to external data, e.g. (Voss and Overend, 2012); and extending the IFC schema (i.e. the data model), e.g. (Weise et al., 2003). The first two options are temporary solutions that require additional agreements on the usage of proxy elements and user-defined properties. The third option guarantees interoperability but requires an official and lengthy procedure to be adopted (Zhiliang et al., 2011). While there is reticence for new extensions to the IFC schema given its increasing size and complexity (Amor, 2015), extending the schema applying the use-case approach in combination with the so-called Model View Definitions (MVD) (Hietanen, 2006) is still the most effective manner to provide robust interoperability.

The general idea of the use-case approach is to define workflows usually followed in practice in a particular area, e.g. the manufacturing and installation of precast concrete elements. Then, the activities of the process in which information exchanges occur are identified. The purpose and intent of the information exchange are defined, and the content necessary to ensure a successful exchange is specified. The exchange requirements are compiled into an Information Delivery Manual (IDM) and amendments to the IFC specification are carried out. Lastly, an MVD is developed, which is a subset of the IFC specification required to satisfy the identified information exchanges. Examples of the development of IDM and MDV for the concrete precast industry are reported in literature (Barak et al., 2009; Panushev et al., 2010).

The generation of process models is an important part of the use-case approach, in which the involved actors, the activities, and information exchanges of a particular process are depicted. Figure 3 presents a template of a process map for generic structural monitoring tasks. Refer to literature for more detailed information (Davila Delgado et al., 2015). Note that this process map only intends to exemplify the required types of actors, activities, and information exchanges. The process map presented in Figure 1 envisions the design, installation, and operation of a generic structural performance monitoring system. The involved actors are: (i) Structural Designer; (ii) Sensor Designer; (iii) Sensor Installer; (iv) General Contractor; (v) Operator; and (vi) Structural Engineer. The stages of the process are (1) Pre-design, (2) Design, (3) Instrumentation, (4) Operation, and (5) Analysis.

Currently, only two proposals to extend the IFC specification regarding structural performance monitoring have been reported in literature (Rio et al., 2013; Smarsly and Tauscher, 2015). Rio *et al.* propose new enumerated types, and their accompanying property sets, of the *IfcSensor* entity for “structural kinematic sensors” such as inclinometers and strain gauges. They also propose to group the sensors with respect to their function to facilitate the selection of suitable sensors. Smarsly and Tauscher, on the other hand, suggest the development of a semantic model to extend the IFC specification capabilities to describe monitoring systems and processes. This work is in an initial phase, and only a conceptual study of the requirements to develop the semantic model has been reported in literature. Note that the current IFC specification (IFC4) does not officially support semantic models, but there are many research efforts on the subject reported in literature, that address ontologies, e.g. (Beetz et al., 2008) and semantic models, e.g. (Pauwels et al., 2011; Vanlande et al., 2008; Yang and Zhang, 2006).

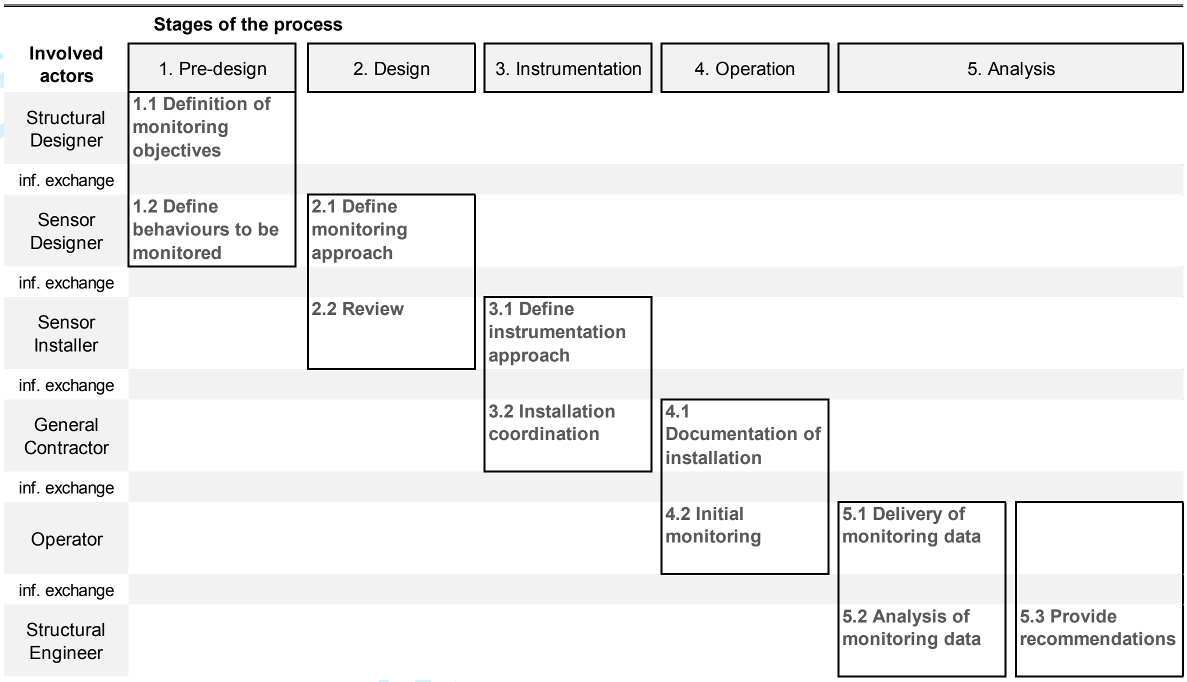

Figure 3. Process map for a generic structural performance monitoring workflow. Adapted from Davila Delgado, Brilakis and Middleton (2015).

4.1 Overarching approach

Most of the proposed extensions to the IFC specification considered the addition of specific entities and enumerated types. These additions are necessary, but they do not address the fundamental lack of capabilities of the IFC specification with respect to structural monitoring systems. Only an all-encompassing approach that considers extending capabilities to various and at different levels domain schemas will result in a robust specification. This will unlock many benefits of the BIM approach for the operational phase that currently are not being exploited. As further explained below, the extension to the IFC specification needs to not only define entities to describe the physical monitoring system but to establish guidelines for data management.

4.2 Monitoring system

Figure 4 presents a diagram with the six main IFC entities that are used for modelling. This study proposes that shaded entities in Figure 4 can be used to describe monitoring systems. The main IFC entities for modelling are: (1) *IfcProduct* is used to model any object that relates to a geometric or spatial context. The entity *IfcDistributionControlElement* is used to describe building control automation systems, which has the subtypes *IfcSensor, IfcActuator*, *IfcAlarm*, *IfcController*, etc. Most structural monitoring systems are composed of physical devices that can be grouped in the following three categories: (i) sensors, devices that detect change and produce an output; (ii) communication network elements, e.g. cables, wireless receivers, etc.; and (iii) processing units, devices that process the signals and output the raw data.

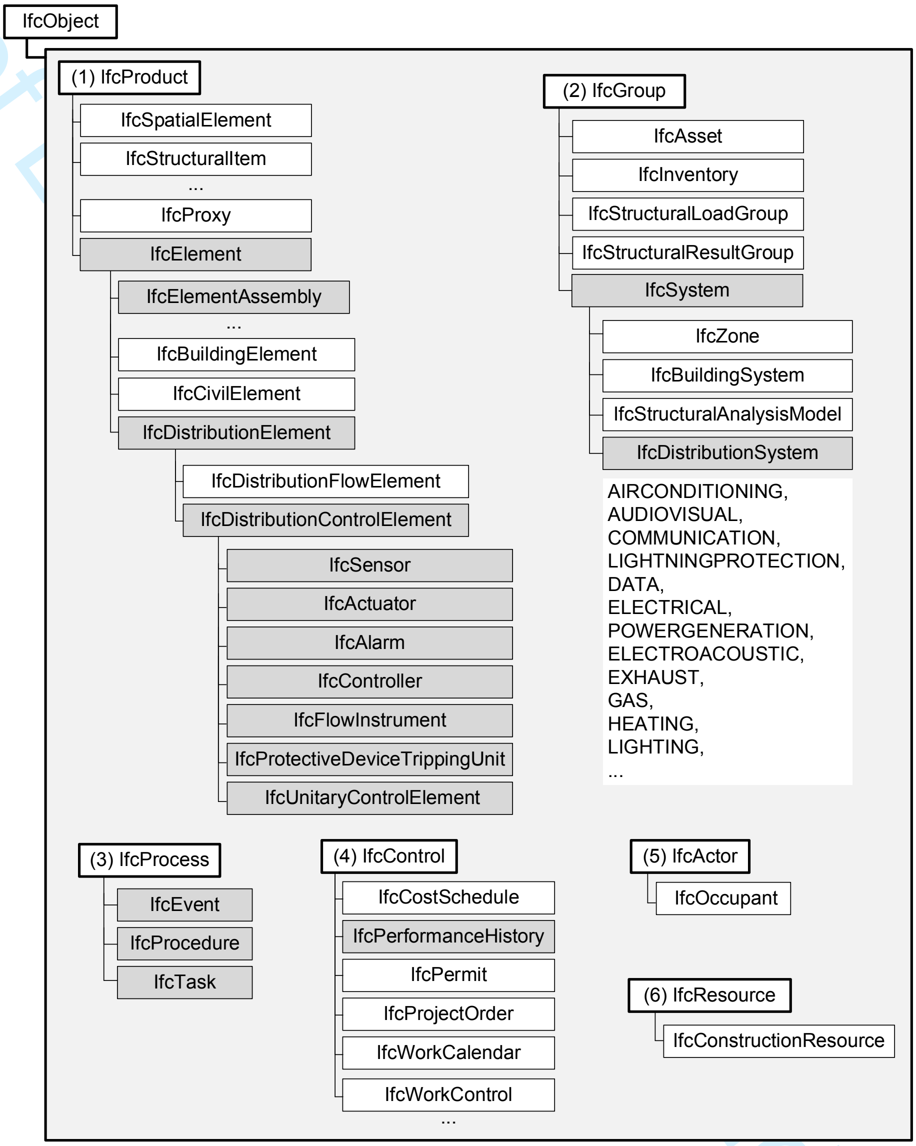

Figure 4. Diagram showing the 6 main entities of the IFC4 specification. This study proposes that shaded entities can be used to describe monitoring systems.

From the above list, the IFC specification only considers an entity that describes sensors and therefore, new entities are required. It should be considered to make the entities in the *BuildingControlDomain* more generic so that they can be used effectively for both building automation control systems and structural monitoring systems. (2) *IfcGroup* is a generalisation of an arbitrary group. Careful consideration should be taken whether a new subtype of *IfcSystem* should be added to model monitoring systems, or if only new enumerated types should be added to the existing *IfcDistributionSystem* (see Figure 2, the capitalised terms are some of the existing enumerated types). (3) *IfcProcess* defines individual activities ordered in time. Its subtypes are sufficiently generic that only new enumerated types would be necessary to describe processes for structural performance monitoring. (4) *IfcControl* is intended to define concepts that constrain the use of products, processes, and resources in general; nevertheless, most of the subtypes relate specifically to construction tasks. The exception is the entity *IfcPerformanceHistory* that can be used to describe the performance of the built asset through time. (5) *IfcActor* defines human agents involved during the entire life-cycle of a built asset. Its subtype *IfcOccupant* has enumerated types that relate to ownership, tenancy, etc. but there are no enumerated types related to the operators, inspectors, etc. (6) *IfcResource* defines the information required to represent costs, schedules, and other concepts that impact a process. It has only one subtype, i.e. *IfcConstructionResource*, which is an abstract entity to describe different resources used in construction projects such as labour, materials, equipment, etc. Amendments to these entities would facilitate to describe resources needed for the installation of monitoring systems and monitoring tasks. Preliminary work on these aspects can be found in literature (J. M. Davila Delgado et al., 2016).

4.3 Data management and analysis

The enumerated types of *IfcSensor* used in combination with *IfcTimeSeries* and *IfcPerformanceHistory* are robust and flexible enough to store data from structural sensors. The data as outputted by processing units cannot be used directly, and it needs to (i) be converted into the correct physical quantity and units and (ii) corrected for any phenomena that may affect the measurement. The IFC specification includes some basic capabilities to store derived quantities, units, and methods. Nevertheless, additional aspects to take into consideration are: sampling rates of the data acquisition; data pre-processing (e.g. signal processing, normalisation and data reduction, etc.); different formats, sources, and ownership of data; the vast amounts of data generated by monitoring systems; and the required linkage to external databases. For the latter, the IFC specification includes the *IfcExternalReference* resource schema, which provides rudimentary capabilities for referencing to classifications, documents, and libraries. In this respect, advances in incorporating structural monitoring data directly into BIM models can be found in literature as well (Davila Delgado et al., 2017; Juan Manuel Davila Delgado et al., 2016), and including dynamic visualisations (Davila Delgado et al., 2018).

4.4 Circular economy principles

None of the existing entities of the IFC specification has been considered to represent the different aspects of a circular economy, although many of them already record the required data. A preliminary method to extend the IFC specification to include data related to the circular economy principles should include the following steps: (i) compile a list of the required entities and enumerated types to describe all the aspects of the circular economy that play a role during the building lifecycle (see Table 1); (ii) map the required entities and enumerated types with the existing entities in the IFC specification; (iii) identify that all the needed attributes of each entity are considered in the IFC specification. (iv) compile a list identifying the existing, non-existing, and partially considered entities. This list will serve as a guideline to different parties to define a standard data model.

As a result of this study, figure 5 presents a diagram of the proposed entities and enumerated types to describe circular economy principles in a standard data model. New entities will be required at the building hierarchy level to represent, for example, the amount and cost of generated waste throughout the building lifecycle, the decommissioning cost, and the ease of deconstruction. In this respect, the data model should consider existing approaches to optimise designs to develop waste efficient buildings (Bilal et al., 2019) and then codify relevant metrics to be included in the data model. Entities and enumerated types at the building component level will be necessary as well. Each building component will need a set of entities and enumerated values grouped according to the building lifecycle stage, i.e. design, construction, operations, and decommission (Figure 5).

For example, for every building component, it must be recorded if all the materials that form that component are reusable, recyclable or disposable; and the corresponding enumerated type should be assigned. Moreover, the data model should define acceptable methods to populate the values of circular economy entities. For example, if the building component is recyclable; then, the standard should determine how to calculate the value of the materials at their end-of-life. In this aspect, the data model should consider reusability analytics tools for assessing end-of-life status of building materials that have been presented in literature (Akanbi et al., 2019a). Lastly, a new MVD that structures all the required information to facilitate the different aspects to implement a circular economy must be developed. The new MVD should be developed, taking into consideration existing research on BIM and circular economy integration (Akanbi et al., 2019b; van den Berg and Durmisevic, 2017).

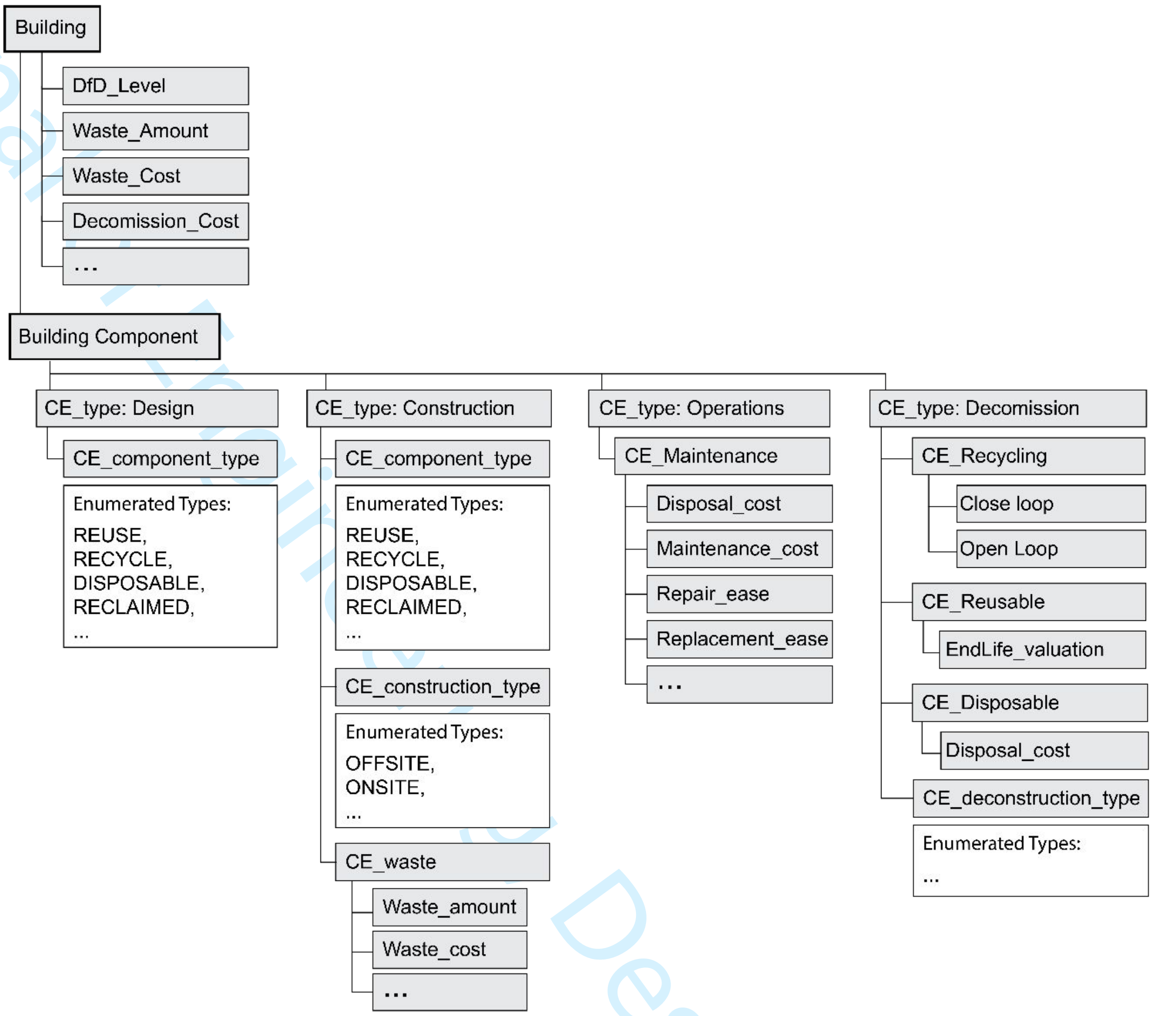

Figure 5. Diagram showing the proposed entities and enumerated types to describe circular economy principles in a standard data model.

6. Conclusions

Adopting the BIM approach during the operational phase of the life cycle of built assets will represent substantial reductions in cost and materials used while increasing performance and quality. Performance monitoring is one of the activities performed during the operational phase, in which monitoring systems are used to monitor the structural behaviour of the built asset. Standard data models that can fully describe monitoring systems, monitoring tasks, circular economy principles, and deal with data management and visualisation are needed to ensure robust interoperability and the implementation.

As identified in this paper, the lack of interoperability is one of the main barriers for the full adoption of the BIM approach and to the successful implementation of circular economy principles. The current standard data models are not sufficient yet, and an overarching approach is needed to extend the current standards to ensure robust interoperability for structural performance monitoring. This article presents an investigation of the current capabilities of open standard data models for performance monitoring and circular economy principles; and systematically presents aspects for consideration, recommendations, and guidelines for an extension to the IFC specification. The IFC specification conceives further extensions of its capabilities, methods to implement such extensions are discussed in the paper. The recommended method is to use the use-case approach, in combination with IDMs and MVDs, to ensure robust interoperability. The other methods and linkage with other standards will not ensure full interoperability and additional agreements between the interested parties would be needed.

The main conclusion is that an all-encompassing approach should be taken to extend the IFC specification bearing into account aspects related to the following three categories: (i) modelling the monitoring system, (ii) data management and analysis, and (iii) circular economy principles. Lastly, in general, the IFC specification still lacks provisions to describe built assets and processes during the operational phase of built assets. Many entities that could be used for the operational phase have been conceived, and to some extent restricted, to describe processes for the construction phase.

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