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SeeBridge Next Generation Bridge Inspection: Overview, Information Delivery Manual and Model View Definition

Rafael Sacks[a], Amir Kedar[b], André Borrmann[c], Ling Ma[d], Simon Daum[c], Raz Yosef[a], Ioannis Brilakis[e], Philipp Huethwohl[e], Thomas Liebich[f], Burcu Barutcu[f] and Sergej Muhic[f]

[a] *Virtual Construction Lab, Civil and Environmental Engineering., Technion – Israel Institute of Technology, Israel*

[b] *Kedmor Engineers, Givatayim, Israel*

[c] *Computational Modeling and Simulation, Technical University Munich, Germany*

[d] *University of Huddersfield, UK*

[e] *University of Cambridge, UK*

[f] *AEC 3, Munich, Germany*

Abstract

Innovative solutions for rapid and intelligent survey and assessment methods are required in maintenance, repair, retrofit and rebuild of enormous numbers of bridges in service throughout the world. Motivated by this need, a next-generation integrated bridge inspection system named SeeBridge has been proposed. An Information Delivery Manual (IDM) was compiled to specify the technical components, activities and information exchanges in the SeeBridge process, and a Model View Definition (MVD) was prepared to specify the data exchange schema to serve the IDM. The MVD was bound to the IFC 4 Add2 data schema standard. The IDM and MVD support research and development of the system by rigorously defining the information and data that structure bridge engineers' knowledge. The SeeBridge process is mapped, parts of the data repositories are presented and the future use of the IDM is discussed. The development underlines the real potential for automated inspection of infrastructure at large, because it demonstrates that the hurdles in the way of automated acquisition of detailed and semantically rich models of existing infrastructure are computational in nature, not instrumental, and are surmountable with existing technologies.

Keywords:

Building Information Modelling Bridge inspection, Information Delivery Manual, Model View Definition, Semantic enrichment, Remote sensing.

1. Introduction

Highway asset owners face severe problems acquiring status data for their bridges. The data available in many Bridge Management Systems (BMS) does not meet the standard of information needed for subsequent bridge repair, retrofit and rebuild work. In this context, the value of using Building Information Modelling (BIM) in assets management is becoming clearer [1], and researchers have begun exploring the use of BIM applications (such as Bentley's LEAP Bridge, Tekla Structures, Revit, etc.) for modelling a bridge and manually mapping identified defects of the bridge to the model [2].

There have also been several advances toward semantic bridge data modeling. Chen and Shirolé [3] introduced the concept of Bridge Information Modeling (BrIM) for the design and engineering of bridges. The concept was partially implemented by TransXML – a data model developed by the

Transport Research Board in the USA [4]. The Federal Highway Administration (FHWA) has finished a project that provides specifications for using IFC Version 4 (without infrastructure extension) for exchanging model-based information between the design and the construction phase of bridge projects [5]. With the increasing worldwide interest in BIM for infrastructure, buildingSMART International (bSI) launched an effort to extend the IFC schema to include bridge semantics was launched, based on earlier work by the French and the Japanese chapters [6]. The result was the 2007 IFC-Bridge proposal [7,8] which included a set of new entities capturing the semantics of bridge elements as well as advanced shape representations, such as freely definable cross-sections and alignments. However, the representation of inspection data was out of scope. A purely inspection-oriented data model was proposed by Abudayyeh et al. [9], but it lacks the possibility to associate defects with a 3D bridge model and does thus not support model-based inspection.

BIM can significantly facilitate the managing and retrieval of bridge inspection data. However, the scale of effort required for manual compilation of BIM models for a large number of bridges and identification of defects would be prohibitive. Bridge inspections mean interruption of traffic and are potentially dangerous activities, and in almost all jurisdictions there are insufficient experienced bridge engineers for the extensive work required for inspections. Remote sensing technologies are attracting increasing research interest for inspection for health monitoring and valuation for bridges [10-14]. Among the remote sensing technologies, both laser scanning technology and photo- or videogrammetry can produce point clouds from which 3D primitives can be derived. However, the challenge that must be overcome for implementation of remote sensing in bridge inspection is to enable automatic recognition of bridge components from point clouds and make the model semantically rich [15].

To address the challenges, a Semantic Enrichment Engine for Bridges (SeeBridge) is proposed, targeting the development of a comprehensive solution for rapid and intelligent survey and assessment of bridges. The SeeBridge concept is the subject of an EU Infravation research project comprising seven partners in the US, UK, Germany and Israel. In the SeeBridge approach, various advanced remote sensing technologies are used to rapidly and accurately capture the state of a bridge in the format of point cloud data. A bridge model is automatically generated by a point cloud processing system, an expert system that encodes bridge engineers' knowledge for classification of bridge components, and a damage measurement tool that associates the identified defects with the bridge model.

In order to guide and connect the subsystems in the system as a whole, an Information Delivery Manual (IDM) [16] was compiled to formally specify the user requirements and to ensure that the final model would be sufficiently semantically meaningful to provide most of the information needed for decision-making concerning the repair, retrofit or rebuild of a bridge. Based on the IDM, a Model View Definition (MVD) was then prepared, which defines the information concepts needed and proposes a binding to the IFC 4.2 standard for exchange of building information models. The IDM and the MVD approach is a buildingSMART International (bSI) Standard [17], forms part of the US National BIM Standard [18] and has been used in numerous BIM interoperability research projects [19-22].

The IDM includes:

- A detailed process map defining the Seebridge process, its component processes and its information exchanges.
- A list of typical bridge elements classified by structure types, their function, shape representation and relative importance in the structure.

- Definition of the possible logical connections between the elements in a bridge structure type.
- A defect table for defects modelling and classification.
- Definition of the required information contents of the exchanges specified in the process map.

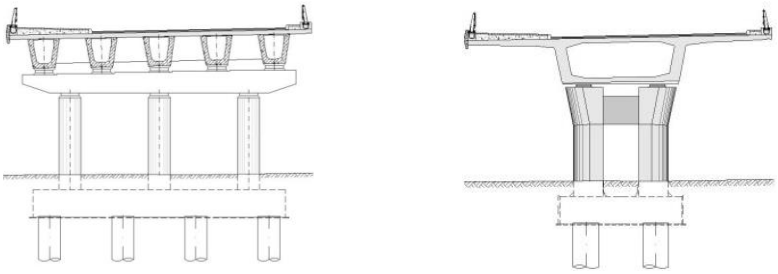
The MVD is the basis for the semantic enrichment step, providing actionable definitions of all of the concepts, their properties, and the possible relationships between them. The MVD aspects that define defects, element defects and inspection are a specific contribution as they lay the foundation for modeling inspection related information for all infrastructure, not only for bridges. When provided in the mvdXML format, the MVD can be used check the SeeBridge output files for compliance to the MVD automatically, using testing tools such as XBIM Xplorer [23] or ifcDoc [24].

The following sections describe the overview and the systematic process of SeeBridge framed by the IDM, explain the information exchange between the component processes, and present parts of the data repositories compiled in the IDM and the MVD. The conclusion section discusses the need for extensions to the IFC Schema [25] for bridges, highlighting the novel aspects incorporated in the concepts and the IFC binding, and summarizes the value of the IDM and MVD approach to research and development of this kind.

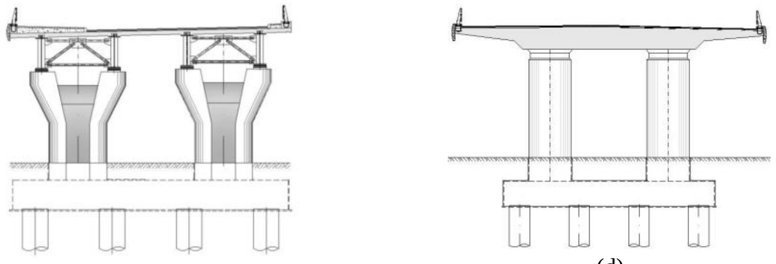
2. SeeBridge Inspection Process

Bridge inspection and management is a part of the bridge life-cycle and is related to the operational and maintenance stage. The data needed for managing the bridge stock within a given defined road network is used for decision making regarding the maintenance, repair, retrofit and rebuild/replacement of the bridges. Bridge inspections are the main source of data regarding the actual condition of a bridge during its life cycle.

Bridge inspection and management methods differ among Departments of Transport (DOT) and authorities in different countries, yet the core innovations of the SeeBridge process are applicable to most if not all. Figure 1 shows four bridge types investigated in the SeeBridge project. These are the most common types in many countries.



(a) (b)



(c) (d)

Figure 1 SeeBridge Bridge Types: (a) Concrete Beam/Girder Bridge, (b) Concrete Box Girder Bridge, (c) Steel Beam/Girder composite Bridge, (d) Concrete slab Bridge

SeeBridge integrates four novel technical components to upgrade the traditional bridge inspection process and produce semantically rich BIM models for the inspected bridges. The new components are:

- A bridge data collection system using remote sensing techniques such as terrestrial/mobile laser scanning and photogrammetry/videogrammetry.
- A bridge object detection and classification software for automated compilation of 3D geometry from the remote sensing data using both parametric shape representation and boundary representation.
- A semantic enrichment engine for converting the 3D model to a semantically rich BIM model using forward chaining rules derived from bridge engineers’ knowledge.
- A damage detection tool for damage identification, measurement, classification and integration of this information in the BIM model.

The workflow of the SeeBridge system is shown in Figure 2. Incorporating the suggested SeeBridge technical components into an existing bridge inspection and management process should be done with great care as the impact on the existing workflow and on the way the BMS is used to manage the bridge stock may be significant. One of the major changes is the introduction of a BIM model as a database for the bridge inspection and management process. There are three options/situations for incorporating BIM models into the process:

- Using the ‘as-built’ BIM models of bridges if and where they exist.
- Automatic creation of 'as-is' BIM models of bridges using the SeeBridge technical components numbered 1-3 above (activities 2.3.1, 2.3.2, and 2.3.3 in Figure 2).
- Preparation of ‘as-built’ BIM models of bridges manually based on drawings.

The second option is the major solution that SeeBridge provides, since most of the existing BMS have not incorporated BIM models. The SeeBridge solution of this aspect should greatly reduce the effort and costs required for BIM model integration into the BMS.

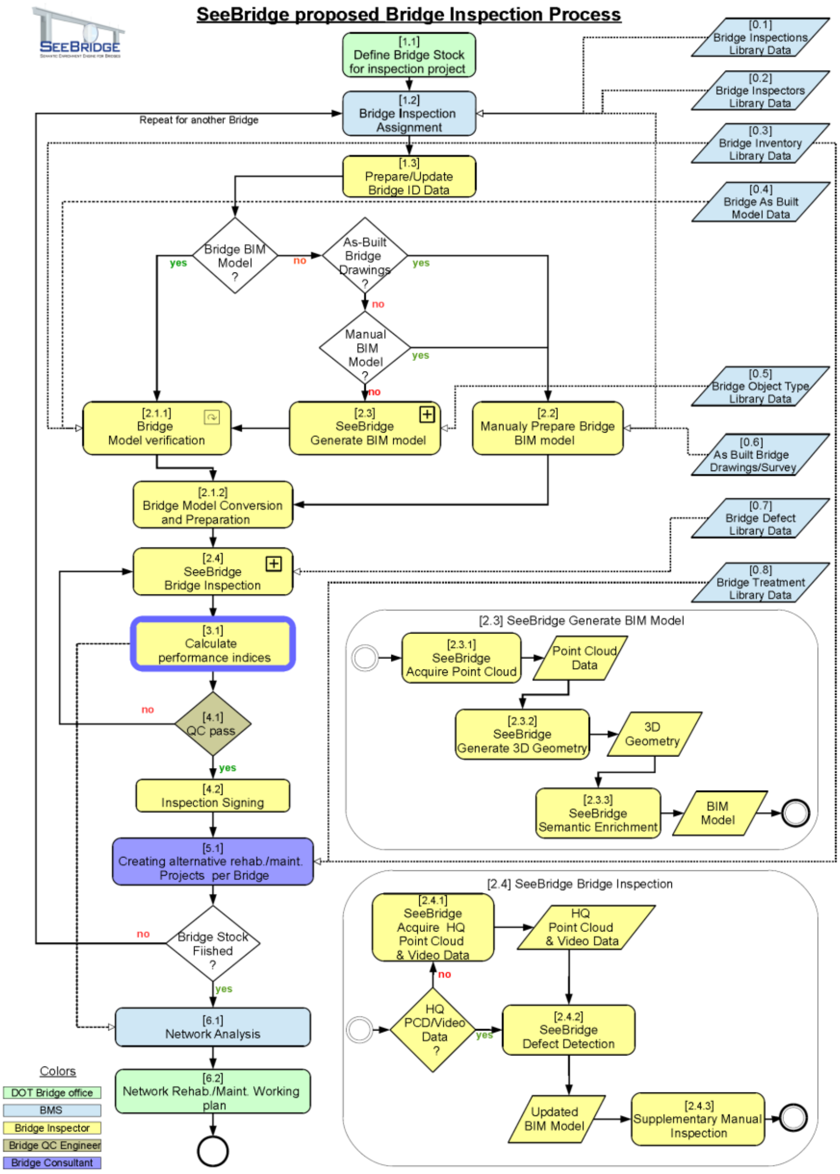


Figure 2 Workflow diagram of proposed SeeBridge Bridge Inspection process.

A detailed SeeBridge process map was developed in the IDM using Business Process Modelling Notation (BPMN), which defines the information exchange, including Non-Model Exchanges (NME) and BIM Exchange Models (EM), between the activities. Part of the process map is shown in Figure 3.

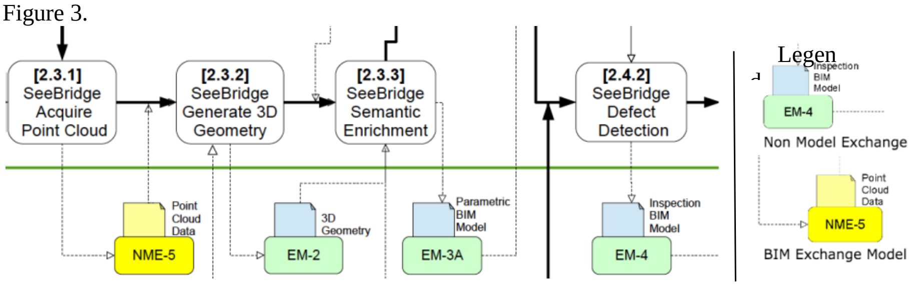


Figure 3 Part of the SeeBridge Bridge Management Process Map

3. Activities and Information Exchange in SeeBridge

The four major activities (technical components) in the SeeBridge system require solutions in the areas of survey and remote-sensing technology, computer vision, information interoperability and information modelling of bridges defects. While all four are outlined in the sections that follow, this paper focuses only on the information engineering aspects. Details of the 3D reconstruction and the semantic enrichment are beyond the scope of this paper, and are reported thoroughly elsewhere [26].

3.1. Remote Sensing Technology

The use of these technologies for capture of existing structures is the topic of much research [12,13]. In activity 2.3.1 shown in Figure 2, the bridge inspector, depending on the bridge type and inspection criteria, selects a proper 3D scanning approach. The options are terrestrial/mobile laser scanning and video/photogrammetry.

In case of laser scanning, the inspector evaluates the site and designs the laser scanning set-points so that they collectively cover the entire bridge structure. The laser scanner is then set at every set-point and a 3D point cloud is captured at each set-point. The individual point clouds are then registered to each other using automated software or manually.

In case of video/photogrammetry, the inspector selects a proper camera resolution based on the project criteria, distance of the camera to the bridge surfaces, and required point cloud resolution. Once the camera is selected, the inspector captures video or takes photographs from the bridge. The important point here is to cover every surface of the bridge from multiple viewpoints. The video or photographs are then input to the processing software. The software automatically estimates camera parameters and trajectory which will lead to the generation of a dense point cloud data (PCD), i.e. the NME-5, as the input of the 2.3.2 activity (as shown in Figure 3).

3.2. Reconstruction of a 3D Model from PCD

Current practice for the generation of as-built models from PCD involves manual conversion through user-guided specification of components combined with automated fitting of the components to specified subsets of the point cloud data. In activity 2.3.2 in the SeeBridge process (as shown in Figure 2), the 3D geometry generation engine processes the PCD created in 2.3.1 and generates a geometric model of the infrastructure associated to the PCD. The engine segments the main bridge components by matching the data with a repository of predefined bridge element shapes defined in the IDM. The techniques used employ a surface primitive extraction algorithm and a component detection and classification algorithm. As the detection and classification is based on machine learning, training data is required for learning the proper relationships between surface primitives and integrated components.

Most of the bridge components can be modelled using extruded, prismatic solid shape representations, while others require a BREP approach. To support component detection of extruded area solid elements, a comprehensive set of parametric cross-sections were defined in the IDM, including all of the typical concrete box, double T and girder sections. An example of the SeeBridge Generic Girder Parametric Cross-Section is shown in Figure 4. Note that all the chamfers are 45°, and filet radii are only relevant for a small group of bulb tees (e.g. North East and California bulb tees). The parameters are specified in Table 1.

The output of this activity (2.3.2) is a simplified building information model of the sensed bridge with the main bridge components identified and modelled, but with no relationships or other information. Elements that are occluded or that are too small to be discerned due to insufficient scan resolution are not provided. The level of detail satisfies or is superior to LoD 300, but is inferior to LoD 400 [27,28]. The data format of the output model will be an IFC or equivalent BIM model file with the component objects and their full geometry (defined as EM-2 in Figure 3).

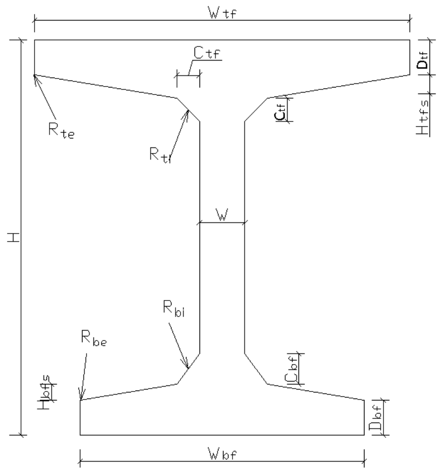


Figure 4 SeeBridge generic girder parametric cross-section

Table 1 Definition of parameters for generic girder parametric cross-section

Parameter	Label
Height	H
Top flange depth	D_{tf}
Top flange slope height	H_{tfs}
Bottom flange slope height	H_{bfs}
Top flange chamfer	C_{tf}

Bottom flange chamfer	C_{bf}
Bottom flange depth	D_{bf}
Top flange width	W_{tf}
Bottom flange width	W_{bf}
Web width	W
Top flange inner filet radius	R_{ti}
Top flange edge filet radius	R_{te}
Bottom flange inner filet radius	R_{bi}
Bottom flange edge filet radius	R_{be}

3.3. Semantic Enrichment of the 3D Model

In activity 2.3.3, the semantic enrichment engine enhances a 3D bridge model to a level of detail where all the tangible objects are correctly typed and the virtual aggregation containers and other objectified relationships are clearly defined. The engine has three major components: 1) it can parse an IFC file and extract the geometric, topologic and functional characteristics from the model; 2) it can be used to compile model enrichment rules; 3) by iteratively processing a set of predefined rules using forward-chaining, it can create, update or delete semantically rich model entities and output a new IFC file.

The second component is the core feature. The rule sets encapsulate the knowledge of bridge engineers concerning the characteristics of the 3D model objects that represent bridge components, including their geometric features (e.g., their parametric cross-sections), their occurrence and the topological and other relationships among them. Such knowledge is structured and documented in the IDM. For example, Table 2 shows the occurrence of bridge elements in different types of bridges; Table 3, which illustrates how knowledge of the existence or absence of physical contact relationships between bridge elements can be expressed, is an example of topological relationship knowledge. Details of the rule compilation approach can be found in [26,29,30]. The output of this activity (2.3.3) is a bridge "Pre-Inspection BIM Model" (EM-3A in Figure 3) with explicit geometry representation and property sets in a verified LoD similar to LoD 350 [27,28], although the data must represent 'as-is' conditions (in the same sense as LoD 500 calls for a ‘field-verified’ model).

Table 2 Part of the IDM Table of Bridge Elements and Occurrence

Bridge type	**Description**	**Element Type**			
		Primary Girders	**Slab**	**Box**	**Transverse Beam/Diaphragm**

Concrete Beam/Girder Bridges	At/Below deck surface	+			+
	Box Girder (exterior & interior)			+	+
Steel Beam/Girder Composite Bridges	At/Below deck surface	+			+
Slab Bridges	Monolithic Slab Bridges	+			
Note: + means that this element type always exists in this type of bridge					

Table 3 Part of the IDM Table of Spatial Relationships between Elements

Element description		**Primary Girders**	**Box (Box girder)**	**Slab**	**Transverse Beam/Diaphragm**
Deck/Superstructure	**Primary Girders**	■			E
	Box (Box girder)		■		E
	Slab			■	
	Transverse Beam/Diaphragm	E	E		■
	Deck Slab - (Concrete Slab)	E	E		P
Note: E = Exists: normally the elements are in physical contact P = Possible: the elements may or may not be in physical contact					

3.4. Bridge Defects Modeling

A pre-processing activity of the damage detection step (2.4.2 activity in Figure 3) supplements all the elements in the BIM model generated in activity 2.3.3 (i.e., EM-3A) with boundary shape representation (BREP), because it is much easier to represent defects on the bridge surface when using BREP, which is a composite of faces (this is illustrated in section 4.3 below). Any bridge elements that were only modelled using solid extrusions and CSG in EM-3A maintain both their original representations and BREP in the resulting model - EM-3B. The objects also have high resolution imagery registered with them at this stage (note that EM-3B is not shown in Figure 3 due to space limitations).

The damage detection algorithm (activity 2.4.2 in Figure 3) iterates over every BIM element in EM-3B and analyses the imagery, shape and function in the structure. First, imagery is used solely to localize visually detectable damage groups. Subsequently, these findings are further refined to a specific damage type (structural crack, non-structural crack, spalling, scaling, efflorescence, corrosion, other) using additional extracted properties such as element type, damage position and damage location. The defects’ types and possible occurrence in bridge elements are listed in bridge defect occurrence tables that are compiled in the IDM; some examples are shown in Table 4.

Meaningful damage parameters (damage type, absolute and relative size measurements, etc.) are extracted from the findings and embedded into the BIM model. The result is an 'Inspection BIM Model' (EM-4) with defect data attached and located on bridge component surfaces.

The 'Inspection BIM Model' enables automatic calculation of performance indicators of the bridges and automatic classification of the defects based on the defect classification tables, which are compiled in the IDM according to the DOTs/Highway Authorities’ regulations. An example of severity levels is shown in Table 5.

Table 4 Part of the Bridge Defect Occurrence Table in the IDM

	Defect Group	**02 Reinforced & Prestressed Concrete**				
				Cracks in reinforced concrete		
	Defect Description	Spalls	Delamination	Cracks likely to affect the stability of the element/ structure	Cracks which do not affect the stability of the element/structure	Cracks in Prestressed concrete
Deck/Superstructure	Primary Girders (Concrete Beam/Girders)	+	+	+	+	+
	Primary Girders (Steel Beam/Girders)					
	Box (Box girder)	+	+	+	+	+
	Slab	+	+	+	+	+
	Secondary Deck element – Transverse Beam/Diaphragm	+	+	+	+	+
	Deck Slab (Concrete Beam/Girders, Box Girder, Composite)	+	+	+	+	+

Note: + means normally this type of defect may be identified in this element

Table 5 Part of the Defects Classification Table in the IDM

02 Reinforced & Prestressed Concrete					
	Severity				
Defect	**1**	**2**	**3**	**4**	**5**

Spalls	No spalling	Slight, but clear, local spalling. Partial exposure of the outer reinforcement layer (stirrups in beams, external reinforcement in slabs) usually accompanied by signs of corrosion	Large, discrete spalls, exposing the cross-section of the shear stirrups and/or longitudinal reinforcing bars. Usually accompanied by general corrosion of the exposed bars, with possible local reduction in cross-section of longitudinal bars	Delamination in regions of low bending or shear, with no influence on the stability of the element	The element is no longer structurally functional, as a result of developments described under “Degree of severity 4”

4. SeeBridge Model View Definition

A Model View Definition (MVD) is a computer implementation of an IDM. It maps the information exchanges in IDM to a subset of the IFC schema, and defines the exchange requirements in a computer readable data model.

The SeeBridge MVD was developed based on IFC4 Add2 with the following goals:

- to identify the required objects, properties and relationships between objects needed to represent bridges according to the IFC schema.
- to provide a resource for the upcoming effort for the IFC Bridge [7,8] and other extensions
- to accelerate the quality control / quality assurance of produced IFC Models by using data validation tools

4.1. MVD process

Development of IDMs and MVDs for specific exchange requirements of business processes within the construction industry is highly encouraged by bSI. Not only does this effort allow the assessment of the capabilities of the current schema in satisfying the industry needs, but also provides opportunities to explore possible shortcomings and specify necessary extensions for future development. Thus, these extensions can be implemented by software developers, and industry practitioners can take advantage of the expanded potentials of open data exchange in projects.

Furthermore, specification of an MVD gives the project stakeholders the ability to validate the project deliverables against the exchange requirements automatically. mvdXML 1.1, developed by bSI [31], is the currently recommended data schema for model validation. An mvdXML file can be used to check any given IFC instance file against conformance with the corresponding IDM with the aid of capable BIM viewers and checkers. It carries a detailed description of the entities, attributes and properties that must be present (*mandatory*) or are allowed to be used (*optional*) in an IFC instance file. An mvdXML file consists of two main components: Templates and Views. Templates include the attribute and entity rules as well as sub templates that are required to support the data exchange scenarios. Views on the other hand, feature information about the exchange requirements and specific checking rules for concepts. This provides the technical basis for either filtering IFC instance models or, more importantly here, checking them for compliance with the exchange requirements of the IDM.

Commented [GC1]: Sergej: This is not exactly true. Concept templates have RuleIDs (mapped to attribute names) defined. Concept instances have the information about being required or not. Concept instance have template rules defined that are used to check the RuleIDs.

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4.2. Development of the SeeBridge IDM and MVD

Figure 5 shows the workflow of SeeBridge MVD development. The workflow required multiple iterations to ensure that the technical specifications of the mvdXML met the information exchange requirements in the IDM and were interpreted in the same way by all the software tools that were used.

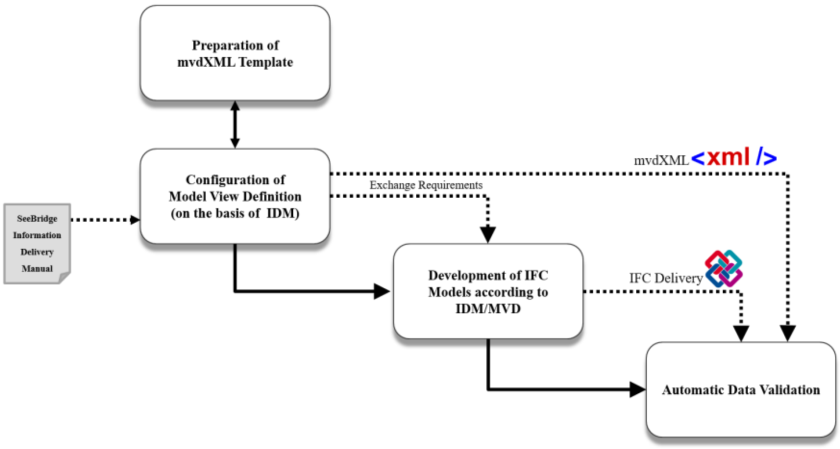


Figure 5 The workflow of the MVD development and usage.

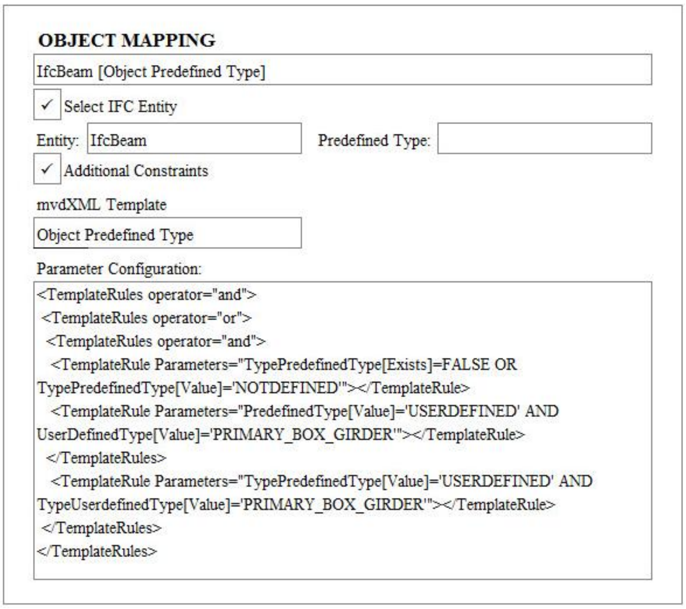
In the SeeBridge project, the BIMQ tool – Requirements and Quality Management Database (developed by AEC3) – was used for MVD development and to generate the SeeBridge mvdXML file. BIMQ is an online platform which allows users to define information items, including objects and properties, and map them to the IFC schema. The information items are identified as mandatory, optional or not required in each information exchange model according to the IDM. The result is a specification that represents the correct definition of BIM models and their data requirements. It can further be used as a single source of information to generate reports (PDF), BIM software proprietary templates, and quality checking rules (mvdXML). XBIM Xplorer [23] was used to validate IFC files of bridge information models using the mvdXML file which encapsulates the rules defined in the MVD.

The SeeBridge IDM was the source of information for the MVD development. For each bridge object, the team chose the most suitable IFC entity from a reference list that includes all IFC4 entities together with their predefined types. Object properties were mapped to the available IFC concepts, and additional data types for each property were defined where necessary. Figure 6 shows part of the SeeBridge MVD defined using the BIMQ interface. This enabled understanding of the required concept templates to support the defined exchange scenarios, thus leading to preparation of the mvdXML Template.

Concept Definition	IFC4	P2-EM1	P2-EM2	P2-EM3A	P2-EM3B	P2-EM4
Project	IfcProject	MAN	MAN	MAN	MAN	MAN
Project ID	Object User Identity	-	-	-	-	-
Project Properties	Property Sets for Override	-	-	-	-	-
Site	IfcSite	MAN	MAN	MAN	MAN	MAN
Project ID	Spatial Composition	MAN	MAN	MAN	MAN	MAN
Site ID	Object User Identity	MAN	MAN	MAN	MAN	MAN
Location	Property Sets for Override	-	-	-	-	-
Bridge	IfcBuilding	MAN	MAN	MAN	MAN	MAN
Bridge ID	Object User Identity	MAN	MAN	MAN	MAN	MAN
Site ID	Spatial Composition	MAN	MAN	MAN	MAN	MAN
Identification	Property Sets for Override	-	-	-	-	-
General Classification	Property Sets for Override	-	-	-	-	-
Ownership	Property Sets for Override	-	-	-	-	-
Bridge Type	Property Sets for Override	-	-	-	-	-
Bridge Axis	IfcAlignment	MAN	MAN	MAN	MAN	MAN
Bridge Grid	IfcGrid.PredefinedType.IRREGULAR	MAN	MAN	MAN	MAN	MAN
Span	IfcSpace	MAN	MAN	MAN	MAN	MAN
Product Local Placement	Product Local Placement	MAN	MAN	MAN	MAN	MAN
Span ID	Object User Identity	MAN	MAN	MAN	MAN	MAN
Spatial Containment	Spatial Containment	MAN	MAN	MAN	MAN	MAN
Aggregated geometric properties	Property Sets for Override	-	-	-	-	-
Drainage	IfcDistributionSystem [Object Predefined Type]	OPT	NOT	MAN	MAN	MAN
Lighting	IfcDistributionSystem [Object Predefined Type]	OPT	NOT	MAN	MAN	MAN
Safety	IfcBuildingSystem [Object Predefined Type]	OPT	NOT	MAN	MAN	MAN
Signs	IfcBuildingSystem [Object Predefined Type]	OPT	NOT	MAN	MAN	MAN

Figure 6 Part of the SeeBridge MVD defined using the BIMQ interface

Each concept has a predefined template rule that serves as a basis to specify the template rules for a particular case. Code snippets following a tailored XML schema can be written for each concept, thereby configuring the mvdXML for checking. The definition of bridge element types in the SeeBridge MVD is a good example of the use of template rules. Many bridge elements were classified by the Object Predefined Type concept of IFC. This concept allows further specification of the type of an object of a given IFC entity. For example, SeeBridge IDM distinguishes among Capping Beam, Primary Girder, Box Girder, Transverse Beam, etc., all of which can be modeled as instances of *IfcBeam* by using the *IfcBeam.PredefinedType*. The MVD code snippet shown in Figure 7 defines how to model a primary box girder. Firstly, a primary box girder should be an *IfcBeam* entity; secondly, its *PredefinedType* attribute value should be 'USERDEFINED' and *ObjectType* attribute should be 'PRIMARY_BOX_GIRDER'. In the case where an object is a primary box girder, it must have these required values. Such template rules define correct IFC model generation and can be used to validate an IFC instance file. Figure 8 shows the results of a validation run performed on an IFC file of a bridge produced by the sematic enrichment engine. During the research project, failed checks (shown as red symbols to the left of the instance text in the result browser) guide the research team to refine the enrichment engine to ensure correct semantic modeling. In implementation, failed checks will indicate areas in which the semantic enrichment is incomplete and must be supplemented by the engineer using the system.



OBJECT MAPPING

IfcBeam [Object Predefined Type]

☑ Select IFC Entity

Entity: IfcBeam   Predefined Type:

☑ Additional Constraints

mvdXML Template

Object Predefined Type

Parameter Configuration:

```
<TemplateRules operator="and">
 <TemplateRules operator="or">
  <TemplateRules operator="and">
   <TemplateRule Parameters="TypePredefinedType[Exists]=FALSE OR
TypePredefinedType[Value]='NOTDEFINED'"></TemplateRule>
   <TemplateRule Parameters="PredefinedType[Value]='USERDEFINED' AND
UserDefinedType[Value]='PRIMARY_BOX_GIRDER'"></TemplateRule>
  </TemplateRules>
   <TemplateRule Parameters="TypePredefinedType[Value]='USERDEFINED' AND
TypeUserdefinedType[Value]='PRIMARY_BOX_GIRDER'"></TemplateRule>
 </TemplateRules>
</TemplateRules>
```

Figure 7 Code snippet of requirement for modeling a primary box girder.

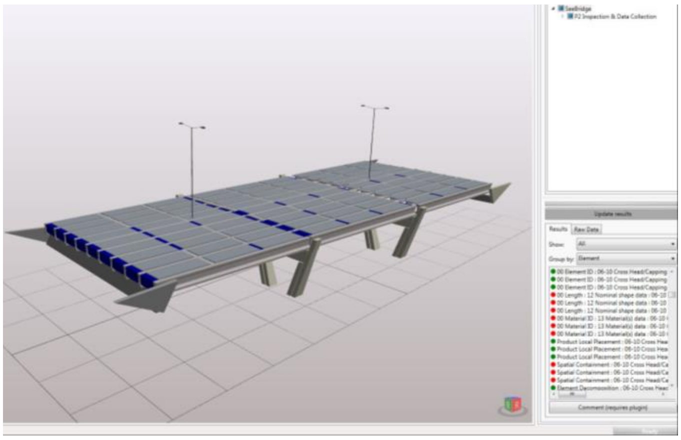


Figure 8 Checking conformance of a SeeBridge IFC output file of the Haifa Route 79 bridge for compliance with the MVD using the XBIM checking facility.

4.3. Defect Description and Modelling

A unique contribution of the SeeBridge project lies in development of the capability to incorporate defect information in a BIM model. Figure 9 shows a UML diagram of a schema for modelling defects that reflects. A *Bridge* can have multiple *Defects*, and each defect can be composed of a number of specific element defects (*ElementDefects*). More than one element defect may be associated with the same bridge element (*BridgeElement*), whereas defects may be spread over multiple elements.

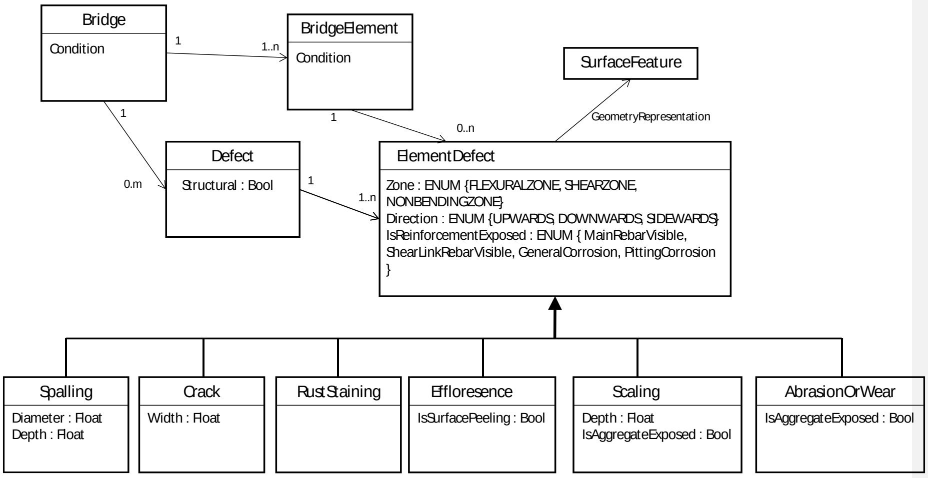


Figure 9 UML diagram of the conceptual schema model for modeling defects

An element defect is a specific occurrence of a deformation identified during an inspection. It represents a finding which is of a single defect type, at a specific location on a single element and at a particular point in time. It has a geometrical representation and property values that are unique to its type. Table 6 lists element defect types and the corresponding properties of reinforced concrete elements, compiled based on bridge inspection guidelines from North America, Australia, Asia and Europe [32]. The predefined ranges for the property values reflect the information needed for classifying the severity of defects. As multiple element defects can be logically linked by cause (over time, multiple elements, different defect types), these element defects are grouped in bridge *Defects*. A *Defect* instance does not have its own geometrical representation. It serves as a group of element defects that may be of different types, that may occur on multiple bridge elements, and may have been identified in multiple inspections. The properties of both element defects and of defects integrate additional information such as measurements, condition ratings and inspection details.

Table 6 Element defect types, their corresponding properties and the ranges of values that distinguish different condition ratings [32].

Element Defect Type	**Property**	**Value Range**
Spalling / Exposed rebar / Corrosion	Diameter	< 6 inch / > 6 inch
	Depth	< 1 inch / > 1 inch
	Shear link rebar visible	Yes / No
	Main rebar visible	Yes / No
	General corrosion on rebar	Yes / No

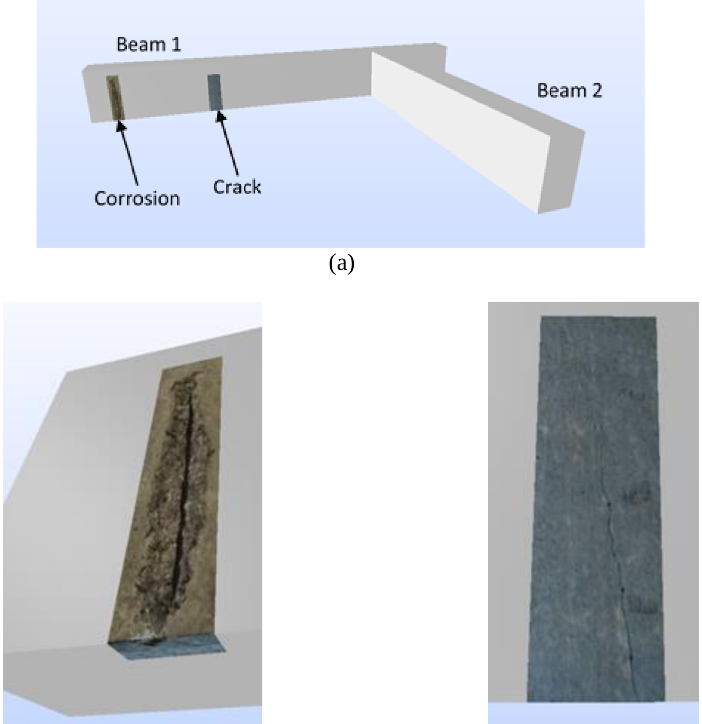
	Pitting corrosion on rebar	Yes / No
Crack	Width	0.3mm, 1mm, 2mm
	Dropping down	Yes / No
	Going up	Yes / No
	Orientation in relation to the support	π/2, π/4, 0, -π/4
	Area of high flexural behavior	Yes / No
	Area of high shear behavior in area	Yes / No
	Close to support	Yes / No
Delamination	Cracks	See 'Cracks'
	Rust staining	Yes / No
	Area of high flexural behavior	Yes / No
	Area of high shear behavior in area	Yes / No
Freeze-thaw	Accompanied by other defect(s)?	Yes / No
	Other defect(s) structurally relevant?	Yes / No
Efflorescence	Severity	Slight/Minor/Major
	Peeling surface	Yes / No
	Exposed reinforcement	See 'Exposed rebar'
Scaling	Depth	6mm, 13mm, 25mm
	Coarse aggregate exposed	Yes / No
	Exposed reinforcement	See 'Exposed rebar'
Abrasion / Wear	Coarse aggregate exposed	Yes / No
	Exposed reinforcement	See 'Exposed rebar'

In the SeeBridge MVD, a defect is modelled as an *IfcElementAssembly* with its *PredefinedType* ='USERDEFINED' and *ObjectType*='DEFECT'. It is an aggregation of defects that occur on individual elements (element defects) An element defect is modelled as an *IfcSurfaceFeature*. Each element defect has a number of descriptive attributes (*Zone, Direction, Is ReinforcementExposed, IsAggregateExposed*). The distinct types of defects are further determined with the concept Object Predefined Type and feature the following: Abrasion/Wear, Crack, Effloresence, Exposed reinforcement, Rust staining, Scaling and Spalling, which are all defined in the IDM. The nature of an objectified aggregation relationship in IFC (*IfcRelAggregates*) determines that the geometry of the whole is determined by the sum of the geometry of the individual parts. In our case, the *IfcElementAssembly* is the whole with the geometry coming from the parts defined as *IfcSurfaceFeature*, as is shown in Figure 9.

Another aggregation relationship assigns element defects to elements. Hence, a bridge element can have several element defects and they can be of different types. The object-oriented concept used for both aggregations (*Defect* as an aggregation of *ElementDefects* and *BridgeElement* as a second aggregation of *ElementDefects*) is decomposition. In the case of the first relationship, the aggregation is mandatory: a *Defect* must have associated *ElementDefects*. On the other hand, a *BridgeElement* may not have any *ElementDefects*.

In standard bridge inspection practice, photographs of defects taken in bridge inspections are stored separately and manually attached to an inspection report. In the SeeBridge process, high resolution raster images of element defects are mapped to the bridge model in the same location, orientation and scale as the defects on the bridge surface. The defect images can be linked to the IFC model through the existing *IfcImageTexture* entity, which maps an image onto a surface of an object. The ability to implementing this facility was considered in the IDM and was the reason for requiring the supplementary conversion of solid geometry defined as extrusions into BREP that was described in section 3.4 above.

Such integration allows easy comparison between the ‘as-damaged’ state and the ‘as-designed’ state of the bridge elements. However, none of the IFC viewers available at the time of writing were able to visualize an instance of an *IfcImageTexture*. As a result, an advanced SeeBridge viewer was developed to load IFC models and display their associated element defect textures. Figure 10 shows a reinforced concrete beam with two element defects displayed in the SeeBridge model viewer.



(a)

(b) (c)

Figure 10 (a) 3D view of an IFC model including the defect location and texture. (b) defect texture image of the corrosion element defect in high resolution mapped to the correct location on the beam; (c) similarly, the element defect texture of the crack in high resolution [32].

5. Conclusion

The SeeBridge research proposed and explored a new approach to acquiring and compiling information for bridge inspection and system management, using point cloud data processing and BIM technologies. The IDM establishes the professional knowledge basis of the domain of highway bridges in order to ensure the correct development of the technical components in the system. It specifies the data collection process; details the activities for 3D model reconstruction and the geometric shape representations needed; presents the process of semantic enrichment and the required structured knowledge; and it specifies the defect identification and modeling activities and the defect classifications that facilitate the process. The IDM was developed, documented and validated with a network of domain experts representing highway departments and DOT's in four countries. It captures general data exchange scenarios relevant to the bridge inspection process in the SeeBridge system, as well as country-specific aspects.

The MVD for bridge data collection and information manasgement defines the implementation of the information schema and a binding to IFC 4 Add2. It includes numerous 'workarounds' to represent bridge elements, properties and relationships as defined in the IDM, with new entities, relationships and property sets that compensated the existing IFC for modeling bridge inspection data. As such, it contributes to the ongoing work to compile IFC Bridge and IFC Infrastructure extensions to the IFC schema[1].

The MVD makes a broader contribution to information modeling of defects and inspections, providing solutions that are applicable to the much broader domain of facility management and maintenance. There is currently no accepted, consistent or thorough way to represent the defects that may occur in bridges, or for that matter, in other structures. Definitions for objects that represent defects, defect patches (element defects) and inspection information have been proposed, implemented and tested, and an advanced model viewer has been developed which can visualize a BIM model with high resolution image texture maps of the defects correctly mapped onto the surfaces of model objects.

Using the XBIM evaluation tool, the MVD (written to an mvdXML file), was used to inform and control development of the bridge model semantic enrichment engine, and in the future it will allow for rigorous validation of bridge information instance models generated by the SeeBridge process. As such, the IDM and the MVD are central components for R&D of this type.

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References

[1] B. Chan, H. Guan, L. Hou, J. Jo, M. Blumenstein, J. Wang, Defining a conceptual framework for the integration of modelling and advanced imaging for improving the reliability and efficiency of bridge assessments, Journal of Civil Structural Health Monitoring 6 (4) (2016) 703-714.

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[1] The IFC Bridge project was reactivated as an official standardization project of bSI in 2017, and the final data model will form part of IFC Version 5, due for release in 2019. The SeeBridge MVD could be referred and adopted by it as an extension for the domain of bridge inspection.

[2] B. McGuire, R. Atadero, C. Clevenger, M. Ozbek, Bridge Information Modeling for Inspection and Evaluation, Journal of Bridge Engineering 21 (4) (2016) 04015076.

[3] S. Chen, A. Shirolé, Integration of information and automation technologies in bridge engineering and management: Extending the state of the art, Transportation Research Record: Journal of the Transportation Research Board (1976) (2006) 3-12.

[4] E. Ziering, TransXML: XML schemas for exchange of transportation data, Transportation Research Board, 2007.

[5] F.H. Administration, Bridge Information Modeling Standardization, Vol. 2017, 2016.

[6] N. Yabuki, E. Lebegue, J. Gual, T. Shitani, L. Zhantao, International collaboration for developing the bridge product model IFC-Bridge, Proc. of the 11th Int. Conf on Computing in Civil and Building Engineering, 2006.

[7] E. Lebegue, J. Gual, G. Arthaud, T. Liebich, IFC-Bridge V2 data model, Technical Report Edition, 2007.

[8] N. Yabuki, Z. Li, Development of new IFC-BRIDGE data model and a concrete bridge design system using multi-agents, Intelligent Data Engineering and Automated Learning–IDEAL 2006 (2006) 1259-1266.

[9] O. Abudayyeh, M. Al Bataineh, I. Abdel-Qader, An imaging data model for concrete bridge inspection, Advances in Engineering Software 35 (8) (2004) 473-480.

[10] E.J. Jaselskis, Z. Gao, R.C. Walters, Improving transportation projects using laser scanning, Journal of Construction Engineering and Management-Asce 131 (3) (2005) 377-384.

[11] P. Fuchs, G. Washer, S. Chase, M. Moore, Applications of laser-based instrumentation for highway bridges, Journal of Bridge Engineering 9 (6) (2004) 541-549.

[12] P.B. Tang, B. Akinci, Formalization of workflows for extracting bridge surveying goals from laser-scanned data, Automation in Construction 22 (2012) 306-319.

[13] A. Endsley, C. Brooks, D. Harris, T. Ahlborn, K. Vaghefi, Decision support system for integrating remote sensing in bridge condition assessment and preservation, SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring, International Society for Optics and Photonics, 2012, pp. 834548-834548-834515.

[14] P. Tang, Extraction of surveying goals from point clouds obtained from laser scanners to support bridge inspection, PhD Thesis, Carnegie Mellon University, 2009.

[15] P. Tang, B. Akinci, J.H. Garrett, Laser scanning for bridge inspection and management, IABSE Symposium Report, Vol. 93, International Association for Bridge and Structural Engineering, 2007, pp. 17-24.

[16] A. Kedar, R. Sacks, L. Ma, SeeBridge Information Delivery Manual (IDM), 2016.

[17] BuildingSmart, Information Delivery Manuals, Vol. 2017, 2017.

[18] N.I.o.B. Sciences, National Building Information Model Standard, 2007.

[19] M. Venugopal, C.M. Eastman, R. Sacks, J. Teizer, Semantics of model views for information exchanges using the industry foundation class schema, Advanced Engineering Informatics 26 (2) (2012) 411-428.

[20] R. Sacks, I. Kaner, C.M. Eastman, Y.-S. Jeong, The Rosewood experiment — Building information modeling and interoperability for architectural precast facades, Automation in Construction 19 (4) (2010) 419-432.

[21] C.M. Eastman, R. Sacks, Y.-S. Jeong, I. Kaner, Building Information Modeling (BIM) for Precast Concrete, National Institute of Building Sciences, Washington DC, USA, 2007, p. 212.

[22] Y.S. Jeong, C.M. Eastman, R. Sacks, I. Kaner, Benchmark tests for BIM data exchanges of precast concrete, Automation in Construction 18 (4) (2009) 469-484.

[23] OpenBIM, XBIM Xplorer, Vol. 2017, 2012.

[24] T. Chipman, IFC Documentation Tool (ifcDoc), Vol. 2017, buildingSMART International, 2016.

[25] BuildingSmart, Industry Foundation Classes Release 4 (IFC4), 2013.

[26] R. Sacks, L. Ma, R. Yosef, A. Borrmann, S. Daum, U. Kattel, Semantic Enrichment for Building Information Modeling: Procedure for Compiling Inference Rules and Operators for Complex Geometry, Journal of Computing in Civil Engineering in press (2017).

[27] J. Bedrick, A Level of Development Specification for BIM Processes, AECbytes Viewpoint 68 (2013).

[28] T.A.I.o. Architects, G202-2013 Project Building Information Modeling Protocol Form, AIA Contract Document, The American Institute of Architects, 2013.

[29] M. Belsky, R. Sacks, I. Brilakis, Semantic Enrichment for Building Information Modeling, Computer-Aided Civil and Infrastructure Engineering (2015) n/a-n/a.

[30] M. Belsky, R. Sacks, I. Brilakis, A framework for semantic enrichment of IFC building models, Proceedings of the 30th CIB W78 International Conference, Beijing, China, 2013, pp. 514-523.
[31] BuildingSmart, mvdXML 1.1, Vol. 2017, 2016.
[32] P. Huethwohl, I. Brilakis, A. Bormann, R. Sacks, Integrating RC bridge damage data into BIM models, Structural Health Monitoring Under review.