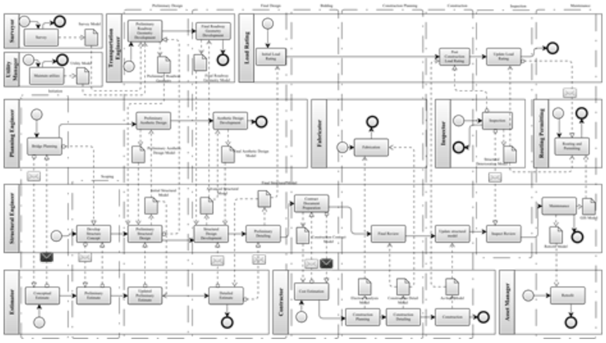
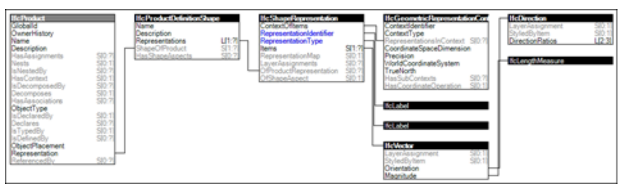
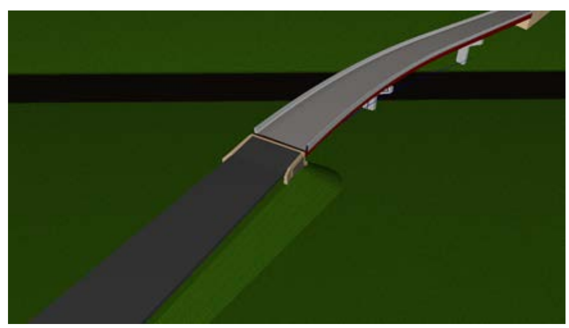
Bridge Information Modeling Standardization

INTRODUCTION

April 2016







U.S. Department of Transportation

Federal Highway Administration

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Foreword

Advancing the capability of computer modeling and analysis tools and techniques is clearly in the best interest of the U.S. bridge engineering practice. Without industry consensus standards for Bridge Information Modeling (BrIM) and related data exchange protocols, there is no common way to integrate the various phases of a bridge design and construction project and benefit from that information in the inspection, maintenance, and operational phases associated with its asset management. This work seeks to develop, validate, identify gaps, implement, and build consensus for standards for BrIM for highway bridge engineering.

The contributions and constructive review comments received from many professionals across the country are greatly appreciated. In particular, I would like to recognize Scot Becker of Wisconsin DOT, Christopher Garrell of National Steel Bridge Alliance, Danielle Kleinhans of Concrete Reinforcing Steel Institute, Josh Sletten of Utah DOT, Steven Austin of Texas DOT, Brad Wagner of Michigan DOT, Todd Thomson of South Dakota DOT, Ahmad Abu-Hawash of Iowa DOT, Mike Keever of Caltrans, Ali Koc of Red Equation Corporation, Hanjin Hu of Michael Baker International, and all those who participated in our workshops described in the Report.

Joseph L. Hartmann, PhD, P.E.
Director, Office of Bridges and Structures

Notice

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Bridge Information Modeling Standardization is a multi-volume Report that analyzes options for standardized approaches for modeling bridges across their lifecycle. The goal of the Report is to identify and evaluate candidate open standards that can be used to document all aspects of bridges to identify viable standards that can be used by bridge owners to specify information delivery requirements and by software providers to meet those requirements. After evaluation of the viable available options, the Report goes on to provide an in-depth analysis based on test cases of real bridge projects of a viable alternative. Accompanying the Report is a comprehensive exchange specification to assist software developers to implement the findings to the benefit of bridge owners.</td></tr>
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)A 508 compliant version of this table is available at http://www.fhwa.dot.gov/publications/convtabl.cfm.

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Executive Summary

Bridge Information Modeling (BrIM) refers to an advanced modeling approach that is based on generalized definition of the "objects" that make up the physical asset. It is a holistic digital representation of physical and functional characteristics of the facility, which provides a shared knowledge resource for information to support a reliable basis for decisions during its life-cycle. Using a standard for representing bridge information in a digital format which can be rapidly adopted by software tools with minimal ambiguity will offer the opportunity to use digital project delivery, 3-d visualization, virtual assembly, automated machine control, fast routing and permitting, network-level study, smart inventory, and more, as a routine part of project development and asset management. This effort seeks to identify, analyze, validate, expand, and build consensus for an open, non-proprietary set of BrIM standards through research and analysis, applied case study and industry outreach.

To effectively achieve such a broad goal, this current phase of work involves focusing the efforts into a specific data exchange in the bridge life cycle with measurable scope. While there are potentially hundreds of information exchanges over the life cycle of any particular bridge, spanning design, construction, and management phases, it was concluded that the highest initial value would be on defining and preparing to automate the exchange of information found in bridge design plans as they go out for bid, for which the rationale is further described in the Findings & Conclusions section later in this introductory volume.

In defining this information exchange for bridge design plans, it was deemed critical to model actual bridges that are most representative of bridge types in the U.S. by quantity, and to model such bridges in full detail that captures the same information provided on design plan documents. While it cannot be asserted that the particular information models proposed will accommodate all past and future needs, it can be concluded whether or not such common bridges may be supported and indicate any gaps that would need to be resolved to be supported by proposed information models. As even the simplest bridges consist of thousands of components and measurements, this initial effort is based on modeling of two specific, relatively simple case study bridges: a 4-span steel girder bridge with curved alignment, super-elevation transition, and constant grade; and a 5-span concrete box girder bridge with curved alignment and parabolic vertical curve. Both bridge case studies are discussed in detail in *Volume III* of this Report.

In defining information models (referred to as "schemas" herein), it was deemed preferable to attempt to leverage existing schemas that may be adapted rather than starting from scratch for the following reasons: (a) for vendors already supporting existing information models, it may cost significantly less for them to support added functionality compared to new separate models; (b) based on the fact that existing schemas having been applied to a wide range of structures, many unforeseen scenarios have already been addressed; and (c) software tools and developer communities already exist for accelerating development of sample data and additions to such schemas.

The case study bridges were modeled using several schemas: Industry Foundation Classes (IFC) which is supported by all major software vendors in the building industry; LandXML, which is supported by major software vendors for infrastructure; and OpenBrIM, recently introduced as part of FHWA standardization initiatives. In addition to published open standards, proprietary software and formats from major vendors were reviewed, including Bentley and AASHTOWare, where corresponding software functionality was mapped to representations within these information models. While none of these standards currently support all functionality required for the case study bridges, none were necessarily developed with that intention.

For the case study bridges modeled, all information was captured using entities already defined in IFC, with exception of a new positioning structure relating physical elements to offsets along alignment curves. Other than that, additional non-critical extensions are proposed, including repetitive pattern placement such as for piles and rebar, derivation of camber ordinates from assigned structural models, and documented use of constraint-based parameterization. A recommended use is for representing full detail of bridges as defined in construction plans, with minimal additions proposed to capture only the most critical gaps.

After analyzing each of the applicable schemas to identify scope and overlap, it became clear that Industry Foundation Classes (IFC) was the most suitable candidate to use as a basis to document complete design models, based on the fact that (a) most applicable data types are already fully defined and documented; (b) IFC has already been implemented by most vendors in the design/construction industry, including those comprising most of the market share for bridge design software; (c) as an ISO standard, it is supported and maintained by a worldwide organization with chapters in all major countries; (d) there is an active international community working on using IFC to model bridges and other forms of infrastructure that can contribute to the effort; and (e) it has already been proven, going through several generations of vendor validation and certification. Component modeling was then conducted to validate this proposed approach, for IFC as well as other schemas.

As a result of the component modeling, it became evident that the latest version of IFC (4.1) was not entirely sufficient, as it lacked the capability to position physical elements relative to alignment curves. To accommodate such capability, yet retain compatibility with existing software, one additional data structure was proposed to do just that. Additionally, several new usages of existing data structures were proposed for handling repetitive elements commonly found in bridges, such as rebar, shear studs, and stiffener plates. Similarly, new usages of existing data structures were also proposed for specifying camber ordinates. Such additions were intentionally kept at a minimum to only address critical requirements, and done in such a way to support upward and downward compatibility, such that existing software already on the market may read the new files without issue. Compatibility assumptions were confirmed by loading the bridge models into Tekla Structures 21.0 and Autodesk Revit 2016, where several adjustments were made to the data structures in use, based on current vendor support.

The technical details describing the subset of data definitions needed to use IFC for capturing bridge construction detail were encapsulated in a specification for software developers. While the IFC specification overall is rather comprehensive, the documentation is highly focused towards building construction. To clarify usage for bridges, the documentation relates specific data types to how they apply to bridge construction, and includes annotated files for the two sample bridges evaluated, where all data in the file is cross-linked with definitions in the documentation. This documentation is referred to as an “IFC Model View Definition”, and is one of many other such derivative specifications that have been published for particular uses such as facilities management, structural analysis, energy analysis, and more. The term “Model View Definition” is used by buildingSmart International to refer to such derivative specifications[1]. For example, the transportation authority in Korea has developed an IFC Model View Definition for road construction, while the authority in China is developing an IFC Model View Definition for rail – these are further discussed in *Volume II*.

With these technical specifications complete, and two documented examples of bridges fully developed with files tested on multiple software platforms, the technical foundation has been set for software providers to support IFC for exchanging bridge design plan information.

The next phase of this effort would involve implementation by software vendors, where future efforts may include coordinating with software vendors to achieve interoperability, resolving unforeseen issues during implementation and holding industry workshops and events to provide coordination and business incentives for software vendors. At the same time, efforts to make the bridge owner community aware of the potential and encourage them to require IFC-based exchanges of bridge models should accompany the effort to provide incentive for the software community to provide tools to support implementation.

Based on the extensive work already done to develop and implement IFC, the bridge community has an opportunity to quite rapidly move ahead with the delivery of open-standard based models of bridges that quite fully document design and construction requirements and pave the way to support additional high value uses of model data such as fabrication and maintenance management.

[1] http://www.buildingsmart-tech.org/specifications/mvd-overview/mvd-overview-summary

Background

Over the last several decades, many industries have benefited from the efficiencies generated by moving from document-based information exchanges to integrated data models. The construction industry (including the building and heavy/highway industries) has lagged behind the manufacturing industry in this regard for various reasons. These include much lower economies of scale due to larger numbers of industry participants, larger diversity of domain specialization, and the high level of detail that is often very project-specific and might not be leveraged for future use.

Following the pattern of other domains, progress will be made as business processes are mapped and implemented throughout the bridge industry. When the steps in a business process are defined, one sees how data changes form as it is passed from one job function to the next, similar to the old "telephone game". Very often data is transformed as it is passed to the next job function as paper or in a PDF format, both of which require the receiving party to have to re-enter partial data for use for their job function. The steel industry (AISC) defined a business process many years ago around a standard they had implemented called CIS/2. In documenting their business process, they were able to observe the number of times data was transformed at each job function (information exchange) and the time and effort it took to accomplish that along with the data and integrity loss. Recently, AISC moved to a new standard, Industry Foundation Class (IFC) (International Standards Organization (ISO) 16739), because they realized that they could not interface with the rest of the construction community, or expect the rest of the industry to change to CIS/2. In changing to IFC, it gave them the opportunity to re-examine their original business processes (2nd generation) and work to eliminate some of the cycling between paper/PDF and data, and keep data in a usable format throughout the business process, only printing documents when needed for legal purposes from the full set of data. They are now using the data as the truth, and the paper as the physical representation of that truth. This reversal of thinking allowed them to optimize significantly their business processes. They are now able to fabricate directly from an IFC data model by delivering CNC (computer numerical control) commands to robotic fabricating equipment, thus eliminating significant risk, job steps, and the chance for error, without affecting their ability to print off a paper/PDF version, if needed, at any point in the process. This advancement has eliminated the need to generate and approve shop drawings, for example.

When industry practitioners, as has been demonstrated in the steel industry, obtain consensus on their common business processes and therefore standardize, it becomes cost effective for software vendors to develop software built around business processes they can rely on as representing common needs. Having common processes potentially expands their market making it more profitable to develop the software.

Today the bridge industry remains largely paper centric, operating as if the paper is the primary document and not yet of the mindset that paper is only a representation of the data that can be produced when or if needed. The end result is that in current practice digital formats are typically provided for convenience only, and are explicitly disclaimed to be relied upon as part of a contract. It is felt that the cost of doing so exceeds the benefit, which is in reality, the absolute reverse of the desired state. It has always been the case that the data are what drive the production of the paper. This endeavor seeks to reduce this barrier by establishing the digital standards necessary for bridge information modeling (BrIM) with process documentation that can be referenced in contracts, similar to how other reference standards are used today, such as ASTM design standards.

In developing BrIM standards and with any information standard, the primary goal is creating open, interoperable and repeatable processes that will ultimately result in optimized technical solutions from engineers, owners, and software providers.

The focus on IFC is not by chance, but with a complete understanding that it is being adopted in the facilities and infrastructure industry worldwide. In addition, the IFC standard did not start from scratch, but was built on ISO STEP and existing models and existing geometry structures used in manufacturing. While over many years such standards have ended up becoming rather large, such scale is also reflective of the very large subject matter of the facilities and infrastructure industries. However, it is noted that typically advancements are made incrementally in order to leverage existing investments.

The goal of this project is to identify the building blocks (information exchanges – see *Volume I*) to advance standardization of digital information for bridges in the United States. As the number of data elements is well into the tens of thousands, and various standards vary significantly in formats and documentation level, a thorough analysis can be more predictably achieved in a systematic way with automation, rather than ad-hoc approaches, which may easily overlook detail. In supporting a systematic approach, all schemas under review were first incorporated within a linked information model initially developed for IFC documentation. The results are represented in the schema analysis in *Volume II*. This serves several purposes:

- Cross-linking the content enables evaluating similar concepts across schemas consistently, and makes any information gaps obvious. With increased productivity, efforts will be focused on content, not formatting of information. With dozens of schemas and thousands of data types, an automated approach is a necessity to achieve the desired scope.
- This approach enables comparing apples-to-apples by focusing on function (not form), independent of the originating specification format (UML, XSD, Express, etc.). To encourage the widest participation, every schema is presented in a consistent form readable to domain experts (cross-referenced tables with diagrams), in addition to formats familiar to programmers of various backgrounds (XML/XSD, IFC/EXPRESS, C#, Java, etc.), which should make all content approachable by all audiences involved.
- This approach validates the underlying schemas and provided examples to verify if they actually work. This has already revealed obvious issues upfront with existing schemas; the same checks will ensure the final result of this effort conforms as well.
- This approach supports quality assurance of the effort with traceability. What happens too often on software projects is that a customer engages domain experts to put together requirements, and then engages software experts to implement those requirements. Communication only happens in one direction if those generating results do not put it in a

form that can be understood by those issuing the requirements. If such a feedback loop is missing, the success or failure of a project may not be known until after the project is finished. To provide an automated feedback loop in validating the results of this effort, data definitions are referenced back to requirements, and a matrix is generated of schemas (e.g. LandXML) and concepts that apply across schemas (e.g. structural load cases). Summary diagrams are automatically generated based on mappings so that if something is included or not, there is an organized place to indicate the specific mapping and rationale for chosen alternatives.

The detailed schema analysis is captured in *Volume II*. The proposed schema extensions resulting from this analysis are also captured in *Volume II*.

Since many schemas exist today, such as Open Bridge Information Model (OpenBrIM 2.0), Land Topography (LandXML), the National Bridge Inventory (NBI), Industry Foundation Classes (IFC), Precast Concrete, Cast-In Place Concrete and BIMsteel (with varied levels of completeness), this study endeavors to identify the benefits, issues, and missing parts of those schemas in *Volume II*. The goal is to ultimately lead the industry to a consensus solution that is acceptable to all involved, so that standardization can eventually be realized and software developed based on defined business processes.

To achieve comprehensive review of the subject matter, it is critical to base such analysis on real projects, including the same level of detail published on such projects. While it would certainly be beneficial to analyze a large variety of bridge projects, it is felt that realistically this initial analysis can be accomplished using two common bridge types that are representative of many and include complexities that exercise many scenarios. *Volume III – Components* contains the bridges used to analyze the schemas. It is assumed that capturing every last detail of two representative bridges will yield a more comprehensive review than would be achieved with higher level reviews of multiple bridges. This also provides a basis of objective data points where particular needs for functionality may be reduced to binary decisions according to what is captured in the plans for a specific bridge. There certainly may be a need for other requirements not discovered within these particular bridges; however, such requirements can only be comprehensively analyzed by reviewing other specific bridges in the same level of detail.

As more bridges are reviewed in detail, and more phases of the bridge lifecycle are evaluated, increasingly comprehensive models may be developed of business processes, using the information presented in these volumes as part of an Information Delivery Manual (IDM). Practitioners can then build on such process models over time in fully reaching the goal to optimize and progress the bridge design industry to a model-centric workflow.

A process model (represented graphically by a process map) identifies the information flows between the different actors and tasks the actors carry out. The different data exchanges needed to realize a project are identified in the process model. Because of the differing scopes of sub-processes in process models, there are gaps as well as redundancies in information flows. These gaps, typically present in domain-crossing exchanges, are important barriers to identify in order to realize effective workflows for a whole project. More detail about process models and exchanges is in *Volume I Exchange Analysis*.

Document Organization

This Report summarizes the study of domain data models for bridge engineering in a format usable by A/E/C/O domain experts. As part of this work, a detailed analysis of data structures, schema extensions, process workflows, and testing of sample data was carried out. It is provided within separate documentation intended for software developers, referred to as the ***IFC Bridge Design to Construction Information Exchange (U.S.)*** available from the Federal Highway Administration and National Institute of Building Sciences (NIBS).

This endeavor reviews FHWA BrIM work performed to date, relates it to other industry initiatives and data models in use, and proposes adaptations intended to achieve consensus and widespread adoption by providers within this market of the software industry. With the end goal of achieving widespread interoperability of bridge data, emphasis is placed on framing existing BrIM specifications within that context, identifying gaps/mismatches at either end and evaluating possible approaches to align exchanges where needed. For clarity in comparisons, the organization of the detailed review sections of this document is intended to mirror that of the referenced documents. In authoring information exchange specifications, there is a natural dependency on defining roles, processes, and data exchange requirements before determining the resulting data schemas. In reviewing such work, each stage is reviewed in parallel; it is acknowledged that any higher-level change recommendations may impact the resulting data schemas.

This Report is divided into three subsequent Volumes based on the major thrusts of the analysis as follows:

Volume I: Exchange Analysis

This Volume describes the development of the process map for the bridge life cycle, which identifies types of information flow (exchange requirements) among activities in the process. The main topics covered in the Volume are:

Process Model identifies what a process model is and how to properly represent it in Business Process Model Notation (BPMN) format. The origins of the process model developed for the bridge lifecycle is discussed and a new model integrating previous efforts, current practices and analysis provided.

Exchange Requirements identifies information exchanged on bridge projects, the roles of participants involved, and the specific data required. This is intended for all audiences with civil engineering background, and assumes no software expertise.

Gap Analysis reviews previously defined exchange models and describes what information is still needed.

Terms indicates terminology spanning domain knowledge and software knowledge. It is expected that domain experts may not be initially familiar with software terms and vice-versa.

Volume II: Schema Analysis

This Volume of the Report describes standardization efforts related to bridge information modelling, and performs a cursory review regarding the specific technical structure and functionality resulting from current standardization efforts. The main topics covered in the Volume are:

International Activities provides an overview of past and present work relating to bridge standardization in other countries.

Review of Existing Schemas provides an overview of schemas reviewed which are to be considered as input or output data for the proposed schema.

Gap Analysis indicates information modeling concepts that may be incorporated into data structures used by software. Such concepts are described in a high-level manor (block diagrams with commentary) intended for collaboration by domain experts and software developers, and relate existing data models in how they support such concepts.

Proposed Definitions indicate existing and proposed software schemas. These sections are intended for software developers and present information in various programming languages targeting different technical backgrounds. It is not expected or required that domain experts understand the various notations.

Volume III: Component Modeling

This Volume of the Report describes the modeling of specific components of bridges to the level of detail as conveyed on design contract plans, using two real-world case studies. The main topics covered in the Volume are:

Component Modeling applies existing and proposed definitions to two example bridges, detailing how information found in construction plans is described according to the information models under review.

Examples introduce the files and formats used for representing the case study bridges, and cross-reference the plans to data within the files.

Summary of Findings and Conclusions

Key findings from the project and related conclusions and recommendations for next steps identified in Volumes I and II are summarized here:

Exchanges – Volume I

Business processes, actors fulfilling roles, and information exchanges were documented based on prior process models documented in a previous FHWA project (Chen S. S., 2013a) (Chen S. S., 2013b), process models used for steel and concrete design and fabrication, and processes observed at U.S. DOT agencies including Requirements, Surveying, Utilities, Structural Analysis, Templates, Plan, Bid, Fabrication, Construction, and Inspection. Integration of these various exchanges is proposed, and needs to be validated by industry.

It was concluded that the highest initial value would be on automating the exchange of information found in bridge design plans as they go out for bid. This decision was based on the following:

- this information is most often contracted between different parties rather than used within the same organization, where there is shared incentive in documenting such an exchange;
- examples of this information are already widely known to Department of Transportation (DOT) agencies, and it can be used to unambiguously define requirements of an information model;
- providing design results is more likely to be in the business interests of existing bridge software vendors, as opposed to information during the design process which may substantially vary between vendors and provide competitive advantages; and
- such detailed information is a prerequisite for other exchanges that refer to detailed design information

Future endeavors may elaborate other information exchanges discussed into similar detail as was done for the Design to Construction Contract Model exchange. However, many of these other exchanges depend on detail provided in this exchange, so only after fully documenting usage of the Design to Construction exchange does it become possible to define dependent downstream exchanges that reference this information.

In addition to describing exchanges, a need was found to document specific usage of terms for bridges, which vary substantially across building domains (e.g. buildings, infrastructure), phases (e.g. design, fabrication), localities (e.g. countries, DOT agencies), and across software. For example, the terms “profile”, “cross-section”, and “alignment” have different, and in some cases overlapping meanings in different software.

Schema Analysis – Volume II

Technical specifications for information exchange were reviewed, which included established standards and proposed concepts in various stages of development. It is generally understood that given enough development time and industry participation, any of the specifications reviewed could be sufficiently extended to support information required for bridge construction. Some of the specifications reviewed were more applicable to bridge construction than others, some were more completely documented than others, and some were adopted in industry more than others. It should be noted that such review can only be based on what is documented and observable, as is also the case for anything to be considered a standard to be adopted by more than one vendor. The review discussed the building blocks of information exchanges applicable to each schema and related similarities and differences at a technical level, describing specific data types and attributes for capturing information.

While this Report largely evaluated schemas based on their technical content, ISO uses the following criteria for consideration of standards:

- Validation: is there market interest demonstrated by widespread adoption by software vendors?
- Verification: do software applications comply with the specification?
- Conformance: are there test files and testing tools to check that software complies?
- Interoperability: can multiple software platforms import and export data according to the standard?

LandXML is a data model that describes terrain, road alignments, pipe networks, and other information of interest to land surveying and development. LandXML is widely adopted across civil design software platforms; according to landxml.org, Version 1.1 (2006) is supported by 13 registered applications (many with multiple versions). Initially sponsored by Autodesk, this data model was driven to support the needs of various U.S. Departments of Transportation. Support and documentation for LandXML has been non-existent until 2015, where the Open Geospatial Consortium (OGC) has worked to adapt and replace this schema with new data definitions that are harmonized with other OGC schemas and IFC. For LandXML, the ISO criteria map as follows:

- Validation: Yes (all major software vendors involved)
- Verification: No (no program in place)
- Conformance: No (various test files may be found, but no testing tools beyond XSD)
- Interoperability: Yes (multiple platforms)

The Open Bridge Information Model (OpenBrIM) was developed for the Federal Highway Administration in 2013 by the University of Buffalo and Red Equation Corporation to meet the perceived need for an open standard for defining and modeling bridges and their components. As a schema in its early stages of development, there have been multiple iterations, where documentation has been evolving, and the classes, attributes, syntax, and usage has substantially changed each time presented. However, the general capabilities appear to remain similar as of August 2015. OpenBrIM has a loosely-defined schema consisting of two main data types: "O" for an object, and "P" for a parameter; thus, the actual meanings of anything need to be defined on top of the XSD-based schema. OpenBrIM is designed such that any parameter may be set to a value or a formula, where the syntax of such formula is based on arithmetic expressions and several dozen functions such as for trigonometry. As sample bridge models presented using OpenBrIM have been primarily focused on design parameters, rather than detail for construction, it may be most suitable for developing reusable component templates (e.g. bridge deck types, pier types), and then based on discovery of needed parametric capabilities, adapt such templates to support specific data models having wide adoption such as IFC. For OpenBrIM, the ISO criteria map as follows:

- Validation: No (only one software vendor, the same one that defined specification)
- Verification: No (no program in place)
- Conformance: No (test files and viewer available, but no checking, XSD is open ended)
- Interoperability: No (only one software vendor)

Industry Foundation Classes (IFC) is a data model that describes details of buildings throughout their lifecycle of design, construction, and maintenance. Initially developed by Autodesk in 1994, an independent organization was established to promote and further this standard, initially called International Alliance for Interoperability, then later renamed to buildingSmart. IFC is the most widely implemented standard for exchanging building information between leading CAD/BIM software platforms, supported by approximately 150 registered software applications. IFC is also registered as an international standard - ISO 16739. IFC is being adopted and extended to support infrastructure in several other countries. The Korean government has an ongoing project ($5M USD) for defining information exchanges for road construction. China has a similar ongoing project for rail construction. France (CSTB) recently completed a project for bridge design. Universities in Japan and Germany have investigated IFC for tunneling. Work is underway at buildingSmart International to coordinate results of these efforts, along with this FHWA effort in the U.S., into a cohesive standard that can be implemented by software vendors once. As the design software industry increasingly competes globally, it is expected that successful software standards must also have worldwide implementation to achieve such economies of scale. IFC altogether consists of around 800 data types and supports the full range of geometry found in most design platforms, where any arbitrary curved surface or volume may be modeled precisely using NURBS, CSG, swept geometry, or tessellation, which provides compatibility with manufactured product models as input and fabrication models as output. IFC enables relationships between physical elements to be fully defined, such as indicating order of construction, parametric layout, construction joints, embedded elements such as rebar, and derivation of structural analysis models. While IFC also provides a facility for defining formulas at any attribute (referred to as “constraints”), historically this has not been implemented as each software vendor in the building industry models design parameters very differently. For most vendors, there is no business reason to exchange such information, as IFC has been used to represent the results of what their program produces rather than serving as an alternative to native formats. A criticism of IFC has been that it is very large, where such size may deter usage by newer vendors; to circumvent this, specific uses of IFC have been narrowed to smaller subsets using a fraction of the data definitions (called “Model View Definitions”), which has also been done for bridges as part of this effort. For IFC, the ISO criteria map as follows:

- Validation: Yes (Over 150 software vendors including all major platforms as listed at http://www.buildingsmart-tech.org/implementation/implementation-summary)
- Verification: Yes (certification program at http://www.buildingsmart-tech.org/certification/ifc-certification-2.0/ifc2x3-cv-v2.0-certification/participants)
- Conformance: Yes (test files and test tools at gtds.buildingsmart.org)

- Interoperability: Yes (results of file exchanges on platforms logged at GTDS)

In addition to documented schemas, corresponding concepts in Bentley software were also highlighted. As many domain experts are already familiar with Bentley software, such descriptions were included to help in understanding of how such information relates to how it is input. Though the Bentley website has indicated forthcoming data exchange specifications called "iModel", this was not available at the time of this review, so discussion was limited to what could be observed in software.

Based on reviewing the above schemas, Industry Foundation Classes was deemed to be the best fit, based on fulfilling technical requirements in capturing bridge data as modeled in *Volume III*, and in meeting ISO criteria. However, the IFC 4.1 schema is not entirely sufficient; it needs one new data structure for positioning physical elements relative to alignment curves, which is scheduled for IFC 4.2 in 2016. This is not to suggest that any one schema is particularly "better"; the evaluation is based on fitness for a particular purpose - capturing details of bridges as found on construction plans. For other purposes, the other schemas referenced may be better fit: for example, OpenBrIM may be a better solution for describing high-level design parameters, while LandXML may be a better solution for describing overall site conditions. Evaluating multiple schemas is also helpful to encourage discussion of why certain information should be modeled in a particular way, based on independent paths coming up with different approaches.

Component Modeling – Volume III

In evaluating the schemas for consideration and making recommendations, it is critical to base such recommendations on actual data. To ensure that details are captured that reflect common usage and reflect the level of information presented in design plans, two specific bridges were chosen for case study deemed to be representative of common highway bridges in the U.S., yet containing certain complexities that exercise the proposed information model.

- The first bridge evaluated is Pennsylvania Turnpike - Ramp 1195N over SR 51. This bridge follows a horizontal alignment consisting of circular and straight sections at a constant vertical grade, with varying super-elevation and varying cross-section. It consists of steel framing, with reinforced concrete abutments, piers, and decking.
- The second bridge evaluated is the Van White Memorial Overpass in Minneapolis, MN. This bridge follows a horizontal alignment consisting of circular and straight sections with a parabolic vertical curve, with varying super-elevation and constant cross section. It consists of a reinforced concrete box girder, abutments, and piers. As this bridge is situated in an urban area, it consists of decorative railings, walkways, and lighting, and makes use of geometry consisting of curved surfaces that cannot be described by polygons alone but requires B-Spline surfaces and Constructive Solid Geometry (CSG).

While it would certainly be preferable to model additional bridges, for this exercise it was deemed critical to first go through the process of modeling a limited set of specific bridges in the same detail as described in design plans before attempting to accommodate additional bridges at a lower level of detail. As with any such modeling effort, the Pareto principle applies, where the last 20% takes 80% of the time: the initial layout of the bridge deck, girders, and piers ended up being rather trivial (i.e. several days effort) compared to capturing the more detailed aspects found in the plans such as rebar, architectural railings, electrical, and drainage (i.e. multiple weeks effort).

While capturing every rebar instance and every detail of decorative railings having complex curvature can be exhaustive, it is only after modeling bridges completely as found in the plans that enough information has been uncovered to make objective evaluation. Once all detail is captured, file sizes of bridges approach those of buildings, on the order of 50MB. Doing so also makes considerations of scalability very apparent, such that time for loading, saving, or processing such files must stay within intervals that users of such files are willing to accept. Such exercise has made it very clear that built-in data structures (as opposed to dynamically defined structures) are a necessity for maximizing performance and minimizing memory usage. In capturing such detail, various errors were discovered in the underlying plans for the Van White Memorial bridge, which could result in unnecessary change orders – while the impact of these errors is unknown, quantifying these provides another justification for preferring digital formats over paper/PDF output, where checking tools (or simply looking at resulting geometry that doesn't look right) may easily find such errors.

After going through the exercise of modeling these bridges in full detail, it was demonstrated that existing data structures in IFC could sufficiently describe all details as found in the plans, with several exceptions. These exceptions were remedied by proposing one additional data structure, and several new usages of existing data structures, as documented in *Volume II*.

After creating these model files, work was done to check the files with existing software including Tekla Structures and Autodesk Revit. While such software is not specific to bridges, these companies have large market shares, and the same software components are used by these companies across product teams. Though companies expressed willingness to adapt their software to support any new requirements for bridges, there were instances where very simple changes could be made to enable the files to work with current software, such that development costs for these companies can be reduced to help bring solutions to market sooner.

Bridge Information Modeling Implementation

To achieve successful initial launch of IFC support for bridges, vendors have indicated that they need active coordination with those defining the standard, as well as other vendors implementing the standard, in addressing issues or ambiguities as they come up. While every effort has been made to minimize risk by leveraging known quantities where possible (by using existing data definitions that have already gone through many years of deliberation by many vendors), inevitably there will be issues uncovered that will need to be addressed. To help mitigate such errors, the technical specifications containing the data definitions, usages, and examples have been generated using automated tools, which guarantee consistency and correctness for everything that can be machine-validated. That said there still may be limitations of particular platforms that will need to be accommodated in refining such specifications. However, with the availability of the technical specifications, vendors are encouraged to move forward in adding or extending support for IFC in their products to support bridge construction.

The *IFC Bridge Design to Construction Exchange Requirements U.S*. was presented at a workshop for bridge design software vendors in August 2015. Based on the feedback from this workshop, several adjustments were made. For example, representatives from several fabrication companies and industry associations attended; as fabrication machines already use IFC as input, they indicated a desire to leverage the same solution for bridges compared to buildings, as from their perspective, the data is identical. Leading design software vendors (Autodesk, Bentley, Trimble) indicated their full support to continue to use IFC, and desire that use for bridges remain consistent with buildings where practical. In discussions with several software vendors, while there were several new data definitions proposed for geometry, feedback was that such extensions were unnecessary, as their design platforms already convert geometry into existing data structures that sufficiently describe the detail as found on plans. Thus, some data structures were removed from the Model View Definition and proposed to be considered for the future, if at all. Additional feedback indicated that there should be fewer ways of modeling the same thing – ideally only one way, so many of the definitions were restricted to allow for fewer possibilities, and clear guidance was added for favoring particular approaches where multiple are possible.

While the IFC schema could have been extended much further to support other scenarios within the lifecycle of bridges, it was agreed that for purposes of construction plans, less is more, as the barrier to entry for software vendors who already support IFC must be kept at a minimum to achieve industry adoption. Various data definitions were proposed for the future to accommodate more specific classification of bridge elements, more complex positioning patterns for rebar, spatial and transportation network usage relating to physical elements, among others. These data definitions are described in *Volume II* within a separate section, for consideration in the future after going through the first industry adoption cycle.

Bibliography

Chen, Stuart S.; Hu, Hanjin; Ali, Najaf; Srikonda, Rohit (2013a). *“Bridge Data File Protocols for Interoperability and Life Cycle Management: Information Delivery Manual for Highway Bridge Interoperable Data Protocols.”*. State University of New York at Buffalo.

Chen, Stuart. S. ; Hu, Hanjin; Ali, Najaf; Srikonda, Rohit. (2013b). *“Bridge Data File Protocols for Interoperability and Life Cycle Management: Model View Definitions for Highway Bridge Interoperable Data Protocols.”* . State University of New York at Buffalo.

Appendix I:1 - Acknowledgements

This Report has been prepared by the National Institute of Building Sciences under contract DTFH6114C00047 Advancement of Bridge Information Modeling with the Federal Highway Administration Office of Bridges and Structures. The Institute acknowledges the participation of the following individuals in the project:

Federal Highway Administration Office of Bridges and Structures

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Carolyn Wilson	Contracting Officer
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National Institute of Building Sciences

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Mahmoud Reda Taha	AIMT Engineering Services	Information Exchange SME
Michael Angel Gonzalez	AIMT/U New Mexico	Information Exchange SME
William Klorman	Klorman Construction	Concrete Bridge SME
Stuart Chen	Stuart Chen / U Buffalo	Bridge Modeling SME
Dana K. Smith	DKSC Information Consulting	BIM SME
Thomas Liebich	AEC3	buildingSMART Standards SME

Throughout the project efforts were made to reach out to members of the bridge design, fabrication, construction and owner community through participation in meetings of the American Association of State Highway and Transportation Officials (AASHTO), buildingSMART International, Engineers Society of Western Pennsylvania/International Bridge Conference, the National Steel Bridge Association (NSBA) and the Transportation Research Board. These efforts culminated in a Bridge Information Modeling Workshop hosted by FHWA at their headquarters in Washington, DC. The Workshop, further described in Appendix A to this Volume, brought together participants from AASHTO T19 Technical Committee for Software and Technology, FHWA Office of Bridges and Structures, a parallel FHWA project on Technical Review and Industry Outreach for Bridge Information Modeling (BrIM) Standards, the NSBA Bridge Definition Task Group, members of this project team, representatives from bridge design and analysis software companies, material suppliers and fabricators and bridge designers. A list of all participants in also included in Appendix A along with the notes from the Workshop. Discussions at the workshop informed the content of this Report.

In addition to the Institute project team members, valuable input to the Report was also received from a parallel project on BrIM led by Mike Bartholomew of CH2M.

Specific review comments on the first version of the Report were received from the following individuals:

Ahmad Abu Hawash	Iowa DOT
Steven Austin	Texas DOT
Scott Becker	Wisconsin DOT
Michael Keever	CALTRANS
Todd Thompson	South Dakota DOT
Bradley Wagner	Michigan DOT
Hanjin Hu	Michael Baker International
Mark Mylinarski	Michael Baker International

Appendix I:2 - FHWA BrIM Modeling Standards Workshop

Bridge Information Modeling (BrIM) Standards Workshop
Organized by Federal Highway Administration, HQ Office of Bridges and Structures
USDOT Building West Conference Center
1200 New Jersey Ave. SE
Washington DC 20590
August 25-26, 2015

Overview

The Federal Highway Administration, Office of Bridges and Structures has worked over the last few years to determine the needs of the bridge industry when it comes to applying Building Information Modeling (BIM) methodologies to bridges. Initial work on Bridge Information Modeling (BrIM) was conducted in cooperation with The State University of New York at Buffalo.

Recently FHWA contracted with CH2M Hill to review and summarize progress to date on the work begun at SUNY Buffalo and further its development towards the goal of producing standardized bridge objects, digital definitions, and protocols that can be interchanged between different software platforms (CAD, Design & Analysis applications, visualization, etc.) and ultimately benefit end users (Designer, Owner, Contractor, Supplier, etc.).

FHWA has also contracted the National Institute of Building Sciences (NIBS), to review and evaluate the BrIM work as well as other existing and potential approaches to modeling bridges. In particular, NIBS is focusing on evaluating the buildingSMART International Industry Foundation Class (IFC) standard which is widely used for modeling buildings, but is also being extended to cover civil infrastructure. NIBS prepared a BrIM Standards Evaluation Report reviewing the various options and providing a gap analysis of approaches that is being readied to share for industry review. The Report includes complete modeling of a sample steel and concrete bridge using IFC as well as documentation of the required exchanges between software across the bridge lifecycle to identify how these could be implemented using buildingSMART and related ISO standards. The analysis has focused on the detailing and development of the Design to Bid Plan exchange.

FHWA and NIBS hosted this two day workshop in Washington, DC to help review and discuss the results of the Evaluation Report and the corresponding Information Delivery Manual (standard exchange protocol) that the NIBS team has developed. Workshop participants were invited from federal agencies, state DOTs, standards organizations, design firms, modeling and software organizations with the goal of determining an open standard based approach for Bridge Information Modeling.

FHWA BrIM Workshop 2015-08-25-26

Workshop Participants:

	Group	Contact	Organization/Company
1	FHWA	Brian Kozy	FHWA
2	NIBS	Roger Grant	NIBS
3	AASHTOWare Bridge Committee	Todd Thompson	South Dakota DOT, Chair
4	AASHTO T-19	Scot Becker	Wisconsin DOT
5	AASHTO T-19	Dennis Golabek	Florida DOT
6	AASHTO T-19	Ahmad Abu-Hawash	Iowa DOT
7	AASHTO T-19	Michael Keever	CAL Trans
9	AASHTO T-19	Brad Wagner	Michigan DOT
10	AASHTO T-19	Johnson, Bruce	Oregon DOT
11	NSBA Steel Bridge Modeling Group	Chris Garrell	NSBA
12	NSBA Steel Bridge Modeling Group	Ronnie Medlock	NSBA/High Steel Structures
13	Bridge Design SME	Mike Grubb	M.A. Grubb & Associates, LLC
14	Bridge Design SME	Mike Bartholomew	CH2M
15	Bridge Design SME	Kelley (Rehm) Severns	CH2M
16	Bridge Design SME	Joe Brenner	Gannett Fleming, Inc.
17	Bridge Modeling SME	Chuck Eastman	Georgia Tech
18	Bridge Modeling SME	Donghoon Yang	Georgia Tech
19	Bridge Modeling SME	Tim Chipman	Constructivity
20	Bridge Modeling SME	Aaron Costin	Georgia Tech
21	Bridge/Civil Software	Mark Mlynarski	AASHTOWare/Michael Baker, Intl.
22	Bridge/Civil Software	John Sullivan	Autodesk, Inc.
23	Bridge/Civil Software	Saeid Sadoughi	Bentley, Inc.
24	Bridge/Civil Software	Alistair Wells	Trimble, Inc.
25	Bridge/Civil Software	Josh Tauberer	LARSA 4D
26	Bridge/Civil Software	Rob Tovani	CSIBridge
27	Bridge/Civil Software	Brian Barngrover	Eriksson Software
28	Bridge/Civil Software	Chris Garrell	LRFD SIMON
29	Bridge/Civil Software	Ali Koc	Red Equation Corporation
30	Industry organizations	Roger Becker	PCI
31	Industry organizations	Will Ikerd	Ikerd Consulting/PCI
32	Industry organizations	Francesca Maier	P-B
33	FHWA Staff	David Unkefer	FHWA
34	FHWA Staff	Richard Duval	FHWA
35	FHWA Staff	Romeo Garcia	FHWA
36	FHWA Staff	Reggie Holt	FHWA

Notes from the Workshop are available along with this Report in the document entitled FHWA BrIM Workshop Summary Aug 25-26.pdf.