Open data model standards for structural performance monitoring of infrastructure assets

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Abstract
Employing the BIM approach during the operational phase of an infrastructure asset's life cycle represents the largest opportunity for reducing the total life cycle cost. One aspect of the operation of an infrastructure asset is to monitor its structural performance to ensure safety, for which structural sensors are increasingly being used. Semantically rich as-built BIM models that represent the actual conditions of the constructed assets can improve and quicken the structural performance monitoring of infrastructure assets. Nevertheless, the current open data model standards are not fit for this purpose yet, which greatly reduces the usefulness of the BIM approach during the operational phase of an infrastructure asset. This paper examines the capabilities of existing data model standards and, based on alternative approaches to overcome the lack of current capabilities and a proposed use-case, makes recommendations for possible extensions to the standards. The paper concludes that amendments to current data model standards are needed to enable modelling of complex monitoring systems and appropriate management and visualisation of sensor data.

Keywords: IFC, SensorML, as-built BIM models, structural sensors.

1 Introduction

During the life cycle of an infrastructure asset (e.g. a bridge, a tunnel, a road etc.) several parties are involved in multidisciplinary tasks ranging from planning, design, and construction to operation and decommission. Building Information Modelling (BIM) is being adopted to efficiently manage information related to the infrastructure asset during its complete life cycle (Gu & London 2010) to improve productivity and to reduce costs.

Currently, the BIM approach is mostly employed for the generation of as-designed BIM models, which are digital representations of an asset to be built. It is widely accepted that, the generation and utilisation of as-designed BIM models increases productivity and reduces costs in the design and construction phases of the asset life cycle. However, the operational phase represents a larger opportunity for reducing costs. This is because the operation, maintenance, and alteration of the asset represents the largest share of the total life cycle cost. Semantically rich as-built BIM models enhanced with condition data are necessary to fully employ the BIM approach during the operational phase of the asset.

Management of infrastructure assets deals with operation, maintenance, and alterations, for which constant monitoring of the actual conditions of the assets is required. The traditional objectives of these monitoring tasks, known as Structural Health Monitoring (SHM), are damage and anomaly detection, improving safety and maintainability, remote management, and measuring structural performance (Webb & Middleton 2013). The work presented here focuses exclusively on structural performance monitoring.

Three components are required to perform structural performance monitoring: structural sensors, to acquire measurements of variable attributes of infrastructure assets; sensor networks, to transmit the measurements to a given location; and a storage and processing unit, to generate and maintain useful information. This paper mostly deals with the development of guidelines for open data standards for structural sensors, but recommendations for the other two components are also discussed.

Central to the full adoption and success of the BIM approach is the robust exchange of digital information between the involved parties (i.e. without any data loss), regardless of the authoring application in which the information has been generated. To this end, open BIM data model standards have been developed to facilitate the exchange of information. Several different data models for BIM exist; of those, the Industry Foundation Classes (IFC) specification, developed by buildingSmart, has become the de-facto open BIM data model standard for the Architecture Engineering and Construction (AEC) area.

Current IFC specifications for infrastructure assets are not capable to accommodate data from structural performance monitoring. Consequently, the large amount of collected data from structural sensors is of little use as it lacks context on the infrastructure asset or if is difficult to access it.

This paper seeks to aid in the implementation of the BIM approach for structural performance monitoring of infrastructure assets. More specifically, it (i) examines the capabilities of existing data model standards to describe structural monitoring systems, (ii) discusses alternative approaches to overcome the lack of current capabilities, (iii) proposes examples of use-cases to determine the required information exchange for structural performance monitoring, and (iv) defines recommendations for possible extensions of current data model standards.

In the next section 2, a brief description of structural performance monitoring and the types of existing structural sensors is presented. Section 3 presents a brief overview of the open data model standards for infrastructure and sensors and in section 4 the current capabilities of these data standards and alternative approaches to model monitoring systems are discussed. In section 5 an example of use-cases for information exchange of structural performance monitoring is presented. Lastly, section 6 presents recommendations for the development of open data standards for structural performance monitoring and in section 7 conclusions are given.

2 Structural performance monitoring and structural sensors

SHM is essentially an assessment of structural performance and damage identification (Farrar & Worden 2007). Structural performance monitoring then can be regarded as one of the main activities performed for SHM. It has various objectives which vary depending on different stakeholders at different phases of the life cycle of the infrastructure asset. For example, the asset owner, the operations manager and the structural engineer would have different interests (objectives) for monitoring during the planning, design, construction, operation, and decommission phases of the life cycle of the infrastructure asset; as has been noted in literature (Webb & Middleton 2013).

For example structural performance monitoring can be performed for model validation. Numerical models, rules of thumb, and assumptions are often used during the design of infrastructure assets. Data collected from structural sensors can be used to determine if the models and assumptions truly represent the real physical situation. It can be verified if a bridge is actually subjected to the loads assumed during its design. Another example is threshold check. In this case, threshold values of certain monitored parameters are set. When a monitored parameter exceeds the threshold value is an indication that a problem may exist. An example could be to monitor relative displacements of bearings in a bridge. If the displacements surpass the defined thresholds it may indicate that increased stresses are occurring, for which the asset could not have been designed for.

Structural sensors are needed to measure parameters that indicate the structural performance of an infrastructure asset. The parameters mostly relate to loads applied to the asset and its response.

The most often used structural sensors can be categorised as follows: strain and displacement sensors, accelerometers and inclinometers, acoustic sensors, and fibre optics. Note that there are other types of sensors such as corrosion and fatigue sensors, but they have not been presented here because they are at early stages of development and its usage is marginal.

Strain and displacement sensors. These are the most common used sensors for structural performance monitoring. Usually, they consist of a metal wire that exhibits changes in some of its properties when subject to strain. These types of sensors are attached to structural elements and when the structural elements displace or deform the metal wires deform as well.

Accelerometers and inclinometers are used to measure relative displacements or rotations of particular points on an infrastructure asset, respectively. Accelerometers measure the proper acceleration needed to displace a given mass and the inclinometers measure angular tilt with respect to a predefined horizon.

Acoustic sensors are used to detect breakage of steel cables or cracks forming in concrete. They use microphones to record the sound generated when a steel cable snaps or a crack bursts; by analysing the signal, the location of the breakage can be inferred.

Fibre optic cables are used to infer relative strains by measuring changes on optical properties of the cables. Fibre optic cables are being increasingly used to measure strains given its relative ease and flexibility of installation and low cost. They can be installed within reinforced concrete elements, attached to reinforcement bars, or directly attached to steel elements such as I-beams or corrugated sheets.

3 Open data models standards for infrastructure and sensors

Data model standards define principles to organise and prescribe relationships between data, so to ensure interoperability among parties in a particular industry. Open data model standards are non-proprietary, which means that the defined principles are publicly available. This facilitates interoperability among parties because various authoring applications (proprietary or otherwise) can use the same standard and ensure information exchange without any data loss.

Data model standards that define principles to describe information related to infrastructure assets and monitoring systems are necessary to utilise the BIM approach to its full potential for structural performance monitoring.

The most used data model standard for the AEC area is the IFC specification developed by buildingSmart. The IFC specification seeks to enable modelling of data related to all phases of the life cycle of a building. Related to infrastructure, buildingSmart is developing ad hoc data models, or extensions, for specific infrastructure assets, e.g. IFC Bridge and IFC Road. These extensions are under development and are not official parts of the IFC specification or supported by authoring tools; therefore its application is very limited.

The Open Geospatial Consortium (OGC) also develops open data standards for AEC area; its efforts are primarily focused on facility planning, emergency management, asset management, and navigation. OGC developed the Geography Markup Language (GML), a XML (eXtensible Markup Language) adaptation for describing geographical features. Based on GML, several standards have been developed such as CityGML, for 3D modelling of cities; IndoorGML, for indoor navigation; and WaterML, for representing data from water observations.

LandXML, developed by LandXML.org, is another open data standard for specifying civil engineering and surveying data and it is used mainly for land development and transportation. It is supported by most of the main authoring applications. The OGC is also developing a standard for infrastructure called InfraGML, which will be a subset of LandXML but implemented with GML.

There are several data model standards for sensors developed specifically for particular industries, as noted in literature (Hu et al. 2007; Lee 2007). However, in here only the ones developed by buildingSmart and OGC are presented because they are the only ones related to the AEC area.

SensorML has been developed by OGC to describe devices and processes associated with measurement of observations of complex monitoring systems (Botts & Robin 2007). It focusses on describing physical and non-physical processes defined by inputs, outputs, and parameters. In essence it's a generic processes model defined from the dataflow perspective, which cannot directly model the monitored objects.

BuildingSmart includes, in the IFC specification (Liebich et al. 2013), an entity to describe basic properties of sensors located in buildings. It does not have the same amount of capabilities as SensorML, but it enables the description of simple monitoring systems in a data model that can describe infrastructure assets and it is widely used in the AEC area.

4 Current capabilities and alternative approaches

As presented in the previous section, several initiatives exist to standardise data modelling and information exchange related to monitoring infrastructure assets; however, none of them entirely fulfils all the needed requirements. Data models to describe infrastructure assets are not sufficient yet, e.g. IFC Bridge and IFC Road. Additionally, specifications to describe monitoring systems are not able to directly model infrastructure assets (SensorML) or lack the needed capabilities to describe complex monitoring systems (IFC).

Next, a brief description of the capabilities of SensorML and the latest version of IFC (IFC 4) to describe monitoring systems is presented. After that, some examples in literature are presented where IFC and SensorML have been used to model monitoring systems. In all the presented examples some sort of adaptation to the data models and to the information exchange workflow was made to compensate the lack of capabilities of the existing data models.

SensorML is used to model complex monitoring systems to enable automatic processing of sensor data by generic software (Robin & Botts 2006). The main elements of SensorML are (i) *component*, is a physical process that transforms information from one form to another; (ii) *system*, is a group of components; (iii) *process model*, is a non-physical process; (iv) *process chain*, is a group of processes; (v) *detector*, is a type of component that defines a response given an stimulus, it has one input and one output; (vi) *sensor*; is a set of all the other elements which represent a complete sensor, e.g. a complete airborne laser scanner (Botts & Robin 2007). SensorML has descriptions to model simulations, planning processes, alert systems, and storage and archiving systems as well; however, the measured object cannot be directly modelled.

The IFC specification contains a class to model sensors in its *IfcBuildingControlsDomain* schema. It is the *IfcSensor* class, which is used to model occurrences of sensors in a building (e.g. temperature sensors in a room). Common properties of the same type of sensors are defined with *IfcSensorType*. A finite set of predefined types of sensors are considered in the IFC specification, and are presented in Table 1. As can be seen in the table most of the types of sensors relate to building services monitoring activities such as Heating Ventilation and Air Conditioning (HVAC). Nevertheless, there is the possibility to model user-defined type of sensors. Specific properties of each sensor type are defined via *Pset_SensorTypeCommon* and user-defined properties for user-defined sensor types can be defined via *IfcPropertySets*. Common properties for all sensor relate to quantity (measurements), shape, materials, connection with other objects, and ports (inlets or outlets of substances).

Alternative IFC classes can be used as proxies to model processes of monitoring systems such as *IfcTask*, which is used to model activities with time related attributes and *IfcEvent*, which is used to define anticipated or actual occurrences of events. Both of these entities are primarily intended to model construction processes. Additionally, *IfcPerformanceHistory* is used to record performance measurements over time, which in the last specification (IFC 4) can be used in combination with *IfcSensor*.

As example of the common usage of SensorML, two research efforts found in literature are presented next.

An executable process model has been developed based on SensorML (Chen et al. 2012). It intends to aid in real time collaboration between web-based sensor resources for complex monitoring tasks. For example, to determine, in real-time, a vegetation index that categorises water bodies, green areas, and bare soil based on satellite imagery.

Table 1 Enumerated list of the types of sensors considered in the IFC specification. The first two columns show in which IFC version they were introduced.

IFC version 2x2	2x4	Type of sensor	Description
	•	CONDUCTANCESENSOR	senses or detects electrical conductance
	•	CONTACTSENSOR	senses or detects contact, such as for detecting if a door is closed
•		FIRESENSOR	senses or detects fire
	•	FLOWSENSOR	senses or detects flow in a fluid
•		GASSENSOR	senses or detects gas concentration
•		HEATSENSOR	senses or detects heat
	•	IONCONCENTRATIONSENSOR	senses or detects ion concentration, such as for water hardness
	•	LEVELSENSOR	senses or detects fill level, such as for a tank
•		HUMIDITYSENSOR	senses or detects humidity
•		LIGHTSENSOR	senses or detects light
•		MOISTURESENSOR	senses or detects moisture
	•	MOVEMENTSENSOR	senses or detects movement
	•	PHSENSOR	senses or detects acidity
•		PRESSURESENSOR	senses or detects pressure
	•	RADIATIONSENSOR	senses or detects electromagnetic radiation
	•	RADIOACTIVITYSENSOR	senses or detects atomic decay
•		SMOKESENSOR	senses or detects smoke
•		SOUNDSENSOR	senses or detects sound
•		TEMPERATURESENSOR	senses or detects temperature
	•	WINDSENSOR	senses or detects airflow speed and direction
•		USERDEFINED	User-defined type
•		NOTDEFINED	Undefined type

SensorML has been used as well as the basis to develop the architecture of a grid network of sensors, i.e. a network of many spatially distributed devices with sensors to monitor conditions at different locations (Aloisio et al. 2006). The proposed SensorML-based grid architecture intends to address (i) the different data formats of different types of sensors, (ii) that the sensors are owned by different parties, and (iii) the large amount of data continually recorded by the sensors. The SensorML-based grid architecture was tested in a small network of sonic detection and ranging sensors.

SensorML and IFC have been linked together to describe monitoring systems for buildings (Liu & Akinci 2009). A prototype of a model editor was developed to model and visualise monitoring systems in buildings. The IFC specification was used to model the building and the location of the instances of the sensors and SensorML was used to model the properties of the sensors in detail; for which *IfcSensor* was linked with the element *component* of the SensorML specification.

Structural sensors have been “virtually” modelled with the IFC specification 2x3 as well (Rio et al. 2013). In this case, *IfcSensor* has been used to model vibrating wire sensors (VWSGs) installed at selected structural elements of a building. This type of structural sensor is not included in the range of sensors that can be specified with IFC 2x3, (see Table 1). For that reason the VWSGs were modelled as smoke sensors. The specific properties and measurement types of the VWSGs were defined using *IfcPropertySets*, which allow user-defined property definition. In this case, manual adjustment of the generated IFC files using a text editor was necessary due to incompatibilities with the used authoring applications. Nevertheless, it successfully generated an IFC 2x3 model with structural sensors including sensor data, which could be visualised with a common IFC viewer.

Appropriate handling and visualisation of data collected by sensors is an important aspect to consider as well. There are examples in literature (Chen et al. 2014) in which data collected by temperature sensors has been included in BIM models using specific authoring tools (Revit). A specific element type (a family in Revit’s terms) is created to represent a temperature sensor. The sensor data, stored in plain text files, is then incorporated to instances of the element type by generating user-defined parameters (shared parameters). These parameters can then can be exported as *IfcPropertySets*. The sensor data stored in the text files was also visualised via charts in the authoring tool; this charts however cannot be included in the IFC files. In this case, the data handling and visualisation were implemented using the authoring software API (Application Programming Interface).

Lastly, an example of the linkage between IFC models and an external database is given in (Voss & Overend 2012). The application case presented in that paper is not related to monitoring, but it is referred to because it represents an example of alternative management of data with IFC models. The

IFC specification cannot exhaustively describe processes and detailed information required to manufacture curved glass panels for facades. For that reason, the required information is inputted in an external database and it is linked to instances of the facade panels modelled with IFC via *IfcPropertySets*. In this case, the additional data resides in an external database and it is incorporated into the IFC model only when a query related to that data is made.

5 Use-cases for information exchange in structural performance monitoring

Structural performance monitoring of infrastructure assets is becoming common practice in the AEC area. However, it is still a not a mature practice and there are not defined guidelines and standards for information exchange. Usually, different parties monitor different structural behaviours; e.g. in a bridge, one company may monitor steel cables breakage using acoustic sensors while another company monitors relative displacements of bearings using accelerometers. The data provided to the client, by different parties, is, in most cases, not in a uniform format; it could vary from coma separated value (csv) files—sent via email—to bespoke web applications in which the clients can visualise the recorded data. Normally, the data lacks spatial context related to the infrastructure asset and the data cannot be visualised directly in the BIM model.

The development of new standards is a difficult task and, within the AEC area, it has taken researchers and industry several years to come up with a method to create reliable and sufficient standards (Eastman et al. 2010). The currently adopted method is the use-case approach (Hietanen 2006).The general idea is to define workflows followed in practice and then to identify the activities in which data exchanges occurs. After that, the purpose and intent of information exchange is defined and the necessary content for the information exchange to be successful is specified. Based on this approach, current data model standards are extended and new ones are generated.

An important part of the use-case approach is the generation of process models, which depict information exchanges between actors while performing particular activities. The actual process maps and other documentation, e.g. Information Delivery Manuals and Model View Definitions (Hietanen 2006), used to develop new standards are prepared by a team of experts from the interested parties belonging to industry and academia. In this section, a template of a process map for generic structural performance monitoring tasks is presented (Figure 1). This process map intends to exemplify the types of activities and information exchanges required for generic structural performance monitoring tasks.

The process map has been developed by envisioning the design, installation, and operation of a generic structural performance monitoring system for an infrastructure asset under construction. The process map (Figure 1) presents the stages of the process, the involved actors, and the main activities to be performed at each stage. The involved actors in the process are (i) Structural Designer; (ii) Sensor Designer; (iii) Sensor Installer; (iv) General Contractor; (v) Operator; and (vi) Structural Engineer. The proposed process consists of five stages (see Figure 1): (0) Pre-design, in which the Structural Engineer designs, in detail, selected structural elements to be monitored and the Sensor Designer defines structural behaviours to be measured; (1) Design, where the Sensor Designer develops the overall monitoring system. For example, the type, number, and location of sensors to be used is defined, as well as the data retrieval and storage methods; the Sensor Installer comments on the monitoring system regarding the physical installation of the sensors; (2) Instrumentation, in which the Sensor Installer installs the sensors and coordinates with the General Contractor concerning construction schedule, installation time, etc.; (3) Operation, in which the General Contractor coordinates with the Operator to perform the initial monitoring and to provide documentation related to the installed monitoring system; and (4) Analysis, in which at a later point in time, the Operator collaborates with the Structural Engineer to deliver monitoring data and the Structural Engineer analyses the data and provides recommendations.

Based on the defined information exchanges at every stage of the process, the specific data required to ensure that the activity is completed successfully is defined; e.g. during the Design stage, the Sensor Installer may require detailed specifications for powering the sensors to be installed. Using this required data, a standard data model can then be developed. Note that to be able to develop sufficient and robust data models, exhaustive process maps that describe specific activities and actors should be generated.

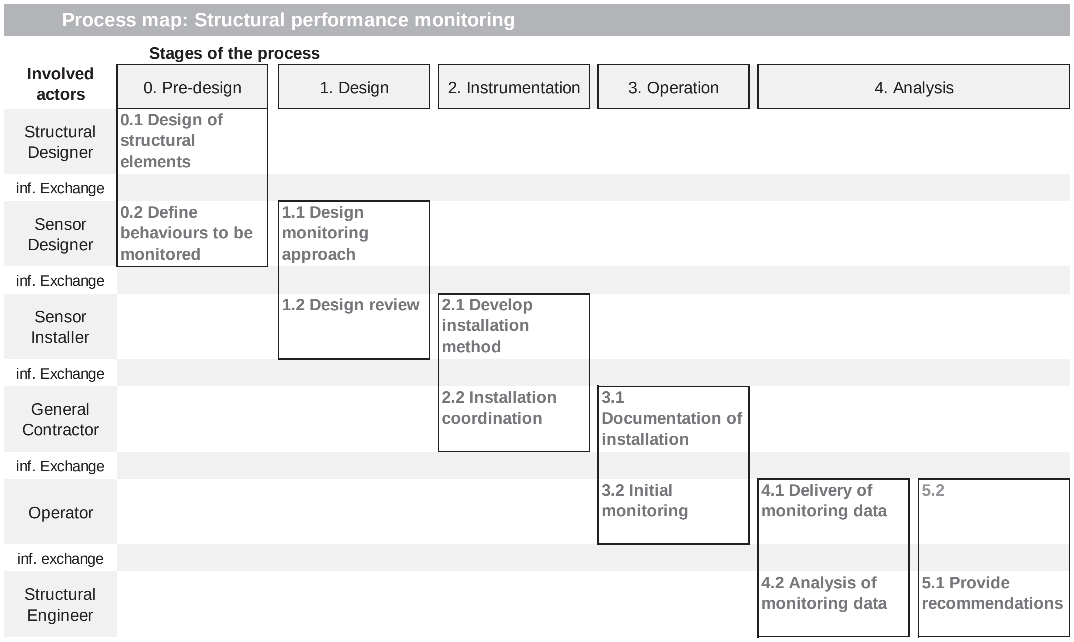

Figure 1 Process map for a generic structural performance monitoring tasks.

6 Recommendations

An overarching approach to amend existing open data model standards for structural performance monitoring is required. The amendment should take into account three main components of monitoring systems: (i) the physical sensor network, which includes the sensors, the communication network (interconnection among sensors), and the interrogation system (equipment that processes raw sensor data); (ii) sensor data management, which considers formatting, storage, and retrieval of sensor data; and (iii) visualisation of relevant information to facilitate decision making. In this sense, specific amendments to open data model standards for describing both infrastructure assets and monitoring systems are required.

Related to infrastructure assets, open data model standards are currently under development (e.g. IFC Bridge, IFC Road, InfraGML, etc.); it is very important that aspects regarding structural performance monitoring (and monitoring in general) are considered in their development. It could be argued that the need for structural performance monitoring is more significant for infrastructure assets than for buildings; therefore, one of the main priorities in their development should address ways to facilitate description of structural performance monitoring systems.

For that, two approaches can be followed. One is to include all the required data structures into the open data model standards and the other one is to facilitate direct links with other open data model standards specifically intended to describe monitoring systems. For the latter, a successful example of linkage between IFC and SensorML exists in literature (Liu & Akinci 2009). This capability should be formally implemented; for that, a collaborative effort between buildingSmart and OGC will be required. Such collaborative efforts have occurred in the past e.g. with the development of a standard approach to prescribe alignments for infrastructure assets. This standard approach is observed by IFC, InfraGML, and LandXML and was developed by buildingSmart, OGC, and industry partners.

Regarding to amendments for open data model standards that describe monitoring systems, two standards have been revised in this papers i.e. SensorML and IFC. SensorML specialises in describing complex monitoring systems. In essence, it is a generic standard that describes sequences of processes and how they transform data; it allows the description of any monitoring system in an infrastructure asset. Its big disadvantage is that the monitored object cannot be described. Extending SensorML to include monitored objects is not advisable because it will be difficult to include all the types of objects that can be monitored. Even though SensorML can be used as a stand-alone solution, its usage is intended in combination with other data model standards developed by OGC (Robin & Botts 2006). Thus, amendments to SensorML that enable direct coupling with other standards, e.g. IFC and LandXML, is a more suitable approach.

In the case of IFC, the standard includes entities to describe basic monitoring systems related mostly to building services. To be able to describe generic and complex monitoring systems, extensions to the IFC standard should be comprehensive. Only adding other types of sensors to the enumerated list (Table 1) will not be sufficient. The IFC specification has four hierarchical layers (Liebich et al. 2013) i.e.: the *core*, the *shared*, the *domain* and the *resource* layer. Extensions to the *shared* and to the *domain* layers are necessary.

The *shared*, or interoperability, layer facilities data exchange between entities in the *domain* layer. It contains the following schemas: Shared Building Services Elements, Shared Components Elements, Shared Building Elements, Shared Management Elements, and Shared Facilities Elements. The *domain* layer includes schemas that define specialized entities related to 8 domains: Building Controls, Plumbing and Fire Protection, Structural Elements, Structural Analysis, HVAC, Electrical, Architecture, and Construction Management.

Amendments to the Shared Building Services Elements schema, which is used for describing monitoring tasks, are needed. This schema defines entities for interoperability between the HVAC, Plumbing and Fire Protection, Electrical, and Building Controls domains. To be able to describe structural performance monitoring systems, entities that enable interoperability between the Structural Elements, Structural Analysis, and Construction Management *domains* are necessary as well.

Regarding the *domain* layer, extensions to the Building Controls domain are required. This domain defines entities to describe building automation, control, instrumentation, and alarm systems. Its main entities are: *IfcActuator*, *IfcAlarm*, *IfcController*, *IfcSensor*, *IfcFlowInstrument*, and *IfcControlElement*. Additional entities should be develop that specify information related to measurements, units, calibration, sensor communication networks, functional and spatial relationships, interrogation systems, sensor data storage, data retrieval interfaces, and data visualisation. Information related to these aspects can be defined with current IFC specifications using user-defined entities as *IfcPropertySets* and *IfcComplexProperty*. However, user-defined entities are only partial solutions that do not ensure full interoperability, because different users would define the entities differently.

One relevant aspect to be considered for the extension of the IFC specification is the amount of data generated by sensors, which is a function of the number of sensors and their recording rates. Low recording rates correspond to static monitoring, in which records are taken at discrete point in time; while, high recording rates correspond to dynamic monitoring, in which records are take continuously. In any case, large volumes of data are created and efficient storage and retrieval capabilities for the IFC specification, in general, should be contemplated. For this, trade-offs between incorporating, all or only parts, of sensor data directly into IFC files or including only references to other files or databases should be evaluated.

Lastly, another aspect to consider is the difference in formats, sources, and ownership of sensor data. Ideally, an IFC model should be able to incorporate sensor data with different formats and stored in different sources (i.e. files or databases).

7 Conclusions

Large cost reductions will be achieved if the BIM approach is used during the operational phase of the life cycle of an infrastructure asset. One of the main activities performed during the operational phase is structural performance monitoring; in which sensors are used to monitor the structural behaviour of an asset for different objectives e.g. model validation and threshold check. To be able to fully implement the BIM approach for structural performance monitoring data model standards that ensure full interoperability are required. However, the current data model standards are not fit for purpose and alternative approaches to enable information exchange have been used. None the less, overarching extensions to the current standards are required to fully enable modelling of complex structural performance monitoring systems.

Concerning open data model standards for sensors, SensorML enables to specify complex monitoring systems; however, it cannot directly specify the monitored objects. The IFC specification, on the other hand, can describe infrastructure assets and it includes entities to model basic monitoring systems. Nevertheless, it is primarily focused to model building services monitoring activities (i.e. HVAC, electrical, plumbing, fire protection) and it is not sufficient for other activities such as structural performance monitoring. User-defined monitoring systems can be defined as well; for that, *IfcPropertySets* and *IfcPerformanceHistory* have been proved very useful to model user-defined monitoring systems. Classes such as *IfcEvent* and *IfcTask* could be used to simulate SensorML capabilities; but, so far, there are not examples in literature.

It may seem that the complex capabilities of SensorML are not needed for the traditional monitoring activities carried out in the AEC area. But structural performance monitoring will only become more ubiquitous and complex. Extensions to the IFC specification to include some of the SensorML capabilities should be considered as well as exploring possibilities to facilitate a direct link between IFC and SensorML.

Most of the proposed extensions to the IFC specification (Rio et al. 2013) contemplate the addition of more types of sensors to the enumerated list (see Table 1); however, very many types of sensors exist and new ones are developed constantly. While these new additions are necessary, they will not address the essential lack of capabilities of the IFC specification regarding monitoring systems. Only all-encompassing amendments that extend the Shared Building Services Elements and the Building Controls Domain schemas capabilities, as recommended in the previous section, will ensure a robust way to describe generic and complex monitoring systems.

Management of sensor data is probably the area in which the IFC specification lacks more capabilities. Appropriate extensions to the specification in this area are vital to enable monitoring systems in general; taking into account the increasing usage of objects in buildings and infrastructure assets that continuously generate data (think of the Internet of Things), it is imperative to amend the IFC specification so to include data management capabilities. Also, the addition of capabilities to visualise sensor data directly on the IFC model and to store charts and graphs should be evaluated as well.

Any extension should be developed using the use-case approach by first defining the purpose and intent of the information exchange and then by specifying the necessary content for the information exchange to be successful. Lastly, some of the required capabilities may already be available in other standards; enabling direct links with other standards should not be discarded.

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