A NEW METHODOLOGY FOR INTEROPERABILITY OF HETEROGENEOUS BRIDGE INFORMATION MODELS

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A NEW METHODOLOGY FOR INTEROPERABILITY OF HETEROGENEOUS BRIDGE INFORMATION MODELS

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To my wife and family.

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LIST OF SYMBOLS AND ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ABC	Accelerated Bridge Construction
ACI	American Concrete Institute
AEC	Architecture, Engineering, and Construction
AEC/FM	Architecture, Engineering, and Construction / Facilities Management
AECO	Architecture, Engineering, Construction, and Operation
AISC	American Institute of Steel Construction
BIM	Building Information Modeling
BPMN	Business Process Model and Notation
BrIM	Bridge Information Modeling
bSdd	buildingSmart Data Dictionary
bSI	buildingSmart International
CAD	Computer-Aided Design
DAML	DARPA Agent Mark-up Language
DARPA	Defense Advanced Research Projects Agency
DB (D-B)	Design-Build
DBB (D-B-B)	Design-Bid-Build
DOT	Department Of Transportation
EM	Exchange Model
ER	Exchange Requirement
FHWA	Federal Highway Administration
GUID	Globally Unique Identifier
IDM	Information Delivery Manual

IFC	Industry Foundation Classes
ISO	International Organization for Standardization
ISO-STEP	ISO Standard for the Exchange of Product model data
KIF	Knowledge Interchange Format
LOD	Level of Development
MVD	Model View Definition
NBIMS	National BIM Standard
NCHRP	National Cooperative Highway Research Program (NCHRP)
NIBS	National Institute of Building Sciences
NSBA	National Steel Bridge Alliance
OCCS	OmniClass Construction Classification System
OIL	Ontology Inference Layer
OMG	Object Management Group
OWL	Web Ontology Language
PCI	Precast/Prestressed Concrete Institute
RDF	Resource Description Framework
RDFS	RDF-Schema
RIF	Rule Interchange Format
SPARQL	SPARQL Protocol and RDF Query Language
TG	Task Group
TRB	Transportation Research Board
W3C	World Wide Web Consortium
WWW	World Wide Web
XML	eXtensible Markup Language

SUMMARY

With the passing of the MAP-21 (Moving Ahead for Progress in the 21st Century) Act in 2012, the United States bridge industry has had a significant push for the use of innovative technologies to advance the highway transportation system. Bridge Information Modeling (BrIM) is emerging as an important trend in the industry, in which various technologies and software are being used in all phases of the bridge lifecycle and have been shown to have a variety of benefits. However, most software are stand alone applications and do not efficiently exchange data among other software. This lack of interoperability creates impediments for the efficient and seamless transfer of information across the bridge lifecycle. In recent years, the building industry developed standards to promote interoperability for Building Information Models (BIM). Unfortunately, these standards lack the ability to incorporate bridges. Therefore, there major need for a standard for Bridge Information Modeling (BrIM). Moreover, as technology and modeling software have been coming more prevalent in other domains (roads, geotechnical, environment systems, etc.) there is an even larger need to expand interoperability standards across multi-disciplinary domains.

The purpose of this research is to develop a methodology that would enable the interoperability of multi-disciplinary information models. The scope of the methodology is for Bridge Information Models, but the approach is extendable to other domains. This research is motivated by the fundamental issues of interoperability, such as semantic, logic, and software issues. In this research, the fundamental issues of interoperability are investigated as well as an in-depth review of literature proposing solutions. Additionally, current standards for interoperability of information models are reviewed.

Based on the findings of the literature review, this research develops, evaluates, and validates a novel methodology for interoperability of information models. The fundamental issues of interoperability are addressed by the use of a taxonomy and ontology. A new standardization process to capture domain knowledge, called in "Information Exchange Standard" is outlined along with a novel method of developing an ontology based on industry workflows. This methodology has been used and validated by an industry domain case study. A software tool to automate the capturing of domain knowledge and development of a taxonomy is presented.

CHAPTER 1

1. INTRODUCTION

1.1. Overview

With the passing of the MAP-21 (Moving Ahead for Progress in the 21st Century) Act in 2012, there has been a significant push for the use of innovative technologies by the US Federal Highway Administration (FHWA). One technological innovation that would produce a paradigm shift in the bridge industry is Bridge Information Modeling (BrIM). As an extension of Building Information Modeling (BIM), this technology has been used to automate and digitalize various aspects of bridge projects. The 2014 SmartMarket Report (Fox 2014) reports that BIM has led to the reduction of errors and omissions, improvement on process outcomes, and reduction of project costs. This is important in the bridge world since the manual data re-entry over the bridge project lifecycle is tedious, time-consuming, and error-prone (Chen et al. 2006; Chen and Shirole 2006; Shirole et al. 2009). Even with the use of BrIM software, the exchange between non-interoperable software will require manual data entry to an extent. For example, the detailed Plans, Specifications, and Estimations reports (PS&E) produced in design software applications are still passed by 2D drawings and paper documents to the erection engineer, detailer, and fabricator, in which they each input the information into their respective software applications. Interoperability, the ability to exchange data between non similar software programs, has been a major hurdle that would be overcome once BrIM technology is embraced. Before the industry is able to exchange data virtually and electronically, there needs to be a neutral data carrier specifically designed to be processed by various software applications involved in a bridge project (Ali et al. 2014). The hypothesis is that an ontology, being the neutral classification upon which computer software is based, would provide the abstract level of classification of terms that would enable interoperability across heterogeneous bridge models. Additionally, an ontology would reduce ambiguity, promote reusability, and provide the necessary semantics for the bridge models.

1.2. Motivation

There is great need for reliable, automatic, and standardized electronic exchange of data for the duration of the bridge lifecycle. To do so requires standards for describing and encoding such data; however, such standards have not yet been established in the bridge industry (Hu 2014). Current approaches for Building Information Models (BIM) are not capable of including bridges and other domains, such as the National BIM Standard (NBIMS) that focuses solely on buildings (more explanation in Chapter 5). With the future becoming more technologically advanced with the modeling all types of information in all types of domains, it is imperative that a methodology be established to allow for interoperability of these heterogeneous model in order to share the information contain in each multi-disciplinary model. For example, it is envisioned that one day there will be "smart cities" that are fully integrated with software and technologies, such as models for energy, sustainability, transportation, buildings, infrastructure, and geotechnical. Since in reality each aspect of a city interconnects, it is feasible that modeling will soon be able to connect to share information. However, without the ability to interconnect and interoperate heterogeneous software and platforms to share the information, the reality of smart cites is practically infeasible due to all the issues and challenges of interoperability.

The scope of this dissertation is bridge information models (BrIM), although the approach is non-domain specific. Having interoperability among bridge software is important to 1) enhance the quality of the bridge model, 2) facilitate a smooth and expedited transition between the various processes for the bridge lifecycle, 3) reduce errors and omissions (to achieve data integrity), 4) reduce costs over the bridge lifecycle, and 5) facilitate further automation as it becomes available. The approach would be ontologically based, meaning the fundamental core idea is based on names, semantics, and relationships. A standard BrIM ontology and taxonomy will be designed using currently define ontologies. The BrIM ontology will be the formal naming and definition of the types, properties, and interrelationships of the entities of the bridge domain.

In order to achieve interoperability, the various software programs need to communicate with each other. However, there are many impediments at the present (proprietary algorithms, different computer languages, etc.). Options include rewriting code, which is infeasible due to its manual intensity and inefficiencies, or creating translators, which is doable. For a translator to be effective, it must be based on a neutral schema that is popular and readily available. Additionally, future software can be based on a neutral schema. The neutral schema needs to be based on a well defined workflow or process. The workflow or process must be suited for the current field, in this case bridges, and be defined by an ontology. An ontology is the highest (abstract) level for a domain that describes the objects, concepts and relationships between them that hold in that domain.

1.3. Organization of the Dissertation

This dissertation is organized in a fashion to achieve two intentions: 1) present a narrative to both highlight the current industry issues (problems, needs, gaps etc.) and emphasize the foundation of the research (purpose, contribution, novelness etc.); and 2) serve as a guide and manual for future continuation of the research. The dissertation is organized as follows:

Chapter 2 reviews the background information about BrIM, including software, usages, studies, and current needs. This chapter also describes interoperability, including types, proposed solutions, and exchange standards.

Chapter 3 introduces workflows and processes. In this chapter, the workflow of a lifecycle of a typical bridge is discusses, including the current approach along with the issues and limitations.

Chapter 4 outlines the research methodology for this dissertation, including the purpose, hypothesis, objectives, and approach.

Chapter 5 reviews the current limitations of the National BIM Standard. In addition, the solutions provided by this dissertation to each limitation are discussed.

Chapter 6 introduces the "Information Exchange Standardization Process" and the step-by-step guide on how it is used. The case study is used as an example throughout this chapter.

Chapter 7 describes the taxonomy and ontology development, which are the technical portions of the "Information Exchange Standardization Process." The case study is used as an example throughout this chapter.

Chapter 8 discusses how to adapt the current National BIM standard to include bridges. This chapter also highlights current ongoing efforts.

Chapter 9 concludes this dissertation by summarizing the research. This chapter also emphasizes the contributions and discusses future research needs.

CHAPTER 2

2. LITERATURE REVIEW

2.1. Bridge Information Modeling (BrIM)

Building Information Modeling (BIM), as defined by the U.S. National Building Information Model Standard Project Committee, "is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle; defined as existing from earliest conception to demolition" (NIBS 2015a). BIM, which is more than a 3D modeling tool, has created new paradigm shift in the Architecture, Engineering, and Construction (AEC) industry, driving the traditional design approach into more technology-centric collaboration. BIM is defined as a product, a collaborative process, and a facility lifecycle management requirement (NIBS, 2008). BIM incorporates the 3D computer-aided design (CAD) model of a building with all the information and properties about that building such as design plans, product information, schedule sequencing, and operations. Building information modeling can be linked with sensing technologies (e.g. Radio Frequency Identification) and has been shown to achieve benefits for field mobility and status monitoring of construction resources (Costin et al., 2012), real-time building protocol and data visualization (Costin et al, 2015), and indoor localization for facilities management (Costin and Teizer, 2015). The use of BIM as an accurate virtual digital model of a project has been found to be one of the most promising advancement in the AEC industry (Eastman et al., 2008)

Modeling technologies that have evolved into BIM have been around for a few decades, and there is now a considerable use the AEC/FM industry. However, the use of BIM technologies for bridges hasn't been widely accepted. With the passing of the MAP-21 Act, there has been a significant push for the use of innovative technologies, which include BIM technologies. A portion of the funds set aside is “to accelerate the implementation and delivery of new innovations and technologies that result from highway research and development to benefit all aspects of highway transportation” (FHWA, 2013). Internationally, national bridge information modeling guidelines were ordered by the Finnish road administration to set national standards of producing and utilizing the information models (Kivimaki, T., and Heikkila, R. 2010). In the Finnish private sector, there is a consortium of bridge construction related companies called “5D-Bridge consortium” (Kivimaki, T., and Heikkila, R. 2010).

Bridge Information Modeling (BrIM) is an extension of BIM that focuses on bridges. Although bridges and buildings are similar in that they are both structures and have similar features, there vary greatly in terms of construction, operation, and classification of parts (ontology). Existing 3D-CAD solutions are not sufficient for utilizing information models of bridges since technical improvements are a necessity for the effective exchanging of information among interoperable software (Shim et al., 2011). Therefore, current BIM applications cannot be directly applied to bridges, but rather have to be adopted and modified. Liu et al. (2014) applied BIM to bridge projects to improve the efficiency and effectiveness of design and construction by developing a BIM-based solution to improve design and construction, including conceptual design optimization, detailed design optimization, the optimization of construction sequences, construction scheduling, construction management, and construction process monitoring.

Although there are commercially available software tools for designing bridges (BridgeSite, 2005), BrIM is a generally new topic for industry. Designing and constructing a bridge require many of these software tools, and thus interoperability of these tools is needed to achieve the benefits of bridge information modeling. BrIM has been used for Accelerated Bridge Construction (ABC) workflows to streamline the design approach by reducing manual data re-entry and accelerates integrated project delivery (Hu et al., 2010). 3D information models for bridge structures improve design quality in terms of accurate drawings, constructability and collaboration (Shim et al., 2011).

BrIM has been used for lifecycle and management of bridges from conceptual design through maintenance (Shirole et al., 2008; Shirole et al., 2009; O'Keeffe, 2014). Literature have shown many uses of BrIM including integration surveying (Kivimaki and Heikkila, 2010), machine control (Kivimaki and Heikkila, 2010), cost estimation (Markiz and Jrade, 2014), bill of materials (Lee et al., 2012), bridge inspections (Al-Shalabi, 2015; McGuire, 2014), and maintenance and rehabilitation decisions related to bridges (Marzouk et al. 2010). Shim et al. (2012) describes other uses for BrIM including design check, structural analysis, automated estimation, four-dimensional (4D) scheduling, five-dimensional (5D) construction management, and digital mock-up. Additionally, BrIM can produce engineering documents, such as bridge inspection and assessment reports, hydraulic calculation records, and geological survey reports (Lee et al. 2013).

BrIM benefits the entire bridge lifecycle from project selection through rehabilitation (Peters, 2009). Higher quality, faster delivery, and more economical cost over the bridge lifecycle will be attained by use of BrIM (Shirole et al., 2008). Reductions in project delivery time, errors, and cost are also potential benefits (Ali et al., 2014). Object-based 3D models with metadata can be a shared information model for the effective collaborative design, construction, and maintenance (Shim et al., 2011). Safety is a major priority in the AEC industry and BrIM is able to maintain a high level of safety for the prevention of disasters. BrIM can be used in choosing suitable construction methods and planning site activities to avoid space conflicts, visualize bridge components, and track and assess the structural condition of bridges to prevent failure (Al-Shalabi, 2015; McGuire, 2014; Marzouk et al., 2011). Additionally, development of new best practices can be developed through the use of BrIM (Peters, 2009).

Volk et al. (2014) conducted a literature review on the adoption of BIM in the AEC industry. The results show scarce BIM implementation due to challenges of (1) high modeling/conversion effort from captured building data into semantic BIM objects, (2) updating of information in BIM and (3) handling of uncertain data, objects and relations in BIM occurring in existing buildings (Volk et al., 2014). These challenges are inherently present in BrIM as well.

2.2. Interoperability

Interoperability can be defined as the ability of one system (e.g. software application, workflow, process, ontology, etc.) to work with other systems without any effort on the part of the end user of the system. For example, a user designs a bridge in a modeling application “A” and then opens the model in a structural analysis application “B.” Interoperability throughout the lifecycle of a bridge means that the same model designed in application “A” in the design phase can be used throughout each other application used in the lifecycle of a bridge, such as estimation, scheduling, inspection, and maintenance applications. Moreover, fully interoperable systems would not contain errors, omissions, or data loss when the information is transferred from application to application. Significantly, interoperability has been a basic requirement for the modern information systems environment (Sheth, 1999).

There are a variety of commercially available software tools for various aspects of bridge modeling and development, for example planning, design, detailing, estimating, fabrication, construction project management, and bridge operations and maintenance (BridgeSite, 2005). However, in the development of various computational tools for supporting the various aspects were typically addressed in standalone fashion without sufficient regard for complications arising from multiple data sources (Shirole et al., 2008). These specialized software products are typically “stove-piped,” meaning they lack interoperability with other software products (Hu, 2014). Additionally, many BIM applications need to access multiple heterogeneous data sources, in which these sources may come from different domains, each with their own set of terminologies and modeling tools (Karan et al., 2015). Bridge projects require frequent communication and, without improved software interoperability, these projects can become bogged down with requests for information (RFIs) (Ali et al., 2014). Lack of interoperability will create wasteful activities, such as re-entry of data which has previously been digitalized and hinder value creation due to loss of data and incompatibility (Poirier et al., 2014). Even on the same bridge project, heterogeneous computer platforms cause many problems during transferring and sharing numerous data generated (Lee and Jeong, 2006).

Interoperability has major benefits in saving time, effort, and money. However, interoperability has been identified as a crucial bottleneck in the heterogeneous landscape of software systems (Beetz et al., 2014). In 2002, the cost of inadequate interoperability in the AEC industry in the United States, alone, has been estimated at over $15 billion per year (Gallaher et al., 2004). With the increase in software tools and technology, this conservative amount over a decade ago could be substantially higher in today's dollars. Furthermore, the absence of efficient interoperability among 3D modeling solutions substantially refrain users from reaping remarkable benefits (Gallaher et al., 2004).

There are various reasons that there are issues within interoperability, such as programs written in different (non-compatible) computer languages, companies wanting to keep their software proprietary (i.e. only their software can use the data), and different data formats. There are four levels of interoperability (Sheth, 1999):

1. System Heterogeneity: the use of different operating system, hardware platforms, and coding.
2. Syntactic Heterogeneity: the differences in representation format of data (e.g. visual and textual representations).
3. Structural (Schematic) Heterogeneity: the native model store data differ in data sources (i.e. how the data are structured).

4. Semantic Heterogeneity: differences in interpretation of the semantics (i.e. meaning) of data.

In this research, syntactic and semantic heterogeneity play an important role, and thus will be described in more detail. Syntactic heterogeneity describes the difference in representation format of data among different data sources (Karan et al., 2015), in which the users are able to directly access data and methods from a different software program and exchange project information between heterogeneous platforms (Underwood and Watson, 2003). Syntactic interoperability emphasizes the integration of two or more data models into one single model.

Semantic interoperability makes model data sharable and understandable across multiple design disciplines and heterogeneous computer systems (Yang and Zhang, 2006). Semantic interoperability provides integration at the highest level (Karan et al., 2015) and increases the value of information (Cheng et al., 2008).

In the AEC industry, interoperability between software applications tops the list of areas that need to be addressed to fully realize the benefits of BIM (Young et al., 2009). Poirier et al. (2014) conducted an extensive literature review and identified three main dimensions of interoperability within the AEC industry: technical interoperability, organizational interoperability, and process interoperability. While the framework lacks validation, the research does present a better understanding how interoperability exists in the industry. For example, process interoperability focuses on the development of avenues to allow the mapping, connecting, merging and translating of heterogeneous processes (Chen and Daclin, 2006). Mutis and Issa (2012) discuss semantic interoperability by stating that two important aspects are emphasized in interoperability are the semantic and syntactic information. There are various research efforts to address the issues of interoperability. Beetz et al. (2014) developed approaches for the integration and interoperability for spatial data for the construction of quay walls. Semantic web technology is used to overcome several semantic heterogeneity problems in traditional methods of heterogeneous data sharing (Abanda et al., 2013a; Abanda et al., 2013b; Karan et al., 2015; Karan et al., 2015). Fu et al. (2007) demonstrated the importance of interoperability in lifecycle costing by developing a lifecycle costing (LCC) tool based on industry foundation classes (IFC) models. Elmroth et al. (2010) argue that the methods and techniques required to make systems interoperable depend on the type of interoperability sought and at what level: the activity, sub-workflow, or workflow levels.

2.2.1. Translators

One approach for interoperability between heterogeneous systems is the use of translators. A translator is written exchange that translates one software (source) format into another (receiving). Translators can be either one way (translate "A" into "B") or bi directional (translate "A" into "B" and "B" into "A"). Data exchanges between source and receiving software systems are typically performed through proprietary translators with own data structures (Eastman el al., 2011) which can result in problems. Although properly written translators can be effective for interoperability, they are very manually intensive and can be error-prone since they are written in an ad-hoc manner. For instance, translators are dependent on both the source and receiving systems, and thus with each iteration of software updating, the translator must be updated as well. Hu (2014) explains that "ad-hoc type of data exchange has the following drawbacks: 1) the exchange highly relies on the programming skills of the translator developers and the capabilities of the APIs offered by software products, 2) there is no standard for translator programming, and 3) one translator is specific to one case-study." Translators worked well with early modeling systems since the objectives were limited to geometry, but as these modeling systems became more complex (i.e. parametric and object-based modeling), the limitations of existing file-based methods became apparent (Eastman el al., 2010a).

2.2.2. Data and Information Exchange Standards

Data exchange is the process of sending data from a source format (or schema) and transforming it into another source format. BIM has three distinct levels that each needs a different exchange: tools, applications, and platforms (Eastman et al., 2011). Data exchanges are possible either directly or non-directly, in which they can be proprietary or non-proprietary exchange formats (Eastman et al., 2014). Standards for describing and encoding such data exchanges are needed for reliable and automatic exchange of data. With the rise of complex interoperability issues in manufacturing in the late 1980s, the ISO Standard for the Exchange of Product model data (ISO-STEP) was developed (Eastman el al., 2010a). ISO-STEP (ISO 10303) provides standard for the computer-interpretable representation and exchange of product manufacturing information, including the EXPRESS data modeling language (ISO, 1994).

The Industry Foundation Classes (IFC) has been then most common neutral file format for data exchanges for BIM in the AEC industry (Eastman et al., 2009; Eastman et al., 2010a; Eastman et al., 2011; Karan et al., 2015). Registered as an international standard, ISO 16739:2013, IFC is a schema written in the EXPRESS language. IFC is also public and non-proprietary, and it is facilitated by buildingSMART International (2015a) to increase interoperability in the AEC industry. IFC provides methods to define entities and properties needed for design, production, and maintenance of building facilities. Attributes along with the constraints and structure of IFC document are defined in a schema. IFC is also used to facilitate and support efficient workflows and information exchanges in the AEC industry (Liebich et al., 2013).

IFC is laudable, but has not yet had a significant impact on the broad problems of interoperability in AEC (Eastman el al., 2010a). There are a few documented reasons for this. One major reason is that IFC is complex and has redundancies because of the need to represent objects and relationships for a wide range of AEC subdomains (Eastman et al., 2010a). Venugopal et al. (2012) explains that it lacks formal logic rigidness, in which they demonstrate how a precast floor slab can be defined legitimately for purposes of 1) clash detection; 2) precast fabrication; 3) production and delivery sequencing; 4) and aggregation of geometries. As a result, data exchanges selecting from the redundant data representations can create problems such as mismatching and inconsistencies (Eastman et al., 2010a; Olofsson et al., 2008). Bazjanac and Kiviniemi (2007) show that without well-defined exchange model views, the exchanges are simplifying the information, which can lead to errors, omissions, contradictions, and misrepresentation.

A minor issue has been that the large file size of IFC has been shown to be a burden for data storage and exchange (Zhang and Issa, 2013; Won et al., 2013; Hu, 2014; Sun et al., 2015). To reduce the file size, Sun et al. (2015) addresses this issue by developing a content-based compression algorithm (IFCCompressor) for optimizing IFC data files. Although IFC files can be quite large for sizable projects, this issue is not as big of an impediment as the redundancy issues. Not to mention, computers are becoming more powerful to handle large file sizes.

The U.S. Department of Justice, Department of Homeland Security, and Department of Health and Human Services are in a partnership in the development and management of National Information Exchange Model (NIEM) to exchange federal and governmental data (U.S. Department of Justice, 2015). The domains of this information exchange model include justice departments, biometrics, military operations, human services, immigrations, and other federal, state, and local governmental departments. NIEM uses an XML-based framework, and is related to the Global Justice XML Data Model. The naming and design rules include Object Class Term, Property Term, Representation Term, and Qualifier term. The technical architecture includes reusable XML domain definitions, namespaces, code lists, association types, augmentation, metadata, and XML artifacts (NIEM ESC, 2015).

The U.S. healthcare industry has the Health Information Exchange (HIE) in order to exchange patient medical information throughout various health care providers. Managed by the U.S. Department of Health and Human Services (HHS), the HIE consists of a centralized data model where all the information is stored in centralized repository, a federated (decentralized) model where the information is kept at local repositories, and a hybrid model that is a mixture of both (U.S. HHS, 2015). The three types of exchanges include a direct exchange (e.g. doctor sends records to another provider), query-based exchange (doctor can search for patient records), and consumer mediated exchange (e.g. patient can get online access to records). Other domains that have exchange standards include geographic information and geomatics (ISO/TC 211, 2015), finance (FIX, 2015), aerospace (AIA, 2015), and automotive (AutoCare Association, 2015) to name a few.

2.2.3. National BIM Standard (NBIMS)

Since IFC is broad and redundant, it lacks of coordination regarding what specific information is to be included for an exchange needed for a specific purpose. This means that for each purpose for an exchange, which are considered a “use case,” the details and information about the exchange (i.e. how, what, and why) need to be specified to guarantee consistency in the exchange of information. For example, one use may be bridge design and another use case would be bridge analysis. The data exchange that the bridge designer needs (e.g. geometries, environmental factors, location etc.) would be different than the exchange that is needed for a bridge analysis (loads, material properties, etc.). Formerly the International Alliance for Interoperability (IAI), buildingSMART International (bSI) is an international organization that facilitates and develops the National BIM Standard (NBIMS) to establish standard definitions for building information exchanges to support critical business contexts using standard semantics and ontologies. The United States Chapter is within the National Institute of

Building Sciences (NIBS), and it published the U.S. version, *NBIMS-US.* The purpose is "is to advance the art and science of the entire lifecycle of the vertical and horizontal built environment by providing a means of organizing and classifying electronic object data and thereby fostering streamlined communication among owners, designers, material suppliers, constructors, facility managers, and all stakeholders associated with the built environment," and the focus is "to provide standards to facilitate the efficient lifecycle management of the built environment supported by digital technology" (NIBS, 2015). The current *NBIMS-US* consists of three versions, in which each has a specific purpose. The *NBIMS-US* is viewed as a living and evolving process, and thus additional versions and editions will continue to be published.

The *NBIMS-US Version 1-Part 1: Overview, Principles, and Methodologies* (NIBS, 2007) provides the first comprehensive look at the full scope of requirements and possibilities for BIM. The *NBIMS-US* has six goals: 1) seek industry wide agreement for BIM; 2) develop an open and shared BIM standard; 3) facilitate discovery and requirements for sharing information within the facility lifecycle; 4) develop and distribute machine readable knowledge; 5) define a minimum BIM; and 6) provide for information assurance for BIM throughout the facility lifecycle. Although this version is not a consensus standard, it established the approach for developing an open BIM standard and process.

The *NBIMS-US Version 2* (NIBS, 2012) provides the necessary structure and framework to facilitate and encourage further productive practices by all industry members for the lifecycle of the project. This version is intended for software developers/vendors and implementers. This version provides the reference standards, which include model and dictionary standards, exchange standards, and data structure and identifier standards needed for software developers/vendors to design, code, and implement interoperable BIM programs. This version also provides the practice documents and guidelines for implementers of the built environments (e.g. owners, designers, and engineers) to use as support through the development and implementation of the open BIM standards.

The *NBIMS-US Version 3* (NIBS, 2015b) is a consensus standard that builds off of the previous versions. Again aimed at both software developers/vendors and implementers, this version contains the reference standards, terms and definitions, information exchange standards, and practice documents needed to design, develop, and implement the open BIM standards.

The NBIMS utilizes referenced standards, including ISO 16739 (Industry Foundation Classes), World Wide Web Consortium Extensible Markup Language Specification and Validation (WC3 XML), the OmniClass™ Construction Classification System, International Framework for Dictionaries (IFD) , buildingSMART Data Dictionary (BSDD), the BIM Collaboration Format (BCF), the Level of Development (LOD) Specification, and the United States National CAD Standard® (NCS).

The NBIMS uses an approach called the NBIM Standard Development and Use Process to produce specification and implementation standards. Figure 2-1 illustrates the elements and relationships of the high level view of the workflow associated with the approach. The main tasks of the approach include researching and proposing new specifications, developing and publishing a specification process, facilitating compliance and verification certification, and deploying for industry adoption.

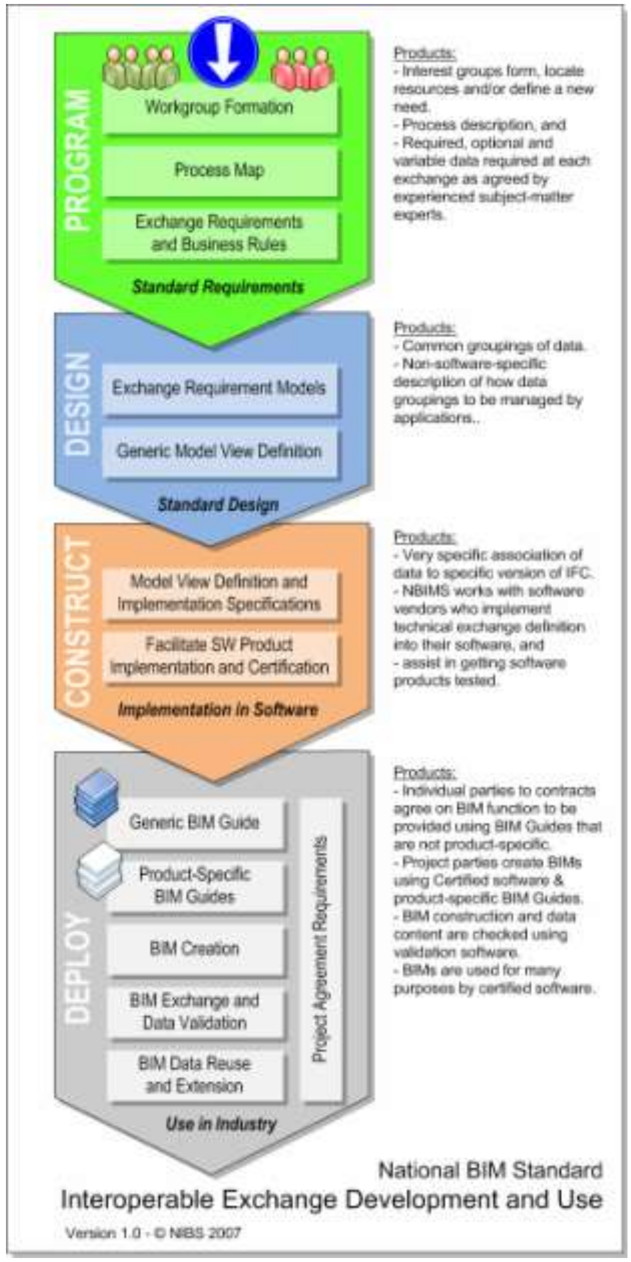


Figure 2-1: NBIM Standard Development and Use Diagram (NIBS, 2007)

The first phase, *program*, utilizes domain experts to provide input about what is needed in the areas, or “use cases.” These domain specific procedures are compiled into information delivery manuals (IDMs). The purpose of an IDM is to capture the knowledge and best practices regarding workflows (and information contents) and to identify the information needed to guarantee that the targeted electronic workflow exchanges will be effective (Eastman el al., 2010a). IDMs target both BIM users (domain experts) as well as the solution providers (software developers). The workflow, or process, is defined in a *process map,* which identifies the information flows between the different actors and tasks the actors carry out during a project workflow. Business Process Model and Notation (BPMN) (OMG, 2015) is typically used to diagram the process map which includes the project workflow, stakeholders, actors, project stages, and activities. The set of information that is passed between actors at a given stage in a process is represented by an *exchange model* (EM). It is common that industry exports collaborate with academia to produce the documents. Examples can be seen in the American Concrete Industry (ACI) (DBL, 2015a), the American Institute of Steel Construction (AISC) (DBL, 2015b), the Precast/Prestressed Concrete Institute (PCI) (DBL, 2015c), and the bridge industry (Chen et al. 2013a). Templates to document the process map, exchange requirements, and functional parts are available on the buildingSMART International webpage (Karlshøj, 2013). The estimated time to complete the first phase is 6-10 months (Eastman, 2012).

In the second phase, *design,* the requirements addressed in the first phase are organized and developed into data models. For instance, the fundamental concepts defined in the information exchange are compiled into a Model Views. A model view is subset of a schema, representing the data structure required to fulfill the data requirements within one or several exchange scenarios. The concepts that were identified in the EMs (defined in the IDM) are preliminary mapped to the target model view and assembled in a set of data model diagram called the Exchange Requirements Model (ERM). ERMs of a given process map (in which multiple processes can be identified in the IDM) are integrated to form a generic, high level model view definition (MVD). This high level MVD includes only the portions that are relevant to the specific model view. The estimated time to complete the second phase is 6-12 months (Eastman, 2012).

In the third phase, *construct*, the information identified in the high level MVD is linked with specific elements that are available in standard IFC schema. After pilot implementation, validation, and certification, the high level MVD proceeds to become a final MVD. A MVD defines a subset of the IFC schema that is needed to satisfy one or many of the exchange requirements. The resulting system that standardizes the processes is called the IMV Framework. The estimated time to complete the third phase is 6-14 months (Eastman, 2012).

In the fourth phase, *deploy*, a wide range of products and activities are facilitated for a successful implementation into certified software. A generic BIM guide, explaining the material produced for the IDM, and a product-specific BIM guide, explaining the operator's manual of the software, are created and published. The estimated time needed to complete the fourth phases is 6-12 months (Eastman, 2012).

One inherit limitation of the NBIMS is that it focuses solely on IFC, as it is intended. IFC is just one of many schemas, and so going through this process limits the user to only choose IFC. However, other non-building industries that want to establish standard definitions for information exchanges cannot use the NBIMS as is, but rather need to adopt and modify the process to fit the current industry needs. The bridge industry, as it is not currently defined in IFC, can be considered as one of the industries that cannot use the NBIMS as is. Therefore, this dissertation proposes a new standardized process that is not specific to one schema, and thus other domains can use it.

2.2.4. Semantics

When data are exchanged between BIM software, it is insufficient to solely rely on 3D visual properties of the objects (Eastman et al., 2010a). Although the geometries of the objects in the 3D model are import, they alone are not enough to describe the meaning and representation of the modeled objects. Therefore these other aspects must be dealt with to give meaning to the data and what they represent. These more detailed aspects of implementation of the objects are called *semantics* (Eastman et al., 2010a).

At the exchange level, semantic issues may cause burdens for humans that are reading them. However, this is not the case for computers, since computers do not need to understand the semantics. For instance, there is no “girder” in IFC (i.e. IfcGirder). A girder can be modeled using the beam function (i.e. IfcBeam) because fundamentally, a beam is a defined by ISO 6707-1:2014 as a “structural member designed to carry loads between or beyond points of support, usually narrow in relation to its length and horizontal or nearly so” (buildingSMART, 2015c). The only difference between a beam and girder essentially comes down to semantics, in which the computer doesn’t care of the different name when passing data. The semantics may cause the human who reads the name to be confused. However, the end user who uses the software application would never see the name since the application would have its own naming convention. The only case of a human who does needs to read the IFC data would be a software developer implementing IFC. In this case, the ontology would play an important role in the differentiations.

At the core level, data are essentially bits and bytes that the computer uses in processes. That data are essentially useless to human function without any context. Therefore, it is important that the data be given the semantic information needed to represent what human function represents. This research addresses semantics by capturing the data in a taxonomy, which is then translated into an ontology. The taxonomy and ontology assigns attributes, properties, relationships, and axioms to define the terminology. Importantly, the taxonomy will be the official, approved terminology for the domain terms, which will prevent same definitions to have multiple terms associated with them. This will help reduce the semantic issues at the software level, since every software program implementing the ontology, regardless of proprietary code, will always refer to the same terms and definitions.

2.3. Product Modeling

A product model is the actual 3D visual data model that represents the physical and functional characteristics of the real-life object. Product models are the primary source and storage of data and information throughout different stages of that object's lifecycle. Product model incorporate knowledge representation, sharing, and exchanging. Most often, when people think of a BIM model, they are referring to the product model (e.g. the CAD model) since they can see and interact with the actual 3D visualization. Solid modeling, a method of geometric modeling in three dimensions (e.g. constructive solid geometry (CSG), boundary representation (B-rep)) is the foundation for most product representations because geometry is essential for design, analysis, and production (Belsky et al., 2015). Parametric modeling is an advance technique that uses parameters and dependencies to define a model. Parametric is essential for large models, such as building and bridges, because the user only needs to change the parameters instead of manually changing each dimension or definition with each change in design. The notions of object-based modeling and parametric modeling of buildings have their roots in the concepts of parametric solid modeling for generic product modeling (Sacks et al., 2004)

An early study by Mikami et al. (1999) developed product models for bridge structure using virtual reality modeling language (VRML) on the World Wide Web (www). The data on the bridge structure was structures based on AP 203(configuration-controlled design), which is a subset of STEP (ISO 10303). Tah and Howes (1999) used information modeling for case-based construction, where they presented conceptual bridges object models that were used to develop a large information repository. Lee and Jeong (2002) used a STEP-based database for information management of steel bridge tried in order to standardize steel bridges data. Since current product models related to bridges are not sufficient to satisfy requirements to standardized data for sharing and reuse, such as shape and structural analysis information generated from existing application programs, Lee and Jeong (2006) again developed a product model based on ISO 10303 to overcome problems such as data loss during transferring and sharing project data. Amann et al. (2013) developed product models for shield tunnels based on IFC. Multi-scale product models present two main benefits: (1) they allow engineers to work on different levels of abstraction appropriate to their design activity and (2) they allow geographic information systems (GIS) to be integrated in the design process (Steuer et al., 2013). The preservation of model's consistency across the different levels of detail, which has been a main challenge of multi-scale product models, has been met by the use of parametric CAD systems and the incorporation of procedural models (Borrmann et al., 2012).

2.4. Current BrIM Studies

There has been a significant push in the U.S. to define a national BrIM standard. In 2006, The National Cooperative Highway Research Program (NCHRP) published a pilot study to develop and tests a 3D-centric model for an integrated design and construction process for highway bridges (Chen et al., 2006). The final report of the study documents the requirements for needed standards and best practices pragmatics for 3D-centric approaches and accompanying electronic data interchange for streamlining construction and design processes. This study lead to further development of a bridge standard that uses a common and neutral electronic data exchange format. Chen and Shirole (2006) present a comprehensive information-centric approach for the accelerated delivery of bridges through a single coordinated shepherding of bridge information.

In 2011, the U.S. Federal Highway Administration (FHWA) Office of Bridge Technology (HIBT) started a 5 year study to investigate and advance technologies to improve the condition and durability of the nation's bridges and highway structure (FHWA, 2011). Specifically, task 12 of the study, *Bridge Data File Protocols for*

Interoperability and Life Cycle Management, investigates the development of a universal bridge data file format that will promote digital exchange of engineering data between all software that may be used in the design, construction, and management of a bridge. The University at Buffalo SUNY and Leigh University were two academic universities that were part of the study. A major result is the formation of a bridge process lifecycle IDM that includes a process map with 18 EMs, in which the final results are published in Chen et al. (2013a). The study also resulted in OpenBrIM, which achieves the exchange of bridge-specific geometric data in several distinct high priority use cases occurring in the process map describing the bridge lifecycle (Chen et al., 2013a; Chen et al., 2013b). OpenBrIM, now on its third release, is still part of an ongoing development effort by the Red Equation Corporation and CH2M Hill (OpenBrIM, 2015). While the intent of this effort is to promote interoperability for bridge models, it still lacks the standards necessary for electronic data exchange. The OpenBrIM approach is to be a central data repository, and not an actual data exchange. In order to use the interoperable capabilities, bridge components would either have to be modeled within the tool or chosen from previously defined library of parts, which ultimately does not promote interoperability as-is between various software programs (i.e. major effort is needed to create new objects to be used for interoperability). The repository is open and flexible for an engineer to create their own objects, but there is currently no governance over the quality of the repository.

The FHWA funded another project, *Integrated Bridge Project Delivery and Life Cycle Management* (DTFH61-06-D-00037), to develop standards for data exchanges throughout the bridge lifecycle (Shirole et al., 2008). The results included an overview of tools and technologies for reliable electronic exchange of bridge data, identification of the data needed to support bridge lifecycle activities, and an integrated prototype system that connects existing commercial software for all major phases of bridge lifecycle. An initial process map that stemmed from this project will be discussed in Chapter 3.

2.5. Ontologies

An ontology is a formal representation of an abstract, simplified view of a domain that describes the objects, concepts and relationships between them that hold in that domain (Gruber, 1993). Researchers and developers use ontologies to define standardized and machine-readable definitions and concepts of a specific domain to be utilized for a broad range of applications. Reasons for using ontologies include sharing common understanding of the structure of information among people or software agents, enabling the reuse of domain knowledge, making domain assumptions explicit, separating domain knowledge from the operational knowledge, and analyzing domain knowledge (Noy and McGuinness, 2001). Ontologies have been proposed as a specification mechanism to enhance knowledge sharing and reuse across different applications (Neches et al., 1991). With the increasing demands for domain-wide integrated construction and infrastructure development, there is a growing need for the development of an ontology for the construction domain that supports the multistakeholder project development process (El-Gohary et al., 2010).

Borst et al. (1997) define three categories of ontologies: highly generic ontologies, or “super theories” (mereology, topology, systems theory); base ontologies valid for a whole field (technical components, physical processes, representing natural categories or viewpoints within a broad field) and domain ontologies (specializations of base ontologies to a specific domain, e.g. thermodynamics). In order to define a useable ontology for the bridge domain, all three categories must be addressed.

Mereology is the theory of parenthood relations, such as the relations to part to whole (child to parent relations) or the relations to part to part within a whole (sibling relations) (Varzi, 2016). Mereology also includes the relation of composition and decomposition, which are essentially how a taxonomy and ontology are represented by. One example is that a bridge (whole) is composed of various components such as beams, columns, girders, nuts, bolts, etc. (parts) and the relations between each can be represent by mereology relations. Topology is the study of shapes and how the properties are preserved due to deformations, in which topology can be used to abstract the inherent connectivity of objects (Weisstein, 2016). Shape representation and relations are an important aspect of modeling bridges, and topology is needed to determine and infer the relations between objects. For example, bridge components are modeled from primitive shapes, such as lines, cubes, and spheres. Knowing how these shapes relate to one another can result in more complex shapes, such as a nut fastening to a screw. Systems Theory is the study of a system, and how system components interact within the system and the outside environment. Systems theory is a way of looking at things, and a systems approach provides a common method for the study of societal and organizational patterns and offers a well-defined vocabulary to maximize communication across disciplines (Walonick, 1993). Systems theory provides the abilities to study how a bridge and its components interact with other environments, while providing the means for enabling the realization and deployment of a bridge as a system. All three of these "super theories" provide the abstract concepts needed in the formation of a taxonomy and ontology, and are utilized in the creation of the BrIM taxonomy and BrIM ontology.

There is an actual science behind the development of an ontology that requires various tools and methods. There is no one set way of developing an ontology, and so there are many methods and theories of how to construct an ontology. In computer science, the formal name of this field of study is referred to as "ontology engineering." Ontology engineering provides the necessary semantics for many fields of knowledge (Noy and McGuiness, 2001). Ontologies have been shown to help in the engineering development process since they can be used to enhance both the quality of the design models and also the tasks that support the design process (Tudorache, 2006). This is important since the end goal of interoperability includes keeping the model at the highest quality. Moreover, ontology engineering is useful for enabling interoperability across heterogeneous systems (Choi et al., 2006), which is the purpose of this research.

Therefore, because of the aforementioned reasons, an ontological approach was chosen for this dissertation to achieve interoperability between heterogeneous BrIM models.

2.5.1. Ontology Languages

Just as there are computer languages to code software, ontology languages are needed to describe and code ontologies in a machine readable form. The Defense Advanced Research Projects Agency (DARPA) played a great role in the development of formal ontology languages. One of the earlier languages was called Knowledge Interchange Format (KIF), and was developed by the InterLingua Working Group, under the DARPA Knowledge Sharing Initiative to facilitate knowledge sharing by proposing a standard knowledge interchange format (Genesereth and Fikes, 1992). KIF is designed for use in the interchange of knowledge among heterogeneous computer system, but neither intended to as a primary language for interaction with human users nor as an internal representation for knowledge within computer systems (Genesereth, 1998). Unfortunately, KIF was never standardized and is no longer used.

The Resource Description Framework (RDF) is a framework for conceptual description and the modeling of information that is implemented in web resources. The RDF Schema (RDFS) provides a data-modeling vocabulary for RDF data (Brickley and Guha, 2014). RDF is composed of three components, known as RDF triples: subject, predicate, and object (Becket, 2014). RDF triples state a single fact about a resource, in which the subject is the subject being described, the predicate is the relationship of the subject, and the object represents what is related to the subject by the predicate. RDF and RDFS are managed by the World Wide Web Consortium (W3C), the main international standards organization for the World Wide Web. “Although RDF is a good basic language for building many other languages, it is not very expressive and has limitations in describing resources, including descriptions of existence, cardinality, localised range and domain constraints or transitive, inverse or symmetrical properties" (Taye, 2011). However, RFD/RDFS provide basic concepts that are used as part of other languages.

The DARPA Agent Markup Language (DAML) + Ontology Inference Layer (OIL), or DAML+OIL, is the integration of the original DAML ontology language (DAML-ONT) and the language components of OIL. Built on RDFS, DAML+OIL is a semantic markup language for Web resources (managed by the W3C) that provides modeling primitives commonly found in frame-based language (Connolly et al., 2001). Compared to DAML-ONT, "DAML+OIL places much more emphasis on clear semantics, using both our updated first-order logic (FOL) semantics and a model-theoretic semantics" (McGuiness et al., 2002). Unfortunately, DAML+OIL has limitation, such as "it lacks property constructors, it has no composition or transitive closure, its only property types are transitive and symmetrical, sets are the only collection type (there are no bags or lists), there is no comparison in data value, it allows only unary and binary relations, and there are neither default values nor variables" (Taye, 2011).

In order to improve these limitations, the Web Ontology Language (OWL) was derived from DAML+OIL and is currently managed by the WC3. There are three levels of OWL: OWL Lite, OWL DL (Description Logic), and OWL Full (Bechhofer et al., 2004). The simplest level, OWL Lite, supports only a subset of the OWL language constructs, and provides a classification hierarchy and simple constraints. OWL Lite is used for by users who want to support OWL full, but want to start at a basic level. In addition to rules and requirements of OWL Lite, OWL DL adds the tools and features of Description Logic to represent the relations between objects and their properties. Description Logic, the basis of any ontology language, is the formal knowledge representation used to express the conceptualization of domains in an organized and formally well-understood manner (Taye, 2011). OWL Full provides the highest freedom of using the OWL language and RDF constructs. A more comprehensive distinction can be found in Bechhofer et al. (2004). The current release, OWL 2, can be found in W3C

OWL Working Group (2012). Additionally, the Rule Interchange Format (RIF) defines a standard for exchanging rules among systems on the Web that specifies how RDF, RDFS, and OWL interoperate (Bruijn and Welty, 2013).

Taye (2011) surveys the ontology languages which are used to express ontology over the Web. The author compares RDF/RDFS, DAML+OIL, and OWL, and concludes that there are "many limitations to RDFS, among which are its inability to express equality and inequality, and its limited ability to define enumeration of property values. DAML+OIL has many limitations, such as property constructors; it has no composition or transitive closure, in property types contain transitive and symmetrical" (Taye, 2011). However, as mentioned before, OWL does not have the limitations that are seen in RDF/RDFS and DAML+OIL.

2.5.2. Building and Managing Ontologies

As mentioned before, there is no once set way to construct an ontology. Since ontology engineering has been a major field of study, there have been many researchers that formulated and validated their own methods. This section describes a few common methods in the building and managing an ontology. Noy and McGuinness (2001) present three fundamental rules for building an ontology:

Rule 1. There is no one correct way to model a domain; there are always viable alternatives. The best solution almost always depends on the application that you have in mind and the extensions that you anticipate.

Rule 2. Ontology development is necessarily an iterative process.

Rule 3. Concepts in the ontology should be close to objects (physical or logical) and relationships in your domain of interest. These are most likely to be nouns (objects) or verbs (relationships) in sentences that describe your domain.

Uschold and Gruninger (1996) present a formal approach in the development of an ontology. In the paper, the authors outline the purpose, use, development, and practical aspects of an ontology. The six step procedure to develop an ontology outlined in Uschold and Gruninger (1996) is as follows:

1. Capture of motivating scenarios
2. Formulation of informal competency questions
3. Specification of the terminology of the ontology with a formal language
4. Formulation of formal competency questions using the terminology of the ontology
5. Specification of axioms and definitions for the terms in the ontology within the formal language
6. Justification of axioms and definitions by proving characteristic theorems

Noy and McGuinness (2001) present their processes to build an ontology:

1. Determine the domain and scope of the ontology
2. Consider reusing existing ontologies
3. Enumerate important terms in the ontology
4. Define the classes and the class hierarchy
5. Define the properties of classes—slots
6. Define the facets of the slots
7. Create instances

A good methodology for managing ontologies is needed that supports modularization and also different ways of interrelating ontologies (Tudorache, 2006). One was of managing the ontology is to build a library and break up the ontology into smaller sections. For the construction and managing of an ontology, Borst et al. (1997) recommend the following:

1. Use and reuse of “super” theories, which are general and abstract ontologies such as mereology, topology, graph theory, and systems theory. These general ontologies can be used and reused as generic building blocks in an ontology construction This approach enhances both the modularity and the reusability of ontologies.
2. Distinguishing natural “viewpoints” or base categories that formalize a conceptual category of concepts in a domain. These broad conceptual distinctions can then be exploited to develop separate base ontologies which are valid and reusable across many sub-domains and tasks.
3. Ontology projection to link and configure smaller ontologies into larger ones. This enables the ability to reduce the scope of building an ontology, since the smaller ontology can be linked to others.
4. Using piecemeal ontological commitment to help reduce the complexity in the development of the ontology.

2.5.3. Taxonomy

In this research, a taxonomy is defined as a hierarchical structure of terms that represent the relationships and attributes among those terms. This dissertation asserts that a well established taxonomy is the imperative first step in defining an ontology to promote interoperability. In other words, defining terminology upfront will help seamless information exchanges at the end user (e.g. software). There are two main reasons for this assertion: 1) the industry experts that define the terminology may not have the technical skills to build an ontology, and 2) ontology development is quicker for software developers when they have the terminology in front of them, versus having to research how to define the terms. Having a well established taxonomy will help clear semantic issues since each term used will be balloted, approved, and become the official term definitions. This means all software that use the taxonomy (via the ontology) will refer to the same term (definitions, properties, attributes etc.), thus eliminating the semantic confusion. Therefore, before a BrIM ontology can be developed, common definitions and concepts would need to be defined and classified in a taxonomy. Specifically, this research develops the BrIM taxonomy, which will be extendable to other domains, and the scope includes the terms needed for steel erection processes (Figure 2-2).

Bridge layout	Bridge control information	Stations	Station at pavement begins
			Station at bridge begins
			Station at centerline of bearings at begin abutment
			Station at centerline of bearings at pier
			Station at centerline of bearings at end abutment
			Station at bridge ends
			Station at pavement ends
			Station at road work ends
		Azimuths	Azimuth of CL bearings at begin abutment
			Azimuth of CL bearings at pier
			Azimuth of CL bearings at end abutment
		Skew angles	Skew angle of CL bearings at begin abutment
			Skew angle of CL bearings at pier
			Skew angle of CL bearings at end abutment
	Bridge configuration	Span	Number of spans
			Number of supports
		Length	Bridge length
			Pier to pier length
			Girder length
			Bearing to bearing length
			Release span length
			Pier centerline to beam end
		Clearance	Minimum vertical clearance
			Minimum horizontal clearance

Figure 2-2: Portion of the Erection Process Taxonomy

Defining all the terms and definitions in the real world would be impractical and unnecessary. Therefore, it is imperative to follow a strict standard of development in order to enable extensibility and expansion as a small subset of knowledge can be defined and then continue to grow. Chapters 6 and 7 outline a standard to develop a consistent taxonomy. Different taxonomies have different purposes, and thus not all relationships and properties in a domain will be defined. Therefore, defining a purpose of the taxonomy is required to minimize time and effort of the development. Some questions to be answered to define the purpose include the following:

- What will the taxonomy be used for?
- What domain will the taxonomy cover?
- What is the end goal of the taxonomy?
- Who will use, manage, and maintain the taxonomy?

Uschold and Gruninger (1996) define these types of questions as competency questions. Competency questions are important to lay out all the assumptions and foundations in the development of ontologies, in which the use of competency questions are extended to taxonomies in this dissertation, because an ontology is essentially a taxonomy with more constraints in the forms of axioms (i.e. assertions). Additionally, asking the same questions for the ontology will help define the purpose of the taxonomy. However, this research defines a new method of capturing the information that is needed in the taxonomy. Instead of defining the purpose of the taxonomy, the purpose will be inherent with the defining of the workflow of the domain that will use the taxonomy. Instead of defining the taxonomy upfront, the workflow of a specific use case in the domain is what will be defined. In other words, the taxonomy is just the device needed to capture the information that is identified in the use case. Chapter 3 explains workflows, and this discussion will be brought up later in this dissertation.

In order to make design knowledge effectively accessible without imposing an unnatural standard vocabulary on everyone, a well-defined taxonomy supported by axioms are required (Lin and Harding, 2007). In this research, an axiom is a stated rule or principle that helps govern the taxonomy. Axioms are an important part of developing a taxonomy because they provide truths and assumptions that give meaning to the taxonomy. Axioms can be defined both abstractly (logically) and operationally (structured), and are defined in detailed in Chapter 7. Without axioms, the taxonomy would essentially be a hierarchy of terms without meaning or direction. Moreover, definitions alone in the form of classification systems and product data models lack effective modeling of concept semantics, which is a fundamental requirement for human-based exchange of knowledge (El-Diraby et al., 2005). A classification system is important to have because they can supply the core definitions, but it important to add meaning to those terms, in which a taxonomy can achieve. "A standardized terminology needs to be semantically consistent across organization boundaries, since the communication aspects of information require that communicating parties have the same understanding of the meaning of the exchanged information" (Lin and Harding, 2007). Since specific taxonomies represent the vocabularies that are commonly used by the practitioners, taxonomies are being developed and used by industry practitioners to facilitate information interoperability and retrieval (Cheng et al., 2008). Therefore, it is feasible to argue that a BrIM taxonomy would help increase interoperability for the bridge domain, and thus it why it is the imperative first step in the development of an ontology to promote interoperability.

Taxonomies differ from classification systems, such as OmniClass. The OmniClass Construction Classification System (OCCS) is the leading ongoing classification system for the construction industry. It is structured in 15 tables (e.g. elements, phases, disciplines, materials, etc.) that provide the structured data for many applications (OCCS, 2015). Table 2-1 is an example from OmniClass which displays the construction disciplines.

Table 2-1: Example of OmniClass: Portion of Table 33-Diciplines (OCCS, 2015).

OmniClass Table 33 - Disciplines	
OmniClass Number	**OmniClass Title**
33-41 00 00	**Construction Disciplines**
33-41 01 00	Material Moving Operations
33-41 01 11	Conveyor Tending and Operations
33-41 01 13	Crane and Tower Operations
33-41 01 14	Hoist and Winch Operations
33-41 01 16	Dredge, Excavating, and Loading Machine Operations
33-41 01 21	Industrial Truck and Tractor Operations
33-41 01 31	Laborers and Material Moving, Hand Operations
33-41 03 00	Site Preparation
33-41 03 11	Remediation Services
33-41 03 11 11	Hazardous Material Abatement Services
33-41 03 21	Demolition Services
33-41 03 31	Fence Erection Services
33-41 03 41	Foundation Preparation Services

Each term is designated by a classification number, which has up to 6 levels of titles. These levels serve as sub headings (Figure 2-3). For example, take “33-41 03 11 Remediation Services.” The first number, 33, signifies the table “Disciplines” with a dash to the second number (level 1), 41, signifying “Construction Disciplines.” The third number (level 2), 03, signifies “site preparation” and the fourth number (level 3), 11, signifies “remediation services”, which is a type of site preparation. Since there is a subtype of remediation services, “Hazardous Material Abatement Services” goes another level down and is designated by a fifth number, 11. Now, “Hazardous Material Abatement Services” classification number is “33-41 03 11 11.”

33 -	41	03	11	11	00	00
Level 0	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6

Figure 2-3: Levels of OmniClass Construction Classification System

Table 2-2 shows the hierarchical structure of this example. Note that OmniClass is structured to have two more sublevels and a column for the definition of the level title.

Table 2-2: Example of Omniclass Levels (OCCS, 2015).

OmniClass Table 33 - Disciplines				
Number	**Level 1 Title**	**Level 2 Title**	**Level 3 Title**	**Level 4 Title**
33-41 00 00	Construction Disciplines			
33-41 03 00		Site Preparation		
33-41 03 11			Remediation Services	
33-41 03 11 11				Hazardous Material Abatement Services

Although a classification system can be in hierarchical form, the major difference is that a taxonomy includes object-oriented features which provides for reasoning and future expansions (El-Diraby et al., 2005). The four major features of object-oriented systems include abstraction, encapsulation, inheritance, and polymorphism. *Abstraction* is using data without knowing (or caring) how that data work, and is used to decompose complex and varying systems. Moreover, abstraction focuses about the functionality of the data. For example, a bridge can be abstract because it's has the function of allowing passage over an obstructed path. The type, structure, and features of the bridge are irrelevant as long as the function of providing clear passage is met. Specific bridge types can be then be defined (e.g. steel, suspension, etc.) and then access the abstract functionality of the term bridge. *Encapsulation* is the protection of data by packaging and providing restricted access to the user. For a taxonomy, a user is able to gain access to the data by the use of the term, but cannot add or modify the data about that term. *Inheritance* is the access of metadata (i.e. behavior, characteristics, propertied, etc.) in which data lower in the hierarchy can inherit the metadata from higher. For example, since a girder bridge is a type of bridge, anything defined in the bridge term is inherited by the girder. Hierarchy is used to avoid the duplication of having to program the same metatdata. *Polymorphism* is the ability for data to change functionality or form. For example, the functionality of a "door" is to restrict access in and out of a room. However, what happens if a door is flipped horizontal and used as a table… is it a door or a table? Therefore, polymorphism allows for such cases to exist (although the semantic issues still need to be addressed).

Additionally, OmniClass is product oriented, meaning it focuses on the noun (product), rather than the verb (action). Therefore, classification systems cannot be used alone in the development of an ontology, but can provide the foundation of organization. The BrIM taxonomy takes advantage of classification systems to provide the source information (e.g. structure and classification).

Building a taxonomy with the full semantic information and well-organized structure is challenging because of the complexity of the natural languages and the broad scope and large amount of scientific knowledge accumulated (Li et al., 2015). Therefore, it is important to understand the usage and the vernacular of the terminology based on the domain. This research proposes a process that collects and organizes domain terminology and utilizes a balloting or approval process to define the terminology in the taxonomy. This way, once a term has been defined and approved, it will always be the same. For example, once a term has been approved, it will be given a Globally Unique Identifier

(GUID). The purpose is to have consistency of terminology and usage over all platforms and software.

Since taxonomies can require large amounts of terms and information, automated approaches have been proposed to help minimize or eliminate manual construction. Term extraction been identified as the first step in process of building a taxonomy, and automated approaches have been proposed (Buitelaar et al., 2009; Chen, H. et al., 2009; Cimiano et al., 2003; Makrehchi and Kamel, 2007; Sclano and Velardi, 2007). Li et al. (2015) proposes a new method for term extraction and the construction of taxonomies based on the weighted keyword co-occurrence analysis. Meijer et al. (2014) developed a four step framework for the automatic building of a domain taxonomy from text corpora, called Automatic Taxonomy Construction from Text (ATCT). A text corpus is a large and structured set of texts, which can be from databases or documents. Automated approaches may be useful for large amount of data, however, full automation is out of the scope of this research, but future work can potentially integrate automated approaches to help reduce the manual reduction of taxonomy. This work introduces a tool, the Taxonomy Editor, to help automate the construction and organization of a taxonomy. The taxonomy editor is discussed in Chapters 6 and 7.

2.5.4. Taxonomy and Ontology for the Construction Domain

Very few research projects have undertaken formalizing an ontology for the construction domain. Moreover, of those few research projects, there hasn't officially been a formalized taxonomy specifically tailored for the construction domain since the focus has been on formalizing the ontology. Thus, there is a need to standardize a taxonomy to encompass the whole construction domain, and this dissertation is the first project to do so in the scope of the bridge domain. Although the scope is for bridges (i.e.

BrIM taxonomy), the taxonomy can be extended to the whole construction domain since the terminology will be similar.

The most prominent work for a construction taxonomy is started by El-Diraby et al. (2005). As part of a construction project called e-COGNOS ("COnsistent knowledGe management across prOjects and between enterpriSes in the construction domain"), the researches viewed that the taxonomy was a first step in the establishment of domain ontology. The taxonomy was developed to be process-centered and to allow for utilization of already existing classification systems including IFC, BS6100, and UniClass. This work classifies construction concepts into seven main classes: Project, Process, Product, Actor, Resource, Technical Topics, and Systems. The purpose of the ontology is to support semantic knowledge management for applications, including semantic indexing and collaborative project development. Unfortunately, this work has been discontinued and cannot be utilized for further development. However, the methodologies and background knowledge are used in the development of the BrIM taxonomy and ontology.

El-Diraby and Zhang (2006) present a semantic framework to support corporate memory management in building construction by the use of a taxonomy that was extended from the e-COGNOS project. The methodology consists of five major steps: 1) define the scope of the domain and specifications of the taxonomy; 2) review existing classifications systems and domain ontologies; 3) develop the taxonomy/ontology which includes the extracting of concepts, organizing the concepts into a taxonomy, and implementing the concepts into an ontology; 4) validate the taxonomy/ontology through competency questions, expert interviews, and analysis; and 5) implement the taxonomy/ontology into a corporate memory architecture, which includes the creation, indexing, storing, and retrieval of the knowledge items that utilize the taxonomy/ontology. The final taxonomy includes concepts developed in the web ontology language (OWL). Additionally, the research presents a prototypical ontology and a framework to support the generation of reports. The current progress and the accessibly of the taxonomy and ontology are unknown (i2c, 2010), but the major steps proposed are used in the development of the BrIM taxonomy and ontology.

El-Gohary et al. (2010) propose the Infrastructure and Construction PROcess Ontology (IC-PRO-Onto) for supporting knowledge-enabled process management and coordination across the construction project process. A domain ontology "would serve as a core domain process model that can be used as a basis for developing further model extensions, domain or application ontologies, software systems, and/or semantic web tools" (El-Gohary et al., 2010). This work is seemingly built from the research of the e-COGNOS project. Unlike the seven classes in the e-COGNOS, IC-PRO-Onto classified concepts as an Action (events and processes), Actor, Actor Role, Family, Mechanism, Product, Project, or Resource. The taxonomy they presented was based on a two step approach: 1) identify and extract main concepts from the domain, and 2) organize the concepts in a hierarchical fashion. The researchers define a "thing" at the highest level of abstraction as an entity, constraint, attribute, modality, or family. "Modalities define the belonging criteria of entities to families" (El-Gohary et al., 2010). This research and ontology is no longer active, but concepts and axioms presented are utilized in the development of the BrIM taxonomy and ontology.

El-Diraby (2013) presents the domain ontology for construction knowledge (DOCK) "to provide a shared (base) platform to develop additional subdomain and application level ontologies; to facilitate the linking of construction informatic systems to already existing ontologies in other domains; and, fundamentally, to represent a conceptual model that can spur discussions about how to represent construction knowledge." This ontology was created from the taxonomy developed in the e-COGNOS project and builds of the work from El-Diraby et al. (2005) and El-Gohary et al. (2010). This work categorizes construction knowledge across three main dimensions: concept, modality, and context. Additionally, this work includes an ontological model, types of modalities, list of attributes, types of relationships, and defined axioms that are needed to build an ontology for construction knowledge. Unfortunately, the current status is unknown as the online web portal seems to be inactive (i2c, 2010). However, this work sheds great light on the philosophical and practical applications of developing an ontology.

El-Diraby (2014) presents approaches and lessons learned from his previous works about ontologies in informatics systems. Although the author states that “an ontology is essentially a philosophical claim regarding the theory of knowledge in a domain,” this dissertation focuses on the practical aspects of having human semantics on a machine readable level (i.e. this dissertation is neither debating nor instantiating philosophical approaches). The author (El-Diraby, 2014) does ask the practical questions of validity of creating a information model: “is the model being built right?... is the right model being built?... Does it represent or match reality?” These questions are important in determining how information is transferred and interpreted with integrity, consistency, and accuracy. Although the philosophical dimensions can be debated forthcoming, the practical aspects are usually answered and agreed upon by standards, such as the Level of Development (LOD) Specification. The Level of Development (LOD) Specification is a “reference that enables practitioners in the AEC Industry to specify and articulate with a high level of clarity the content and reliability of Building Information Models (BIMs) at various stages in the design and construction process” (BIM Forum, 2015). Importantly, the author presents two arguments to consider in the creation of an ontology: “1) embrace more rigorous methodological approaches with particular focus on the various validity types, and 2) seriously consider the epistemological foundations of any ontology” El-Diraby (2014). Moreover, a roadmap and best practices are presented that can be used in the formation of any ontology, including the BrIM ontology presented in this dissertation.

Cheng et al. (2008) propose a systemic approach to map industry specific taxonomies to regulations, which include the AEC industry specific standards CIM steel

Integration Standards (CIS/2), IFC, and the OmniClass construction classification system. The researchers argue that taxonomies have the potential to enable interoperability, as well as facilitate information retrieval, by utilizing machine readable data to capture and represent the semantics of domain specific information. This work does not focus on the development of a taxonomy, but rather how to use and map various taxonomies in order to retrieve information.

2.5.5. Geometry and Component Representation

Geometries are critical components in any 3D modeling software. Section 2.3, "Product Modeling," presents an overview of the ways of representing geometric shapes, which can be in various formats, such as AutoCAD's Drawing Exchange Format (DXF), ACIS's Standard ACIS Text (SAT), and Trimble's Sketchup File (SKP). Having ontological representations of such features (e.g. holes, shapes, and graphics) are imperative for software applications to adopt the logic into their own respective formats. Since the limitations of existing file-based methods became apparent in complex modeling systems (Eastman el al., 2010a), utilizing logical modeling in the form of ontologies can be a way to establish the semantics and syntax needed. There will always be a need to support translation between various alternative representations of shapes, complex attributes, or part (Stouffs et al., 1996).

There is a large community of academics and industry utilizing the use of ontologies for shape representation, which is called Graphic Ontology. Stouffs et al. (1996) define a method for analysis and application or translation to different solid modeling representations used in building product models. It has been shown that subsumption relations can determine the relation between geometries (Stouffs et al. 1996). Therefore, subsumption relations can be used to determine if the taxonomy or ontology contain the correction relations need fully transfer the data needed for geometric representation. For example, a shape can go from being defined as an extrusion in one program and transfer to another program as a B-Rep without losing any information. Guarino et al. (1997) introduce using a Logical Model (reference ontology) to provide product knowledge for STEP to exchange geometric information, which include Computer Aided Design (CAD), Computer Aided Manufacturing, and Product Data Management (PDM) which can be seen in Figure 2-4.

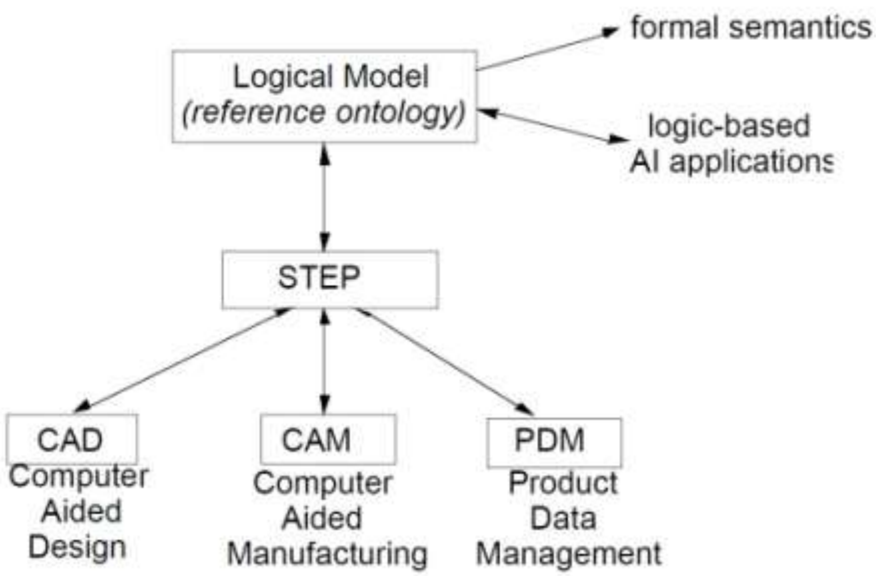


Figure 2-4: The Advantage of a Logic-Based Reference Ontology for STEP (Guarino et al., 1997).

Niknam and Kemke (2011) present the development of ontology for the graphics domain that was integrated with a natural language interface and graphics generation module, Lang2Graph, significantly showing that an ontology can be used for developing shape representation of software applications. Likavec (2013) utilizes the Web Ontology Language (OWL) to model shapes in an ontology as property restrictions on classes, rather than exhaustively defining each shaper characteristic. Property restrictions enable classes of objects to be defined based on properties, rather than explicit class definitions (more detail is provided in Section 7.6.1.2). Representing shapes as property restrictions make it possible to introduce a very natural similarity measure based on properties, allow for more relevance to certain properties in different situations, bring new insights into modeling forms and patterns, and provide a flexible environment for expressing various features of complex forms (Likavec, 2013).

2.6. Semantic Web

2.6.1. Semantic Web for Building and Construction Domain

With the benefits of ontologies for interoperability becoming more popular over the internet (i.e. Semantic Web), there have been research efforts to map various non-web based languages to web based ontologies, such as the Web Ontology Language (OWL). Schevers and Drogemuller (2005) was the first to propose that the building and construction industry make use of the Semantic Web by proposing that IFC, as part of ISO-STEP, should be available as an OWL ontology. The authors propose various ways of converting (mapping) an IFC file to an OWL file, which sets the foundation for more developed mapping techniques. Beetz et al. (2009) introduces the development of the first ontology for the building and construction sector. Coined "ifcOWL" (properly named for the IFC naming convention), the ontology is transforms from the EXPRESS schema (which IFC is based off) by a semiautomatic approach using various methods, including generic query, RDF, and reasoning algorithms. Additionally, this approach can be tailored to fit the scope of other works. Eiter et al. (2011) introduced nonmonotonic description logic programs (dl-programs) to combine logical programming with OWL, providing evidence that dl-programs are a versatile and robust combination approach that are implementable using legacy engines.

While the previous research focuses specifically on IFC, Krima et al. (2009) proposes a general ontology version of the EXPRESS schema and STEP file to OWL called OntoSTEP. This first effort focuses on AP203 the exchange protocol of CAD files and STEP Part 21 CAD files. The goal of this work is to improve interoperability of product data by defining the semantic of STEP models by translating EXPRESS into OWL-DL (a sublanguage of OWL). This first version of OntoSTEP focuses on the product information mainly related to geometry, and therefore, it still needs to be extended to include information such as function, behavior, and assembly requirements. Later work by Barbau et al. (2012) addresses these needs of OntoSTEP, and presents an approach that translates the STEP schema and Part 21 files (defined in EXPRESS) to OWL. This enriched version does combine the geometry information with other information, including the as function, behavior, and assembly requirements. In addition to providing the mapping rules, the authors developed a plug-in to Protégé, the most widely used program for developing OWL ontologies (Protégé is discussed in Chapter 7). Importantly, the mapping rules that the authors present can be used to map other languages to OWL.

Terkaj and Šojić (2015) present an enrichment of the EXPRESS to OWL conversion patterns in ifcOWL by adding class expressions that explicate the links between IFC object occurrences, object type and pre-defined property sets. However, there are still issues that need to be addressed, and so the author recommends the following requirements:

1. The ifcOWL ontology should remain in OWL2 DL.

2. The ifcOWL ontology should match the original EXPRESS schema as closely as possible.

3. The ifcOWL ontology is to be used primarily to allow the conversion of IFC instance files into equivalent RDF graphs.

Pauwels et al. (2015a) focuses on dealing with aggregations, since they do not map well into OWL. Therefore, the authors outline and discuss the main decisions that can be made in converting **LIST** concepts in EXPRESS to equivalent OWL expressions, which allow for extensibility and reuse in the building and construction domains.

de Farias et al. (2015) argue that the current version of ifcOWL is limited in such as ifcOWL does not allow the full OWL features and it contains the current limitations imposed by EXPRESS. Additionally, they argue that the approach in (Beetz, et al., 2015) "is limited to RDF vocabulary and only considers the *IfcPropertySingleValueentity* for property mapping. Furthermore, no method is proposed for semi-automatically or automatically translating *IfcRelationship* and *IfcProperty* (a super-type of *IfcPropertySingleValue*) entities as OWL properties" (de Farias et al. 2015). Therefore, de Farias et al. (2015) proposes the IFC Web of DataOntology (IfcWoD), which is a semi-automatic method for semantically linking IFC data to OWL, including IFC entities, relationships, properties, and attributes. Although IfcWoD uses terms from ifcOWL, it is not intended to be another version and ifcOWL.

In response to alternatives to ifcOWL, such as IfcWoD, Pauwels and Terkaj (2016) state these alternatives are not appropriate options for the general purpose of the ifcOWL ontology "because they cannot be generally applied and they diverge from the original EXPRESS schema." The authors examine and analyze previous efforts of ifcOWL and present our implementations of an EXPRESS-to-OWL converter and the key features of the resulting ifcOWL ontology.

Recently, buildingSMART has adopted ifcOWL and is currently managing the development, as well as hosting the current and live versions of ifcOWL (buildingSMART Linked Data Working Group, 2016). To help users and developers, buildingSMART has published a recommended usage guide for using ifcOWL (Pauwels et al., 2015b). Additionally, the BuildingSMART Linked Data Working Group is currently collaborating on developments to use linked data and semantic web technologies for support to other buildingSMART International development efforts, such as MVD, bSDD, regulations, and BIM Guides.

2.6.2. Ontology Mapping and Query Language

Having access to an ontology is just as important as the established ontology; i.e. what's the point of the ontology if an application can't use it? In order to gain access, an ontology must me mapped to (i.e. create connections between) or queried (i.e. retrieved) by the software application that needs access to the information store in the ontology. The SPARQL Protocol and RDF Query Language (SPARQL) is the standardized query language for Semantic Web, which retrieves and manipulates the data stored in data models that are formatted using semantic web standards (W3C, 2013).

Since ontologies are and the use of the Semantic Web are relatively new topics in the AEC industry, there has been very few research studies for mapping and query language for BIM tools. As such, there is no universally accepted standard that is compatible with existing BIM tools. Adachi (2003) describes the overview Product Model Query Language (PMQL) that queries partial model information from the IFC Model Server. The PMQL is an XML language to describe product model operations (Select, Update and Delete) and describes the partial model by partial model object structures by XML element structures. Borrmann et al. (2006) introduces the 3D Spatial Query Language that has been developed to query Building Information Models using spatial conditions. The approach uses logical operators based on an octree representation of the geometric objects of 3D topography. Nepal et al. (2012) describes the process and methods of extracting spatial data directly from a BIM model using ifcXML and representing the information in the Extensible Markup Language (XML) format. The researchers develop a richer model for construction users by the use of a custom 2D topological XQuery predicates to answer a variety of spatial queries. Karan et al. (2015) focuses on the development of a process for query and access to ontology-based web services that converts query results from SPARQL into ifcXML, to allow BIM users to query and retrieve building data at any time over the web from heterogeneous data providers.

The previous research focusing on mapping and query language for BIM tools can only work on IFC compliant software application. Very few bridge software applications try to utilize IFC, and those that do fail due to IFC limitations for bridges. Therefore the use of these querying languages and techniques for BIM tools that support bridges are practically non-existent. Thus, the need for an open and non-schema dependant technique is apparent (which is not in the scope of this dissertation).

CHAPTER 3

3. BRIDGE LIFECYCLE WORKFLOW

Understanding the high level bridge lifecycle workflow is important in order to comprehend the low level exchanges that are required to pass information. This chapter introduces how to define a workflow in terms of processes, phases, activities, and actors. In addition to the dissertation, the author was part of a parallel project sponsored by the FHWA. Section 3.1 was contributed by the author to the project report (Costin et al., 2015). The work below assumes a traditional design-bid-build project, in which the design of the bridge is fully completed before construction begins. Additionally, the bridge project is a traditional “plain vanilla” bridge, that has minimal complexities. These type of bridges are referred to as “workhorse bridges” as defined by Hu (2014). Covering about 90% of all bridges in the U.S., workhorse bridges include box beam, girder, slab bridges, channel beam, and tee beam bridges.

3.1. Workflow and Processes

A workflow is a sequence of processes that pass data from initiation through completion. A workflow for the bridge lifecycle is rich and complex, and may contain various processes to complete a bridge project from conceptual design through operation and maintenance. A process can be defined as a set of activities or steps taken in order to achieve a particular end or goal. The steps can be sequential (one follows another) or concurrent (happen at the same time), as well as being dependent (step B requires step A to be finished) or nondependent. Each step has an outcome or goal that needs to be achieved in order to proceed to succeeding steps or phases in the process. Understanding each step and how they interact with one another is critical to achieve the end goal in a safe, cost-effective and timely manner. Figure 3-1 displays a high level view of the bridge lifecycle workflow, in which contains four high level phases that can structure most general design-bid-build projects: planning, bidding, construction, operation and maintenance (O&M). Within these four major activities contain sub activities and sub processes.

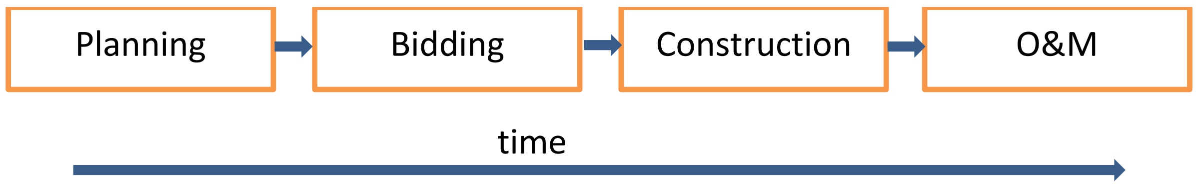


Figure 3-1: High Level Process for Bridge Lifecycle

3.1.1. Phases, Activities, and Actors

Phases are temporal disjointed segments of a period of time, usually occurring sequentially. In construction, “stage” is a common synonym for phase, but this dissertation uses the term phase. Each high level phase can then be broken down into subphases. For example, planning can be broken up into initiation and design. In order to build a bridge, the plan first needs to be initialized (what the problem is, what the constraints are, etc.). Afterwards, the bridge needs to be designed (type of bridge, capacity, aesthetics, etc.). These phases can further be broken down into smaller subphases (Figure 3-2). Subphases are disjointed partitions of the phase they are part of.

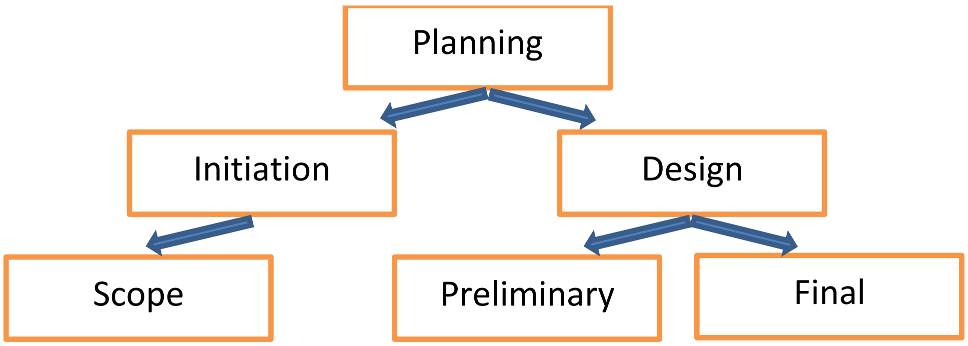


Figure 3-2: Subphases of Planning

The University at Buffalo from an earlier FHWA project identified the phases for bridge construction (Chen et al., 2013a; Chen et al., 2013b; Hu, 2014). Below lists of the phases identified in the bridge lifecycle process, in which each term is followed by its number of the OmniClass Construction Classification System (OCCS, 2015):

- Initiation (I), 31-10 14 17
- Scoping (S), 31-10 14 24
- Preliminary Design (PD), 31-20 10 00
- Final Design (FD), 31-20 20 00
- Bidding and Letting (BL), 31-30 30 00
- Post Award/Pre-Construction Construction Planning/Detailing (CD), 31-40 10 00
- Fabrication (F), 31-40 40 14 21
- Construction (C), 31-40 40 14
- Inspection and Evaluation (IE), 31-50 20 21
- Maintenance and Management (MM), 31-50 20 31

Within each subphase, various activities are required to reach the end goal. An activity applies resources (people time, equipment, computation, expertise, etc.) to complete the activity. Activities can be repetitive, or iterated until the outcome of that activity is achieved. Often, activities are dependent on conditions that are realized by other activities. This is a dependency between one activity and another. The second activity depends on the state of the first activity; the second activity can only be meaningfully applied if the first activity has been completed. In addition, if the first activity is iterated, the second activity may have to be repeated. For instance, initiation has two activities: "bridge planning" and "conceptual estimate". The "bridge planning" activity determines the project plan, which may include a description of the problem, preliminary project objectives, and description, project elements to be investigated and a preliminary schedule. The "conceptual estimate" activity creates a preliminary cost estimate report of the bridge plan. Therefore, any changes to the plan will create changes in the cost estimate report, which makes the "conceptual estimate" activity dependent on the "bridge planning" activity. Since there is a dependency, the two activities repeat until a final bridge plan is achieved and the final cost estimate is generated (Figure 3-3).

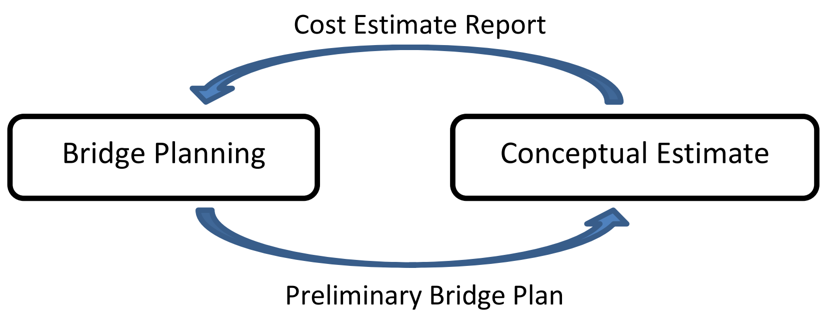


Figure 3-3: Bridge Planning and Conceptual Estimate Cycle

The bridge life cycle process contains many activities and sub activities. Below is a list of the high level activities identified in the bridge lifecycle process identified by (Chen et al., 2013a; Chen et al., 2013b; Hu, 2014):

- Bridge Planning
- Conceptual Estimate
- Structure Type, Size and Location Design
- Preliminary Estimate
- Preliminary Roadway Geometry Development
- Preliminary Aesthetic Design
- Preliminary Structural Design
- Updated Preliminary Cost Estimate
- Final Roadway Geometry Development
- Aesthetic Design Development
- Structural Design Development
- Preliminary Detailing Design
- Detailed Engineer's Cost Estimate
- Initial Load Rating
- Construction Documentation Preparation
- Initial Cost Estimate
- Bid Development
- Final Review / Integration of Structural System
- Detailing Design Development
- Construction Planning and Scheduling
- Production Scheduling
- Erection Plan and Analysis
- Modification / Integration of Final Detailing Documents

- Product Manufacturing
- Structural As-Built Data Development
- Project Contract Claim / J.O.C. Cost Estimates
- Construction Coordinating and Monitoring
- Construction Execution
- Post-construction Load Rating
- Inspection Review
- Inspection
- Updated Load Rating
- Maintenance
- Routing and Permitting

It is important to note that this is not an exhaustive list of all the activities in the bridge lifecycle. The bridge lifecycle of a typical design-bid-build workhorse bridge, let alone the different variations of bridge types, is complex and contains substantial amount of activities and tasks.

In order to make an activity happen, there needs to be one or more people to complete the tasks. These people are called ‘actors’ because they act upon a certain activity in the process. The same person may carry out different activities, different roles for each activity. Anybody that has a role in a process is considered an actor, which can be a person, an organization, or a person acting on behalf of an organization. In the example above, a city planner (whether it’s a single person or a company) would be the actor in the “bridge planning” activity and an estimator hired by the bridge owner would be the actor in the “conceptual estimate” activity.

Below is a list of the disciplines (in which the actors reside) identified in the bridge lifecycle process, in which each term is followed by its number of the OmniClass Construction Classification System (OCCS, 2015):

- Transportation Engineering (TE), (33-21 99 45 21)
- Planning, Aesthetics, Landscaping (PAL), (33-11 00 00)
- Structural Engineering (SE), (33-21 31 14)
- Detailing (D), (33-21 31 14)
- Estimation (E), (33-25 11 00)
- Construction Management (CM), (33-41 14 00)
- Fabrication (F), (33-25 41 11)
- Construction Engineering (CE), (33-41 11 00)
- Inspection (I), (33-21 31 14)
- Load Rating (LR), (33-21 31 14)
- Routing and Permitting (RP), (33-21 31 11)
- Maintenance and Management (MM), (33-55 24 00)

The above list comes from Table 33, *Disciplines*, from the OmniClass Construction Classification System. Currently, an actor is a person doing the task, and the OmniClass number of the actor should reference Table 34, *Organizational Roles*, which by definition are “the technical positions occupied by the participants, both individuals and groups, that carry out the processes and procedures which occur during the life cycle of a construction entity” (OCCS, 2015). Moreover, Table 33, “Disciplines are presented without regard to the job functions that may be performed by individuals or teams, which are classified by Table 34 – Organizational Roles. Disciplines from Table 33 can be combined with entries from Table 34 - Organizational Roles to provide a more complete classification of a construction participant's role, such as an Electrical Contracting (discipline) Supervisor (organizational role)" (OCCS, 2015). Therefore, a combination of both tables is important to identify the true scope of the actor and responsibilities.

3.1.2. Exchanges

An estimator needs specific and reliable data from the planner in order to make an accurate cost estimate report. If the data is erroneous or unreliable, the cost estimate report would be inaccurate which can cause later problems in the project. Therefore, a system needs to be set up to verify that the estimator gets the needed reliable information. This system is called an exchange. An exchange is the process of transferring the needed information at a given phase in a process from one actor to another. The information sent from the planner to the estimator, in the form of the bridge plan, is one exchange. The information sent back from the estimator to the planner, in the form of the cost estimate report, is a separate exchange (Figure 3-4).

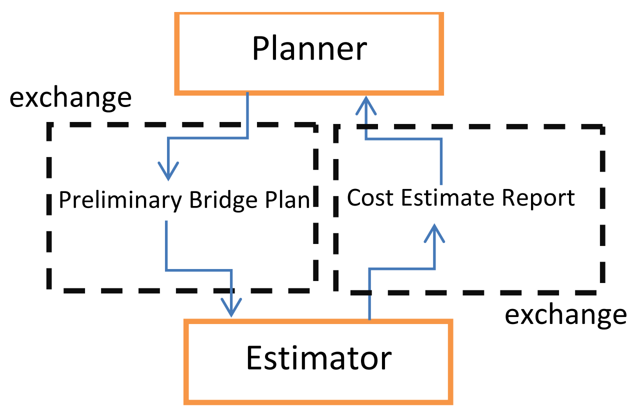


Figure 3-4: Exchanges between Two Actors; Planner and Estimator

An exchange model (EM) defines the content and requirements of the exchange, including how the data is being sent (e.g. PDF, BIM model, etc.), the purpose of exchange, who the actors are in the exchange, and what data and metadata is needed.

Each EM is unique such that it describes one and only one exchange (although some EM's may be similar). Table 3-1 is an example of an EM identified by the University at Buffalo for the above mentioned exchange between the planner and the estimator.

Table 3-1: Example Exchange Model (EM) (Chen et al., 2013a)

	EM.I/PAL-E Bridge Concept Model
Project Stage	31-10 14 17 Initiation
Exchange Disciplines	(33-11 00 00) Planning, Aesthetics and Landscaping
	(33-25 11 00) Estimation
Description	**Purpose:** this model is created by engineer to help define candidate projects based on program goals.
	Major elements: the content of this model includes but is not limited to 1) a description of the problem, 2) a preliminary project objective(s) and description, 3) project elements to be investigated, 4) preliminary environmental classification, 5) issues or circumstances which may arise, and 6) preliminary schedule.
	Level of detail: conceptual
	Special attributes: project objectives, environmental recommended classification, etc.
Example Software: Export and Import	**Import from:** Mathcad, Microsoft Excel
	Export to: Mathcad, Microsoft Excel
Related Exchange Models	EM.S/SE-E, Bridge Engineering Concept Model EM.PD/SE-E-PAL, Initial Structural Model EM.FD/SE-D-TE-PAL, Final Structural Model

An exchange model can be one of two types: 1) model exchange or 2) non-model exchange. A model exchange is an exchange in the format of a Building Information Model (BIM), which is a digital representation of a building or structure. The format of the BIM model can be any format, which varies by the software program that produced it. A model exchange needs to be software-neutral in order to pass the data from one program to another. A non-model exchange (NME) is an exchange that is not in the form of a digital BIM model, such as PDF, Excel spreadsheet, Word document, BCF, etc. Only the digital BIM model exchanges are described in the exchange models (EM).

3.1.3. Process Model

The bridge lifecycle process can be intense and complex, with numerous phases, actors, and activities. In order to help reduce the complexity and make the process more understandable, a process model is defined to lay out the process in a clear and concise fashion. Processes in construction vary, because of the different contexts, locations, and requirements. No process model is likely to describe exactly what is entailed in the process. A process model roughly classifies the information flows between the different *actors* and *activities* within a *phase* or between *phases*. The classification provides a guide for identifying salient exchanges for a given purpose. They identify the different data exchanges needed to realize a project. Because of the different scopes of process models, there are typical gaps over which information flows cannot automatically span. That is, there is no automated exchange model to map the data between the heterogeneous models. These missing exchanges are important barriers to identify to realize effective meaning of workflows in the project. A process map (often used interchangeably with process model) is defined using BPMN diagram of the process model. The process map represents the project workflow, including the actors (or stakeholders), project phases (or stages), and activities.

As part of a previous FWHA project, the University at Buffalo developed a process map that reflects the workflow of the bridge project lifecycle and specified use cases in the information delivery manual. An information delivery manual (IDM), defined by ISO 29481-1:2010, “specifies a methodology that unites the flow of construction processes with the specification of the information required by this flow, a form in which the information should be specified, and an appropriate way to map and describe the information processes within a construction life cycle."

Figures 3-5 and 3-6 display the notation of the process map. The map is broken up into lanes (rows) and columns. The leftmost column shows the actors (stakeholders). The top most lane identifies the phases (stages) in the process in order of involvement (i.e. the far left is start of the design project and the far right is the end). Each phase and actor has a unique number (e.g. Initiation is 31-10 14 17) associated by the OmniClass Construction Classification System (OCCS, 2015). There are two types of lanes: activity and exchange. The activity lanes, denoted by the actors, display the activity (A) (white rectangles with rounded edges) carried out by the actors at a specific phase in the project. The lanes labeled "exchange" display the exchange models and are there to facilitate exchange flows. The green box exchange models (EM.) identify digital models, and the yellow box non-models exchanges (NME) are non-model files (e.g. PDF, notes, etc.). Since each exchange is uniquely different, they have been named according to phase and stake holders. The format is EM.Phase/Sender-Receiver(s). For example, the "Preliminary Roadway Geometry Model" is in the Preliminary Design (PD) phase and is sent from Transportation Engineering (TE) to Structural Engineering (SE). Therefore the name is EM.PD/TE-SE. Non-model exchanges (yellow) are denoted by NME rather than EM. The direction and flow of the activities are shown by solid arrows, and the direction and flow of the exchanges are shown by dashed arrows.

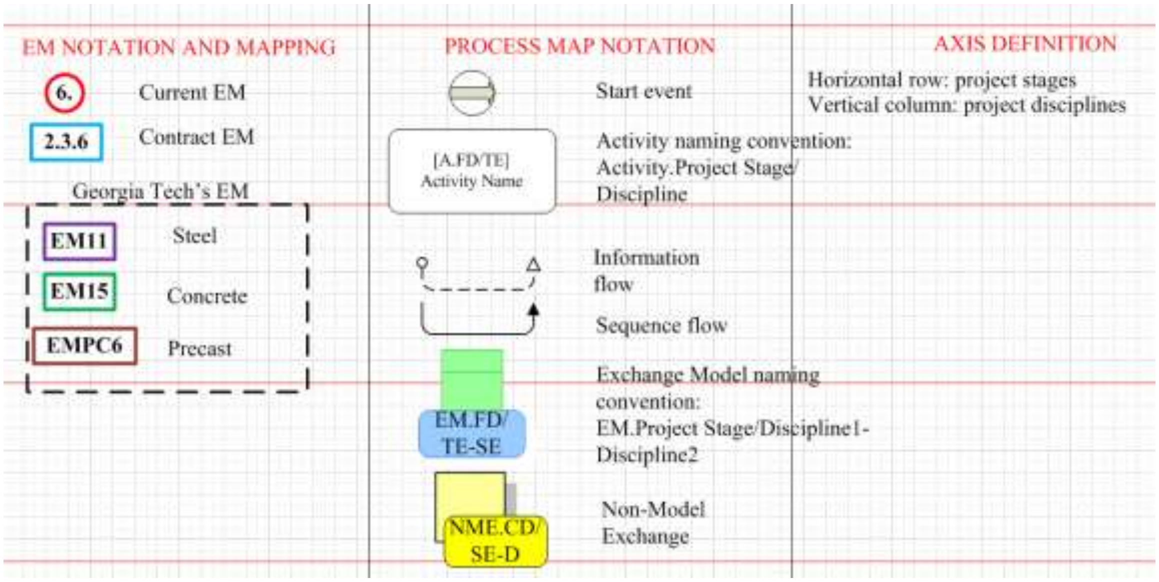


Figure 3-5: Notation of the Bridge Lifecycle Process Map

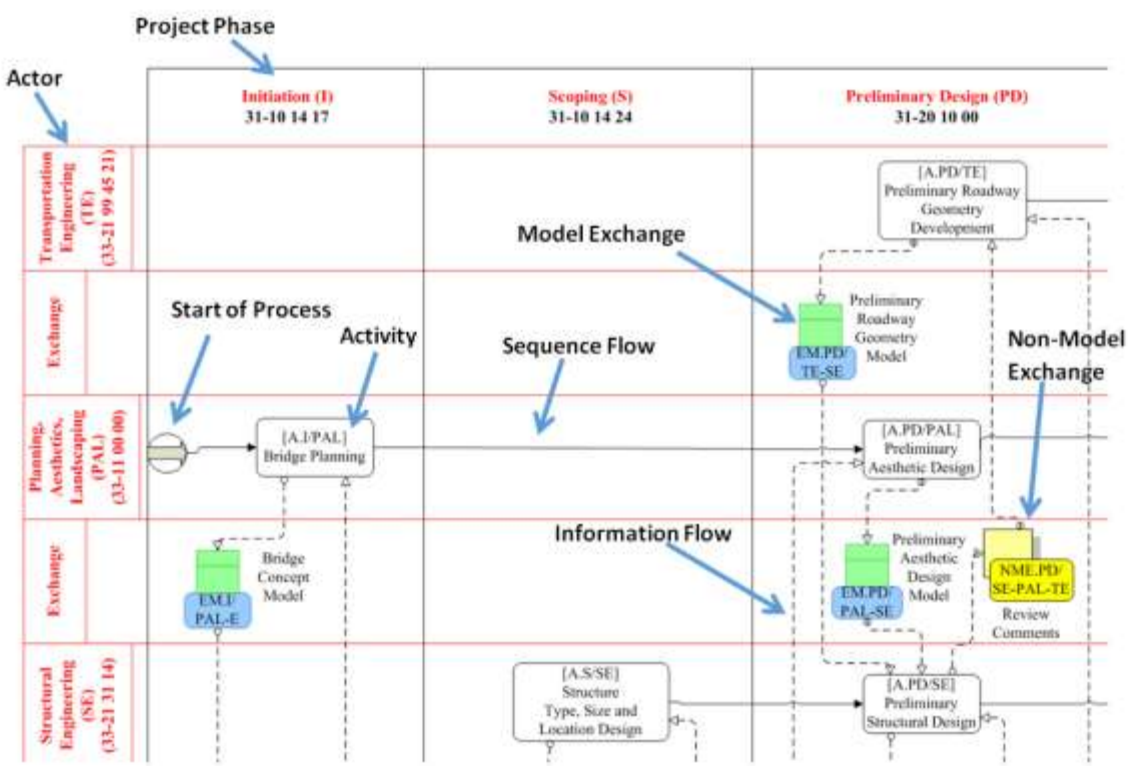


Figure 3-6: Portion of the Bridge Lifecycle Process Map

An initial effort was made to compare the various exchange models defined by 1) initial process map (Chen et al. 2013a; Chen et al. 2013b; Hu 2014); 2) the FHWA contract model (Costin et al., 2015); and 3) Georgia Tech collaborations with industry (DBL 2015a; DBL 2015b; DBL 2015c). Among the theses three sets, there are slight misalignments due to scope, purpose, and exchange model being passes. Therefore, it was proposed that all three sets of exchanges are to be investigated in more detail and determine the best way to merge or "reuse" the information. For example, some exchanges can be one-to-one (use "as is"), while most are partially filled (only some of the data can be used). The intents of the exchanges need to be defined with more detail. Additional work is needed to develop the new exchanges, since it relies heavily on industry input. An initial integration of these is shown in Figure 3-7. However, there is still much work needed to refine the process map and include all the defined exchanges.

In order to visualize the complexity and overarching goal of this BrIM lifecycle process map, the small piece that will be elaborated in this dissertation is indicated by the black arrow in Figure 3-7. This piece, erection processes and analysis, will be discussed in an ongoing case study throughout this dissertation.

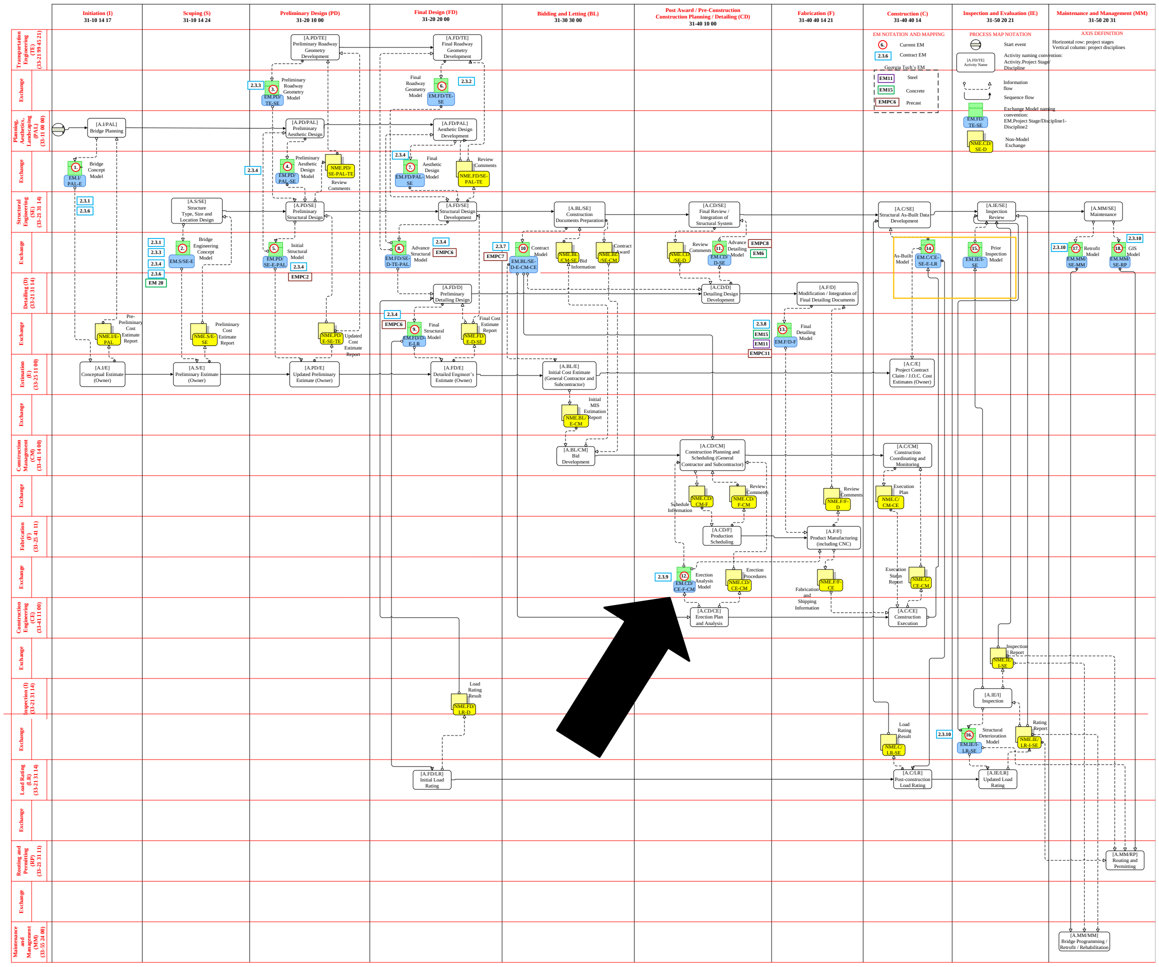


Figure 3-7: Integrated Bridge Lifecycle Process Map

3.2. Summary and Issues

The work and research efforts presented has achieved great amount of success and progress in the steps for achieving interoperability from BrIM. However, there contains some major challenges that need to be addressed, modified, and agreed upon. Although the workflow in this chapter identifies the high level processes in the lifecycle of a bridge, it is not detailed enough to encapsulate all the workflows an activities that are needed in the lifecycle of a bridge. For example, this dissertation identifies the workflow of an erection engineer as part of the case study. In such, the current BrIM process map cannot be used "as-is," but can be viewed as a general guide and as a placeholder of sub process maps.

These issues and changes will be addressed, along with propositions of how to modify throughout this dissertation. If these issues are not dealt with, then problems will continue to aggregate into more problems down the road in a "snowball" effect, which would ultimately derail the effort for achieving BrIM interoperability. In order to continue and promote the work, the following lists the major issues and needs to be addressed:

3.2.1. BrIM Interoperability Process

- Standardize the BrIM Process to increase efficiency and consistency
- Clearly define terminology and definitions
- Identifying what the ultimate goal is, and the steps needed to get there
- Identify the bridge workflow, including the variations

3.2.2. BrIM Documentation

- Standardize the BrIM documentation for consistency throughout the development and process
- Understanding that the current bridge lifecycle process map is not a "one-size fits all" map, but rather a general place holder of an undefined number of "use cases"
- Identify the major "use cases" that will play a major role in developing the bridge lifecycle process map
- Identifying all the major actors, roles, disciplines, phases etc.
- Labeling with the correct notation

3.2.3. BrIM Effort Leadership

- Identify the entity or industry group that will lead the BrIM effort and act as the official authority for the balloting and approval for various standards. As buildingSMART International is the authority for the built environment industry, a similar entity will be needed for BrIM.
- Identify the industry groups to lead their domain in the development of their respective

CHAPTER 4

4. RESEARCH METHODOLOGY

4.1. Research Purpose, Hypothesis and Objectives

4.1.1. Purpose

The purpose of this research is to develop a methodology to achieve interoperability of heterogeneous bridge models. The approach uses a BrIM ontology, which is the formal classification of terms and relations of the bridge industry. This research also develops a new standardization process to establish standard definitions for information exchanges to a general schema. This purpose of this dissertation is not to oppose the current ongoing BrIM standardization processes, but to propose a new methodology that supports and promotes the current efforts to extend to other domains not currently supported.

4.1.2. Hypothesis

The current process of mapping heterogeneous models is done manually for each specific "use case". The hypothesis is that an ontology would allow for automation of this manual process by providing the abstract level of classification of terms that would enable interoperability across heterogeneous bridge models. It is also hypothesized that this ontological approach can provide a method for heterogeneous processes in other domains.

4.1.3. Objectives

The objective of this research is to build a BrIM ontology that would promote interoperability for heterogeneous bridge models by:

- Reducing ambiguity of terms and definitions
- Providing the necessary semantics
- Promoting reuse among bridge and other domains

4.2. Approach

4.2.1. Define New Process for Information Exchange Standardization

Achieving interoperability among heterogeneous bridge models requires a large amount of work and collaboration across many stakeholders, including domain experts, software vendors, and users. There are many processes and workflows that go into the development of any one single software program, and to have interoperability of multiple software programs requires much cooperation and agreement. Additionally, having the software representing and meeting the needs of industry requires the expertise of the industry the software is being developed for. In such, it is imperative that a standard is used for the lifecycle of a piece of software, from conception to implementation, in order to maintain alignment in the process. As there are many ways and processes for developing industry driven software, this dissertation attempts to integrate the best practices into one single process, called the Information Exchange Standardization (IES). In order to be extensible, it is important that this process to not be dependent on any one software, program, computer language, schema, domain etc.

4.2.2. Define a BrIM Taxonomy

Defining the BrIM taxonomy is the first step in developing the BrIM ontology. At the 2015 August FHWA workshop for BrIM, the author proposed that the next step for the project was to define a BrIM taxonomy, which was agreed upon (Appendix A). As the person in charge of the task of developing the taxonomy, the author has the support of the American Association of State Highway and Transportation Officials (AASHTO)

Subcommittee on Bridge and Structures (SCOBS) T-19 Software & Technology subcommittee, National Steel Bridge Alliance TG10/TG15 subcommittee (and others), various State Departments of Transportation (DOT), the National Institute of Building Sciences (NIBS), and the Federal Highway Administration (FHWA).

The scope of the BrIM taxonomy is for steel bridge erection, since that is the case study. The terminology will be captured from all associated documents for steel erection, and utilizes the BrIM Data Dictionary to provide the data attributed needed in the development of exchange requirements. The metadata and specific components needed for the lifecycle of a bridge are defined in the BrIM Data Dictionary, but only the terms needed for steel bridge erection are used in the taxonomy. Chapter 6 and 7 define the development of the BrIM taxonomy in more detail.

4.2.3. Develop a BrIM Ontology

The BrIM taxonomy will be extended into an ontology that can be implemented into software. A thorough review of current ontologies that can be utilized for bridge information modeling is also conducted. The current ontologies that exist in general and for the civil and bridge industries would be summarized. The scope of the BrIM ontology is based on the taxonomy for steel bridge erection. Chapter 6 and 7 define the development of the BrIM ontology in more detail.

4.2.4. Develop a BrIM Workflow

A workflow for the use of BrIM is necessary to define how information is passed through the various stages of the bridge lifecycle. Previous efforts (Chen, 2013a; Chen, 2013b; Hu, 2014) defined a preliminary process model for the lifecycle of a bridge. The process map, including all 18 defined EMs, will be the starting point. As part of the FHWA BrIM project, the author has been in charge of identifying any gaps or misalignments, as well as updating this process map. The project has identified an additional ten exchanges to be used. The goal to incorporate both sets of BrIM exchanges into one process model. In additional, exchange models (EMs) from other industries (ACI, PCI, AISC, etc.) are reviewed to see what can be reused. Reuse of EMs is an important objective of the information exchange process, including the NBIMS. With the development of the process map, it is critical for industry input. At the 2015 August FHWA workshop for BrIM, it was agreed upon that the continued development of this process map is an important task. The scope of the process workflow is for steel bridge erection, which is designated by the black arrow in Figure 3-7 of the bridge lifecycle process map.

4.2.5. Develop a Steel Bridge Erection Information Delivery Manual (IDM)

The scope of the Steel Bridge Erection Information Delivery Manual would only include "workhorse bridges." A workhorse bridge is a typical, simple bridge, such as highway overpasses or interchange ramps. Hu (2014) developed criterion to define workhorse bridges, and based from the U.S. National Bridge Inventory (NBI), workhorse bridges comprised about 90% of all bridges in the U.S., include box beam, girder, slab bridges, channel beam, and tee beam bridges. There are approximately 610,749 bridges in the U.S. according to the NBI (FHWA, 2014). Although there are both steel and concrete workhorse bridges, the scope of the IDM will be the information needed for steel bridge erection of a typical steel girder workhorse bridge. A case study will be used to develop and validated the IDM.

4.2.6. Validation

In order to validate the methodology, one exchange will be selected for further development and a case study. The AASHTO/NSBA TG10/TG15 steel erection subcommittee has been chosen for industry validation for the exchange. They have agreed to support the research effort, and will continue to help define and validate any aspect of the approach (Appendix B). The author has been selected to chair the group through this effort.

CHAPTER 5

5. CURRENT LIMITATIONS OF THE NATIONAL BIM STANDARD

This chapter highlights the current limitations of the National BIM standard (NBIMS) for use of non-building domains. These limitations reveal the need of non-domain specific process to standardize information exchanges. The National Institute of Building Sciences (NIBS), published the U.S. National BIM Standard (NBIMS) to establish standard definitions for building information exchanges to support critical business contexts using standard semantics and ontologies (NIBS, 2015a). In such, it supports and promotes the use of a non-proprietary, software-neutral data file to transfer information between the heterogeneous software: the Industry Foundation Classes (IFC). As the most widely accepted interoperability information exchange standard in building and construction, IFC is becoming the "go to" schema for building information modeling software, which is beginning to include bridges. However, there are current limitations that need to be met before bridges can fully benefit from the NBIMS process and IFC standards.

5.1. IFC Lacks Entities for Bridge and Transportation Domains

Since IFC was intended for buildings, the current release of IFC4 (buildingSMART 2015b) is not domain specific for bridges. It lacks some of the information (e.g. definitions, entities, concepts) needed to design bridges. There have been efforts to expand IFC to accommodate bridges. One way to use IFC for bridges it to develop extensions to be adopted in future releases of IFC. A major international research effort was undertaken to produce the IFC-Bridge extension (Yabuki et al., 2006). This effort lead to a proposed an extension of IFC to capture information related to the whole bridge lifecycle, which includes roadway alignment, general bridge structures, geometries, and other properties specific for the bridge domain (Lebegue et al., 2012). It aims to expand IFC for transportation infrastructures, but it has some drawbacks, such as it does not have a definition for a parabola, which is an important type of vertical curve (Hu, 2014). Efforts have been made to better define alignments and curves in IFC (in which IFC currently lacks), which are critical components for designing roads and bridges. Lee and Kim (2011) contain a number of extensions that led to dedicated model extensions covering bridges and roads. Amann et al. (2014) identifies some drawbacks of proposed alignment extensions, such as that LandXML is missing a C-Clothid curve type, OKSTRA is missing a sinusoid curve type, and RoadXML and the IfcAlignment Proposal (Amann et al., 2013) lack the support of a Bloss transition curve type. Therefore the Lee and Kim (2011) proposed to extend IFC4 to describe a general alignment model that can be used in the field of infrastructure to describe road, tunnel and bridge alignments. In order to integrate logic models, which incorporates the design knowledge and intent into the model, into IFC, Jubierre and Borrmann (2014) presented an alignment model, a tunnel axis model, and a ring configuration model. The previous extensions provide significant breakthroughs for modeling bridges in IFC. However, until they are certified and incorporated into the next release of IFC, they are not able to be used as a standard.

Even with efforts by buildingSMART International to create "IFC-Bridge," it is still not being used due to limitation and issues. Dumoulin and Benning (2014) identify that IFC-Bridge lacks major components such as prestressing system, suspension system, and alignment. Moreover, Dumoulin (2015) states that the major limitations include 1) no integration with authoring tools, 2) no viewers available, 3) major concepts in IFC are missing, and 4) geometric representations are inadequate. Therefore, additional effort is needed to modify the previous work in order for bridges to be adequately represented in IFC.

The previous efforts of proposing extensions are tedious, time consuming, and shown to be inefficient. It has been nearly a decade since the extension of IFC to incorporate bridges has been proposed, and it is still not in the current release. The extensions will have to be validated and approved by buildingSMART, which is a long and slow process, and will result in new releases of IFC. Moreover, creating new IFC entities will increase the redundancy and complexity of the IFC schema (which has been previously discussed in Chapter 2). Having new releases on an adopted schema causes software developers to have to implement any new changes, which is time consuming and may lead to additional errors.

Chapter 8 discusses in more detail how the current IFC4 can be extended for bridges and other infrastructure. It highlights the current progress of ongoing projects. Additionally, Chapter 8 presents an approach to minimize the addition of redundant entities to the IFC schema by utilizing already defined entities with the use of concepts and semantic exchange modules (SEMs).

5.2. NBIMS Not Extensible to Other Industry Domains

The purpose of NBIMS is "is to advance the art and science of the entire lifecycle of the vertical and horizontal built environment by providing a means of organizing and classifying electronic object data and thereby fostering streamlined communication among owners, designers, material suppliers, constructors, facility managers, and all stakeholders associated with the built environment" (NIBS, 2015b). Since the focus is on the building and facilities, the NBIMS process is tailored and specified for the building industry, such as using IFC, the OmniClass™ Construction Classification System, buildingSMART Data Dictionary (BSDD), etc. Therefore, NBIMS cannot be directly used for other non-building domains, including the bridges, "as-is."

“The Information Exchange Template, BIM Exchange Database, the Information Delivery Manual (IDM), and Model View Definition (MVD) activities together comprise core components of the NBIM Standard production and use process” (NIBS, 2007). Each of these documents is heavily geared towards the development of IFC software implementation. A supplemental document, “An Integrated Process for Delivering IFC Based Data Exchange” (Davis et al., 2012), was published buildingSMART International to outline the IDM and MVD process in more detail. An IDM captures and defines the processes from a specific industry domain. Its purpose is to identify exchange requirements of the information being exchanges, and the software that is exchanging the information. The four phases of this document are: 1) requirements definition (IDM); 2) solution design by creating model view definitions (MVD) of IFC subsets; 3) software implementation and certification of the IFC data exchanges; and 4) BIM validation. Although Davis et al. (2012) states that the IDM and IDM development can be extended to be used for other schemas outside of IFC, it still is heavily favored IFC and does not provide any details or examples for non IFC implementation. The document also states that “the main goal of MVD is to enable high quality IFC implementations that satisfy a given set of data exchange requirements defined in one or more IDMs.”

While Davis et al. (2012) lacks the information needed to create information requirements from other non-building domains, it does provide key general concepts that will be used in a formal information exchange standard outlined in Chapter 6. However, there is still need to have the process outlined in a way to not be dependent on any one schema, software applications, domain, etc. in order to be expandable and extensible.

5.3. The Processes within the NBIMS are Vague, Ad-Hoc, and Time Consuming

The NBIMS does include guides on the processes and timelines needed to create and use interoperable exchanges, however, but there is no standard way to do so. In other words, it lacks the “how” in achieving this. For example, there is no guide or order to get industry input to produce the documentation. The current method to capture the information is to use Excel spreadsheets and continuously have meetings to agree over matters. This has been shown to be tedious and time consuming, and the productiveness and progression is based up each group that uses the standard to build their own exchanges. Without a set standard and process to capture industry input, the process of creating interoperable exchanges will continue to be a tedious process and will minimized the widespread use and adoption in industry.

This dissertation focuses on data capture from industry, and it will propose a set standard and methodology that will minimize the current ad-hoc approaches. This methodology is presented Chapter 6 and is intended to be used in conjunction to the NBIMS.

Model Views are an important aspect of defining the subset of IFC schema needed for a specific task, since the IFC schema is very redundant. Eastman (2012) reviews the current BIM Standards for Model Views. In summary, Eastman (2012) states that concepts are defined too low level and incompletely, concepts are not formally defined, Model View Definitions (MVD) are too time consuming to develop (18-36 months), MVDs are very rigid and too poor for collaboration, and testing is onerous and not supported by many companies. Therefore, to address these issues, there has been a push by academia in the development of Semantic Exchange Modules (SEMs) (Venugopal, et al. 2011; Eastman, 2012; Venugopal, et al. 2012, Belsky et al., 2014). Am SEM is a structured, modular subset of the objects and relationships that layers IFC and native data objects binding. SEMs are discussed in more detail in section 8.4, and how they can be utilized to integrate bridge concepts into IFC.

5.4. The Terminology and Definitions are Ambiguous

The NBIMS contains a lot of definitions from the various sources that are very similar. Additionally, publications (including those in the literature review section) in the fields of AEC and process modeling that reference the NBIMS also have similar terminology. Since there is no set clarification of each term or distinction of use, many terms are used wrongly. Because of this, exchanging information and understanding the NBIMS process can be confusing, tedious, and error prone. Below lists the groupings of words that are commonly used synonymously:

- Process map and process model
- Information exchange, data exchange, exchange model, and exchange
- Life-cycle, lifecycle, and life cycle
- Stage and phase
- Actors, stakeholders, and disciplines
- Model, data model, information model, BIM model
- Workflow and process
- Information, data, and knowledge
- Neutral file, neutral form, neutral schema, neutral format, and neutral exchange

The NBIMS utilizes the terminology from IFC, such as "exchange", "exchange model", "model view definition", etc. However, the use of ambiguous terms that are not explicitly defined cause miscommunications and misunderstandings between those who are knowledgeable in IFC understand the terminology and those who are not knowledgeable in IFC. This is seen commonly in the industry development phase. Although seemingly inconsequential, these miscommunications can potentially cause larger issues in the process. Therefore, it is important that clear definitions are made available upfront.

The documents of buildingSMART reference a published glossary (buildingSMART, 2007) that identifies the terminology that is currently used in the processes that was accessed from the current buildingSMART website (buildingSMART, 2016a). Unfortunately, where each term was referenced from and how the final definition of each term was approved are unknown. There are some few grammar mistakes, and the document says “DRAFT” as its status. Additionally, there are some commonly used terms that are not in the glossary. The following terms are not defined in the glossary (buildingSMART, 2016a):

- Exchange Model (EM)
- Model View Definition (MVD)
- Information Exchange
- Information Delivery Manual (IDM)

As part of the BrIM taxonomy, this dissertation clarifies the definitions and use of the terms used in attempts to centralize the terminology used in buildingSMART with the various terminologies published in the bridge industry (AASHTO, DOTs, FHWA, etc.). In order to be aligned with the current buildingSMART terminology, the BrIM taxonomy will use the definitions “as-is,” but further consensus and approval will be required.

CHAPTER 6

6. INFORMATION EXCHANGE STANDARDIZATION PROCESS

Information exchanges to support critical business workflows are important aspects to achieving interoperability. Establishing standard definitions for information exchanges are critical for reuse, which requires a standardized process to do so. As mentioned before, the National BIM Standard (NBIMS) is one example of an information exchange standard for standardizing information exchanges. NBIMS was chosen since it is the primary standard for BIM, in which BrIM extends from. However, NBIMS is limited to only the building industry as the only output is IFC. At the time of this writing, the current IFC release (buildingSMART, 2015b) does not include bridges, and thus the NBIMS cannot be used for BrIM. Therefore, it is imperative that there be an information exchange standard that does not rely on a single schema, but allows the user (or software vendor) to choose the schema. Not only will this be significant for BrIM, it will allow for other industry domains to use it as well.

This chapter explains the new information exchange standard (IES), which is a methodology to create standardized information exchanges for any domain. Instead of creating a new standard, it was deemed more appropriate to leverage existing standards. The IES utilizes the methods presented in the NBIMS (NIBS, 2015b), but will keep the output open and objective. For instance, instead of having IFC as the only neutral information exchange, the output allows for any neutral information exchange. This is important because 1) it allows for IFC and 2) it allows for other standards outside of the building industry to use this process. The bridge industry is considered to be the latter, since IFC does not support bridges in its current state (Chapter 8 discusses how IFC can be used for bridges). This chapter also uses a case study that validated the IES.

Although “data exchange” and “information exchange” are commonly used interchangeably, it is important to note there is a subtle, but meaningful difference between the meanings of the root words "data" and "information." Simply put, data are facts while information provides context and meaning to data. For example, a data exchange sends the data from one source to another (and then the computer produces information from that data), but an information exchange sends data along with meaning and context of how to use the data. Therefore, in this research, the exchange between schemas (i.e. transformation of structured data) will be referred to as “data exchanges,” but exchanges between processes or actors will be referred to as “information exchanges.” With this clarification, data exchanges are a subset of information exchanges, thus information exchanges can be assumed to include data.

One important clarification to note is that a taxonomy is developed, approved, and used by industry experts and users. An ontology is the extension of the taxonomy that can be mapped into other schemas or directly to software, which is more geared toward software developers (more distinction and technical details are provided in Chapter 7.) Therefore, with this distinction, the goal of this chapter is to have the final output be a taxonomy, since the IES is geared towards industry use. Moreover, this chapter explains how to define terms and create a taxonomy. However, once a domain taxonomy is developed and approved, the terminology would neither need to be defined again nor the taxonomy need to be created again, as one of the major benefits of this approach is reuse.

It is important to note that the purpose of the IES is not to replace or become an alternate solution to the NBIMS, but rather to allow other domains (including bridges) that cannot utilize IFC to be able to develop interoperable models. In fact, one of the goals of the IES is to have IFC as one output schemas that the taxonomy and ontology can map to. The IES separates out all depended schemas and software programs to keep the process open and extensible. The final output schema and software solution can be determined by the industry using the IES.

A case study was used to validate the methodology of the IES and show the feasibility of industry development and implementation. The selected industry group was the AASHTO/NSBA Steel Bridge Collaboration, which is a joint effort between the American Association of State Highway and Transportation Officials (AASHTO) and the National Steel Bridge Alliance (NSBA). The collaboration contains representatives from the Federal Highway Administration (FHWA), state departments of transportation (DOT), academia, and various industries related to steel bridge design, fabrication and inspection. The mission of the collaboration is “to provide a forum where professionals can work together to improve and achieve the quality and value of steel bridges through standardization of design, fabrication and erection.”

The presented information exchange standardization process was developed based on the current NBIMS, open standards, previous research, and the ongoing case studies. Although the scope of this dissertation is for the bridge domain, this process and methodology is designed to be open and extensible so that any domain can use this process. It is important to note that this is not intended to be a technical standard, so it does not focus on minute details of each step, but rather the overall methods for the process. In addition to the process outlined in this chapter, the technical portion of this process is explained in more detail in Chapter 7. Therefore, both chapters work in tandem. The IES consists of the following major steps:

1. *Capture Domain Knowledge*: Capture the knowledge of a specific domain that will need to be exchanged in various forms. Any and all data about the specific use case need to be addressed. Information includes documentation about various processes, needs, and requirements needed to achieve the end objectives.
2. *Organize Knowledge in Usable Format*: The information captured in step one needs to be organized in clear and legible format. The information will be

sorted based on a specific use case. This format needs to be in a machine readable form so that software applications can implement the information.

3. *Design and Approval of Specification*: The organized data need to be approved to continue the development of specification.
4. *Implement into Software*: The approved specifications will be implemented by software vendors into applications.

Each step of this process consists of sub steps within. This process is intended to be evolving, and thus will contain iterations. In order to illustrate each process, the case study will be presented throughout the steps.

6.1. Step1: Capture Domain Knowledge

As with the first phase of the NBIMS approach, *program*, the first step is to collect the domain knowledge. This domain knowledge is the real-world information that needs to be modeled in software applications. Industry input and collaboration is critical since they provide the information needed to be exchanged.

6.1.1. Step1.1: Organize Industry Collaboration Group

Industry involvement is imperative to gather the information that is needed to be modeling in software. Whether an official organization or a joint collaboration organizing, a group is important to gather and vet information. Each industry will have its own respective governing bodies, so it is important to investigate what is the most appropriate way to form a group. It is important that the group has a variety of domain experts in order to discuss and vet the information. Eventually the group will need to incorporate software vendors to discuss implementation options.

There are three categories that need to be represented in the group formation: 1) domain experts, 2) end users, and 3) software developers. Domain experts are the people who work, have experience, and are knowledgeable in the domain, and thus can provide the most accurate knowledge base. End users are the people (who may be domain experts) that would be using the final software. Their input is critical because they know what they need from the software application, and they will understand the subtleties that are commonly missed by software developers. Software developers provide the practicalities of how the applications could be developed, and having them on board early can help address and reduce any software issues that may have arisen without them.

One possible limitation that would need to be addressed when forming a group would be the financial incentive of people allocating their time for the group. It is expected that most people have very limited time to spend, so it is important to address time and cost commitments upfront. The need for interoperability of software applications has shown that there are great financial incentives in the long run, and many companies are willing to support the efforts. Moreover, there are funding opportunities through various organizations to support research and interoperability efforts, such as the case study in this dissertation and the ongoing efforts detailed in Chapter 8.

6.1.2. Step1.2: Identify the Workflow

A workflow is a sequence of processes that pass information from initiation through completion. The purpose of a workflow is to identify and document the necessary activities in order to complete a task. A workflow contains actors, activities, and phases that need to be identified. Essentially, any person or organization that has a part in the workflow, no matter how small or seemingly insignificant needs to be identified. The iteration process will refine the scope and filter out any unnecessary information, while identifying important information. Before identifying the information that needs to be exchanged, it is important to identify and understand the process in which the information are produced and consumed. As part of the NBIMS, the process model is an excellent tool to identify the actors, stages, and activities that are involved in the workflow. Chapter 3 describes in detail what a workflow is and how one is created (within the scope of bridges).

There may be cases in which a workflow can contain multiple variations or scenarios to achieve the final goal. One major example in construction is design-bid-build (DBB) projects versus design-build (DB) projects, in which both project types follow a general workflow for construction and achieve a final goal of a build environment, but the processes within vary vastly. Therefore, it is important to identify each specific scenario, which is considered a use case. It is recommended to start with one use case to understand how the process works, and then continue to develop other use cases. The information and data exchanges will be able to be reused.

There is no standard of how industry knowledge needs to be captured since each industry domain may have its own standard or methodology that governs the industry. It is recommended that the industry standards are utilized first. From there, workflows within can be identified to fit the scope.

6.1.3. Step1.3: Modeling the Workflow

Process modeling is an appropriate tool to document and visualize processes of a workflow. A process model identifies the information flows between the different actors and tasks the actors carry out during a project workflow. A process model is a narrative of how the specific process works. In order to visualize a process model in graphical form, a process map is used with various modeling notation.

Business Process Model and Notation (BPMN), organized by the Object Management Group (OMG), is an international standard for business process modeling that is used to support business processes (OMG, 2015). As part of the IES, BPMN was chosen as the basis of the modeling standard, which includes utilizing the rules and best practices for modeling a process. For instance, there is no one way to design the process map (which is called a Business Process Diagram in BPMN) as long as it accurately portrays the real-life event and follows the rules. The Object Management Group (OMG) is the not-for-profit international organization that manages and maintains BPMN. As the end goal is to identify and document to workflow, any modeling notation can be used as long as it is clear and concise. Software programs are also available to model a process, but it is not in scope of this dissertation to explore software.

In order rectify some of the issues with the process modeling mentioned in Chapter 3, this dissertation adheres to the rules and guidelines of BPMN (OMG, 2015). BPMN has been one of the most widely used notations to model and visualize business process. Although any notation can be used to model the process of a domain, it is recommended that a well-known and coherent notation is used. In addition to what is outlined in Chapter 3 and the notation in OMG (2015), the following clarifies the notation that is used in this dissertation and case study (note that this list is not exhaustive):

6.1.3.1. Activity

An activity, which includes tasks, loops, and subprocesses, is the individual and executable act that takes place in a process where something is done. The notation for the activity is displayed in Figure 6-1.

- A task is a simple activity, in which the process cannot continue without the task being complete.
- A subprocess is an activity that contains multiple activities that is needed to complete the initial task.
- A loop is an activity that repeats until the desired result is complete.

The proper naming conventions for the activity is in the verb-object scheme, in other words “do-what.” Examples include “Review model,” “Prepare Bid,” and “Erect Bridge.” This format makes the activity names clear and concise.

(a) (b) (c)

Figure 6-1: Activity notation: (a) Task; (b) Subprocess; and (c) Loop.

6.1.3.2. <u>Sequence Flow and Information Flow</u>

A sequence flow connects the objects to represent the order of the process, which typically connects activities and events. An information flow, or message flow, represents the passing of information from one source to another, such as messages or data objects. Figure 6-2 represents the notion of both flow objects.

Figure 6-2: Sequence Flow (left) and Information Flow (Right)

6.1.3.3. <u>Data Object</u>

An artifact is an object representing information relevant to the process. A data object is a type of artifact that represents information passed from one source to another. As mentioned in Chapter 3, this dissertation distinguished between two types of data object. The first is called a model exchange, which represents the data that is passed in model form (i.e. BIM model data). All other information that is not in machine readable model form (e.g. PDF, excel, documents, etc.) is considered a non-model exchange. Figure 6-3 displays the different types of data object.

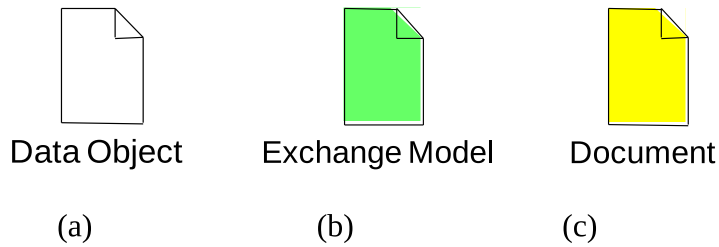


Figure 6-3: Data Objects: (a) General; (b) Model Exchange; and (c) Non Model Exchange.

6.1.3.4. Event

An event is a thing that happens at a point in time that triggers another thing in a process. For example, plain events can signal the start or end of the process, and a message event can dictate a condition at a gateway. Figure 6-4 displays the notations for events.

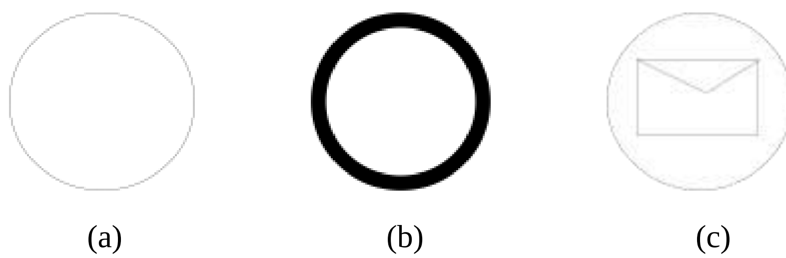


Figure 6-4: Event notation: (a) Plain Start; (b) Plain End; and (c) Message.

6.1.3.5. Gateway

A gateway is used to control sequence flow when there is a decision to be made or a circumstance to be met. Figure 6-5 displays the notation for an event-based gateway, in which an event, such as a message, triggers the process to make a decision. For example, an event for a general contractor might be “Receive Bid Award Response” from the owner (via a message event) in which “yes” would signify to proceed with construction documents (since they got awarded the project), but a “no” would signify to end that process and prepare another bid for another project.

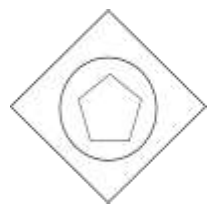


Figure 6-5: Event-Based Gateway Notation

6.1.3.6. Pool

A pool is used to contain the process conducted by an organization. If an organization contains multiple entities that are part of the same process, there may be additional swim lanes within the pool (Figure 6-6).

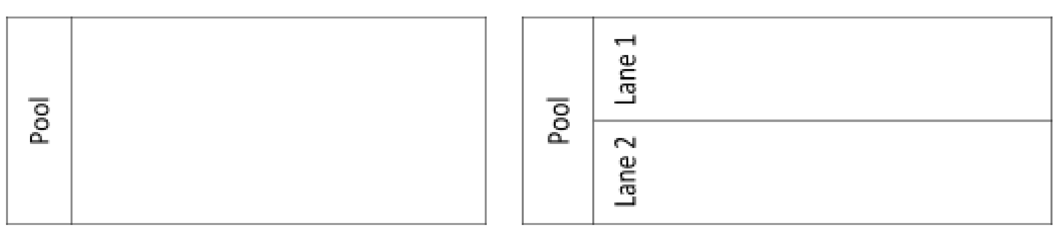


Figure 6-6: Single Lane Pool (left) and Multilane Pool (right).

The current Bridge lifecycle process map (Chapter 3) designates each actor as a separate organization, and thus they are in single lane pools. If two or more actors that are part of the process belong to the same organization, then it is permissible to have multiple lanes. For example, an erection engineering firm may contain both the erection engineer and the erector. However, in order to not constrain the actors into a single organization, this dissertation assumes each actor is its own entity.

Although a pool contains the process of a single organization, processes can be influenced by other organizations. Therefore, it is common that multiple pools are grouped in a process model, such as the cases of the bridge lifecycle process map and the case study. However, it is to note that there are certain rules and restriction that must be adhered to. Only information flows can pass between pools, which means any data object or message can be sent and receive between pools, but not sequence flows. This means pools cannot share activities or gateways.

6.1.3.7. Group

A group is another type of artifact that is used to organize objects that are similar. Although a group is optional, it is used to emphasize the relationships between objects, such as activities (Figure 6-7).

Figure 6-7: Notation of the Group Artifact

For example, since activities and sequence flows cannot be shared across pools, a group can be used to signify that activities of separate pools are related.

6.1.3.8. Modeling Rules

As mentioned earlier in this chapter, BPMN notation has rules and guidelines that need to be adhered to for proper modeling (OMG, 2015). Below highlights and clarifies some rules used in this dissertation:

- Each swim lane (row) denotes a disciple/actor
- Each column denotes a phase
- An activity does not require an input, but does require at least one output
    - Activity could have either a Document Exchange or Exchange Model as an input or output
- An activity is disjoint of other actors, meaning that the activity represents what an actor does
    - "Group" will be used for a common activity, such as "pre construction meeting." This means each actor involved in "pre construction meeting" will have their own activity, and may have an input and/or output
- Sequence flows can be disjoint
    - This means that one activity does not rely on another
- Document Exchanges can have one and only one start point, but one or many receivers (one-to-many relationship)
    - Bi-directional exchanges still need to be one-to-many, but they may be represented by bi-directional arrows.
- Exchanges Models can have one and only one start point, but one or many receivers (one-to-many relationship)

    - Bi-directional exchanges still need to be one-to-many, but they may be represented by bi-directional arrows.
- Both information flows and sequence flows have one and only one start point and may have one or many endpoints (one-to-many relationship)
    - Sequence flows need a gateway to split the flow
    - Gateways are used to separate information flows to multiple destinations
    - Iterations are denoted by 1) the "loop" activity box if the activity itself is iterative, 2) having one arrow from the activity 1 to activity 2, followed by an arrow from activity 2 to activity 1, 3) or bi-directional arrows signifying (but still needs to adhere to one-to-many relationship).
    - A sequence/information flow cannot start and end at the same point
    - A sequence flow cannot pass between pools
    - An information flow can pass information between pools

6.1.3.9. Information Gateway

In this dissertation, the process map has two main uses, or viewpoints, of how it is supposed to be read: 1) For the industry to have a visual representation of the process and how everything works together; and 2) For software programmers to know how the information is being transferred. Unfortunately, these two views of the process map may have discrepancies of how the process model should be represented. For example, the traditional communication about the project happens between the Owner and General Contractor, and not between the Owner and the Subcontractors such as Erection Engineer or the Erector. Thus, anything from the Owner is typically passed through the General Contractor. The Bid Model exchange is from the Owner to the General Contractor, Erection Engineer, and Erector. In reality, the Bid Model is sent from the Owner to the General Contractor, and the General Contractor passes the model to the Erection Engineer, which is then passed to the Erector (assuming that the erector is a subcontractor of the Erection Engineer). This passing of information is represented in Figure 6-8a. However, as far as the information flow is concerned, the Bid Model originates from the Owner (i.e. sender), and is received by each actor (receiver). Thus, this information flow is represented in Figure 6-8b. Both representations are true; Figure 6-8a represents the reality of information flow in the viewpoint of industry, and Figure 6-8b represents the true information flow in the viewpoint of software programmers.

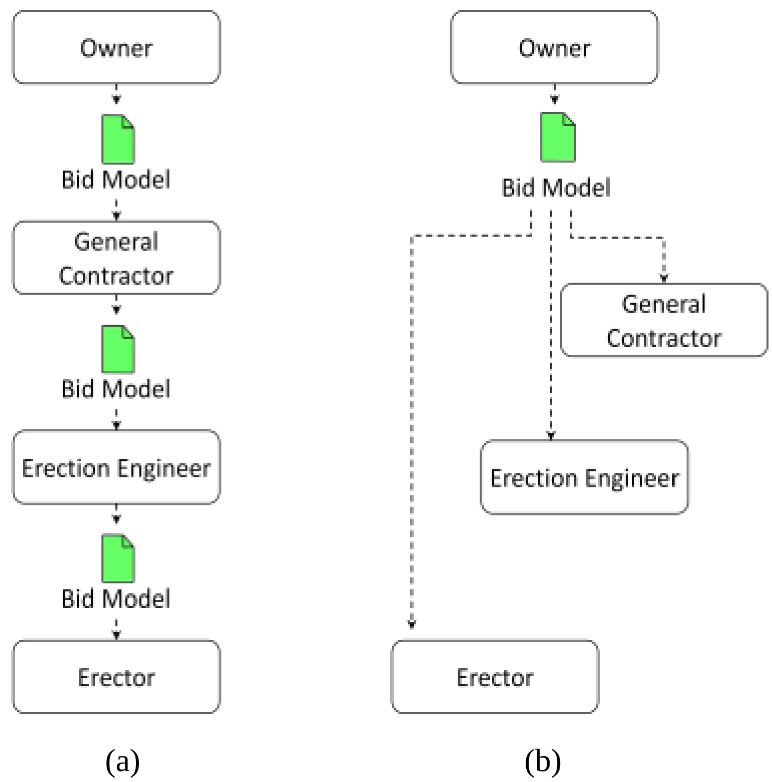


Figure 6-8: Process Diagram of Information Flow: (a) Industry Viewpoint of Reality; (b) Software Programmers Viewpoint of Information Flow.

Currently, there is no proper way in BPMN to combine both the viewpoints. One way to do so would be to us a gateway, in which the model can pass to multiple receivers. Unfortunately, information flows (dashed lines) cannot connect to gateways (VPI, 2009). Another way is to use Text Annotations to annotate the meaning of the information flows, but this may still confuse the readers. Therefore, in order to merge both viewpoints, this research created the “information gateway”. Information gateways are modeled from the traditional BPMN gateways, but are solely intended for data/information transfers. Specifically to the case above, the “Pass-Through” information gateway was created (Figure 6-9a). The design of the pass-through gateway is taken from the traditional gateway with the diamond shape, but is a dashed line to signify information flow. In the middle, the right arrow crossing the vertical line signifies the pass-through. Figure 6-9b displays how the gateway works. Information is sent in from the left to the gateway. The arrow on the right signifies the entity that the information passes through. It is to note that the pass through entity can have its own copy of the information, but cannot modify the original information that is passed along. Finally, the arrow on the bottom is where the information is actually being sent to.

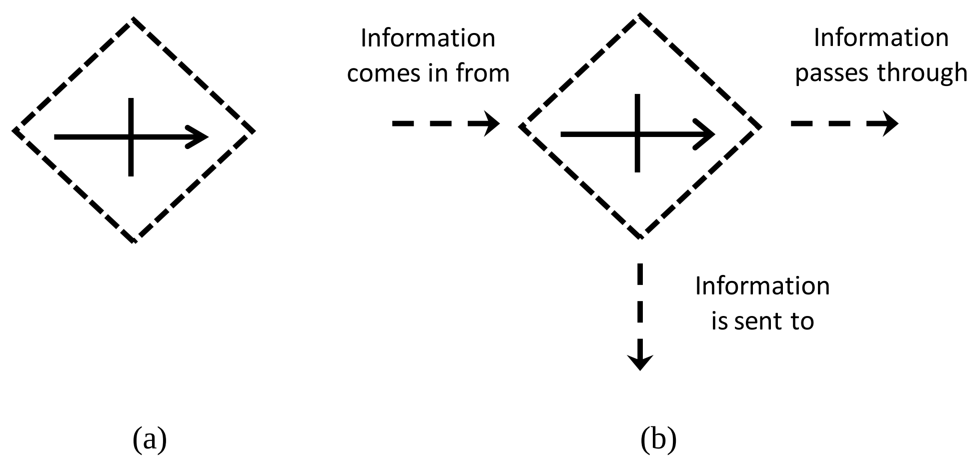


Figure 6-9: (a) Pass-Through Information Gateway; (b) Pass-Through Information Gateway with Notation of Use.

Figure 6-10 displays the actual use of the scenario mentioned above. Note that the boxes are not in proper form, but is for demonstration purposes only. The Owner sends the Bid Model to the General Contractor. The General Contractor then passes the un-modified Bid Model to the Erection Engineer. If the General Contractor sent a modified model, the original exchange model (Bid Model) between the Owner and Erection Engineer would be null, and a new exchange model between the General Contractor and Erection Engineer would be needed. Next, the Erection Engineer passes the Bid Model to the Erector. Now, each the General Contractor, Erection Engineer, and Erector have the Bid Model sent from the Owner.

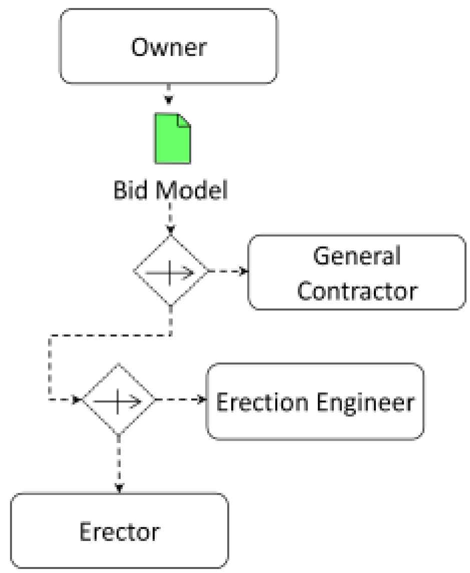


Figure 6-10**:** Process Diagram of the Bid Model Being Sent from the Owner to Each of the Receivers Using the Pass-Through Data Gateway.

It is important to note that the current process map is not written in machine readable BPMN, but just adopts the notation for modeling purposes. Although it was originally indented to be a modeling language, BMPN 2.0 has guidelines to implement with Web Services Business Process Execution Language (WSBPEL), which is a standard executable language for business processes (OMG, 2015). Together, these two provide both the graphical representation and execution language for business processes.

6.1.3.10. Definitions

The current NBIMS has ambiguous and undefined terms that are commonly used, resulting in miscommunications and misunderstandings. In order to align and clarify the terminology, this section organizes and defines the terms in a clear and concise fashion. Although these terms are used in this dissertation, they will still need to be officially approved before implementation. This list is not exhaustive of the terms, but highlights the terms that are ambiguous or undefined.

Data: The quantities, characters, or symbols on which operations are performed by a computer, being stored and transmitted in the form of electrical signals and recorded on magnetic, optical, or mechanical recording media. Data are the bits and bytes, in which information is needed in order to give meaning to the data.

Data Exchange: Exchange of data (i.e. bits and bytes) between two sources, often involving the transformation of the structure from one schema to another. A data exchange differs from an information exchange because information gives meaning to the data that is being exchanged.

Exchange Model (EM): A software-neutral and semantically rich data definition of the content needed in the Information Exchange. An EM is typically passed in model form, such as a 3D BIM model or the analytical model. The

Exchange Requirement (ER): The set of data that needs to be exchanged to support a particular activity or business requirement. An ER can be viewed as a subset of data needed from the Exchange Model, as the whole model is passed, but not all the data is needed for that particular requirement.

Information Delivery Manual (IDM): specifies a methodology that unites the flow of construction processes with the specification of the information required by this flow, a form in which the information should be specified, and an appropriate way to map and describe the information processes within a construction lifecycle (ISO 29481-1:2010).

Information Exchange: The set of information passed between two sources, which include data along with documents and other information that give meaning and context of how to use the data. Information includes all supplemental documents and procedures that give data context and meaning. An information exchange can be in model form (e.g. CAD model), called an Exchange Model, or other forms (e.g. PDF, emails, documents), called Non-Model Exchanges.

Model View Definition (MVD): defines a subset of the IFC schema that is needed to satisfy one or many Exchange Requirements of the AEC industry. An MVD are encoded in a format called MVDXML, and define allowable values at particular attributes of particular data types (buildingSMART, 2016b)

Phase: Temporal, disjointed segments of a period of time in a process, often denoting a where a set of activities take place.

Process Map: The visual representation of a process model in a graphical workflow diagram. Modeling notation, such as BMPN, is used to represent the various objects in the process model.

Process Model: A description of a business process that identifies the information flows between the different actors and tasks the actors carry out during a project workflow.

Use Case: A specific event of a broader defined process, in which there is only one way of completing a specific goal. In other words, there is no “or” option, in which each would be their own use case.

6.1.4. Step 1.4: Document the Workflow

An Information Delivery Manual (IDM) has been the traditional method of documenting the procedure of capturing the domain knowledge and providing the requirements needed for information exchanges. ISO 29481-1:2010 defines an IDM as “the methodology that unites the flow of construction processes with the specification of the information required by this flow, a form in which the information should be specified, and an appropriate way to map and describe the information processes within a construction lifecycle.” However, as the goal of this process is to be non-domain specific, ISO 29481-1:2010 should be used as a methodology guide, rather than a standard, since the purpose of the ISO standard is to provide the specifications for building information modeling.

There have been many developments of IDMs, but they mainly focus on defining the subsets of IFC by the use of Model View Definitions (MVD). Therefore, this dissertation does not detail the use of Model View definitions. Additionally, since the scope of this dissertation is to capture industry knowledge for software development, the software portions will not be defined in detail. Chapter 7 explains the technical portion of capturing the information and conversion into machine readable format (ontology) that software vendors can use to implement into software.

Process modeling is an iterative process, so there is no set way of creating a process model. However, it is important to document the process. The following features need to be identified:

6.1.4.1. Definitions

Definitions allow for better communication since any ambiguous or unfamiliar term can be clear. Additionally, having defined terms in the process is imperative to maintain coherency and consistency. The taxonomy provides the term definitions. Note, for first time defining of definitions (i.e. taxonomy hasn't been created or approved), it is important to use terminology that is defined in the relative domain.

6.1.4.2. Actors

Any individual or organization that plays a role needs to be identified. Actors will be defined in the taxonomy.

6.1.4.3. Assumptions

Listing out assumptions help reduce and clarify the scope of the specific use case. Since there may be multiple scenarios or use cases, listing out the assumptions will align the process and focus on the identified use cases. Assumptions also allow the industry representatives to remain focus and succinct in the taxonomy development.

6.1.4.4. Activities and Events:

All activities and events that are fundamental to the process needs to be identified and described.

6.1.4.5. Exchanges:

Any information that is passed from one actor to another is an exchange. This includes both Models (Models represent the data models) and Non-Models (Documents). Additionally, identifying the exchange requirements are important for the production of the taxonomy.

6.1.4.6. Phases

If a process has various phases, it is important to list and describe the phases. This section can also serve as a high level overview of the processes within each phase.

6.1.4.7. Notes and Comments:

A section to contain all miscellaneous information, such as notes and comments, is important to have to track the progress of the development.

6.1.5. Case Study: Capturing Steel Bridge Erection Domain Knowledge

The American Association of State Highway and Transportation Officials (AASHTO) and National Steel Bridge Alliance (NSBA) collaboration is a national group of steel bridge experts dedicated to improving steel bridge design, detailing, fabrication, and construction through the development of best practice consensus. There are sixteen task groups within the collaboration to accomplish specific goals related steel bridges. Task group 10 (TG10), Erection, is committed to achieve steel bridge design and construction of the highest quality and value through standardization of the erection processes. Task group 15 (TG15), Data Modeling for Interoperability, facilitates the development of bridge standards for data description, modeling, and interoperability. Together, these two task groups formed a subcommittee, TG10/TG15, which has been the forerunner in the development of BrIM standards and this dissertation. The mission statement of TG10/TG15 is "to determine and provide the erection engineering information needed to support the development of bridge information modeling standardization." The author has been the chair of the joint subcommittee, and proposed the methodology documented in this dissertation as the best practices for the industry.

The case study focuses on the development of standardization process for information exchanges for steel bridge erection engineering, which begins with the formation of the current TG10/TG15 subcommittee and then explores the iteration of capturing of domain knowledge. Finally, it focuses on the final process to input that knowledge into a useable form for software vendors to implement. Since this is an industry group, the goal of this case study is to develop best practices that are implemented into the IES and ontology development. Moreover, the implementation into software products is out of this scope.

There are various specifications that govern the construction and bridge industry, in which AASHTO is the official United States organization that publishes specifications and standards used in highway design and construction. One document that is published is the "AASHTO LRFD Bridge Design Specifications" and is intended for use in the design, evaluation, and rehabilitation of bridges, and is mandated by the Federal Highway Administration for use on all bridges using federal funding (AASHTO, 2014). Other documents used for this case study include the NSBA S10.1-2014 "Steel Bridge Erection Guide Specification" and other documents produced from DOTs.

The domain knowledge about the steel erection domain was captured in the document "Outline of Typical Processes for Steel Erectors" which can be found in the Appendix C. This document was created and vetted from industry experts, whom are members of the TG10/TG15 subcommittee. This document outlines the workflow for erection engineers on a typical design-bid-build steel bridge project. It acknowledges all assumptions, defines definitions, and identifies in general terms the information needed for steel erection.

Next, a narrative of the domain knowledge was captured in the "Process Model Development for Steel Erection." Extracting the information from the "Outline of Typical Processes for Steel Erectors" document, a process model outlines all the needs of the case study process, including who is involved (actors), what activities are needed, definitions of terminology, and sequence of events. Each part of the process model was succinctly described to explain how it was used. Below identifies each section of the "Process Model Development for Steel Erection."

6.1.5.1. Definitions:

Actor: A person, an organization, or a person acting on behalf of an organization that has a specific purpose and role in the process.

Bid: The pricing and other documents forming the Contractor's Proposal that are submitted at a point in time to the Owner and that are required by the Owner in the selection of a Contractor. Synonym: Proposal.

Bid Document: What is submitted by the Contractor to the Owner at bid time. This is to be distinguished from the plans and specifications issued by the Owner to prepare the Bid/Proposal and that will form part of the Contract Documents included in the Contract formed between the Contractor and Owner. Synonym: Proposal Document

Bid Model: The Exchange Model provided by the Owner to General Contractor during the Bidding and Letting Phase.

Contract Documents: Contract Documents refers to the documents that define the responsibilities of the parties that are involved in bidding, fabricating, and erecting structural steel (and other elements of the project). These documents normally include the design drawings and the specifications. The design drawings and specifications are issued by the Owner to the General Contractor during the bidding phase. The General Contractor bases its bid on these documents, and they are later incorporated into the Contract between Owner and General Contractor.

Data: the quantities, characters, or symbols on which operations are performed by a computer, being stored and transmitted in the form of electrical signals and recorded on magnetic, optical, or mechanical recording media. Comment: Data is what is passed through information exchanges that create the BIM models. This can be seen as bits and bytes, where there is no semantic information.

Data Exchange: Exchange of data between two sources, often involving the transformation of the structure from one schema to another. Comment: Data exchanges are how computers communicate. The data exchange is usually a neutral file.

Exchange Model (EM): A software-neutral and semantically rich data definition of the content needed in the Information Exchange. Synonym: neutral file.

Information: What is conveyed or represented by a particular arrangement or sequence of things, such as explanation of data. Comment: Information includes all supplemental documents and procedures that give data context and meaning.

Information Exchange: The set of information passed between two sources, which include data along with documents and other information that give meaning and context of how to use the data. Information includes all supplemental documents and procedures that give data context and meaning. An information exchange can be in model form (e.g. CAD model), called an Exchange Model, or other forms (e.g. PDF, emails, documents), called Non-Model Exchanges. Comment: information exchanges are how humans communicate what is needed in a specific data exchange. Synonyms: exchange; exchange requirement. Documents that provide context for the Exchange Model are an essential component of the Information Exchange and may consist of plans, specifications, reference documents and other information.

Phase: Temporal, disjointed segments of a period of time in a process, often denoting a where a set of activities take place. Synonym: stage.

Process Map: Visual Representation of the process model, often in the Business Process Model and Notation (BPMN). Comment: This map represents the project workflow, including the stockholders, actors, project stages, and activities.

Process model: Identifies the information flows between the different actors and tasks the actors carry out during a project workflow (Information = EM and Documents)

Use Case: A specific event of a broader defined process, in which there is only one way of completing a specific goal. Comment: There is no "or" option; each would be their own use case

6.1.5.2. Actors

The actors who have been identified in this use case are listed and explained below.

Owner: The owner is the actor paying the Contractor to fulfill the terms of the Contract. The Owner also encompasses the following: those preparing the Contract documents, including those responsible for the structure's adequate design; and those authorized to represent the Owner during construction, commonly called the "Engineer" and the "Inspector". The Engineer and Inspector may be employees either of the Owner or of professional firms contracted for the work.

Designer: The designer is the actor who is the licensed professional who is responsible for sealing the contract documents, which indicates that he or she has performed or supervised the analysis, design and document preparation for the structure and has knowledge of the load-carrying structural system. The designer is also referred to as the Designer of Record or the Engineer of Record.

General Contractor: The general contractor (GC) is the actor who is responsible for proper completion of all tasks required by the Contract. Subcontractors, including fabricators, erectors, and field painters, may be used by the GC, but the GC retains responsibility for all material, operations, and the final product. The GC may permit direct subcontractor interaction with the Owner to expedite the project, but subcontractors must inform the GC of any proposed modifications to contract requirements accepted by the Owner. The GC is also referred to as the Contractor.

Erection Engineer: The erection engineer is the actor who is responsible for developing, evaluating, and specifying the General Contractor's specific procedures and plans for erecting the structural steel of the bridge. The erection engineer also prepares erection drawings (field-installation or member-placement drawings to show the Erector the location and attachment of the individual fabricated shipping pieces). The erection engineer is also referred to as the Construction Engineer.

Erector: The erector is the actor who is responsible for the erection of the structural steel. The erector is also referred to as the Erection Specialty Subcontractor.

Fabricator: The fabricator is the actor operating the facility(ies) performing such shop activities as cutting, welding, drilling, punching, cleaning, and painting of structural steel. "Fabricator" also includes any agents of the Fabricator, such as subcontract fabricators. In most cases, the Fabricator is subcontracted by the Contractor.

Detailer: The detailer is the actor who converts the design drawings and Exchange Model to shop drawings (digital or paper) and data files that can be applied by the Fabricator to perform the fabrication of structural steel.

6.1.5.3. <u>Case Study Assumptions (use case):</u>

The case study was designed to represent the most basic case so it doesn't needlessly complicate the exchange process. Below lists the assumptions for this specific use case.

- Design-Bid-Build Projects (ignore Design-Build projects, P3, etc.)
- Erector, Erection Engineer and Contractor are separate actors
  - Typical bridge project is a steel I girder or tub girder bridge (single or multispan and may be straight, skewed or curved). Trusses, arches and other more complex steel bridge types are not considered at this time.
- Owner communication comes through the General Contractor to subcontractors
  - Owner would give model (data) to contractor
  - Contractor gives model (data) to erector and erection engineer
    - This includes instructions from Contractor to Erector and Erection Engineer to download from another site
    - For the Contractor – Erection Engineer Exchange, assume that the Erection Engineer is a separate actor from the Contractor or the Erector.
    - Must distinguish between Erector and Erection Engineer, as each actor has a particular role and function.
  - Future exchange model to focus on erection engineer will send model to contractor
- Typical steel workhorse bridge (I girder and tub girder bridge)
- The information flow will theoretically stay the same among the various actors, even if the Contractor performs the actor functions of "Erector" and "Erection Engineer."

- Actor definitions below have been extracted from the NSBA S10.1-2014 “Steel Bridge Erection Guide Specification” and AISC Code of Standard Practice for Steel Buildings and Bridges (v2010)

6.1.5.4. Activities

The activities for completing the erection engineering for a typical design-bid-build project that have been identified in this use case are documented in this section. It is important to note that in order to follow the requirements of BMPN, activities that involve multiple actors are listed out separately for each actor and their respective duties.

Tables 6-1 to 6-7 are the activities that are performed by the Owner, Table 6-8 to 6-13 are performed by the General Contractor, Tables 6-14 to 6-18 are performed by the Erection Engineer, and Tables 6-19 to 6-25 are performed by the erector. It is important to note the naming convention of the activity, in which is in “do-what" form, such as “Prepare (do) Contract Document (what).” Additionally, in order to help identify where the activity is location on the process map, typical grid pattern notation has been placed on the map, such as what is commonly see on directional maps. For instance, each phase is designated by letters “A, B, C…”, the actors are designated by the numbers “1, 2, 3...”, and the activity number in a specific actor pool per phase is denoted by “.1, .2, .3…” For example, [A 1.1] designates the first activity, in the first phase, conducted by the first actor. In the steel erection process map, [A 1.1] designates the Owner (1) conducts the activity Prepare Contract Document (.1) in the phase Bidding and Letting (A). It is important to note that this notation is per process map, and thus each will have their own respective grid pattern notation. This notation is more readable and user friendly than the notation in the current bridge lifecycle process map (Figure 3-6) since a grid pattern is more conventional and the user doesn’t need to know what the abbreviations (e.g. TE, SE, etc.) represent.

Table 6-1: Owner Activity: Prepare Contract Documents

Type	Activity
Name	[A 1.1] Prepare Contract Documents
Project Phase	Bidding and Letting
Description	Prepare Request for Proposal
Models	Sent: “Bid Model” sent to General Contractor and passed through to subcontractors
Documents	Sent: “Bid Documents” to General Contractor and passed to subcontractors
Messages	none
Related	none

Table 6-2: Owner Activity: Award Contract

Type	Activity
Name	[A 1.2] Award Contract
Project Phase	Bidding and Letting
Description	Review Bids submitted by the various General Contractors. Based on the internal processes and requirements, award the contract to the General Contract.
Models	none
Documents	none
Messages	Sent: “Award Notification” to the General Contract that is being awarded the contract.
Related	none

Table 6-3: Owner Activity: Approve Contract

Type	Activity
Name	[A 1.3] Approve Contract
Project Phase	Bidding and Letting
Description	Accept or reject changes, additions, clarifications to Bid Exchange Model, make changes to Bid Model. Send a message to the General Contractor when the General Contract can proceed with the project.
Models	none
Documents	Received: “Contract” from the General Contractor
Messages	Sent: “Notice to Proceed” to the General Contract to proceed with the project.
Related	none

Table 6-4: Owner Activity: Evaluate RFIs

Type	Activity
Name	[B 1.1] Evaluate RFIs
Project Phase	Pre Construction Planning / Detailing
Description	Review the RFIs and provide feedback, information requested, or clarifications.
Models	none
Documents	Sent/Received: Bidirectional "RFI" correspondence to/from the General Contractor
Messages	none
Related	none

Table 6-5: Owner Activity: Review and Approve Contractor's Planning Model

Type	Activity
Name	[B 1.2] Review and Approve Contractor's Planning Model
Project Phase	Pre Construction Planning / Detailing
Description	
Models	Received: "Contractor's Planning Model" from the General Contractor
Documents	none
Messages	Sent: "Notification of Approval" to the General Contractor
Related	none

Table 6-6: Owner Activity: Receive Erection Plan

Type	Activity
Name	[B 1.3] Receive Erection Plan
Project Phase	Pre Construction Planning / Detailing
Description	Review erection plan and message the Erector if more time is needed before proceeding with the bridge erection.
Models	none
Documents Sent	Received: "Final Erection Plans and Procedures" from the General Contractor
Messages	Sent: "Time Notification" to Erector indicating the wait time needed to proceed with the bridge erection
Related	none

Table 6-7: Owner Activity: Accept Erection

Type	Activity
Name	[D 1.1] Accept Erection
Project Phase	Substantial Completion
Description	Depending on what is required by the Contract Documents, finalization of some substantial completion activities listed above may not occur until final completion by the Contractor and formal acceptance of the project by Owner.
Models	none
Documents Sent	Received: “As-Built Drawings and Records” from General Contract and Subs
Messages	none
Related	none

Table 6-8: General Contractor Activity: Prepare Bid

Type	Activity
Name	[A 2.1] Prepare Bid
Project Phase	Bidding and Letting
Description	Collaborating with the Erection Engineer and Erector, the General Contractor appends contract documents (scope of subcontracts) and incorporates the Erector and the Erection Engineer’s bids (scope and price) in the General Contractor’s Bid to the Owner.
Models	Received: “Bid Model” from the Owner and passed through to the Erection Engineer and the Erector
Documents	Received: “Bid Documents” from the Owner and passed through to the Erection Engineer and the Erector Received: “Bid Price and Scope” from the Erection Engineer Received: “Bid Price and Scope” from the Erector Sent: “Bid” to the Owner
Messages	none
Related	Erection Engineer [A 3.1] Prepare Bid Erector [A 4.1] Prepare Bid

Table 6-9: General Contractor Activity: Finalize Contract

Type	Activity
Name	[A 2.2] Finalize Contract
Project Phase	Bidding and Letting
Description	After receiving the “Award Notification” message from the Owner, the General Contractor reviews and signs the contract.
Models	none
Documents	Sent: “Contract” to the Owner
Messages	Received: “Award Notification” from the Owner
Related	none

Table 6-10: General Contractor Activity: Review Model

Type	Activity with Subprocesses
Name	[B 2.1] Review Model
Project Phase	Pre Construction Planning / Detailing
Description	After receiving the “Notice to Proceed” message from the Owner, the General Contractor notifies the Erection Engineer, the Erector, and all other parties (e.g. owner, designer, and fabricator) to Preconstruction Meetings and Bid Exchange Model Review where there are discussions of missing or incomplete information, location of splices, and other details and minor changes as allowed by the Contract Documents. Information is exchanged via RFIs and other messaging.
Models	none
Documents	Sent/Received: Bidirectional “RFI” correspondence to/from the Owner Sent/Received: Bidirectional “RFI” correspondence to/from the Erection Engineer Sent/Received: Bidirectional “RFI” correspondence to/from the Erector
Messages	Received: “Notice to Proceed” from the Owner Sent: “Notice to Proceed” to the Erection Engineer Sent: “Notice to Proceed” to the Erector
Related	• Erection Engineer [B 3.1] Review Model • Erector [B 4.1] Review Model

Table 6-11: General Contractor Activity: Conduct Preliminary Erection Study and Decide Model Changes

Type	Activity
Name	[B 2.2] Conduct Preliminary Erection Study and Decide Model Changes
Project Phase	Pre Construction Planning / Detailing
Description	The General Contractor holds collaboration meetings with the Erection Engineer and Erector to suggest changes, additions, and clarifications to "Bid Model."
Models	Sent: "Contractor's Planning Model" to the Owner
Documents	Sent/Received: Bidirectional "Model Changes" to/from the Erection Engineer Sent/Received: Bidirectional "Model Changes" to/from the Erector
Messages	none
Related	• Erection Engineer [B 3.2] Conduct Preliminary Erection Study • Erector [B 4.2] Conduct Preliminary Erection Study

Table 6-12: General Contractor Activity: Review Erection Analysis, Plans, and Procedures

Type	Activity
Name	[B 2.3] Review Erection Analysis, Plans, and Procedures
Project Phase	Bidding and Letting
Description	After receiving the "Notification of Approval" message from the Owner, there are collaboration meetings with the General Contractor, the Erection Engineer, and Erector to review, revise, or confirms final erection analysis, erection plans and erection procedures to be submitted to Owner.
Models	
Documents	Sent/Received: Bidirectional "Erection Plans and Procedures" to the Erection Engineer Received/Sent:"Final Erection Plans and Procedures" pass through from the Erection Engineer sent to the Owner
Messages	Received: "Notification of Approval" from the Owner Sent: "Notification of Approval" to the Erection Engineer Sent: "Notification of Approval" to the Erection Engineer
Related	• Erection Engineer [B 3.3] Perform Erection Analysis, and Prepare Plans and Procedures • Erector [B 4.3] Review Erection Analysis, Plans, and Procedures

Table 6-13: General Contractor Activity: Assemble Documents and Confirm Work Completion

Type	Activity
Name	[D 2.1] Assemble Documents and Confirm Work Completion
Project Phase	Substantial Completion
Description	The General Contractor Assembles Steel Erection Record Documents and confirms Erection "Punch-list" Work is completed. Once the General Contractor receives the notice of completion from the Erector, the General Contractor submits all documents to the Owner.
Models	none
Documents	Received/Sent: "As Built Drawings and Records" pass through from the Erector sent to Owner
Messages	Received: "Work Completed" message received from Erector to send final documents and notice to the Owner
Related	• Erector [D 4.1] Assemble "As-Built" Drawings and Records

Table 6-14: Erection Engineer Activity: Prepare Bid

Type	Activity
Name	[A 3.1] Prepare Bid
Project Phase	Bidding and Letting
Description	Collaborating with the General Contractor and the Erector, the Erection Engineer sends the Bid (scope and price) to be appended in the General Contractor's Bid to the Owner.
Models	Received: "Bid Model" from Owner and passed through General Contractor
Documents	Received: "Bid Documents" from Owner and passed through General Contractor Sent: "Bid Price and Scope" to General Contractor
Messages	none
Related	• General Contractor [A 2.1] Prepare Bid • Erector [A 4.1] Prepare Bid

Table 6-15: Erection Engineer Activity: Review Model

Type	Activity
Name	[B 3.1] Review Model
Project Phase	Pre Construction Planning / Detailing
Description	After receiving the "Notice to Proceed" message from the General Contractor, the General Contractor notifies the Erection Engineer, the Erector, and all other parties (e.g. owner, designer, and fabricator) to Preconstruction Meetings and Bid Exchange Model Review where there are discussions of missing or incomplete information, location of splices, and other details and minor changes as allowed by the Contract Documents. Information is exchanged via RFIs and other messaging.
Models	none
Documents	Sent/Received: Bidirectional "RFI" correspondence to/from the General Contractor Sent/Received: Bidirectional "RFI" correspondence to/from the "RFI" to the Erector
Messages	Received: "Notice to Proceed" message from the General Contractor
Related	• General Contractor [B 2.1] Review Model • Erector [B 4.1] Review Model

Table 6-16: Erection Engineer Activity: Conduct Preliminary Erection Study

Type	Activity
Name	[B 3.2] Conduct Preliminary Erection Study
Project Phase	Pre Construction Planning / Detailing
Description	The General Contractor holds collaboration meetings with the Erection Engineer and Erector to suggest changes, additions, and clarifications to "Bid Model."
Models	none
Documents Sent	Sent/Received: Bidirectional "Model Changes" to the General Contractor Sent/Received: Bidirectional "Model Changes" to the Erector
Messages	none
Related	• General Contractor [B 2.2] Conduct Preliminary Erection Study and Decide Model Changes • Erector [B 4.2] Conduct Preliminary Erection Study

Table 6-17: Erection Engineer Activity: Perform Erection Analysis and Prepare Plans and Procedures

Type	Activity
Name	[B 3.3] Perform Erection Analysis and Prepare Plans and Procedures
Project Phase	Bidding and Letting
Description	After receiving the “Notification of Approval” message from the General Contractor, there are collaboration meetings with the General Contractor, the Erection Engineer, and Erector to review, revise, or confirms final erection analysis, erection plans and erection procedures to be submitted to Owner.
Models	none
Documents	Sent/Received: Bidirectional “Erection Plans and Procedures” correspondence to/from the General Contractor and Erector Sent:“Final Erection Plans and Procedures” pass through the General Contractor to the Owner Sent:“Final Erection Plans and Procedures” to the Erector
Messages	Received: “Notification of Approval” from the General Contractor
Related	• General Contractor [B 2.3] Review Erection Analysis, Plans, and Procedures • Erector [B 4.3] Review Erection Analysis, Plans, and Procedures

Table 6-18: Erection Engineer Activity: Consult Erection Changes

Type	Activity
Name	[C 3.1] Consult Erection Changes
Project Phase	Construction
Description	The Erection Engineer consults the Erector if any questions, issues, or problems arise.
Models	none
Documents Sent	none
Messages	none
Related	Erector [C 4.1] Erect Bridge

Table 6-19: Erector Activity: Prepare Bid

Type	Activity
Name	[A 4.1] Prepare Bid
Project Phase	Bidding and Letting
Description	Collaborating with the General Contractor and the Erection Engineer, the Erector sends the Bid (scope and price) to be appended in the General Contractor's Bid to the Owner.
Models	Received: "Bid Model" from Owner and passed through General Contractor and Erection Engineer
Documents	Received: "Bid Documents" from Owner and passed through General Contractor and Erection Engineer Sent: "Bid Price and Scope" to General Contractor
Messages	none
Related	• General Contractor [A 2.1] Prepare Bid • Erection Engineer [A 3.1] Prepare Bid

Table 6-20: Erector Activity: Review Model

Type	Activity with Subprocesses
Name	[B 4.1] Review Model
Project Phase	Pre Construction Planning / Detailing
Description	After receiving the "Notice to Proceed" message from the General Contractor, the General Contractor notifies the Erection Engineer, the Erector, and all other parties (e.g. owner, designer, and fabricator) to Preconstruction Meetings and Bid Exchange Model Review where there are discussions of missing or incomplete information, location of splices, and other details and minor changes as allowed by the Contract Documents. Information is exchanged via RFIs and other messaging.
Models	none
Documents	Sent/Received: Bidirectional "RFI" correspondence to/from the General Contractor Sent/Received: Bidirectional "RFI" correspondence to/from the "RFI" to the Erection Engineer
Messages	Received: "Notice to Proceed" message from the General Contractor
Related	• General Contractor [B 2.1] Review Model • Erection Engineer [B 3.1] Review Model

Table 6-21: Erector Activity: Conduct Preliminary Erection Study

Type	Activity
Name	[B 4.2] Conduct Preliminary Erection Study
Project Phase	Pre Construction Planning / Detailing
Description	The General Contractor holds collaboration meetings with the Erection Engineer and Erector to suggest changes, additions, and clarifications to "Bid Model."
Models	none
Documents Sent	Sent/Received: Bidirectional "Model Changes" to the General Contractor Sent/Received: Bidirectional "Model Changes" to the Erection Engineer
Messages	none
Related	• General Contractor [B 2.2] Conduct Preliminary Erection Study and Decide Model Changes • Erection Engineer [B 3.2] Conduct Preliminary Erection Study

Table 6-22: Erector Activity: Review Erection Analysis, Plans, and Procedures

Type	Activity
Name	[B 4.3] Review Erection Analysis, Plans, and Procedures
Project Phase	Bidding and Letting
Description	After receiving the "Notification of Approval" message from the General Contractor, there are collaboration meetings with the General Contractor, the Erection Engineer, and Erector to review, revise, or confirms final erection analysis, erection plans and erection procedures to be submitted to Owner.
Models	none
Documents	Sent/Received: Bidirectional "Erection Plans and Procedures" correspondence to/from the General Contractor and Erection Engineer Received:"Final Erection Plans and Procedures" from the Erection Engineer
Messages	Received: "Notification of Approval" from the General Contractor
Related	• General Contractor [B 2.3] Review Erection Analysis, Plans, and Procedures • Erection Engineer [B 3.3] Perform Erection Analysis and Prepare Plans and Procedures

Table 6-23: Erector Activity: Erect Bridge

Type	Activity
Name	[C 4.1] Erect Bridge
Project Phase	Construction
Description	After receiving the "Time Notification" message from the Owner, the Erector proceeds with erection the bridge.
Models	none
Documents Sent	none
Messages	Received: "Time Notification" message from the Owner to designate the wait time before erection the bridge
Related	Erection Engineer [C 3.1] Consult Erection Changes

Table 6-24: Erector Activity: Assemble "As Built" Drawings and Records

Type	Activity
Name	[D 4.1] Assemble "As Built" Drawings and Records
Project Phase	Substantial Completion
Description	The Erector assembles the "As Built" drawings and records that are sent to the General Contractor to be sent to the Owner.
Models	none
Documents	Sent: "As Built Drawings and Records" pass through the General Contractor to the Owner
Messages	none
Related	• General Contractor [D 2.1] Assemble Documents and Confirm Work Completion

Table 6-25: Erector Activity: Complete "Punch List" Work

Type	Activity
Name	[D 5.2] Complete "Punch List" Work
Project Phase	Substantial Completion
Description	The erector performs the "punch list" tasks. Once completed, the Erector sends a message to the General Contractor signifying completion.
Models	none
Documents	none
Messages	Sent: "Work Completed" message to General Contractor
Related	• General Contractor [D 2.1] Assemble Documents and Confirm Work Completion

6.1.5.5. Exchange Models

The Exchange Model (i.e. data passed in model form) identified in the use case is identified below. It is important to note that these represent the current process, and as technology and modeling techniques improve to allow passing data in model form (currently passed in document form), there may be more exchange models to incorporate in the future.

Table 6-26: Exchange Model: Bid Model

Type	Exchange Model
Name	Bid Model
Project Phase	Bidding and Letting
Exchange Disciplines	**Sender**: Owner **Receiver**: General Contractor, Erection Engineer, Erector, Fabricator, Detailer
Description	**Purpose**: Provide the scope of the project needed to be bid as part of the solicitation. The information contained must include all information for the bidders to adequately assess the project and provide an accurate bid. **Level of detail**: Sufficient for bid cost estimation and procedures
Software Functionality	**Export**: 2D or 3D Architectural or design intent building modeling tool **Import**: Various non-modeling software (e.g. PDF, Excel). Typically involves non-model feedback
Related Exchange Models	

6.1.5.6. Exchange Requirements

The first exchange model that was identified in the case study is the Bid Model. Exchange requirements (ER) are specific data requirements needed by each actor for a specific task. Since each actor receiving the model requires their own subset of data from the model, each actor will have their own ER associated with an Exchange Model.

6.1.5.7. Non Models Exchanges – Documents

Additional information not in model form is needed to support various activities. Non-model exchanges represent the information exchanges in other forms, including documents, spreadsheets, emails, faxes, etc. Below are the non-model exchanges identified in the case study.

- Bid Documents
- Bid and Price Scope
- Bid
- Contract
- RFI (bidirectional)
- Model Changes (generally documents exchanged at contractor collaboration phase until incorporated into a contractor revised EM)
- Erection Plans and Procedures
- Final Erection Plans and Procedures
- "As-Built" Drawings
- Records Construction Means and Methods

6.1.5.8. Process Map

Using BMPN notation, the process map was created to reflect the information outlined in the process model. Together, both the process model and process map contain the same information but in different forms. Since the industry group was not familiar with process modeling, the BMPN notation was gradually applied. The purpose was to not overwhelm the process. There were approximately 5 iterations of the process map for the case study, with smaller adjustments in between. Figure 6-11 displays the current draft of the process map, (there is larger process map in Appendix E). Due to the lack of availability and knowledge of BPMN software (e.g. Visio) Microsoft PowerPoint was used to draft the process map. As long as the notation is consistent with the rules, any graphical program can be used to model the process map.

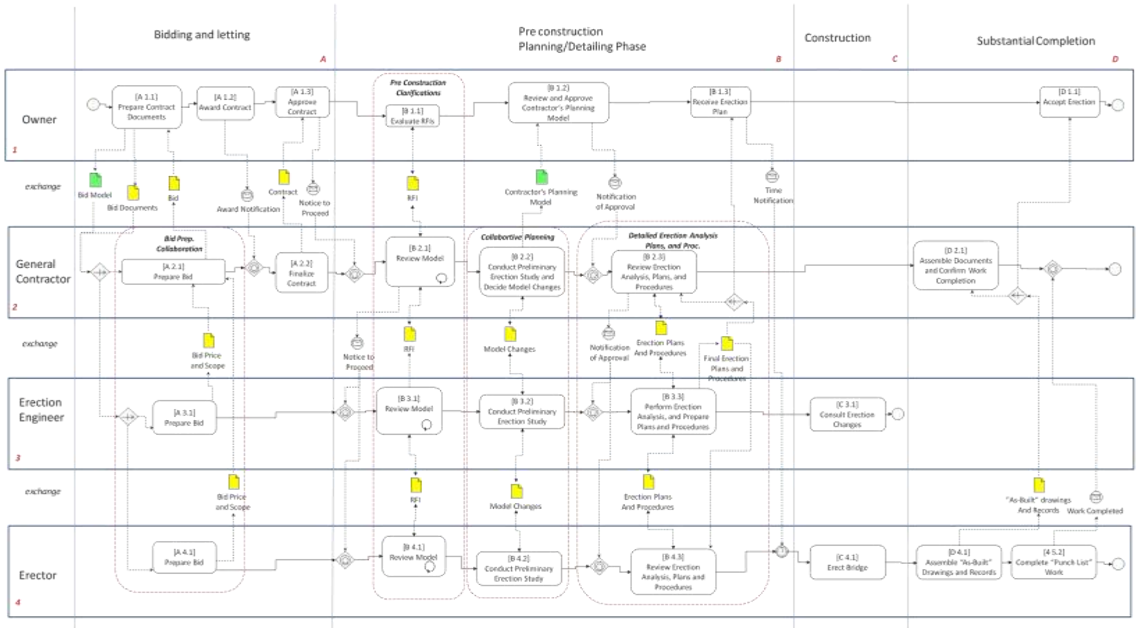


Figure 6-11: Steel Bridge Erection Process Map

6.1.5.9. <u>Phases and Processes</u>

This section outlines the typical processes that occur in each phase of the case study project.

1. Bidding and Letting Phase
    a. Owner Activity - Prepare Request for Proposal (Contract Documents and Exchange Model)
    b. Owner to General Contractor Exchange
        i. Contract Documents (plans and specifications) DOCUMENTS
        ii. Exchange Model – BID model

c. General Contractor Activity - Append Contract Documents (Scope Subcontracts)
d. General Contractor to Erector/Erection Engineer Exchange
    i. Contract Documents (plans and specifications with subcontract scope) DOCUMENTS
    ii. Exchange Model- Bid Model
e. Erector/Erection Engineer/General Contractor Group - Collaborate and discuss scope and coordination issues necessary for Erector and Erection Engineer to prepare detailed bid scope and price (phone calls, meetings, emails, etc.)
f. Erector Activity - Prepare Erection Bid (scope and price)
g. Erector to General Contractor Exchange
    i. Erection Bid (scope and price) - Document
h. Erection Engineer Activity - Prepare Erection Engineering Bid (scope and price)
i. Erection Engineer to General Contractor Exchange
    i. Erection Engineer Bid (scope and price) - Document
j. General Contractor Activity - Incorporate Erector and Erection Engineer Bids (scope and price) in General Contractor's Bid to Owner
k. General Contractor to Owner Exchange
    i. General Contractor Bid to Owner – Document

2. Post Award/Pre-Construction Planning/Detailing Phase (from FWHA process map)
    a. Owner Activity - Award Contract
    b. Owner/Designer/General Contractor/Erector/Erection Engineer/Fabricator/Detailer Activity - Preconstruction Meetings and Bid

Exchange Model Review - discussion of missing or incomplete information, location of splices, other details and minor changes as allowed by the Contract Documents

c. General Contractor/Erector/Erection Engineer/Fabricator/Detailer Activity - Suggest changes, additions, clarifications to Bid Exchange Model
d. Owner/Designer Activity – Evaluate and respond to the RFIs
e. General Contractor/Erector/Erection Engineer Collaboration Activity- Contractor's Planning Model Exchange
f. Erection Engineer Activity after receiving Contractor's Planning Model - prepare detailed erection analysis, erection plans and erection procedures
g. Erector/Erection Engineer/General Contractor Activity - review and revise or confirm final erection analysis, erection plans and erection procedures to be submitted to Owner.
h. Erection Engineer to General Contractor Exchange (copies to Erector)
    i. Erection Plans and Erection Procedures
    ii. Erection Analysis if required by contract or requested by Owner
i. General Contractor to Owner Exchange
    i. Erection Plans and Erection Procedures
    ii. Erection Analysis if required by contract or requested by Owner

3. Construction
    a. Erector Activity – "Steel Bridge Erection"
        i. Consult with Erection Engineer if changes in erection plans or erection procedures are required (generally handled in RFI's or NCR's depending on the circumstances, not sure this should be considered an exchange)

ii. Consult with Contractor/Fabricator/Detailer/Owner/Designer if steel modifications are required due to field conditions or shop or detailing errors (generally handled in RFI's or NCR's depending on the circumstances, not sure this should be considered an exchange)
iii. Record changes on "as-built" drawings (as defined by the Contract Documents)
iv. Maintain QC Records (as defined by the Contract Documents)
v. Monitor Safety of workers and the public

4. Substantial Completion
   a. Erector Activity: Assemble "As-Built" drawings and Record Documents
   b. Erector Activity: Complete "Punch-list" work for acceptance by Contractor (and Owner if required by Contract Documents and/or Contractor)
   c. Erector to Contractor Exchange: Submit "As-Built" Drawings and Record Documents
   d. Contractor Activity: Assemble Steel Erection Record Documents and confirm Erection "Punch-list" Work is completed
   e. Contractor to Owner Exchange: Submit "As-Built" Drawings and Record Documents pertaining to Steel Erection

5. Final Completion: generally all activities and exchanges associated with Steel Bridge Erection are completed before final project handover from Contractor to Owner; however, depending on what is required by the Contract Documents, finalization of some substantial completion activities listed above may not occur

until final completion by the Contractor and formal acceptance of the project by Owner.

6.1.5.10. Notes and Comments:

See Appendix D for the notes and comments.

6.2. Step2: Organize Knowledge in Usable Format

The second step is to organize the captured information into a usable format that can be passed and modified, similar to the NBIMS *design.* Unlike the NBIMS where the information exchange are compiled into a Model Views (subset of the IFC schema), this section organizes the information into a taxonomy, which is non-domain specific. In fact, if IFC was chosen as the schema, the Model Views can still be created based on the information in the taxonomy. Model views still require the domain knowledge to be identified and documented, which the taxonomy does provide. Therefore, not only does a taxonomy not require any more additional time to create than a Model View, it actually can save time and effort by its reuse capabilities.

Current approaches that only use electronic forms of communication run into inefficiencies such as rework, version control, and loss of information. One example of inefficient communication is an email chain. Keeping track of comments and information in an email chain is difficult, and information is often overlooked. A commonly used tool to capture information is a programmable spreadsheet (e.g. Excel). Spreadsheets can be effective if proper version control, document updates, and organizations are maintained. However, this process it typically done manually, resulting in wasted times. Therefore, and semi-automated approach is presented to help minimize the manual processes that result in errors and inefficiencies.

The end format of the IES is an ontology, which can be converted to any schema or used directly by software vendors. However, before an ontology can be developed, the domain information needs to first be captured in a taxonomy. In order to maintain proper format and help automate the capturing of domain knowledge, this dissertation presents the Taxonomy Editor. The editor utilizes various functions to automate the manual tasks associated with creating a taxonomy, which is explored throughout this chapter.

Creating a taxonomy from scratch may seem like a daunting task. However, utilizing the domain knowledge already capture in the process model drastically reduces the time and effort spent gathering the information. Additionally, a well formed taxonomy models the domain, and thus can be reused for other use cases. Chapter 7 explains in detail the technical development of a taxonomy.

6.2.1. Taxonomy Editor Overview

The taxonomy editor was developed to help automate the process of capturing and putting domain knowledge into usable forms. As the editor was created solely as a tool based on functionality, it does not contain all the "bells and whistles" and aesthetics that may come with traditional software applications. Figure 6-12 displays a screen capture of the main components of the editor.

The editor has two main components: DataSet and Taxonomy. The DataSet is an XML formatted dataset of all the terms. It essentially is a dictionary of the components that are used to populate the taxonomy. The purpose of the DataSet is to contain all the information of the domain in one central location, in which each term is identified by its GUID. The keyword shows the information about any term that has been selected in the taxonomy.

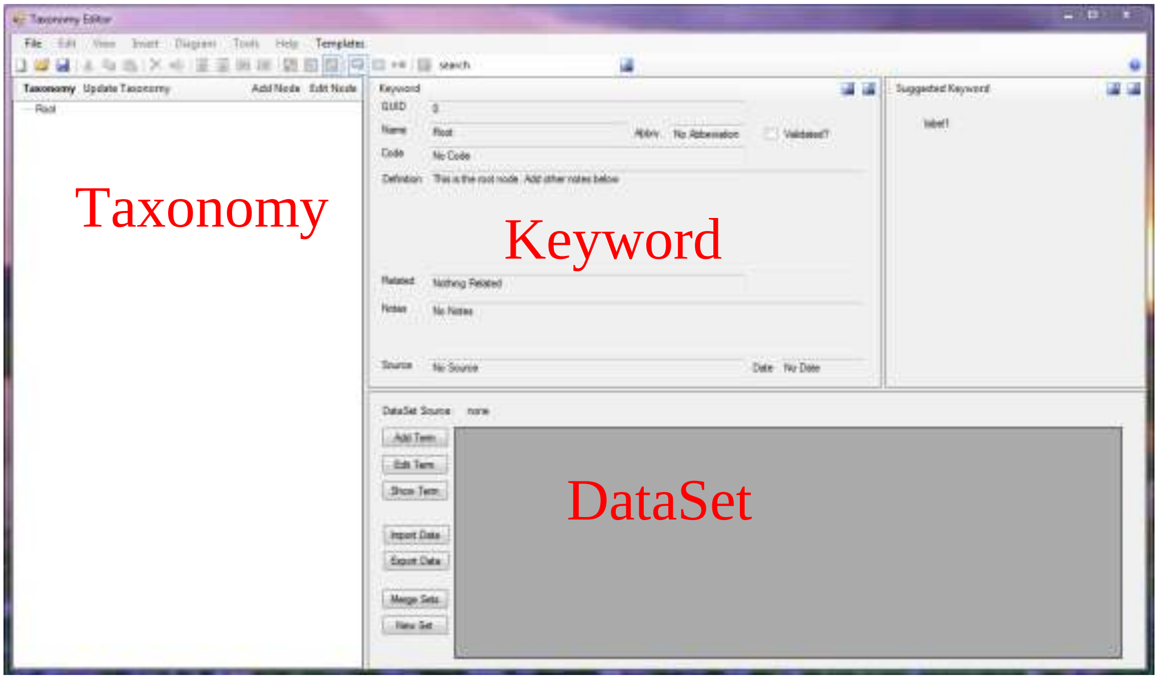


Figure 6-12: Screen capture of the main components of the Taxonomy Editor.

6.2.2. Step 2.1: Define Terminology

Defining the terminology only applies to the development of a DataSet. Ideally once a DataSet has been approved by the domain, defining terms again would be irrelevant and unneeded. The only exceptions are if new terms need to be added to the Dataset or if the consensus of the domain determines that a term needed to be edited or modified. Therefore, this step explains how terminology is defined and a DataSet is developed.

Terms represent the data and information that is needed to be exchanged in the process. The first step is to define each term, along with the definition and metadata. Terms can be defined in the DataSet in the editor using the “Add Term” function (Figure 6-13). The format of the term includes:

GUID: The Globally Unique Identifier is a computer generated 128-bit value to reference a unique value. Although theoretically there can be duplicate GUIDs referencing two different unique values, it's highly improbable. The purpose of the GUID is to be the identifier of that unique term. In the case of the BrIM taxonomy and ontology, a unique term (once balloted and approved) will be assigned a GUID that will be the reference to the term definition. Therefore, every application that uses that term will be reference to the same term definition and attributes. This field can be left blank since the taxonomy editor will automatically produce a GUID.

Abbreviation: The Abbreviation is the shortened form of the term. This is used as a reference. Many words in the industry are references by the abbreviation, such as AASHTO or NSBA. Abbreviation is optional, and this field can be left blank.

Term: The term is the actual entity that the definition supports. Although "name" is often used, the word "term" is more appropriate since "name" is a description of what something is called. For example, instances of the term "bridge" may have names such as "Brooklyn Bridge" or "Golden Gate Bridge." Term is mandatory, and this field cannot be left blank.

Definition: The definition is what describes the meaning of the term. It is important to be clear and concise. Definition is mandatory, and this field should not be left blank.

Notes: The notes can be anything that is needed to support the term or any of the other fields. This field can be left blank. Notes are optional, and this field can be left blank.

Related: The related box is any other term that relates to the defined term. Having related terms are important for the meaning and use of the term. Related is optional, and this field can be left blank.

Validate: Validated is a Boolean (true/false) that signifies if the term has been balloted and approved. Once validated, the term will no longer be enabled for modification. Any modification would have to go through another approval process. Validated is optional, and this field can be left blank (although once validated and approved it will be checked to prevent modification).

Reference Code: The reference code serves to be a reference to where the code is from. For example, MasterFormat and Omniclass reference numbers can be used to reference other definitions. However, the GUID is the main identifier. This field can be left blank, but it should contain the reference number if the term does have one. Reference code is optional, and this field can be left blank.

Source: The source is where the term is from. This is important for quality control. Many terms in the bridge industry are already defined and approved, such as those published by TRB or other organization body. Source is optional and this field can be left blank, but it is important to know where the term and its original definition came from.

Date: The date is important for quality control since terms may have been updated. The date goes hand-in-hand with the source. This can be in any format, e.g. “year,” “month, year,” and “month, day, year.” Date is optional and this field can be left blank. However, if there is a source, it is important to have the date as a reference to when the source definition was created.

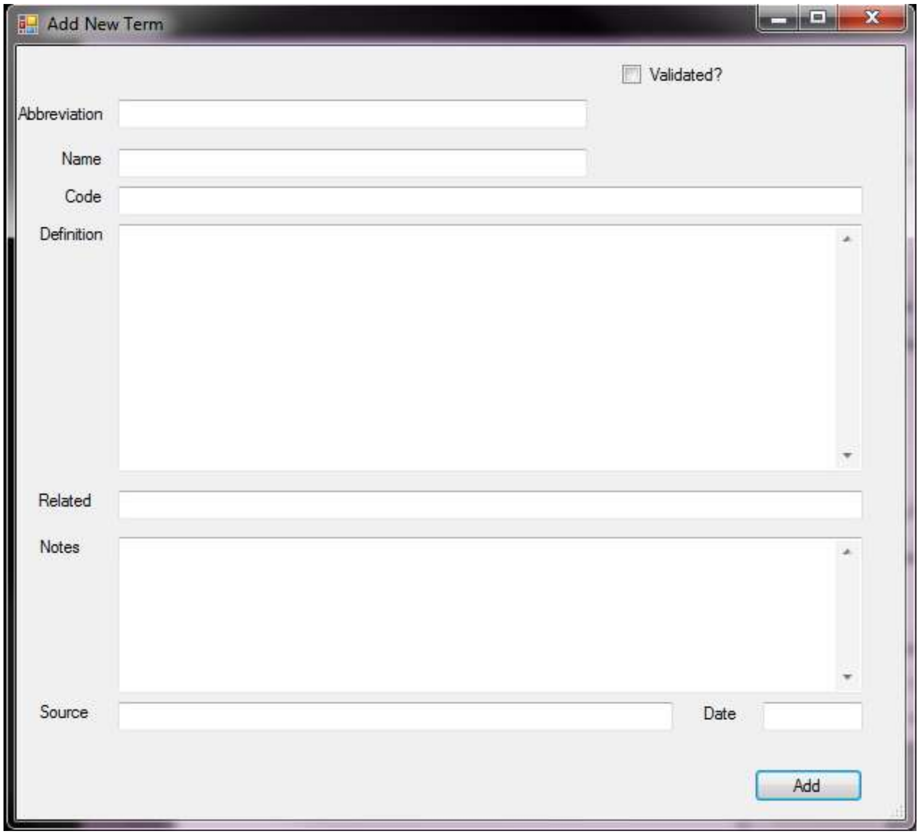


Figure 6-13: Screen Capture Add Term Function.

In addition to adding terms through the Add Term function, the editor has a template for an Excel spread sheet. The purpose of the template is to enable more flexibility in defining large subset of terms, including the “copy and paste” ability. As long as the spreadsheet columns are in the order as shown in Figure 6-14, the editor can import the file and assign the terms into the DataSet (safeguards to verify the correct order can be eventually incorporated). The editor automatically assigns the GUID, and once the term has been validated in the approval process, the GUID will always be the same.

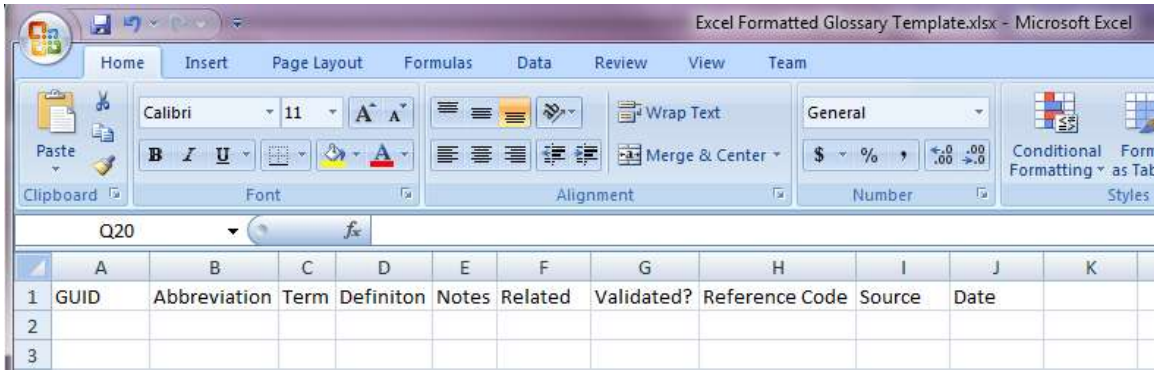


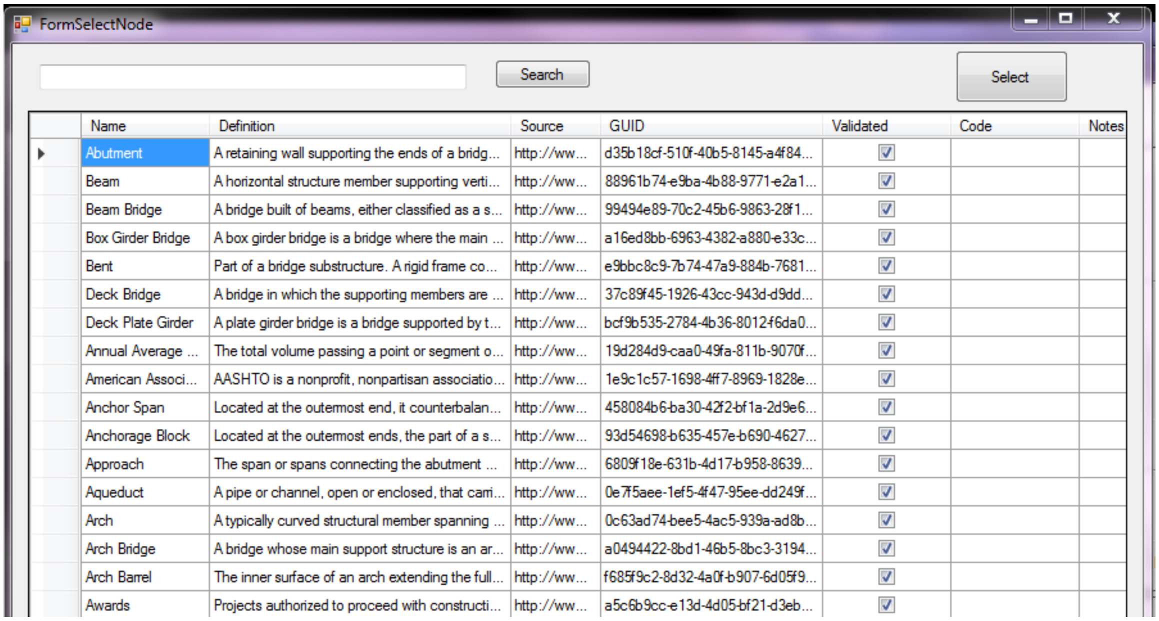
Figure 6-14: Screen Capture of the DataSet Template.

DataSets can be imported and exported using the editor, either in XML or Excel format. These two formats where chosen since they are both widely utilized, simple to use, and easily exchanged. Additionally, the editor makes the editing of the terms simple. Ideally, once a DataSet has been validated and approved, the ability to edit the terms would be locked. The purpose of locking the terms is to prevent modification without further approval.

6.2.3. Step 2.2: Assign Term Relationships

The basic format of a taxonomy is a hierarchy tree with a parent-child relationship. Each term, which is called a node, can contain sub nodes (children), but one super node (parent). This means that the node belongs to the parent, and the children belong to the node. This form allows for attributes of the parent nodes to be passed to the children. Additionally, relationships can be added to add more detail.

The taxonomy can be built by assigning terms from the DataSet to the taxonomy tree. Assigning terms to the taxonomy is simple by using the “Add Node” function (Figure 6-15).



Name	Definition	Source	GUID	Validated	Code	Notes
Abutment	A retaining wall supporting the ends of a bridg...	http://ww...	d35b18cf-510f-40b5-8145-a4f84...	☑		
Beam	A horizontal structure member supporting verti...	http://ww...	88961b74-e9ba-4b88-9771-e2a1...	☑		
Beam Bridge	A bridge built of beams, either classified as a s...	http://ww...	99494e89-70c2-45b6-9863-28f1...	☑		
Box Girder Bridge	A box girder bridge is a bridge where the main ...	http://ww...	a16ed8bb-6963-4382-a880-e33c...	☑		
Bent	Part of a bridge substructure. A rigid frame co...	http://ww...	e9bbc8c9-7b74-47a9-884b-7681...	☑		
Deck Bridge	A bridge in which the supporting members are ...	http://ww...	37c89f45-1926-43cc-943d-d9dd...	☑		
Deck Plate Girder	A plate girder bridge is a bridge supported by t...	http://ww...	bcf9b535-2784-4b36-8012-f6da0...	☑		
Annual Average ...	The total volume passing a point or segment o...	http://ww...	19d284d9-caa0-49fa-811b-9070f...	☑		
American Associ...	AASHTO is a nonprofit, nonpartisan associatio...	http://ww...	1e9c1c57-1698-4ff7-8969-1828e...	☑		
Anchor Span	Located at the outermost end, it counterbalan...	http://ww...	458084b6-ba30-42f2-bf1a-2d9e6...	☑		
Anchorage Block	Located at the outermost ends, the part of a s...	http://ww...	93d54698-b635-457e-b690-4627...	☑		
Approach	The span or spans connecting the abutment ...	http://ww...	6809f18e-631b-4d17-b958-8639...	☑		
Aqueduct	A pipe or channel, open or enclosed, that carri...	http://ww...	0e7f5aee-1ef5-4f47-95ee-dd249f...	☑		
Arch	A typically curved structural member spanning ...	http://ww...	0c63ad74-bee5-4ac5-939a-ad8b...	☑		
Arch Bridge	A bridge whose main support structure is an ar...	http://ww...	a0494422-8bd1-46b5-8bc3-3194...	☑		
Arch Barrel	The inner surface of an arch extending the full...	http://ww...	f685f9c2-8d32-4a0f-b907-6d05f9...	☑		
Awards	Projects authorized to proceed with constructi...	http://ww...	a5c6b9cc-e13d-4d05-bf21-d3eb...	☑		

Figure 6-15: Screen Capture of the Add Node to Taxonomy Function.

6.2.4. Case Study: Organizing Steel Bridge Erection Knowledge into a Taxonomy

As the steel erection process contains many interactions and exchanges, one was chosen in order to be used as a test case for the development. The exchange model that was selected was the “Bid Model” and the exchange requirement is the data the Erector needs to prepare a bid. The assumptions are specified in section 6.1.5.3.

The case study made use of the BrIM data dictionary provided by Hu (2014). Additional terms and definitions were added that were needed for steel bridge erection. The BrIM taxonomy was created first based on the hierarchy of the BrIM Data Dictionary. However, the BrIM DD is constrained to four columns or levels: Information Groups, Information Items, Attribute Sets, and Attributes. The BrIM Taxonomy does not put any level constraints on the taxonomy.

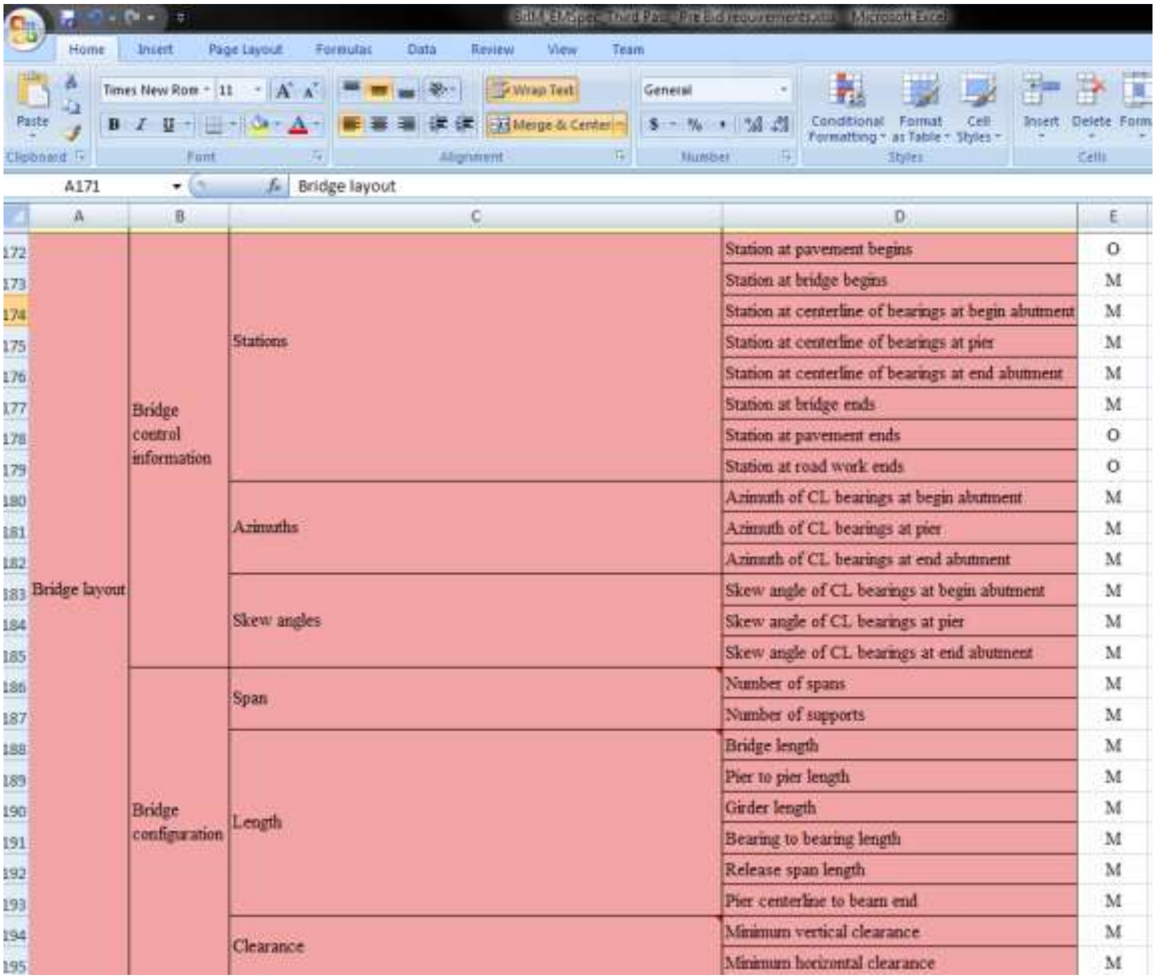
For this case study, the exchange requirement used the Data Dictionary to discuss and select the appropriate information. Next, the information was used in the development of the taxonomy and approval in the next step.

6.3. Step 3: Design and Approval of Specification

6.3.1. Step 3.1: Design of Specification

Once the taxonomy is built with the associated DataSet terms, it can be exported for validation per each Exchange Requirement of the Exchange model. The current method for validating is using Excel and assigning an "M" (mandatory), "O" (optional), or "N" (not required) to each data cell. The purpose of the assignment is to let the software vendors know what data is needed for the application. Since each receiver has different data requirements, it important for software functionality of the application. Figure 6-16 displays the exported taxonomy with the data requirements.

It should be noted that the difference between the original Data Dictionary and the taxonomy exported Excel file is that the taxonomy has the GUID embedded and the cells are locked. This will prevent any modifications to the cell during voting and approval. Any comments or suggestion can be implemented by using the Excel "add comment" feature.



	A	B	C	D	E
172	Bridge layout	Bridge control information	Stations	Station at pavement begins	O
173				Station at bridge begins	M
174				Station at centerline of bearings at begin abutment	M
175				Station at centerline of bearings at pier	M
176				Station at centerline of bearings at end abutment	M
177				Station at bridge ends	M
178				Station at pavement ends	O
179				Station at road work ends	O
180			Azimuths	Azimuth of CL bearings at begin abutment	M
181				Azimuth of CL bearings at pier	M
182				Azimuth of CL bearings at end abutment	M
183			Skew angles	Skew angle of CL bearings at begin abutment	M
184				Skew angle of CL bearings at pier	M
185				Skew angle of CL bearings at end abutment	M
186		Bridge configuration	Span	Number of spans	M
187				Number of supports	M
188			Length	Bridge length	M
189				Pier to pier length	M
190				Girder length	M
191				Bearing to bearing length	M
192				Release span length	M
193				Pier centerline to beam end	M
194			Clearance	Minimum vertical clearance	M
195				Minimum horizontal clearance	M

Figure 6-16: Screen Capture of the Taxonomy Export for Validation.

6.3.2. Step 3.2: Balloting and Approval of Specification

In order for a standard or specification to be approved for official use, it typically goes through a balloting process. Since each domain industry may have its own process of approval, it is best to go that route. The timeline of this process will varies based on the official process that governs the domain group. The typical process is as follows:

1. Group members agree and finalize specifications
2. Group prepares documentation for ballot. If there is a hierarchy of the approval process, then the documents must be voted by any authoritative powers before final ballot.
3. Ballot is sent out to all committee members for commentary.
4. Any comments or suggestions are remedied in the ballot documents.
5. Ballot is sent for official vote. There may be specific rules of how the ballots are to be cast and counted
6. Upon successful ballot, the documents are approved for becoming a standard. If there are more levels of hierarchy, the ballot will keep being sent until the highest power approves.
7. Specifications will be design into the official specification format.
8. Specification will be published.

6.3.3. Case Study: AASHTO/NSBA Approval Process

The Erector exchange requirement for the "asBid" model was modeled after the hierarchy of the Data Dictionary since it was the first model. Utilizing the Data Dictionary model has proven a success in the data requirement. Future exchange requirements will explore adding the ability to assign the "M" "N" or "O" requirement directly into the Taxonomy Editor. As mentioned before, the development of the editor was minimal to meet the needs of the group, and so further development is needed for full functionality.

The balloting and approval process for the AASHTO/NSBA can be found in the operations manual (Appendix F). Below summarizes the process of becoming an Official AASHTO/NSBA Collaboration Standard or Guide Specification.

6.3.3.1. Becoming an Official AASHTO/NSBA Collaboration Standard or Guide Specification:

The following document outlines the stages from the development of a Collaboration Standard or Guide to its final publishing by American Association of State Highway and Transportation Officials (AASHTO). Each stage is shown in Figure 6-17 below.

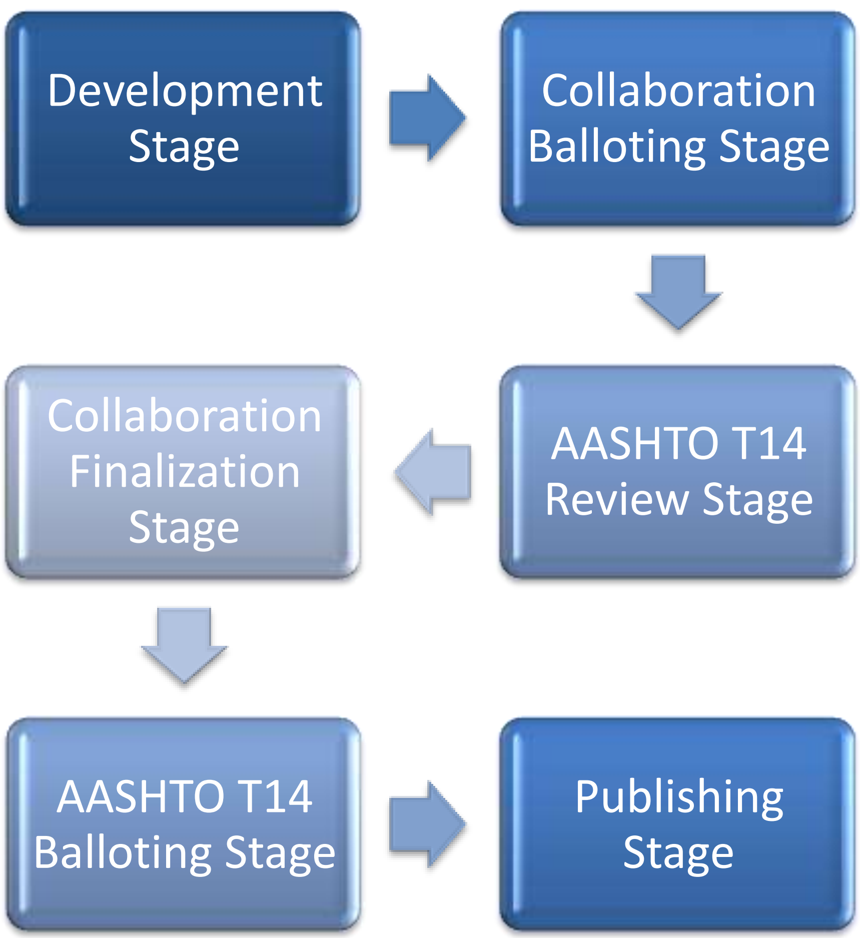


Figure 6-17: Stages in Developing an AASHTO/NSBA Collaboration Standard or Guide (*Courtesy of NSBA*).

A document should be entirely finished and in a final condition before it is submitted to the AASHTO T14, the subcommittee in charge of steel bridges, Balloting Stage at the annual AASHTO Subcommittee on Bridges and Structures (SCOBS) meeting. AASHTO SCOBS meeting occur once a year either in the spring or early summer. The development, balloting, review and finalization stages must be completed in a timely manner to ensure publishing of a Collaboration document in a specific year.

6.3.3.2. Development Stage

At this stage an existing Collaboration document is being updated. Updates would include those that reflect current practices which may not have been captured in the previous revision. It may also include correction to errors and/or omissions that were discovered after initial publishing. Lastly, updates may include improved or expanded upon content. Note that a new Collaboration documents will also go through a development stage. During the development stage, the Collaboration document has only been typically reviewed by members of the specific Task Group that developed it.

Once the document has been finalized, the document is then moved to the "Balloting Stage".

6.3.3.3. Balloting Stage

When a Collaboration Task Group Chair has finalized all updates and changes to their document, the document is then readied for balloting by the entire Collaboration. This stage is intended to provide Collaboration members beyond that of the document's task group time to review and provide their comment. While this ballot is not intended to include AASHTO T14 members, there may be instances where a person is a member of both the AASHTO T14 and the Collaboration.

Note that the document to be balloted should be given to the NSBA Collaboration Administrator as both a Microsoft Word file and an Adobe PDF. Only the PDF version of the Collaboration document will be provided with the ballot. The ballot will be administrated by the NSBA Collaboration Administrator.

Each person submitting a ballot is asked to vote in one of three ways:

- Approve - I accept the balloted item(s) in full.
- Approve with comment - I accept the balloted item(s) with the technical comments shown in the next section. I acknowledge that my comments may not be incorporated into the document and therefore I find the balloted item acceptable even if my comments are not incorporated.
- Do not approve - I do not accept the balloted item(s) for the reason expressed in the next section.

It is expected that comments should be provided by the person submitting the ballot if voting either “Approve with comment” or “Do not approve”. Comments are organized in a Google Spreadsheet where each row represents a specific section reference to the document being reviewed (Figure 6-18).

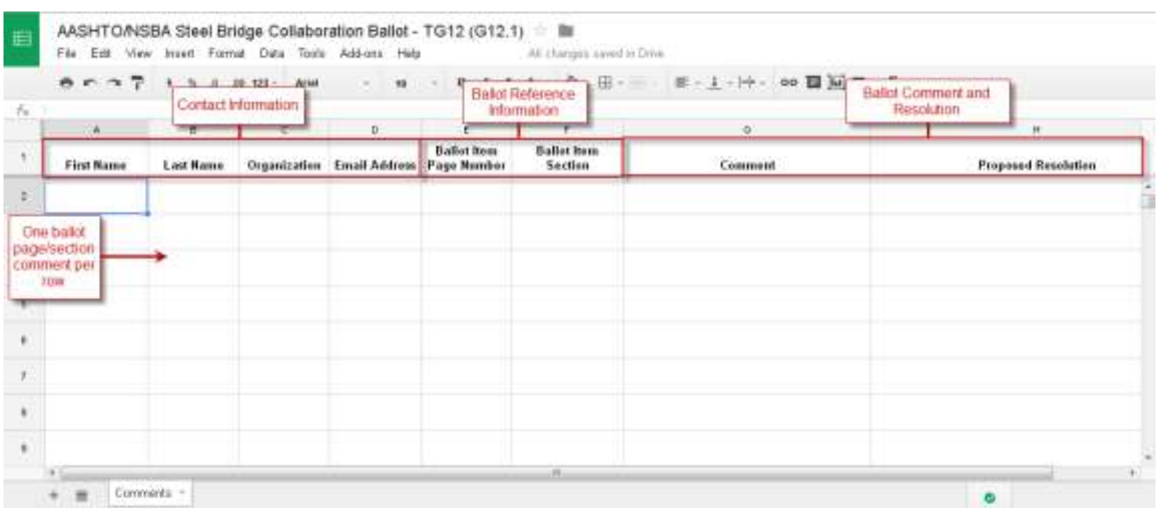


Figure 6- 18: Example Ballot Comment Collection Spreadsheet (*Courtesy of NSBA*).

During balloting, any questions related to the document being balloted will be directed to the specific Task Group Chair. Any technical issues related to the operation of the ballot itself will be directed to the NSBA administrator.

All ballots are administered and submitted online using a combination of Google Survey Form and Google Spreadsheet. Ballots may be open anywhere from 2-weeks to 1-month. At the conclusion of the ballot, the comments are then compiled and considered by the Task Group Chair.

There are instances where a particular person is unable to access the online ballot form. In cases like these, an alternative submission method is provided using email. All emailed ballot responses should be sent to the NSBA Collaboration Administrator who will the manually add them to the other ballot responses that have been submitted so that all responses are all in one location. The final date to submit a ballot response and comments by email will be the same date that the online ballot closes.

As previously stated, ballots are open for response for a fixed amount of time. At the end of this time, the ballot is closed and no additional responses are allowed. A ballot is closed by disabling the online form and denying access to the comments Spreadsheet. Anyone trying to access a closed ballot will encounter a message similar to that shown below in Figure 6-19.

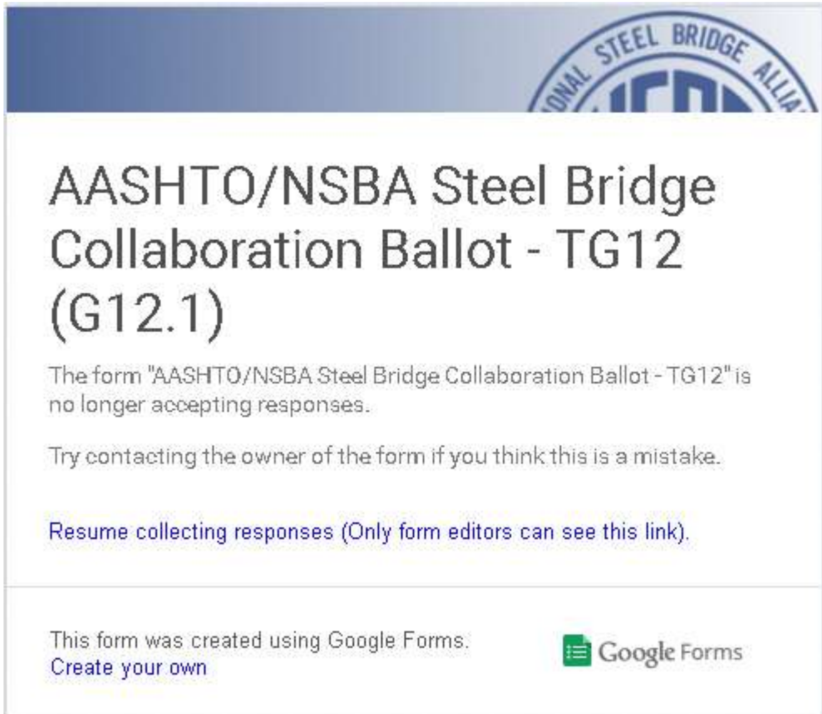


Figure 6- 19: Example "Ballot Closed" Message (*Courtesy of NSBA*).

At the conclusion of the ballot, the Collaboration Task Group Chair then reviews the ballot votes and comments. Any document that has received a majority "Do not approve" should be reconsidered before being forwarded to the AASHTO T14.

It may make sense for the Task Group Chair to address comments or changes regarded as "significant" before the document is submitted to AASHTO T14. Once the document has been "approved" by ballot, it is then moved to the "AASHTO T14 Review Stage".

6.3.3.4. <u>AASHTO T14 Review Stage</u>

At this stage, a Collaboration document has been balloted by the entire Collaboration and has received a majority "approved". The document is then provided to the member of the AASHTO T14 for review and comment. Review and comment will be handled similar to the balloting process so that all comments can be collected in a single location.

The AASTO T14 members are given approximately 1-month to review and provide comments on all documents. All comments are compiled by the Task Group Chair and then reviewed by the corresponding Task Group who will decide how to best respond to the comments. Ideally, the processing of comments will happen before the next Collaboration meeting where the document will be finalized.

6.3.3.5. Collaboration Finalization Stage

At this point, a Collaboration document has been reviewed and commented on by both the entire Collaboration and the AASHTO T14 members. The Collaboration Task Group Chair will assemble all of the comments for discussion at the next Collaboration meeting. The Task Group may choose to incorporate or not incorporate comments at this time.

It is important to understand that at the end of this stage, the final document submitted to AASHTO SCOBS will be automatically forwarded to AASHTO for publishing if approved.

6.3.3.6. AASHTO T14 Balloting Stage

Before a document can be published, it must go through the AASHTO T14 Balloting Stage at the annual AASHTO SCOBS meeting. The document is first put to vote by the AASHTO T14 members for approval. If a move is made to approve the document, a recommendation is made to forwarding to document to the SCOBS Main Committee. The SCOBS Main Committee will then vote to approve or reject the document for publishing.

Note that the document to be reviewed at AASHTO SCOBS should be given to the NSBA Collaboration Administrator as both a Microsoft Word file and an Adobe PDF.

Both files will be provided to the AASHTO SCOBS main committee by the NSBA Collaboration Administrator.

6.3.3.7. Publishing Stage

A document at this stage has been approved by the entire AASHTO SCOBS committee and has been forwarded to AASHTO for publishing. The final file format for a submission for publishing should be a Microsoft Word DOC or DOCX file and an Adobe PDF. Any images used in the document should be available in a high enough resolution for publishing. In some instances, AASHTO may make a request for original images and figures. Collaboration Task Group Chairs should have all supporting images, figures and charts that are used in their document available in the event that AASHTO request them. These files should be provided to the NSBA Collaboration Administrator prior to the AASHTO SCOBS Review Stage.

Figure 6-20 represents the flow chart of the development of standards of the AASHTO/NSBA Steel Bridge Collaboration.

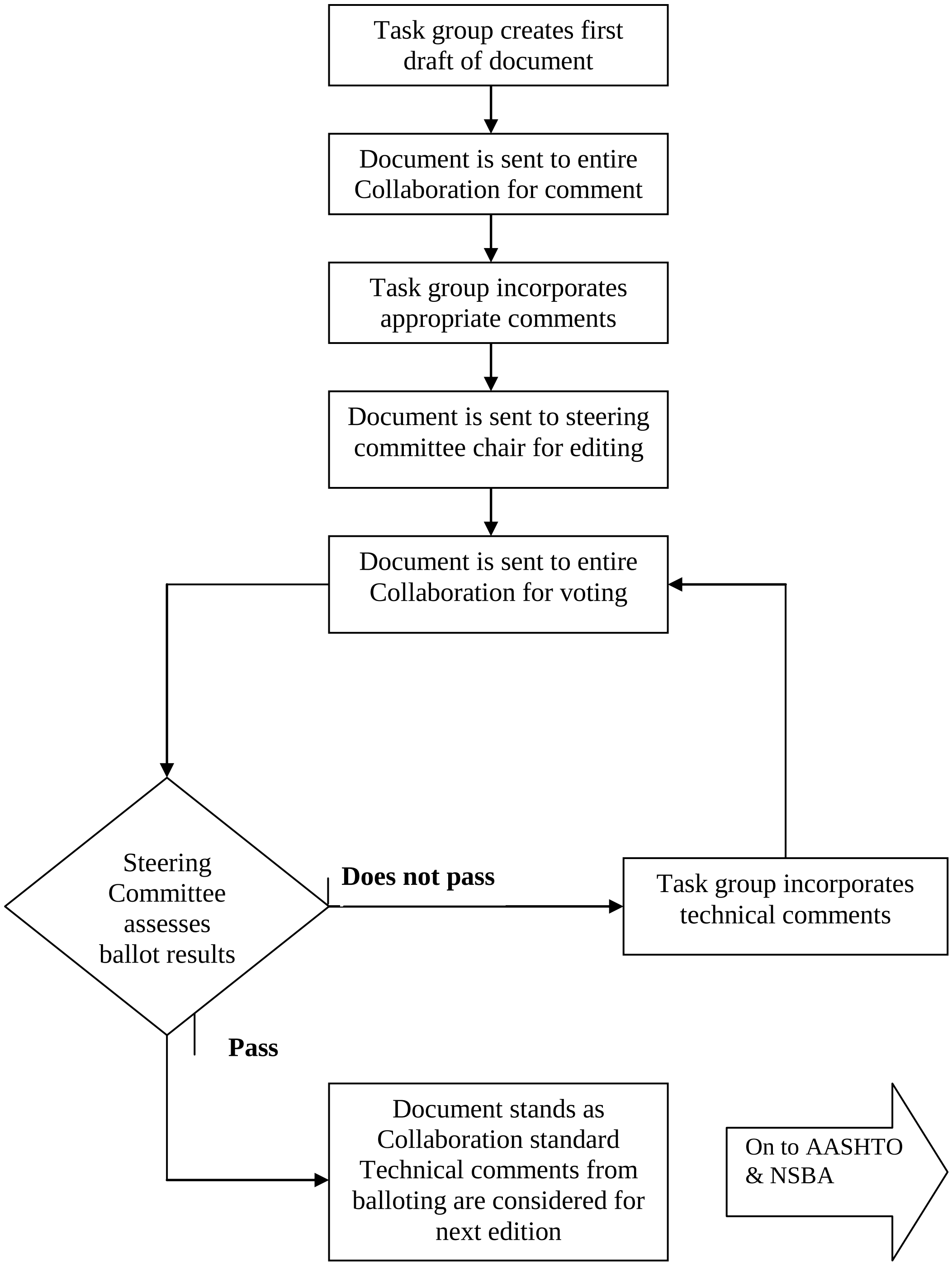


Figure 6-20: AASHTO/NSBA Steel Bridge Collaboration Development of Standards (*Courtesy of NSBA*)

6.4. Implement into Software and Validate

Although out of the scope of this research, the fourth step is to convert the taxonomy into an ontology to be developed into software. Additional axioms and constraints will be added by the software developers. It is important that this is also and iterative process since the industry experts need to again approve of the ontology, since the ontology represents the domain knowledge in a logic structure. Chapter 7 discusses these axioms in more detail.

Validation usually requires test case models to use and implement the schema (in this case ontology). After it is determined that the test case models, then a pilot application program is sent out to a select bunch of industry users. Feedback and development is an iterative process. After the application has been accepted to be validated, the software application may need to go through a standardization process, depending on the domain. Finally, documentation on how to use the application is published, and the application is rolled out for commercial use.

6.5. IES Summary

This chapter outlined the information exchange standardization process that captures domain knowledge and puts it into form of a taxonomy that software developers can use to program interoperable software. The steps of IES is summarized as follows:

1. Capture Domain Knowledge
   - 1.1. Organize Industry Collaboration Group
   - 1.2. Identify the Workflow
   - 1.3. Modeling the Workflow
   - 1.4. Document the Workflow
2. Organize Knowledge in Usable Format

2.1.Define Terminology

2.2.Assign Term Relationships

3. Design and Approval of Specification

   3.1. Design of Specification

   3.2.Balloting and Approval of Specification

4. Implement into Software and Validate

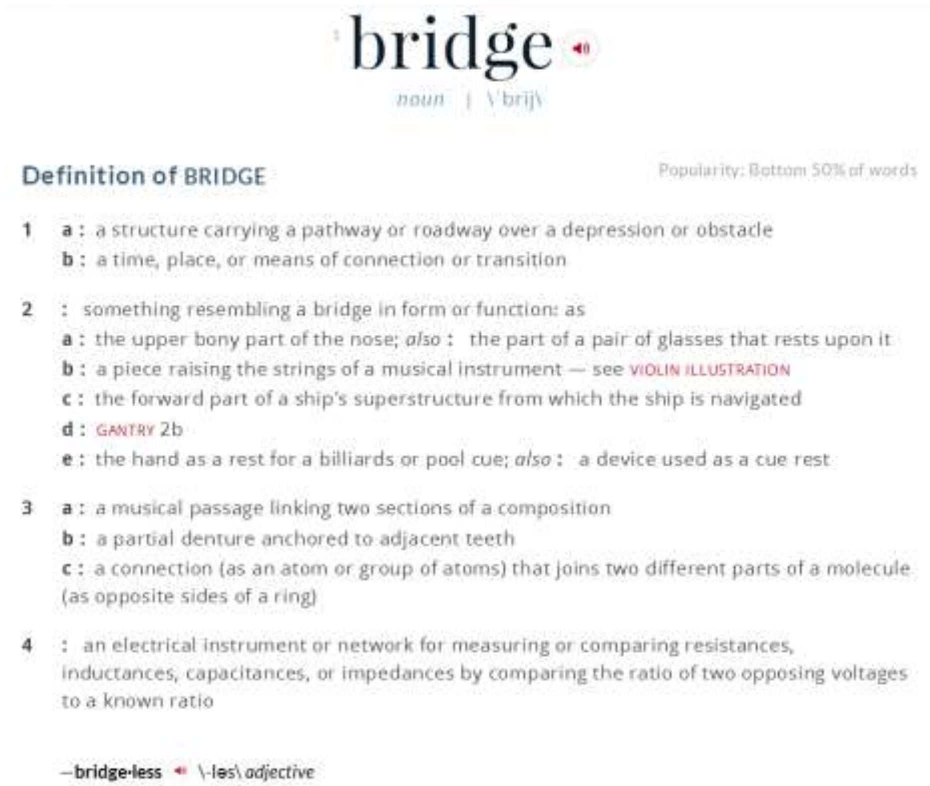
CHAPTER 7

7. TAXONOMY AND ONTOLOGY DEVELOPMENT

This chapter presents a novel method of creating an ontology based on a domain workflow. As there is no one correct way to build an ontology, this method was determined from an accumulation of research papers, articles, and other methods for the development of other ontologies identified in Chapter 2. The ontology development process in this research is different from the other processes identified since it emphasizes that the taxonomy is the imperative first step. It utilized the information and knowledge produced by the Information Exchange Standardization process in the previous chapter.

A taxonomy and ontology are very similar, and in a non-technical sense can be difficult to distinguish. Chapter 2 defined these terms in the technical sense from literature. In order to clarify the difference between a taxonomy and ontology, below is a recap and illustration of how they are used in this dissertation.

Dictionary: A collection of terms with definitions and examples of use. Additional information about the terms (origin, phonetics, grammar, etc.) may be included. Dictionaries contain a wide variety of words, often spanning a wide variety of terms. Moreover, each term contains all the definitions and uses to the particular word, such as the term “bridge” in Figure 7-1.



bridge

noun | \ˈbrij\

Definition of BRIDGE — Popularity: Bottom 50% of words

1 **a :** a structure carrying a pathway or roadway over a depression or obstacle
b : a time, place, or means of connection or transition

2 **:** something resembling a bridge in form or function: as
a : the upper bony part of the nose; *also* **:** the part of a pair of glasses that rests upon it
b : a piece raising the strings of a musical instrument — see VIOLIN ILLUSTRATION
c : the forward part of a ship's superstructure from which the ship is navigated
d : GANTRY 2b
e : the hand as a rest for a billiards or pool cue; *also* **:** a device used as a cue rest

3 **a :** a musical passage linking two sections of a composition
b : a partial denture anchored to adjacent teeth
c : a connection (as an atom or group of atoms) that joins two different parts of a molecule (as opposite sides of a ring)

4 **:** an electrical instrument or network for measuring or comparing resistances, inductances, capacitances, or impedances by comparing the ratio of two opposing voltages to a known ratio

—**bridge·less** \-ləs\ *adjective*

Figure 7-1: Screen Capture of the Merriam-Webster Online Dictionary for “Bridge”

Glossary: A collection of specialized terms used in a particular domain, often found at the end of a chapter of a publication. A glossary defines the meaning of the terms that applies to that specific publication or domain. Some terms may have a “refer to” another term instead of a definition. A glossary differs from a dictionary in the fact that it only contains the definition of term, but it is the correct definition of how it is used in context. This is important when terms have multiple meanings for different domains. Figure 7-2 displays a portion of the glossary from AASHTO LRFD.

6.2—DEFINITIONS

Abutment—An end support for a bridge superstructure.

Aspect Ratio—In any rectangular configuration, the ratio of the lengths of the sides.

Beam—A structural member whose primary function is to transmit loads to the support primarily through flexure and shear. Generally, this term is used when the component is made of rolled shapes.

Beam-Column—A structural member whose primary function is to resist both axial loads and bending moments.

Bend-Buckling Resistance—The maximum load that can be carried by a web plate without experiencing theoretical elastic local buckling due to bending.

Biaxial Bending—Simultaneous bending of a member or component about two perpendicular axes.

Bifurcation—The phenomenon whereby an ideally straight or flat member or component under compression may either assume a deflected position or may remain undeflected, or an ideally straight member under flexure may either deflect and twist out-of-plane or remain in its in-plane deflected position.

Figure 7-2: Screen Capture of the AASHTO LRFD Bridge Glossary

Taxonomy: A hierarchical structure of defined terms that represent the relationships and attributes among those terms. Figure 7-3 displays the hierarchy of a taxonomy.

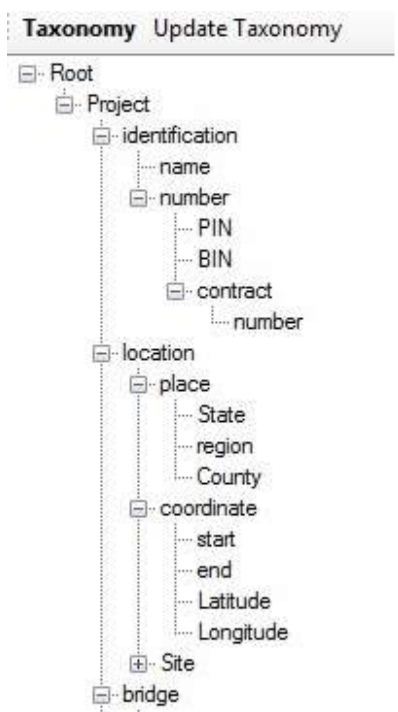


Figure 7-3: Screen Capture of the BrIM Taxonomy Hierarchy.

A taxonomy is essentially the combination of a glossary and dictionary (since it's a subset of terms from a domain with definitions) in a hierarchical form to represent and display the relationships between the terms. It is important that the definitions should be validated and approved from the domain. A taxonomy can be in machine readable form (such as a spread sheet), but it does not contain the appropriate constraints and axioms that are needed to develop into software. Figure 7-4 displays the Taxonomy Editor for the term "Owner" with the information being displayed.

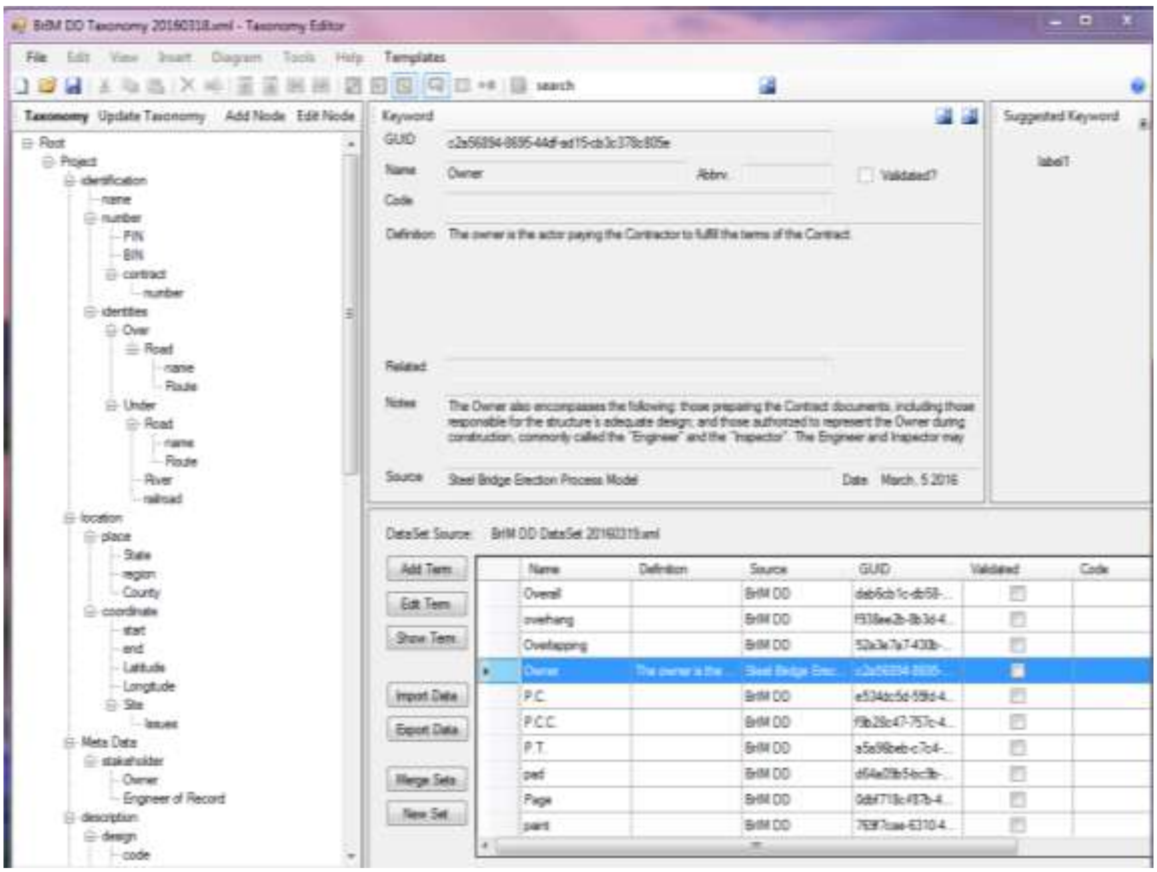


Figure 7-4: Taxonomy Editor with the Term "Owner" being Displayed.

Ontology: In computer and information science, an ontology is the formal classification of entities in a particular domain, that includes the types, properties, relationships, and other attributes about the entities within the domain. Figure 7-5 displays a subset of the BrIM ontology. A taxonomy with additional constraints (via axioms) can create an ontology. A well-formed ontology provide both the semantic (meaning) and syntactic (form) of information that can be used in software. The taxonomy provides the information and basic structure to convert into an ontology, which is the machine readable logic structure that can be implemented into software. It should be noted that the DataSet and Taxonomy are also both machine readable, which allows the information sharing, but they do not contain the logic structure needed by software implementation. The logic structure contains the additional axioms (logic assertions) provided by the ontology language in a common form (structure). Figure 7-6 displays the structure of an ontology in relation to the taxonomy and DataSet.

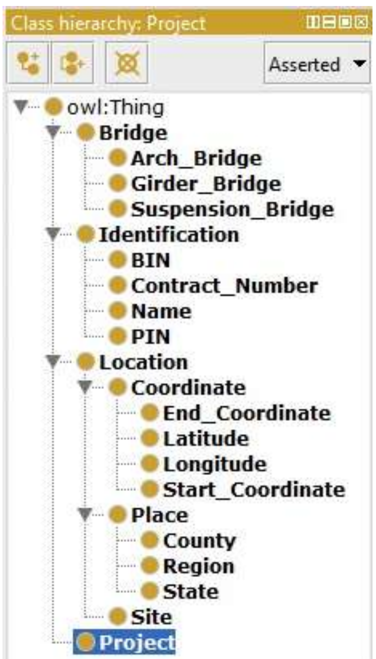


Figure 7-5: Screen Capture of the BrIM Ontology

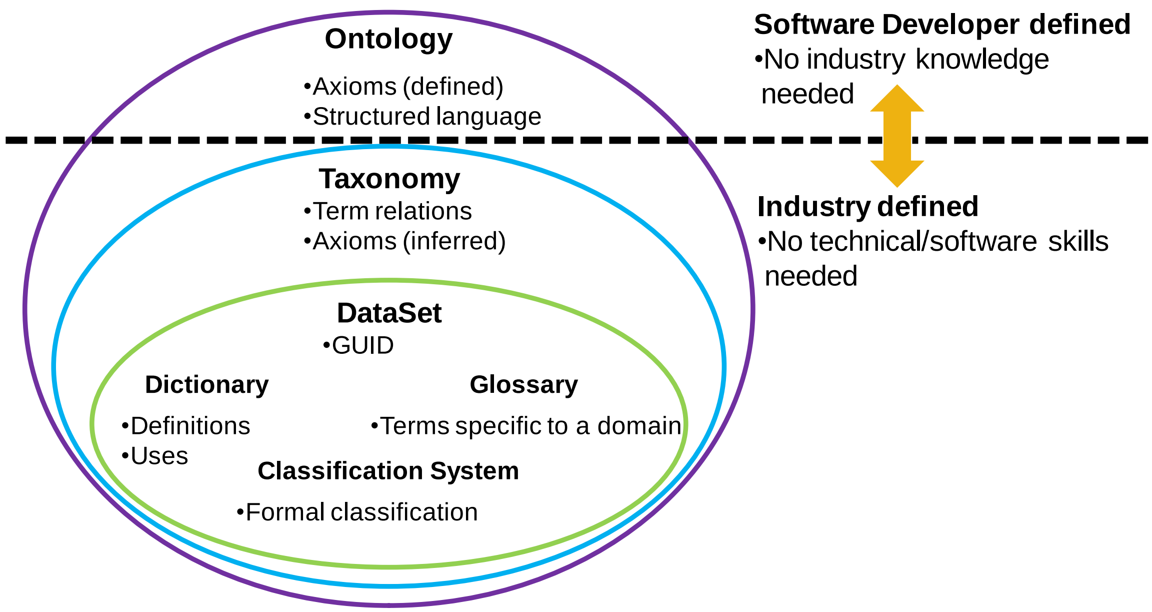


Figure 7-6: Structure of an Ontology in Relation to the Taxonomy and DataSet

A novel contribution of this research is that the ontology is built from the bottom up, i.e. the domain workflow defines the structure of the ontology. This is important because domain experts, who may not have technical or software skills to develop an ontology, are able to define the taxonomy based on the workflow. Additionally, a well defined taxonomy can be implemented into an ontology by software developers, who may not be knowledgeable in the industry domain. Together, both industry experts and software developers can collaborate together to verify that the final ontology represents the domain knowledge. It is important to note that not all current ontologies contain the definition or reference to a term that has been defined. This is one of the reasons that it is imperative to base an ontology on a taxonomy of validated terms to guarantee that the meaning and use of a term will be consistent.

Building a taxonomy prior to the physical development of the ontology is an imperative first step because a well defined taxonomy:

1. *Reduces ambiguities of the domain lingo.* Compiling a list of definitions in a domain will result in ambiguities since there may be synonyms of word. In other words, the same definition might apply two different words. For example, joist, lintel, girder, plank, rafter, and purlin are all synonyms of the word “beam,” which is defined as “a structure member designed to carry loads between or beyond points of support, usually narrow in relation to its length and horizontal or nearly so” (ISO 6707-1:2014). Therefore it is imperative that the most commonly used term will be the default, and each synonym be accurately describe for the function. Having clear and concise definitions, while using that same term definition across the domain will reduce the ambiguities.

2. *Clarifies the semantics of terms.* Likewise with the same definition applying to different words, one word may have multiple definitions. For example, the word “bridge” can mean a ship’s platform, a cue in pool, the top of a nose, an electronic component, a card game, or a structure. Approving one definition that fits the best need to that domain to will reduce the semantic issues that may arise from multiple meanings.

3. *Provides consistency of terminology*. Having a defined set of terminology will be the center of usage in software. For example, a “beam” in application A will always have the same definitions as “beam” in application B if they link to the definition in the taxonomy via the GUID.

4. *Reduces time and effort in building a ontology*. Industry experts, who may not be technologically savvy, can easily provide the information for and produce the taxonomy. Therefore, once a well defined taxonomy is developed, the development of the ontology will be less cumbersome to develop, since all the

information is needed (e.g. purpose, objective, competency questions, terminology, and relationships) to develop the ontology. Essentially all that's left is to incorporate more axioms and convert the information into an ontology language, which puts fewer burdens on the software developers to collect and verify domain knowledge. Although considerable more time is placed in the taxonomy development time and effort is not wasted verifying the terms from domain knowledge as in the case of traditional building of an ontology.

This chapter describes how an ontology is developed from the technological perspective. Unlike the other literature that identify the needs for an ontology, this process identifies the needs of a specific domain, in which the ontology can then be developed from. Moreover, the focus is not on solely creating the ontology, but how ontology can be developed to fit the needs of the domain. In other words, the focus is not on the "end" result, but the "means" needed to get to the end. Focusing on the workflow needs instead of the ontology needs is a novel contribution. The ontology is the final result of the process. For example, an ontology should not be created first and then determine what applications it has, but rather create the application and select the terms needed to be in an ontology. The steps of the ontology development are as follows:

1) Identify the purpose and requirements of the workflow
2) Identify the terms used in the workflow
3) Review existing terminology and select best fit
4) Assign the terms into a taxonomy
5) Define axioms to support the taxonomy
6) Convert taxonomy to ontology

Iteration and domain expert involvement are critical pieces in the development of accurate domain ontology. This section provides the basic steps that are need to build and manage an ontology that is workflow driven. Since the development of the taxonomy is in tandem with the IES, this process will only focus on the technological portions that utilize the information developed from the IES. Additionally, examples from the BrIM ontology developed from the case study will be used throughout this chapter.

7.1. Step 1: Identify the Purpose and Needs of a Domain

An ontology can be viewed as the machine readable format for human knowledge. Since human knowledge is very extensive, it is important to identify the subset of knowledge that needs to be represented. The purpose and needs for the ontology can be determined in identifying the workflow for a specific domain. Instead of choosing the needs for the ontology, let the needs identified in the workflow justify the needs of the ontology. This subset of knowledge is determined in the IES Step 1. The scope of work should be determined in the workflow process. See Chapters 3 and 6 for the instructions how to develop and model a workflow. After a workflow has been developed, the task of exchange requirements will result in the data needed for this step.

7.1.1. Case Study: Identifying the Needs of Steel Erection

The purpose of the taxonomy in this research is to classify all the terms and definitions needed to support BrIM workflows. The taxonomy will only use terms in the United States, but would include all bridge types, including complex structures such as truss and suspension bridges. The taxonomy would also include those terms used in the transportation industry since it is expected that all geospatial and transportation models will need to be integrates. The taxonomy would be used in files and documents (e.g. manuals, contracts, bids, etc.) and software used in the bridge industry. The goal of the taxonomy is to standardize the vernacular and vocabulary of the bridge industry. The taxonomy will be used by transportation officials (e.g. state DOTs, FHWA, etc.), industry stakeholders (e.g. owners, contractors, builders, etc.), and BrIM software developers. The official body to manage and maintain the taxonomy is still undermined, but is anticipated to be stewarded by an official organizing body, such as FHWA, AASHTO, or even buildingSMART International.

Even within a specify domain of use, such as the bridge industry, there are still a large number of terms to define and organize. Defining a scope will help narrow down the work and terms needed upfront. Since the taxonomy will be expandable, additional terms can be added as time progresses. Below are some questions to help develop the purpose and scope:

- What sub domain is the taxonomy for?
- What is the scope of the workflow?
- What is the level of detail provided by the workflow?
- What are the essential tasks that need the taxonomy?
- What is a good starting point (i.e. the lowest hanging fruit)?

This research is working closely with the AASHTO/NSBA task groups in achieving various exchanges. The scope of this taxonomy can be limited to bridge structures, in which more specifically steel bridges. Even within steel bridges, there are various scopes of work. This research is partnered with the AASHTO/NSBA TG10-TG15, which deals with the erection of steel bridges. Therefore, the starting point of terms will deal with those needed for the erection and construction of steel bridges. Naturally, terms needed within this scope will expand and extend to a larger scope and domain. For example, the term “beam” will be need for steel bridge erection, but it will also be used in design of steel bridges, as well as concrete bridges and other structures.

7.2. Step 2: Identify the Terminology Used in the Workflow

The taxonomy needs to be both expandable and extensible because it is infeasible to create a taxonomy that is complete and exhaustive of all terminology of a domain, especially as large as transportation and construction. The taxonomy needs to be expandable to incorporate more information as it grows, and also needs to be extensible to allow further development and incorporation with other domains. However, it is important to note that safeguards need to be in place to prevent such alterations of the taxonomy that would affect end user software development. For instance, an alteration in the taxonomy needs to be in the way that software developers can implement the alterations efficiently and effectively. The terminology can first be identified through the process model development, which is outlined in Chapter X.

7.2.1. Case Study: Identifying Bridge Terms

The industry knowledge for the case study of was captured in the "Outline of Typical Processes for Steel Erectors" document attached in Appendix C. This document outlines the process that erectors follow in the construction of steel bridges. Then the workflow was captured in the "Process Model Development for Steel Erection" document and its corresponding process map. This document adds a more defined narrative and instructions about the workflow and all of its parts. Similar to a glossary, all the terminology for the workflow was defined in the document.

Additionally, the data defined in each exchange was also captured. One of the first exchange requirements (ER) identified for steel erection in the AASHTO/NSBA TG10-TG15 was the "Contractor to Erection Engineer" ER. This exchange identifies the information and data needed by the erection engineer to in order to submit a bid.

7.3. Step 3: Review Existing Terminology and Select Best Fit

In order to accurately define the domain, it is important to use the terminology that is used in that domain. It is important to use terminology that commonly used in the specific domain in order to reduce ambiguities. One way to do so is to first gather and compile all published documentation in that domain, and then sort through similar terms. It is expected that either the same spelling of a term has multiple meanings, or multiple terms have the same definitions. Therefore, it is required that these ambiguities and similarities need to be reduced by selecting the most appropriate term with the most appropriate definition, which then needs to be discussed with the domain experts. Finally, like everything else in the process, the compile list of terms needs to be validated and approved by the domain. Since each domain may have different process, it is up to the experts (or appropriate organization) to determine the rules and procedures to approve the terms.

7.3.1. Case Study: Utilizing Existing Terminology in the Bridge Industry

The American Association of State Highway and Transportation Officials (AASHTO) is the official United States organization that publishes specifications and standards used in highway design and construction. Therefore, the AASHTO published terminologies (AASHTO, 2014) was selected first and take precedence over other published terms. Other domain specific terminology, such as the NCHRP Steel Bridge Erection Practices (NCHRP, 2005), will need to be gathered to narrow down the terminology for each respective sub domain.

The terminology then must be sorted and organize. It will be expected that there will be multiple synonymous of a single term because terminology varies by organization, department, and region. Even within the same bridge project, there might be discrepancies of the terminology.

An initial effort by Hu (2014) compiled bridge terms in an Excel file, called the BrIM Data Dictionary. In order to create one standard term, the synonyms would be complied and ranked by usage. Once agreed upon by the domain experts and balloted, a single term would be the default while the others would be listed (i.e. if a term that is not the default is selected, it would point to the default term to be used).

7.4. Step 4: Assign the Terms into a Taxonomy

Once the terms have been organized, they need to be put in a hierarchy tree. It's important to utilize currently known hierarchies. The hierarchy development in itself is an iterative process. To accurately portray the real world, the hierarchy needs to be developed and approved by domain experts. Then each term will be defined with its own GUID, and all properties and relations will be listed such as "part of," "contains," "synonyms," "etc." For the synonyms, it will be voted upon to have the most widely used term to be the default term, so when a person looks up a term it they will be routed to the default term (this will help people use the correct term). The schematic will be hierarchical base with enumerations and exclusions, i.e. if a "beam" falls under one hierarchy, it may not have the same properties as a "beam" from another tree hierarchy, even though fundamentally they are the same GUID. All this organization is important for neutral software development.

7.4.1. Case Study: Assigning Terms into the BrIM Taxonomy

The BrIM taxonomy makes used of the Data Dictionary initially developed by Hu (2014). Figure 7-7 is a portion of the terms in the hierarchy. Assigning terms may be a difficult step of the taxonomy development because defining a term can be difficult at the fundamental level, most in part due to the amount of terms that may need to be defined. The first difficult question that needs to be asked is: what terms need to be defined?

Another factor is the "type of" or "enumeration" property. "Type of" defines a subset and "enumeration" means part of list. The second difficult question to answer is: how many levels of "type of" and "enumeration" will be sufficient to define the term? For example take a bridge erector. An erector is "a person that erects something" and the AISC Steel Bridge Erection Guide (NCHRP, 2005) defines an erector as "entity that is responsible for the erection of the structural steel."

	A	B	C	D
1	**Information Groups**	**Information Items**	**Attribute Sets**	**Attributes**
117	Roadway geometry	Vertical profile	Reference	Reference number
118			Types	Tangent
119				Parabolic
120			Lines	Vertical control line
121				Theoretical grade line (TGL) / Profile grade line (PGL)
122			Stations	Point of Vertical Intersection (PVI)
123				Point of Vertical Curvature (PVC)
124				Point of Vertical Tangency (PVT)
125			Elevations	Elevation
126			Lengths	Length of vertical curve
127			Grades	G1 (Incoming grade)
128				G2 (Outgoing grade)
129			Roadway information	Stopping Sight Distance (S.S.D.)
130				C.C.
131			Topographies	Existing topography
132				Adjacent topography
133			Offset	Offset from horizontal alignment
134		Cross section	Geometries	Left edge to HCL
135				HCL to right edge
136				Left edge to TGL
137				TGL to right edge
138			Stations	Station
139			Slopes	Slope
140			Widths	Out-to-out width
141			Offsets	Centerline offset from H.C.L.
142				Crown offset from H.C.L.

Figure 7-7: Portion of the BrIM Data Dictionary developed by Hu (2014)

The Data Dictionary contains the hierarchy structure of the attributes and properties that have been identified in various exchanges of the bridge lifecycle. For example, a bridge requires roadway geometry, and thus "roadway geometry" as been identified as an information group. Roadway geometry has information items that describe the geometry, such as vertical profile and cross section. Then each information item can be described by varies attribute set. For example, the vertical profile attribute sets include references, lines, stations, and elevations to name a few. Finally, each attribute sets can be broken into more attributes and properties until the fundamental concept that describes a specific attribute is reached.

7.5. Step 5: Define Axioms to Support the Taxonomy

In this research, an axiom is a "stated rule or principle that helps govern the taxonomy and ontology." Axioms are similar to postulates (e.g. math or geometry postulates), in which they are assertions without any formal proofs. However, these assertions are used for deducing other truths. As mentioned earlier, axioms are an important part of developing taxonomy because they provide truths and assumptions that give meaning to the taxonomy. Axioms can be seen as the most difficult part of this process because they are involved in providing the semantics of the taxonomy (and ontology). However, axioms should be treated as a double edged sword since overly constraining the taxonomy would impede extension and expansion. For instance, Uschold and Gruninger (1996) state "the axioms in the ontology must be minimally sufficient to express the competency questions and to characterize their solutions." Although this is stated for axioms for an ontology, this same principle applies to axioms for taxonomies.

Axioms are typically written out in first order logic, such as in Uschold and Gruninger (1996). As part of mathematical logic, these types of rules are associated with type theory. This dissertation only addresses some basic concepts, and does attend to fully address the topic. Further readings about logic and set theory can be found in Andrews (2002). Table 7-1 summarized the main notation in first order logic that may be used in the development of axioms.

Table 7-1: Notation of First Order Logic

Symbol	Description	Meaning
Quantifiers		
∀	universal quantification	"For all"
∃	existential quantifier	"there exists"
Operators		
∧	conjunction	"and"
V	disjunction	"or"
¬	negation	"not"
→	Implication/conditional	"implies", "if…then"
↔	biconditional	"if and only if" or "iff"
Set Theory		
∈	membership	"includes"
∪	union	"both"
∩	intersection	"overlap"
⊆	subset	"some or all"
⊂	proper subset	"some, but not all"
=	equality	"equals"

The competency questions identified in the prior step specify the requirements that the axioms need to address. Below, Table 7-2 lists some basic axioms and definitions needed in the development of a general taxonomy. From these base axioms additional axioms can be defined.

Table 7-2: Definitions and Axioms

Relations	Axiom	Definition	Example
ComposedOf	Composed-of (A,B) $\leftrightarrow$ (B⊆A) ∧ (A⊈ B)	B is composed of A, if A is a subset of B, and B is not a subset of A	Bridge is composed of smaller parts, e.g. columns, beams, etc.
TypeOf		Aggregation of types, such as material or class	Steel is a type of metal. Metal is a type of material.
PartOf		Aggregation of discrete, physical parts	Beam is a part of bridge substructure
SubclassOf		Classes that inherit the parent class.	Suspension bridge is a subclass of bridge.
InverseTo	∀A,B f(A,B) $\leftrightarrow$ g(B,A)	For all A and B, relation g is the inverse of relation if A maps to B and B maps to A.	If beam is partOf bridge, then bridge hasPart beam.

Although axioms can be defined explicitly, they can also be inherently embedded in the development of the taxonomy, which are called inferred axioms. An inferred axiom is an assertion that is not explicitly defined, but rather inferred based on relationships. For instance, part-whole axiom, which can be referred to as aggregation, can be automatically assigned by placing terms under each node (Figure 7-8). For example, a user starts with a "bridge" class node, and then under that node is place "suspension" type, "girder" type, and "arch" type. Inherently, the user created the part-whole axiom which reads, "suspension, girder, arch are types of [class] bridges."

>Bridge

>Suspension

>Girder

>Arch

Figure 7-8: Example of Aggregation (subclass axiom)

Axioms can have inverse relations (Figure 7-9). Keeping with the example above, “Bridge” hasType “Suspension” and the inverse relation would be “Suspension” isTypeOf “Bridge.”

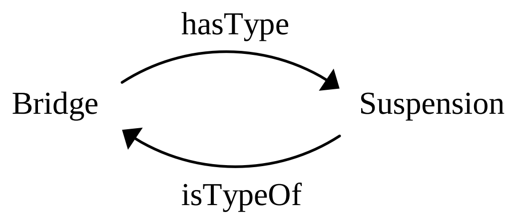


Figure 7-9: Example of Inverse axiom

Although indented to be flexible to let the user to define the axioms, The Taxonomy Editor does contain some constraints. For example, it contains the aggregation axiom, in which an entity cannot be composed of the same entity. In other words, a term cannot be assigned in the same tree as itself. For example, “bridge” is a parent node, and if the same “bridge” entity is placed under it as a child, an error message would pop up notifying of the error.

7.6. Step 6: Convert Taxonomy to Ontology

The previous section discussed the notation of first order logic and a few axioms needed to develop a taxonomy. In order to convert the taxonomy to an ontology, more explicitly defined axioms and properties are needed to provide the semantic meanings that software need. The major difference between the taxonomy and ontology will be the final output file and format. The ontology takes the hierarchical format of the taxonomy and explicitly defines the relationships between the nodes. Additional information is added using property features.

Although any ontology language can be used, this dissertation utilizes the Web Ontology Language since it is the most widely used. Additionally, OWL is an ontology for the Semantic Web and intended to be used and shared over the World Wide Web. Therefore having a widely used ontology enables the extensibility for easily sharing information in other domains. This section provides an overview of OWL 2 and the development of an ontology, but the full guide and development for the second edition of OWL (OWL 2) can be found at (W3C OWL Working Group, 2012). Additionally, an introduction to the syntax of OWL 2 can be found at (W3C, 2012).

The overview of the structure of OWL 2 is shown in Figure 7-10. At the core OWL 2 consists of the abstract notion of the ontology and the structure of the language, which can be represented as the Ontology Structure or RDF (Resource Description Framework) Graph. The bottom half of the dashed line represents defining the semantics (meaning) of the ontology language, which can either be direct or RDF-based. At the top of the dashed line display the syntax (structure) of the ontology, which are needed to store and exchange the ontology. There are various available (and often free) tools and application that can develop the syntax of the ontology.

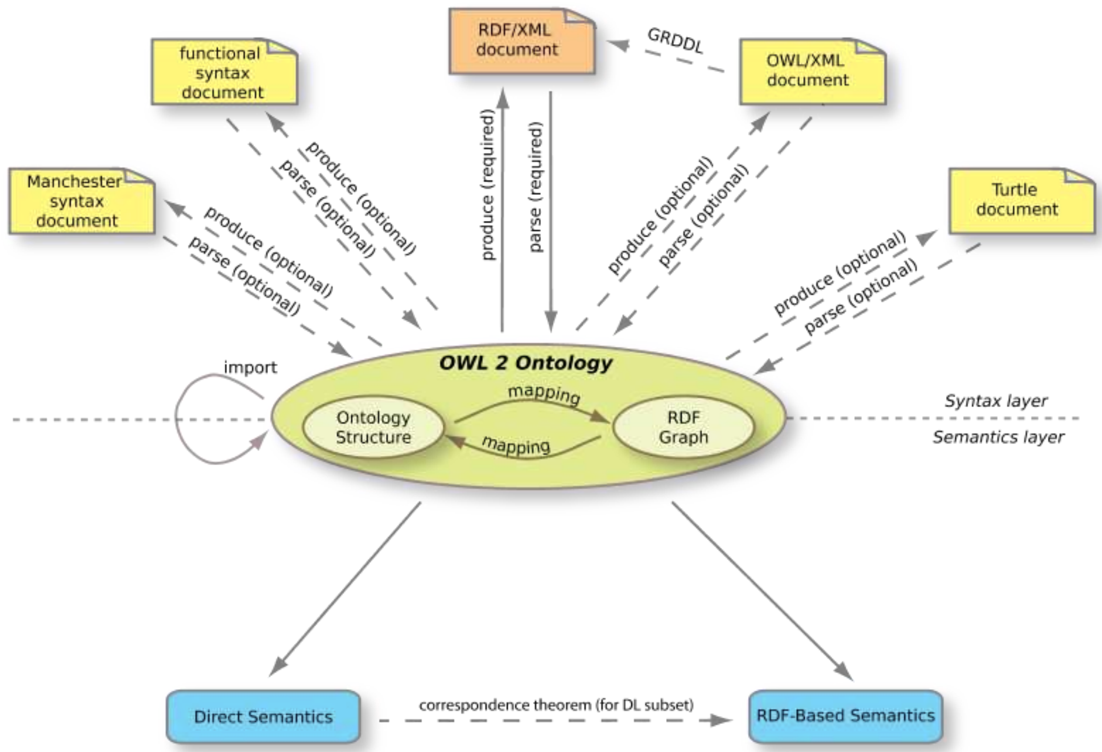


Figure 7-10: The Structure of OWL 2 (W3C OWL Working Group, 2012)

7.6.1. Ontology Components

Like other ontologies, OWL 2 represents and exchanges knowledge by the use of three fundamental notations: axioms, entities, and expressions. Axioms are the basic statements that the ontology expresses, entities are the elements that represent the real-world objects, and expressions are the complex descriptions formed by a combination of entities. The major elements of the OWL ontology structure consist of Individuals, Classes, and Properties, which can be defined as Resource Description Framework (RDF) resources. For the sake of clarity, this dissertation will visually represent the objects by the following: "Individual" (quotations), **Class** (capitalized and bolded), and *property* (italicized with CamelCase).

7.6.1.1. Individual

An individual represents a specific object in a domain. Individuals are also known as instances. In OWL 2, individuals are defined by "individual axioms", which are known as facts. These facts are used to describe each individual, such as class membership, property values, or descriptions. Figure 7-11 displays a representation of individuals in the bridge domain. For example, "California" is an individual of class **State**, "Golden Gate Bridge" is an individual of class **Bridge** and "Joseph Strauss" is and individual of class **Designer**.

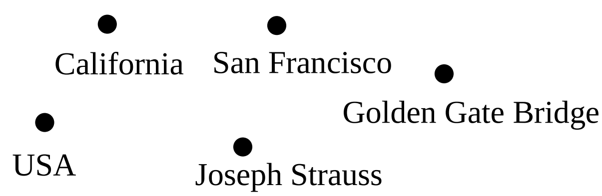


Figure 7-11: Representation of Individuals of the Bridge Domain

It is important to not mistake an individual for a class (which is described in the next section). An individual is a single instance of a class, and thus there should only be one. For example, a beam would be considered a class, since there are many instances of a beam, and a "LMC1113" is the name (piece mark) of an individual of a beam.

7.6.1.2. Classes

The main building blocks of an ontology are classes, which group individuals with similar characteristics. In other words, a class is a set of individuals. In order to be a member of a class, an individual must satisfy the conditions that are set by those class descriptions. These conditions are what enable the distinctions of individuals. OWL 2 distinguishes six types of class descriptions (i.e. a class can be defined by):

1. A class identifier, which is a Uniform Resource Identifier (URI) reference, that it describes a class through a *class name.*
2. An exhaustive enumeration (i.e. list) of individuals that together form the instances of a class. The enumeration description is defined with the owl:oneOf property. Figure 7-12 is an example of an enumeration of bridge types, in which an individual can be only one of the following: Arch, Beam, Truss, Cantilever, Suspension, or Cable-stayed.

```
<owl:Class>
  <owl:oneOf rdf:parseType="Collection">
    <owl:Thing rdf:about="#Arch"/>
    <owl:Thing rdf:about="#Beam"/>
    <owl:Thing rdf:about="#Truss"/>
    <owl:Thing rdf:about="#Cantilever"/>
    <owl:Thing rdf:about="#Suspension"/>
    <owl:Thing rdf:about="#Cable-stayed"/>
  </owl:oneOf>
</owl:Class>
```

Figure 7-12: OWL Syntax of Enumeration of Bridge Types.

3. A property restriction that defines an anonymous class, which is a set of individuals that satisfy the restriction. This means that a class does not have to be explicitly defined to exist. A property restriction describes a class of individuals based on the relationships that members of the class participate in. In other words, an anonymous class contains all the individuals that satisfy the property restriction.
4. The intersection of two or more class descriptions, which creates a set of individuals based on an intersection. Intersection is formed by the AND operator, which is denoted by the symbol ∩. For example, an instance of **SteelBridge** is

any instance of both **Bridge** AND **Steel** classes shown in Figure 7-13. This states that a steel bridge is both a bridge and made of steel.

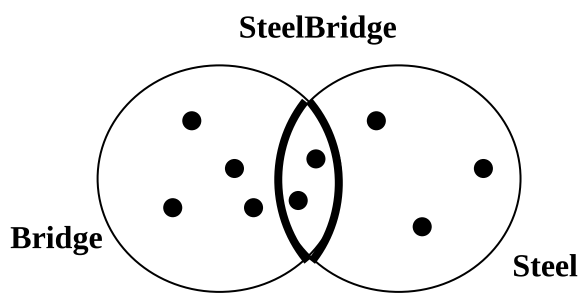


Figure 7-13: Representation of the Intersection of **Steel** and **Bridge** (**Steel** ∩ **Bridge**).

5. The union of two or more class descriptions, which creates a set of individuals based on an intersection. Union is formed by the OR operator, which is denoted by the symbol ∪. For example, a **Person** might be equivalent to the union of **Male** OR **Female** classes (Figure 7-14). This states that a male is a person, and a female is a person.

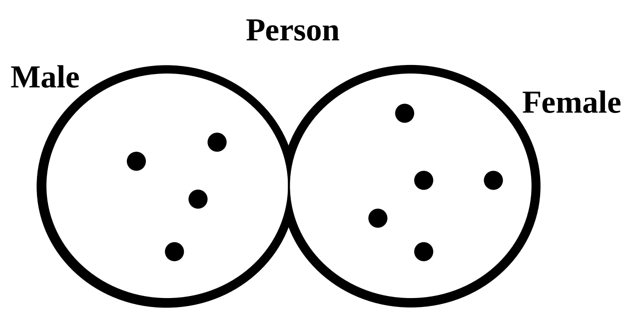


Figure 7-14: Representation of the Union of **Male** and **Female** (**Male** ∪ **Female**).

6. The complement of a class describes a class for which the class excretion contains exactly the individuals that are complement to the class, i.e. do not belong to the

class. The OWL 2 syntax is complementOf. For example, the class **SteelBridge** might have a compliment class called **NonSteelBridge** (Figure 7-15).

```
<owl:Class>
  <owl:complementOf>
    <owl:Class rdf:about="#SteelBridge"/>
  </owl:complementOf>
</owl:Class>
```

Figure 7-15: OWL Syntax of Complement of **SteelBridge**.

In OWL 2, all classes are subclasses to the main class THING. A subclass is a smaller set with of a class with more distinct characteristics, and inversely a superclass is what a class belongs to. In the taxonomy, this was referred to as the parent node and child node. A child node is a subclass of a parent node, and the parent node is the superclass of a child node.

Disjoint Classes: In OWL 2, classes are assumed to overlap and therefore are not disjoint by default. A class that is disjoint from another class cannot contain the same individual (i.e. an individual cannot belong to both classes that are disjoint). For example, “Joseph Strauss” is an individual of the class **Designer**. “Joseph Strauss” is also a human and a male, so he can be an individual of class **Human** and class **Male**, since these classes are not disjoint. In order to have disjoint classes, each class must be explicitly disjoint from another. Classes **Male** and **Female** need to be explicitly disjoint, so as an individual can either be a member of **Male** or **Female** (or neither). Therefore, since “Joseph Strauss” is an individual of class **Male**, he cannot be an individual of class **Female**. Figure 7-16 displays representation of non disjoint classes (**Designer** and **Human**) and disjoint classed (**Female** and **Male**)

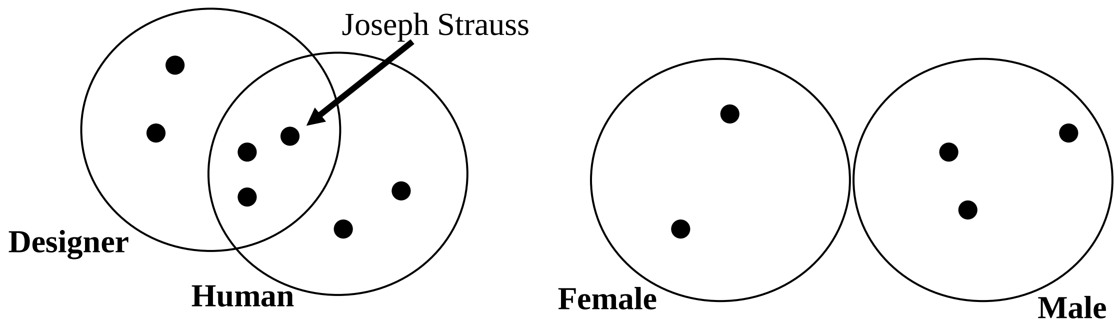


Figure 7-16: Representation Non Disjoint Classes (left) and Disjoint Classes (right).

7.6.1.3. Properties

Properties are relations that link one individual to another. There are two main types of properties: Object and Datatype. There are other property characteristics that associate to these two main types, which include Inverse, Annotation, Functional, Transitive, and Symmetric. Naming conventions are trivial since the relation can be described by many different ways, but is important to have them adequately described the relation. Also, object oriented programming conventions are also used, such as CamelCase.

Object Properties: An object property is a relationship between two individuals, in which property **P** relates individual **A** to individual **B**. For example, aggregation of parts would be considered object properties. Take for example *hasPart*. A bridge is composed of many parts, such as beams, columns, or walls. Since all these instances are objects, then they can be related to **Bridge** by *hasPart*. The syntax is owl:ObjectProperty.

DataType Properties: DataType properties link instances to data values, in which property **P** relates individual **A** to value **X**. For example, *hasCompressiveStrength* or *hasShearModulus* are DataType properties associated with materials. The syntax is owl:DatatypeProperty.

Inverse Properties: Each defined relation has an inverse property. For example, if **Bridge** *hasComponent* **Beam** then the inverse would be **Beam** *isComponentOf* **Bridge** as shown in Figure 7-17.

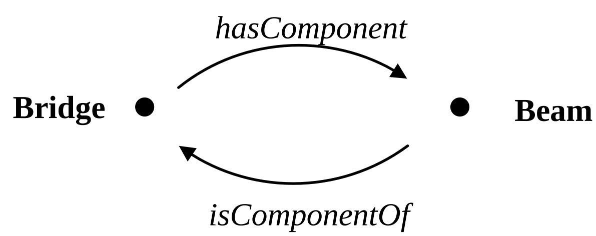


Figure 7-17: Representation of Inverse Properties.

Functional Properties: A property is functional if, for any given individual, there can be at most one individual related. For example, a child (“Lindsey”) will only have one birth mother (“Lezlie”), and thus *hasBirthMother* is a functional property. However, a mother can have multiple children, thus *hasChild* is not functional (Figure 7-18).

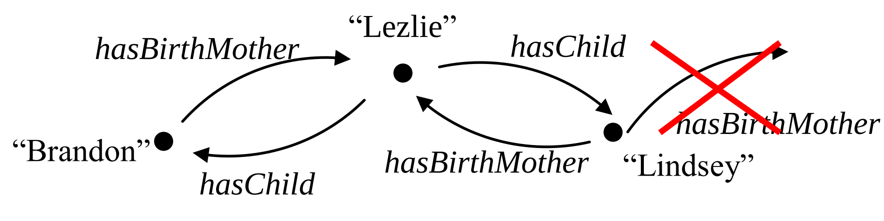


Figure 7-18: Representation Showing *hasBirthMother* as a Functional Property.

Transitive Properties: Transitive properties relate objects through another. For instance, a property, **P**, is transitive if it relates individual **A** to individual **B**, and also individual **B** to individual **C**, and thus can infer that individual **A** is related to individual **C** via property **P**. For example, if **Beam** is *partOf* **Superstructure**, and **Superstructure** is *partOf* **Bridge**, then **Beam** is also ***partOf*** **Bridge** (Figure 7-19).

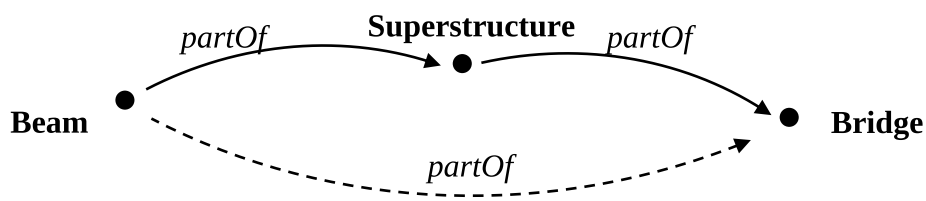


Figure 7-19: Representation Showing *partOf* as a Transitive Property.

Symmetric Properties: Symmetric properties relate two objects by the same property. For instance, **A** is related to **B** by property **P**, and **B** is related to **A** by the same property **P**.A clear example is the sibling relationship: “Lindsey” *hasSibling* “Brandon”, and symmetrically “Brandon” *hasSibling* “Lindsey” (Figure 7-20).

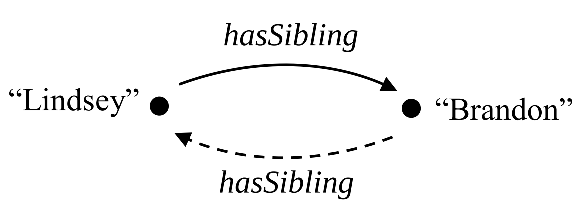


Figure 7-20: Representation Showing *hasSibling* as a Symmetric Property.

Annotation Properties: Annotated properties are used to add metadata to classes, individuals, and other properties. For example, name, definition, and other information are added to the object by the annotation property. OWL 2 has five main predefined annotations, which include:

1. owl:versionInfo – A string that defines the ontology version
2. rdfs:label - A string that adds names to elements
3. rdfs:seeAlso - A URI that can be used to link similar resources
4. rdfs:isDefinedBy - A URI that can be used to link to references
5. rdfs:comment - A string that adds more information to the elements

7.6.1.4. Domain and Range

Properties can have domain and range axioms that can be used for additional constraints. A property links individuals from a domain to individuals from the range. For example, a bridge has various structural components, thus **Bridge** *hasComponent* **BridgeComponent**, thus the domain of *hasComponent* is **Bridge** and the range of hasComponent is **BridgeComponent** (Figure 7-21). Additionally, the inverse property of *hasComponent*, *isComponentOf*, will have the inverse of domain and range.

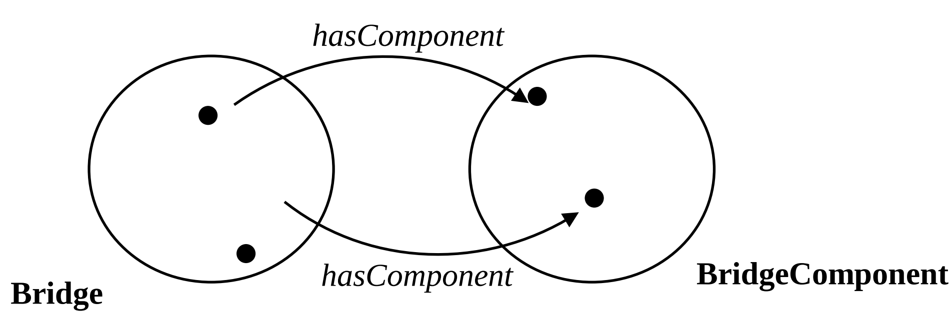


Figure 7-21: Representation Showing *hasCompontent* has domain **Bridge** and range **BridgeComponent**

7.6.1.5. <u>RDF Schema Constructs</u>

OWL 2 uses the RDF (Resource Description Framework) schema to provide a data modeling vocabulary for RDF data in order to have a more expressive ontology language. The full guide for RFD implementation in OWL 2 can be found at (W3C, 2014). Tables 7-3 and 7-4 provide the summary of the RDF Schema Vocabulary.

Table 7-3: RDF Classes (W3C, 2014).

Class name	Comment
rdfs:Resource	The class resource, everything.
rdfs:Literal	The class of literal values, e.g. textual strings and integers.
rdf:langString	The class of language-tagged string literal values.
rdf:HTML	The class of HTML literal values.
rdf:XMLLiteral	The class of XML literal values.
rdfs:Class	The class of classes.
rdf:Property	The class of RDF properties.
rdfs:Datatype	The class of RDF datatypes.
rdf:Statement	The class of RDF statements.
rdf:Bag	The class of unordered containers.
rdf:Seq	The class of ordered containers.
rdf:Alt	The class of containers of alternatives.
rdfs:Container	The class of RDF containers.
rdfs:ContainerMembershipProperty	The class of container membership properties, rdf:_1, rdf:_2, ..., all of which are sub-properties of 'member'.
rdf:List	The class of RDF Lists.

Table 7-4: RDF Properties (W3C, 2014).

Property Name	Comment	Domain	Range
rdf:type	The subject is an instance of a class.	rdfs:Resource	rdfs:Class
rdfs:subClassOf	The subject is a subclass of a class.	rdfs:Class	rdfs:Class
rdfs:subPropertyOf	The subject is a subproperty of a property.	rdf:Property	rdf:Property
rdfs:domain	A domain of the subject property.	rdf:Property	rdfs:Class
rdfs:range	A range of the subject property.	rdf:Property	rdfs:Class
rdfs:label	A human-readable name for the subject.	rdfs:Resource	rdfs:Literal
rdfs:comment	A description of the subject resource.	rdfs:Resource	rdfs:Literal
rdfs:member	A member of the subject resource.	rdfs:Resource	rdfs:Resource
rdf:first	The first item in the subject RDF list.	rdf:List	rdfs:Resource
rdf:rest	The rest of the subject RDF list after the first item.	rdf:List	rdf:List
rdfs:seeAlso	Further information about the subject resource.	rdfs:Resource	rdfs:Resource
rdfs:isDefinedBy	The definition of the subject resource.	rdfs:Resource	rdfs:Resource
rdf:value	Idiomatic property used for structured values.	rdfs:Resource	rdfs:Resource
rdf:subject	The subject of the subject RDF statement.	rdf:Statement	rdfs:Resource
rdf:predicate	The predicate of the subject RDF statement.	rdf:Statement	rdfs:Resource
rdf:object	The object of the subject RDF statement.	rdf:Statement	rdfs:Resource

7.6.1.6. Reasoner

It is important to only constrain what is necessary to accurately capture the meaning of domain knowledge. Over constraining the ontology may cause unexpected errors, so it is important to minimize constraining properties. Since OWL 2 is only a declarative language, and not a programming language, tools called “reasoners” are used to infer the logic of the ontology. A reasoner performs consistency checks and tests the classification of instances. Therefore, if there are any errors in logic (e.g. over constraining) the reasoner will produce an error message for any inconsistencies. Additionally, using a reasoner on the classes in an ontology can compute the inferred ontology class hierarchy. There are various publicly available reasoners, many of which are free to use and may already be embedded in an ontology developer application.

7.7. Criteria for Validation

Validation of the taxonomy is important for implementing into an ontology, and ontology validation is important for implementation into software applications. Chapter 6 highlighted industry validation (i.e. knowledge is validated), and it is imperative that the taxonomy and ontology also get validated with the domain experts to verify that each accurately represents the domain knowledge. This following describes the criteria needed to validate the taxonomy and ontology.

Sufficiency: The taxonomy and ontology needs to meet the needs of the domain requirements outlined in each Exchange Requirement (ER) documented in the Information Delivery Manual (IDM).

Clarity: The taxonomy and ontology should not contain any redundant or ambiguous terminology. Semantic clarity is important to be able to distinguish from similar terms and definitions.

Consistency: There should be no inconsistencies, duplications, or over constraints in the taxonomy and ontology. The use of reasoners or rule engines for consistency checking is recommended for the ontology, especially if property restrictions are used.

Reusability: The taxonomy and ontology need to be expanded and reused by other domains. The taxonomy and ontology also need to be accessible.

Expansibility: The taxonomy and ontology need to represent the fundamental knowledge needed to grow and expand.

Security: Once validated and approved, the taxonomy and ontology need to have safeguards in place to prevent unauthorized modifications. The taxonomy editor does allow for read-only protection once validated, but the final location needs to contain their own safeguards.

Implementable: The taxonomy needs to have sufficient attributes and axioms needed to be implemented into an ontology. Although a taxonomy may be limited by the amount of axioms in place, the supporting documentation (i.e. IDM) should explain the taxonomy used in full detail. Any discrepancies need to be address by the industry domain group and added to the documentation to support full ontology implementation. Only when fully implemented into an ontology with case examples fully vetted by industry users can a taxonomy be validated.

The ontology needs to have sufficient attributes and axioms needed to be implemented into a software application. Any discrepancies need to be address by both the industry domain group and software implementers, and added to the documentation to support full ontology implementation. Only when fully implemented in software case examples fully vetted by industry users can an ontology be validated.

7.8. Change Management

The current output for the processes (e.g. the IDM, taxonomy, and ontology) have been set up to be locked once approved and validated by the industry domain in order to prevent unauthorized modification. The ability to lock the output prevents mistakes, errors, or issues that may arise if any of the information has been changed or altered. However, as technologies progress and mew ideas or methods are created with the change in time, it is expected that the locked information will need to be modified accordingly. Therefore, it is imperative that a mechanism to allow for such changes be in place. Typically, the same process that the taxonomy and ontology went through initially to get validated and approve is the same process to validate and approve changes or additions. For example, if changes are needed for the steel erection IDM, those changes need to follow the same process outlined in Section 6.3.3. Such mechanisms already exist in practice, and are outlined below.

Documents: Any published documents, such as an IDM or standards, can either have addendums attached, new editions, or new volumes. Modifications need to be submitted to the organizing body in charge of maintaining and approving specifications. Any changes to the documents need to be reflecting in the associated taxonomy and ontology.

Taxonomy: An approved taxonomy will have safeguards in place to prevent unauthorized modifications. Any new terms added, or changes to locked terms need to be submitted to the organizing body in charge of maintaining and overseeing the taxonomy. The approval process that is established by the organizing body needs to be adhered to, as well as making the appropriate changes to the associated documents and ontology. The criteria for validation of the modified taxonomy need to be followed.

Ontology: An approved ontology will have safeguards in place to prevent unauthorized modifications. Any new terms added, or changes to the locked ontology need to be submitted to the organizing body in charge of maintaining and overseeing the ontology. The approval process that is established by the organizing body needs to be adhered to, as well as making the appropriate changes to the associated documents and taxonomy. In addition to following the criteria for validation of the modified ontology, a reasoner should be used for consistency checking.

7.9. Software Implementation

The ontology provides the description logic needed for software. However, ontology languages, such as OWL, are not executable languages needed to program software applications. In other words, an ontology language alone cannot be used to develop software applications, but needs executable computer languages (e.g. EXPRESS, java, c#) to develop the software applications. In such, the ontology language is used in conjunction with the native schema of the software application.

Figure 7-22 displays the high level of framework of an ontology being implemented into a software application. The industry user defines and edits the ontology by the used of an ontology editor, in which performs consistency checks via a reasoner (either a separate or embedded in the editor). The ontology is exported to an appropriate syntax that can be used by software applications to access the knowledge via a GUID. The software application uses a native schema for a specific computer language to represent the information model. Finally, the domain user can use the software application, and make any changes to the ontology via the editor.

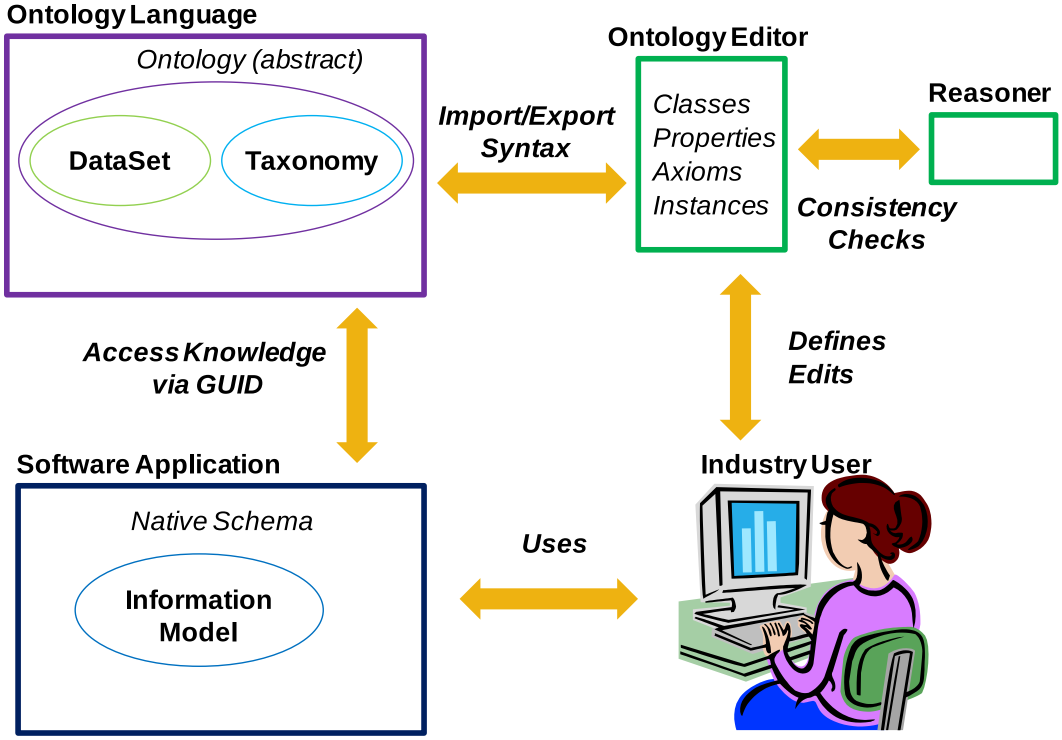


Figure 7-22: Framework of Ontology Implementation into a Software Application

Note that Figure 7-22 is only a representation of how the domain user, ontology, and software application interact, and thus reality may not be as simple as depicted. For example, the domain experts that define and edit the ontology may not be the same as the users. The process to validate and approve the modified ontology is also not depicted.

7.9.1. Case-Study: Ontology and Software Implementation Prototype

The BrIM ontology was created based of the information provided by the BrIM taxonomy. The BrIM ontology was created with Protégé developed by Stanford Center for Biomedical Informatics Research (2015). A simple case study example is detailed below, but full specifications of using the Protégé editor can be found at the Protégé wiki page (Protégé, 2016).

In order to create the ontology, additional axioms are needed to provide more assertions to what has been defined in the taxonomy. OWL 2 is composed of classes, and so each term of the BrIM taxonomy needed to be either classified as an object class, object property, data property, or value associated to a property. For example, physical components (e.g. beam, column, girder) are defined as classes, the relationships between objects (e.g. bridge structure contains beams) are defined as object properties, the relationships between objects (the Bride Identification Number (BIN) is 75132542) and values are defined as data properties, and the values (number, weight, length) are defined as values.

The example will be a simple bridge project at a specific location. The main classes defined in OWL for this example include Bridge, identification, Location, and Project (Figure 7-23). Each class has respective subclasses.

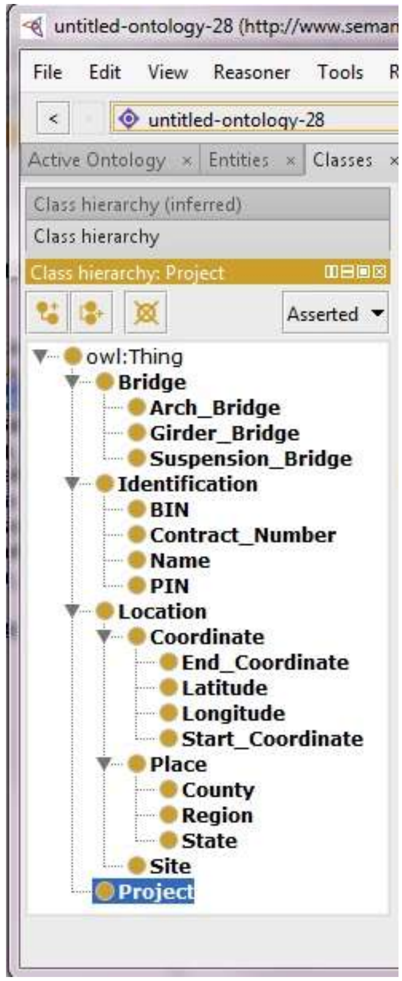


Figure 7-23: Sample of BrIM Ontology

Next, axioms were defined by the way of object properties to set relationships between the object. According to the BrIM taxonomy, a project is defined by having a bridge, identification, and location. Therefore, the following object properties were defined: *has_Bridge*, *has_Identification*, and *has_Location*. Using OWL 2 property restrictions, the following subclasses were defined (Figure 7-24). The property restrictions states that a project needs a bridge, identification, and location associated with it.

Figure 7-24: Sample Property Restrictions to define SubClasses for Project.

Data properties were defined to assign data values to object classes. For example, hasNumber can associate any object to any numbers. This is the case for the project identification number (PIN). Any property restriction can have cardinality, including less than, more than, or exactly. Since a project has only one PIN associate, the cardinality of *has_Identification* was changed to exactly one pin (Figure 7-25).

Figure 7-25: Sample Property Restrictions with Cardinality

Additional axioms were defined to complete the ontology. Finally, a prototype software application program was developed in c# to test the framework in Figure 7-22. The purpose of the application is to validate the framework and to demonstrate the feasibility that an ontology language (e.g. OWL) can provide the logic that can be used with an executable program language (e.g. c#). A portion of the BrIM taxonomy was implemented into an ontology using the Protégé ontology editor. Figure 7-26 displays the relationships used in the application to create a bridge project.

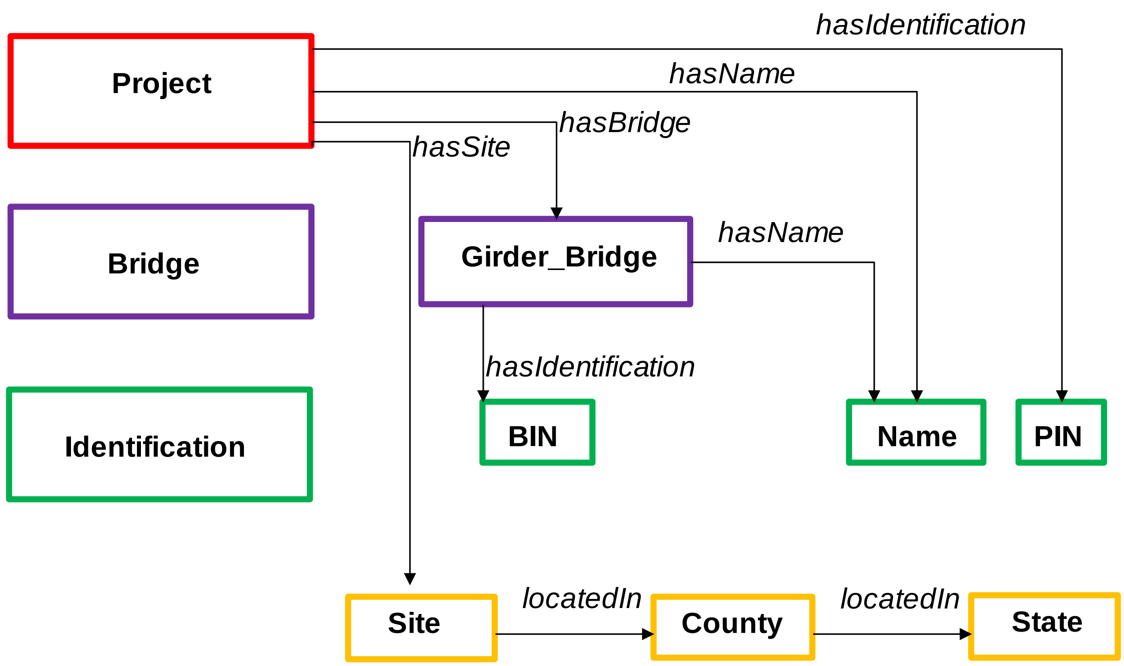


Figure 7-26: Example BrIM Ontology Integration.

It is important to note the reuse of properties, such as *hasName*, *hasIdentification*, and *locatedIn*. This is an example of how the ontology can be developed to promote reuse, while being semantically consistent. The *hasIdentification* could have been defined as *hasPIN* and *hasBIN*, but since both PIN and BIN are both subclasses of Identification, then the most general class, Identification, was used to define the property.

The following example was run through the application. A new project was to be located in Dalton GA, and the bridge was to be a typical steel girder bridge. So the meta data input into the application was the following:

PIN: GA111390

Bridge type: Girder

Bridge Name: The Ellemcee

BIN: 7154231

County: Whitfield

State: Georgia

Although this prototype application is not at the scope of commercial software programs, it still showed the feasibility of using an ontology language to provide the structure to transfer domain knowledge. Each software application is capable of accessing the ontology by integrating the proper syntax, such as RDF/XML, and can produce more elaborate functionalities.

7.10. Taxonomy Editor Data Analytics

Manually entering terms can cause errors that may reflect in the final taxonomy. Manual entries that cause errors include misspellings, having plural form of a word (i.e. number agreement), different letter case (e.g. upper and lower case), and abbreviations. Additionally, having duplicate forms of a word to mean the same thing (e.g. plural, abbreviations, and symbols) can cause redundancies. Having one defined term (designated by a GUID) and using automation to assign the term will drastically reduce these errors and redundancies. Additionally, and changes to the original term will automatically change all the instances.

Data analytics were performed on the BrIM Data Dictionary produced by (Hu, 2014) that was used in TG-10/TG-15. Scripts were written in C# to parse through the file to analyze the data diction in various ways. The purpose of the data analytics was the show the errors of manually typing in terms to a taxonomy.

The English language is very complex with all the rules and forms of a word. It may sound weird to the ear in spoken English when the singular form of the word is paired with multiple objects, e.g. “one people”, “one bridge,” or vice versa “five person,” “five bridge.” However, the computer doesn’t care about how it sounds, and programming plural forms can cause semantic issues, since computers view “people” and “person” as different objects. For example, string compare of the two words will result in false, meaning that the two words are not the same. The only way around these issues is to include sophisticated rule sets or conditionals. Therefore, to reduce the programming complexity while maintaining integrity of semantics, it is important to keep to the “object” and “quantity” format, such as “person” “5.” Although there are cases where the plural form of the word signifies a totally different meaning (e.g. “shear” meaning to cut, and “shears” meaning scissors) these cases are solved by having the two separate words as independent entries in the taxonomy, where each gets its own GUID. This also includes the same spelling of a word with different meaning. The GUID indicates the definition that is meant with the word.

The BrIM DD has 2048 individual entities, which is designated by a single cell per entity. However, some of the entities had multiple words associated. For humans, this is easily readable, but for a machine it inhibits readability. This is one of the reasons why it is important to populate a taxonomy, so each entity will have one term (or grouping if it is an axiom). Therefore, each word was extracted from the cells. The total amount of words in the BrIM DD is 6811. However, as mentioned before, the manual data entry inherently allows for errors and redundant data, and so the distinct words were extracted.

The first extraction took out all of the distinct words, but did not discern about any of the errors. For instance the following are distinct words: “beam,” “beams,” “Beams” and “baem.” Although they are all variation of the word “beam”, they each count as a distinct word. The total number of distinct words is 1394. Next, the script did not account for case sensitive words, and the results reduced to 1101 words. Finally, all errors and plural forms were removed, leaving only the unique word. The final word count is 983. This means of the 6811 words in the BrIM DD, only 983 (14.4%) unique words were used. Further analysis showed that there were 411 errors, which would result in further semantic issues and interoperability issues. This means that 30% of the distinct words were in fact erroneous! Tables 7-5 and 7-6 show additional break down of the data analytics. It is important to note only the abbreviations that mean the same as the non-abbreviated word were taken out and not acronyms. For instance “min.” for “minimum” was taken out, but “AASHTO” was not. Moreover, some common abbreviations used in industry were left in as well (e.g. CL for center line), so technically the unique word count and error count may fluctuate plus or minus a few.

Table 7-5: Data Analytics of Data Entries of the BrIM Data Dictionary

Total Entries	2048
Total Words	6811
Distinct Words	1394
Unique Words	983
Percentage Unique	14.4%

Table 7-6: Errors Found in the Distinct Words

Case errors	293	71.3%
Plural	98	23.8%
Abbreviation	15	3.6%
misspellings	5	1.2%
Total Error	411	

Finally, after the errors were fixed, the instances of the unique words were counted. The top 20 words used are listed in Table 7-7. The rest of the words can be found in Appendix G.

Table 7-7: Top 20 Used Words in the BrIM Data Dictionary

Word	Instances
of	287
number	127
length	105
type	103
at	94
material	93
flange	84
name	82
to	80
top	78
bottom	77
property	74
location	73
width	68
end	65
bolt	60
distance	59
thickness	59
plate	58
dimension	57

Based on the results, the most word used is "of" at 287 instances. This is significant because it is not an actual term, but rather a description of a term. The word "of" expresses the part-whole relationship, which is one of the most used axioms. Moreover, the majority of instances are in fact not terms, but attributes or descriptions used in defining properties or terms. This is important because the human language uses attributes to describe terms, and thus displays the semantic issues that a machine might experience. Therefore, it is imperative to reduce these semantic by the use of a taxonomy and ontology.

Dealing with the root word of terms with different tenses is out of this current scope, since it requires more significant analysis to determine the meaning of each case. For example, “developer,” “developed,” “development,” and “developing” all have the root word “develop,” but since they may have slightly different meaning or uses, they were left as is. However, taking consideration of the root and its variations is important to consider in future research.

After the Data Dictionary was reduced to the unique words, the next step was to transform those unique words into the DataSet format. This format has the following fields (in order): GUID, Abbreviation, Term, Definition, Notes, Related, Validate, Reference Code, Source, and Date. The Taxonomy Editor does have a template that a user can download. It is important that the template is used before it is imported into the editor, as it can produce errors. Chapter 6 explained each field in more detail.

Since not all of the 983 unique words in the BrIM Data Diction are terms, not all need to be incorporated into the DataSet. However, these non-terms are important because they provide details about the term and will be used in the formation of attributes and axioms. One major word is “of,” since it, by definition, expresses the part-whole relationship and will be used in axioms such as “composed of,” “subset of,” and “direction of.”

CHAPTER 8

8. ADAPTATION OF THE NATIONAL BIM STANDARD FOR BRIDGES

As discussed in Chapter 5, the current National BIM Standard (NBIMS) is neither suited nor appropriate for bridges or other non-building domains. Therefore, this section discusses current efforts to include bridges and other infrastructure models into NBIMS by expanding IFC. This section highlights the findings of the FHWA project that the author was involved in, and highlights other international efforts. Additionally, a method to reduce redundancy if IFC were used is presented.

8.1. Bridge Information Modeling Standardization

In a parallel effort to this dissertation, the author was involved with the "Advancement of Bridge Information Modeling" project that the FHWA has contracted the National Institute of Building Sciences (NIBS) under contract DTFH6114C00047. The purpose of the project was to identify and evaluate open standards that could be used for information sharing of bridge models to promote interoperability. The goal was to identify viable standards that can be used by bridge owners to specify information delivery requirements and by software providers to meet those requirements. As this project and this dissertation had the same end goal of achieving interoperability of bridge information models, each had their own focus on how to do so. This dissertation looked at the issues of interoperability and proposed a new methodology at the fundamental level, while the project investigated current uses and provided suggestions at the application level. In such, both efforts are seen in tandem and the results can be integrated to achieve the goal of interoperability.

8.1.1. Project Overview

In particular, the NIBS project focused on evaluating schemas and standards that are currently used in the AEC industry, including the buildingSMART Industry Foundation Classes (IFC), LandXML, and openBrIM. Additionally, proprietary software and formats from major vendors were reviewed, including Bentley and AASHTOWare.

A three volume summary report reviewing the various options and providing the findings have been readied to share for industry review. The report includes modeling of two sample bridge (one concrete and one steel) 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. Below summarizes the three volumes.

Volume I: Exchange Analysis of the report identifies the building blocks to advance standardization of digital information for bridges in the United States. It summaries the previous efforts for a bridge process model, identifies major exchanges in the bridge industry, and proposes a new bridge lifecycle process map.

Volume II: Schema Analysis surveys the current existing schemas used for infrastructure modeling. The goal is to ultimately lead the industry to a consensus solution that is acceptable to all stakeholders involved. In additions to analyzing the schemas, the volume summarizes current international efforts, provides a gap analysis of modeling and software concepts, and proposes new definitions for software schemas.

Volume III: Component Modeling applies the existing and proposed definitions to two example bridges in order to analyze the schemas. The volume describes the modeling of specific components of example bridges to the level of detail as conveyed on design contract plans.

8.1.2. Project Summary

Based on the analysis and findings, it was clear that Industry Foundation Classes (IFC) was the most suitable candidate to use as a basis to document complete design models. However, as a result of the component modeling, it became evident that the latest version of IFC (4.1) was not entirely sufficient and has some limitations. One main impediment is that is lacks the capability to position physical elements relative to alignment curves. Therefore, new data structures as well as new usages of current data structures were proposed to remedy these issues.

8.1.3. Current Status

As of March 2016, the first phase (nearing completion) is summarized in a three volume report with introduction titles "Bridge Information Modeling Standardization" (FHWA, 2016). This report will be published along with all the current supplemental documentation (exchanges, process map, MVD, etc.) The current status into phase two is undetermined at the time of this writing.

8.2. Parallel Interoperability Efforts

8.2.1. FHWA BrIM – CH2M Hill

Parallel with the ongoing NIBS project, FHWA had also contracted with CH2M Hill to another project titled "Bridge Information Modeling (BrIM) Using Open Parametric Objects." The purpose of this contract is to review current industry BrIM standards and to investigate standardization of bridge of bridge objects, digital definitions, and protocols that can be interchanged between different software platforms. The work utilizes the open and free platform, OpenBrIM, which is a cloud based system that is written in XML language (OpenBrIM, 2015).

As of March 2016, the final report has been submitted to the FHWA for approval and publication. The results will soon be available for public use.

8.2.2. Subcommittee on Bridge and Structures (SCOBS) T-19

The AASHTO Technical Committee on Software and Technology (T-19) received a National Cooperative Highway Research Program (NCHRP) 20-07/Task 377 project called "Standardized Format for Bridge and Structure Information Models." The objectives of this project are: (1) synthesize the current state of software used for bridge and structure modeling including formats and requirements; and (2) propose recommendations for future research to develop a common modeling format (i.e., one model for a bridge or a structure) that can be used as a standard input for different software during the life of the asset. The research is currently in progress, and the final completion date is 9/25/2016 (TRB, 2016).

As of March 2016, a draft report summarizing the first two tasks and incorporating the comments from the panel members has been write. The two finished tasks are (TRB, 2016):

Task 1. Conduct a literature review of relevant standards and current practices utilized by State DOT's and international agencies. The literature should include the attached: (1) the state survey conducted by the AASHTO SCOBS, Technical Committee T-19 Software and Technology, and (2) Iowa DOT Survey to determine common software currently used by state agencies to gather information on the models required to produce a successful analysis by the states' software. In addition, use related bridge information modeling being evaluated by FHWA and previous NCHRP research.

Task 2. Synthesize the common modelling formats including developed, proposed (such as TransXML), or used by similar infrastructure industries (e.g., the vertical building industry). Evaluate the ability of these formats to be used across the spectrum of state agencies software determined in Task 1. NCHRP approval of the synthesis will be required before proceeding with the remaining tasks."

The next step is to host a two-day workshop for bridge industry members (owners, designers, contractors, software vendors, etc.) to discuss the current progress and implementation of BrIM, and to discuss possible recommendations to improve current practices. This workshop is scheduled for May 10-11, 2016, and the meeting minutes, notes, and outcomes will be posted.

8.3. Efforts to Implement Bridges and Other Infrastructure into IFC

Although initially intended for buildings and vertical construction, there have been various international efforts by buildingSMART International (bSI) groups to use IFC for other infrastructure models (bridges, roads, tunnels etc.). In order to increase the scope to include infrastructure development, buildingSMART created the Infrastructure Room in 2010 to serve as the center of various international groups implementing IFC for infrastructure. Figure 8-1 displays the overview of the infrastructure components. Since then, various projects were undertaken and the most recent progress is summarized below. More information about the current progress of the projects can be found at the homepage of the buildingSMART International User Group (bSIUG, 2015) and the bSI Infrastructure Room (buildingSMART, 2016c).

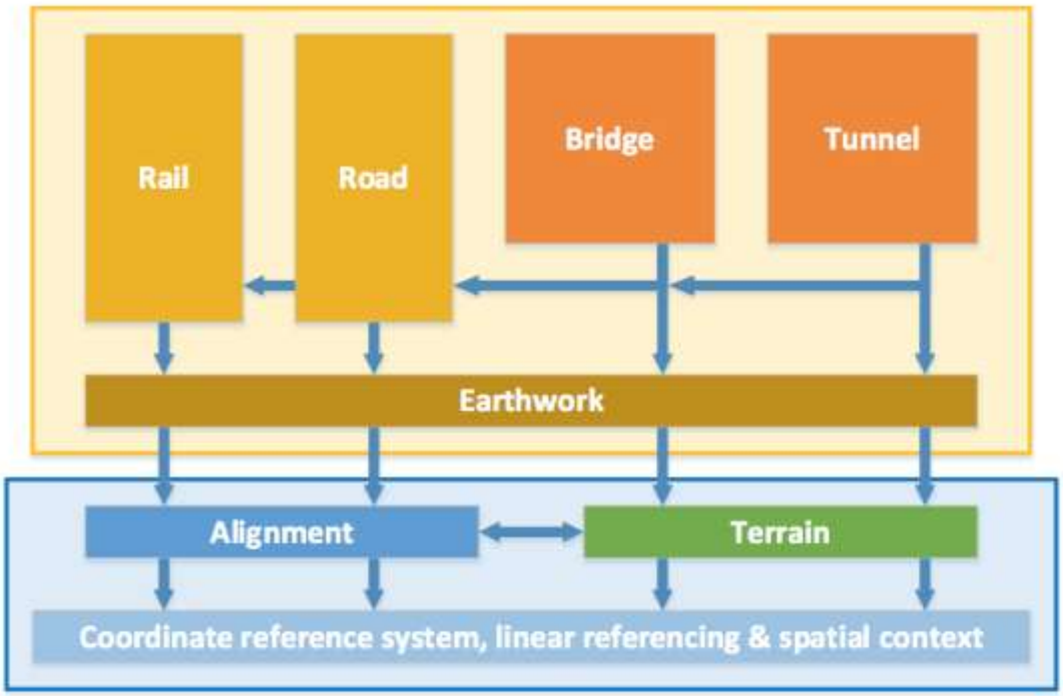


Figure 8-1: Figure 8-1: bSI overview of different infrastructure components and their dependencies (*Courtesy of buildingSMART International*).

8.3.1. IFC Alignment

In order for roads and bridges to be modeled, one critical piece of information needed is the alignment. However, IFC lacked an entity to represent alignment, and thus a major "IFC Alignment" initiative was undertaken since without the entity modeling infrastructure that requires it would be nearly impossible. The Main achievements of the IFC Alignment 1.0 are as follows (buildingSMART, 2016d):

- Ability to exchange alignment information from planning to design, to construction, and finally to asset management phase
- Ability to link alignment information to other project information such as cross sections and full 3D geometry of construction elements (realized by upcoming IFC-Bridge and IFC-Road projects)

- Ability to query alignment information providing data such as linear referencing for positioning
- Ability to allow open data access of alignment information from asset management databases
- Ability to map IFC alignment models to InfraGML (developed by OGC), and LandXML (latest InfraBIM version from buildingSMART Finland)

This project has been the baseline for the other ongoing projects, such as IFC-Road and IFC-Bridge, since it provides the data model for 3D and 2D alignment information for spatial location of infrastructure assets. As of July 2015, the IFC Alignment 1.0 has been accepted as a buildingSMART Final Standard.

8.3.2. IFC-Road

In 2012, the Korean Institute of Construction Technology (KICT) had been awarded a $3 million project to develop a standard for BIM in road design and construction. The project developed the KICT IFC-Road schema based off IFC4 (ISO16739). The recent release of the schema can be seen in KICT (2015).

In 2015, another IFC-Road proposal was submitted to bSI for the “Development of International IFC model extensions and data exchange standards for planning, design, cost estimation, scheduling and construction of roads and associated structures and earthworks” (Grobler, 2015). This project is currently in the development phase.

8.3.3. IFC-Bridge

The French chapter of bSI has been behind the efforts to produce the first IFC-Bridge extension (Yabuki et al., 2006). However there are many issues that have been identified that impede the adoption of IFC-Bridge into the IFC schema. Therefore, the

European research project V-Con has now taken over this work, and is partnering with an additional French working group, MINnD Concepts (Dumoulin and Benning, 2014). This project is currently in the development phase.

8.3.4. IFC Infra Overall Architecture

With the overlapping efforts of IFC development proposing separate solutions, there is a need to align the efforts. Therefore, in order to harmonize the diverse proposals and provide a sound foundation, a plan was proposed to great a common architecture, called "IFC Infra Integration Framework." Currently in the proposal phase, the objectives of the framework aims to achieve (Borrmann, 2016):

- Analysis of the currently available drafts of the IFC infrastructure extension initiatives with respect to joint / overlapping areas project, including
    - the IFC-Road project by the Korean chapter
    - the IFC-Rail project by the Chinese chapter
    - the IFC-Bridge project led by the French chapter
- Definition of jointly used data structures as a common basis, including
- Provision of modelling guidelines for bSI Infrastructure extension projects
- Ability to map common infrastructure information between InfraGML (developed by OGC) and enhanced version of IFC
- A foundation for standardized data exchange during the entire lifecycle, including requirements, design, construction, operation, maintenance and destruction/recycling

8.4. Concepts and Semantic Exchange Modules (SEM)

One of the approaches to achieve interoperability is the use of neutral files, in which each software application maps its code (usually proprietary) to a neutral file code.

The Industry Foundation Classes (IFC) has been the "go-to" neutral schema in the AEC industry for BIM models. IFC can be viewed as a mediation file from one software vendor to another. For instance, vendor B would know what to expect if they are receiving an IFC file from vendor A, without having to give away or show the proprietary information that encoded that IFC file.

There have been arguments to say IFC cannot be used effectively because it does not contain parametric modeling capabilities (Hu 2014), which are in fact false. IFC does allow for parametric modeling capabilities. Firstly, IFC is an exchange format is not intended to be used as software, but rather a data storage format. It allows for the storage of the parametric capabilities, and it is up to the software programs to use and encode the information. Two common ways of parametric modeling in IFC are using declaratives and constraints:

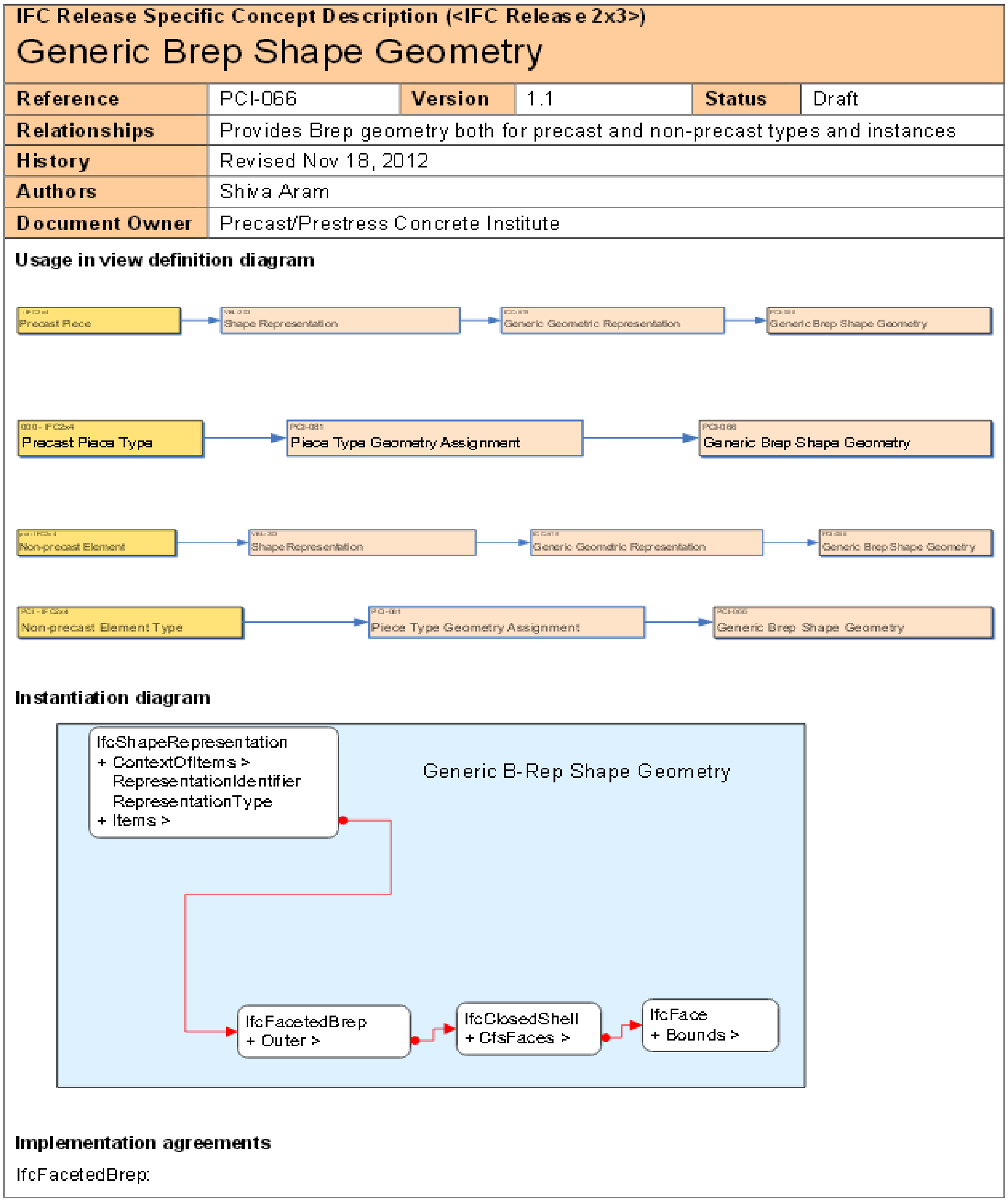
1. *Declaratives*: IFC allows for the declaring of parameters by the use of connectivity relationships. Connectivity is where one object is connected to another object, such as an anchor. This means that if one object is moved, the anchored object goes with it. This can be done by using IfcRelConnects, which is the logical definition, and then confirmed with the defined the geometry. Take a bridge pier for example. The column is connected to the footing, which is fixed below, and the girder, which is fixed above. The bottom geometry of the column can be anchored to the footing and the top of the column can be anchored to the girders, leaving the height variable. If the design of the bridge is to be changed to increase the elevation, the Colum would automatically change its height with the change in elevation of the bridge.

2. *Constraints*: IFC allows for constraints to drive the underneath declarations. Constraint associations can take any attribute as a formula, and it can be

arithmetic, table, or another objects. There is no language to create the equations so it's based off data definitions. An example would be a data constraint table that drives the geometry of a frame.

Since IFC is redundant, there are many various ways to support parametric modeling. However, it is ultimately left up to the software programs to use these capabilities or not. For example, Trimble Tekla 19.1 does not use these capabilities, because they believe that the intent of an object that they receive from and IFC file is to be fixed and not changed.

If IFC is to be used, it is imperative to not overwhelm or complicate the schema with redundant information. This dissertation asserts that reusing information already defined can help reduce the redundant data that is associated with creating errors and efficiencies explained in Chapter 2. Instead of creating new IFC entities, which will increase the redundancy and complexity of the IFC schema, defining specific components for the bridge concepts will make use of currently defined entities. A concept provides the formal Model View Definition (MVD) in a tabular structure. A concept includes the name of which is being described, the definition, the usage diagram, an instantiation diagram, and the needed IFC entities in the schema. Figure 8-2 displays a concept of Generic Brep Shape Geometry developed by Georgia Tech for the Precast/Prestressed Concrete Institute (PCI).



IFC Release Specific Concept Description (<IFC Release 2x3>)

Generic Brep Shape Geometry

Reference	PCI-066	**Version**	1.1	**Status**	Draft
Relationships	Provides Brep geometry both for precast and non-precast types and instances				
History	Revised Nov 18, 2012				
Authors	Shiva Aram				
Document Owner	Precast/Prestress Concrete Institute				

Usage in view definition diagram

Instantiation diagram

Implementation agreements

IfcFacetedBrep:

Figure 8-2: Generic Brep Shape Geometry Concept

Section 5.3 outlined some of the limitations in the current National BIM standard, specifically addressing the Model Views of IFC. In 2012, a SEM work-group was formed to address these limitations by the use of a new approach called a Semantic Exchange

Module (SEM) (Venugopal, et al. 2011; Eastman, 2012; Venugopal, et al. 2012, Belsky et al., 2014).A semantic exchange module (SEM) is a structured, modular subset of the objects and relationships required in each one of multiple BIM exchange model definition. The purpose of an SEM is to enable BIM software companies to code import and export functions in modular fashion and to provide a common high-level specification structure (Figure 8-3).

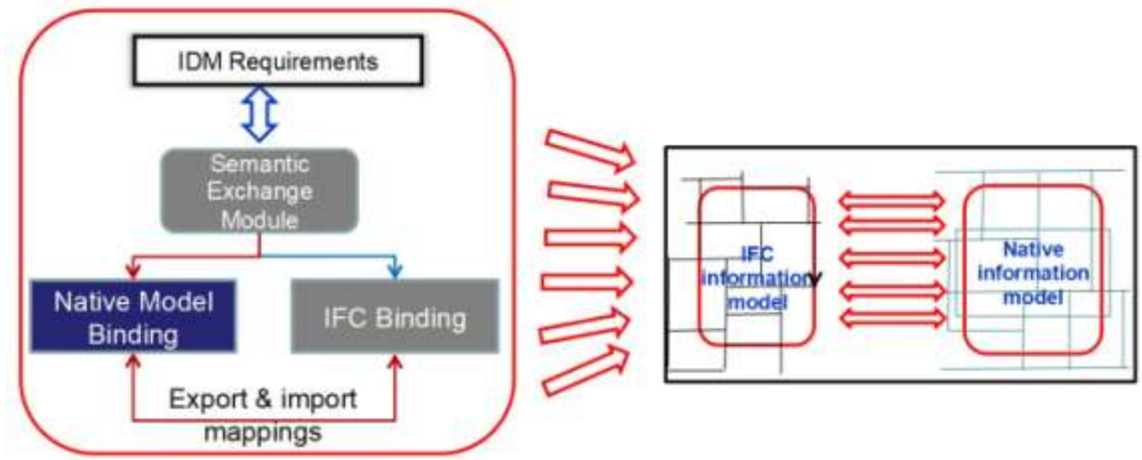


Figure 8-3: Diagram of Semantic Exchange Module (Eastman, 2012).

As seen in Figure 8-3, SEMs link native model bindings and the IFC bindings to the IDM requirements, providing a higher level composition of IFC that allows definitions of translator, and provides semantic information. Moreover, SEMs provide the ability for re-use. What originally took 3-4 years in the original NBIMS process is reduced to only 6-12 months (Eastman, 2012). SEMs are currently being developed and utilized in industry groups, including Precast/Prestressed Concrete Institute (PCI), American Institute of Steel Construction (AISC), and the American Concrete Institute (ACI). Demonstrations and validation of SEMs for PCI can be found in Belsky et al. (2014).

Detailed instructions for developing SEMs are found in Venugopal et al. (2011). Below summarizes the requirements from Venugopal et al. (2011).

A. Composability- Each SEM should be composable with no broken links with other SEMs.
B. Coverage- The available SEMs should address all the semantic definitions now used within IFC translators and support new IFC extensions where needed.
C. Parsimoniousness- SEMs should aggregate bindings to the largest extent possible that does not eliminate semantically meaningful options.
D. Semantic Clarity- Each SEM should define a distinguishable semantic construct, easily distinguished on a use basis from all others.
E. Correctness- Correctness is the ability of entities to satisfy the use case specification.
F. Reusability- Reusability is the ability of SEMs to serve for implementation of many different model views.
G. Traceability- It should be possible to trace the original model view back to exchange requirement (synonomous to revers engineering).

The form of an SEM consists of a header (name, member, description), relations (hierarchy), lineages (placement of SEM), and bindings (diagram, description, methods, concepts). Figure 8-4 displays the IFC Binding of the SEMs BeamType, ColumnType, SlabType, and BuildingElementAssemble developed by Georgia Tech.

SEM Member Name	**SEMS: 04-BeamType-01, 04-ColumnType-03, 04-SlabType-09, 04-12 BuildingElementAssembly**	**4** IFC Binding for Each Member SEM
Version History	14/5/2011 C Eastman	

SEM Member binding diagram <binding diagram using flattened entity shapes, for the general case of SEM family; list in title the cases, if any, that this applies to without elaboration>

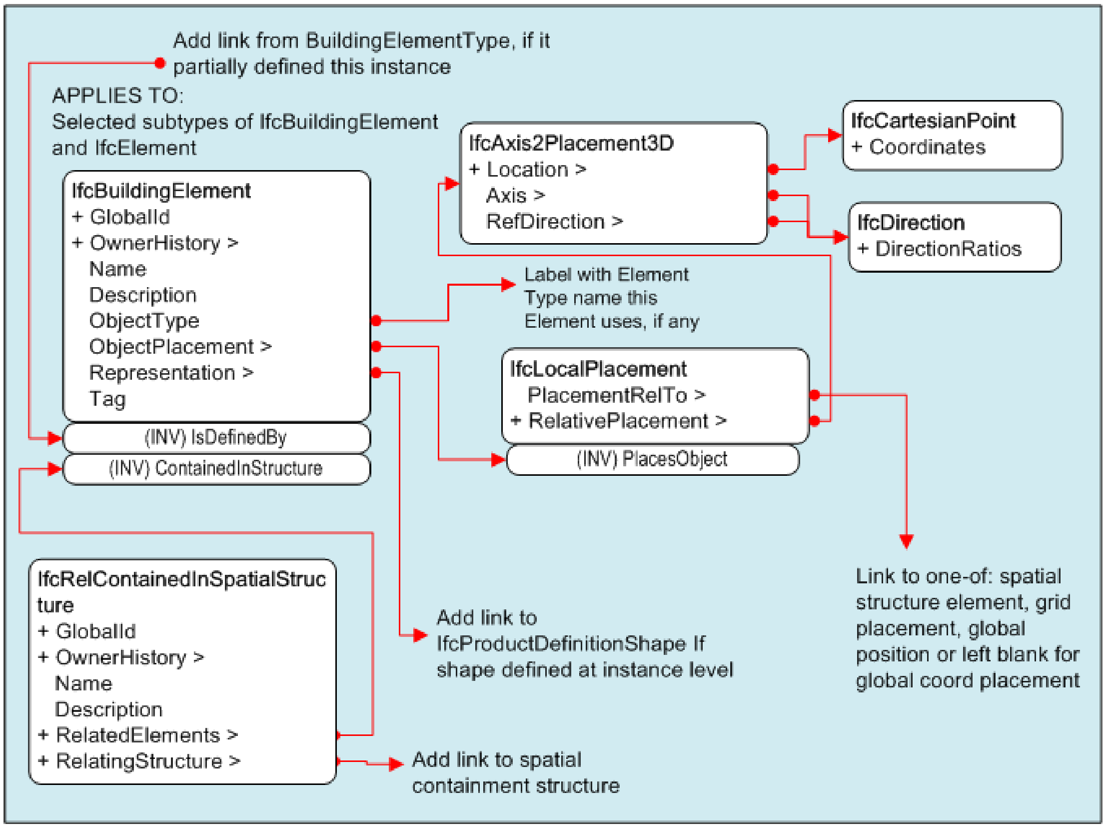


Figure 8-4: IFC bindings of a Semantic Exchange Module

For example, a girder is not explicitly defined in IFC, i.e. “IfcGirder.” This girder concept would contain the recipe for creating a girder using the current data definitions in IFC. The major benefit from defining and using SEMs would increase interoperability by redundancy reduction and not increasing the entities needed to be added to IFC. Below lists some common bridge terms that can be linked to IFC entities in parentheses.

- Bridge Superstructure:
  - Deck (IfcSlab)
  - Girder (IfcBeam)
  - Barrier (IfcBeam)
  - Paraphet (IfcBeam)
  - Median (IfcBeam)
  - Railing (IfcRailing)
- Bridge Substructure
  - Pier Column (IfcColumn)
  - Cap Beam (IfcBeam)
  - Hammer Beam (IfcBeam)
  - Pedestal (IfcFooting)
  - Wall Pier (IfcWall)
  - Drilled Shaft (IfcPile)
  - Footing (ifcFooting)

This list serves and example, and thus is neither exhaustive nor perfect. Future work is needed to identify which IFC entities can be reused. Additionally, concepts and SEMs are needed to be created and validated.

8.5. Summary

The need for interoperability of information models has been seen as a high priority at an international level, as shown by the previous efforts. Each project has identified the needs for a specific area within infrastructure (e.g. tunnel, road, bridge, etc.), and has spent a substantial amount of time and effort trying to modify and expand the current IFC schema to incorporate. Each project has provided the limitations and developments to mitigate those limitations. Optimistically speaking, it seems that great progress has been made to make IFC as the defacto standard for all information models in the AEC/FM industry. Pessimistically, the current NBIMS approach is very time consuming, taking upwards of 3-4 years (and hundreds of man hours) from developing a domain concept and implementing in software. Although each project does show promise to expand infrastructure into IFC, the practical costs and limitations presented in each effort impede a clear and concise method to integrate infrastructure into the current standard. Unfortunately, there has yet to be a cost-benefit analysis to determine whether or not the "brute force" method to expand IFC has been cost effective over the costs associated with the inoperability of models.

CHAPTER 9

9. SUMMARY, CONTRIBUTIONS, AND FUTURE RESEARCH

9.1. Summary

The dissertation presented a novel methodology that would enable the interoperability of multi-disciplinary information models. The Information Exchange Standard provided the ability for industry domains to identify the information that needs to be modeled by software. The Taxonomy Editor proved to be a useful tool for the automation and organization of this processed. Although the scope of the methodology is for Bridge Information Models, the approach is extendable to other domains. This research was motivated by the fundamental issues of interoperability, in which these issues were mitigated by the use of a taxonomy and ontology. An industry approved taxonomy provides the basis of industry needs, which reduces ambiguities of the domain lingo, clarifies the semantics of terms, provides consistency of terminology, and reduces time and effort in building a ontology for software development. The taxonomy can then be implemented into an ontology by the use of an ontology language. Software vendors can then implement the ontology into software applications. This methodology has been used and validated by an industry domain case study. Case study examples have demonstrated the feasibility of developing a taxonomy, ontology, and software based of an ontology.

The next step for this work is to finalize the steel erection IDM, ballot it with the AASHTO/NSBA collaboration, and publish it as a standard. May 3-5, 2016, is the next NSBA annual meeting to discuss the balloting process of this IDM. Additionally, the author has been invited to present the findings of this dissertation the Transportation Research Board (TRB) National Cooperative Highway Research Program (NCHRP) 20-07 Task 377 on May 10-11, 2016.

Stakeholder buy in has been a significant motivation to this research. As the majority of the bridge owners in the U.S. are the Federal and State Departments of Transportation, there has been great push for interoperability of bridge models. Additionally, there have been Companies that have expressed interests in the continuing development of BrIM interoperability are listed below.

- Autodesk, Inc.
- Bentley, Inc.
- LUSAS
- MIDASoft
- LARSA 4D
- CSIBridge
- Red Equation Corporation (OpenBrIM)
- Gannett Fleming, Inc.
- AASHTOWare
- Michael Baker, International
- Constructivity
- Eriksson Software

9.2. Contributions

The fundamental contribution of this research is the new methodology for promoting and achieving interoperability of multi-disciplinary information models. This methodology is captured in the open, non-domain specific Information Exchange Standardization process that utilizes an ontological approach to map to software. The major achievements and contributions of this dissertation are detailed below.

9.2.1. Information Exchange Standard

The Information Exchange Standard (IES) process allows for establishing information exchanges to support critical business workflows, which are important aspects to achieving interoperability. This process demonstrates how a BrIM ontology can be developed and used to promote interoperability of heterogeneous bridge information models. The IES allows for non-technical industry experts to identify and capture domain knowledge to be modeled into software applications. Unlike current methods, the IES is open and flexible, meaning it is not specific for any one domain or any one software language/schema.

9.2.2. Workflow Oriented Ontology Development

The workflow oriented process identifies the needs of a specific domain, in which then the ontology can then be developed from. Unlike the other literature that identify the needs for an ontology, this method builds from the bottom up, in which the workflow drives the ontology and that a taxonomy is the imperative first step. This process also allows non-technical savvy industry experts to identify the knowledge and the needs that the ontology is built for.

9.2.3. Addressed and Corrected Issues to the Current BrIM Process

This dissertation identified the current issues in the current BrIM standardization process. Additionally, solutions were provided to fix the issues, such as proper modeling notation and standardized definitions, which were proved and validated by the case study.

9.2.4. BrIM Taxonomy

The BrIM taxonomy is collection of bridge terms, definitions, attributes, and relationships. These terms are stored in the central BrIM DataSet, where the terms and information can be accessed via the GUID. Unlike classification systems, the taxonomy provides object-oriented features like data encapsulation and inheritance that allows for reasoning and future expansions. As the first taxonomy for the bridge industry, the BrIM taxonomy is living and growing, and the input from the bridge community is imperative to its success.

9.2.5. BrIM Ontology

The BrIM Ontology is the formal representation of the abstract, simplified view of the bridge domain that describes the objects, concepts and relationships in a machine-readable format. This ontology is the logic structure of the BrIM taxonomy that can be used by software. As the first ontology for the bridge industry, the BrIM ontology will be used to define standardized definitions and concepts of the bridge domain to be utilized for a broad range of software and applications.

9.2.6. Steel Erection Information Delivery Manual

The steel erection information delivery manual is the first for the BrIM domain. In includes the documents presented in this dissertation that were developed by the AASHTO/NSBA TG10/TG15 subcommittee. This IDM serves as the first example that other IDMs can be based from. The fact that the IDM was developed in less than 6 months is a major contribution, showing that this method is more time efficient than the current methods.

9.2.7. Reuse of IFC concepts and Semantic Exchange Modules

Demonstrating the reuse of previously defined concepts and Semantic Exchange Modules in IFC will drastically reduce the redundancy in IFC. Additionally, it has been shown that SEMs have drastically reduced the time spent generating Model View Definitions. Utilizing these concepts would have a significant impact of the development of BrIM standards by buildingSMART International.

9.2.8. Education and Facilitation of Industry Alignment

The bridge industry has been lacking in technology and standards to promote interoperability of BrIM. The work presented in this dissertation has educated the U.S. bridge industry about the current issues and development needs. The work has also brought alignment among the FHWA, various state DOTs, and organization that govern the transportation industry. Specifically, leading and educating the AASHTO/NSBA TG10/TG15 subcommittee has provided direction and education about the collaborative effort, which provides the basis for future growth.

9.2.9. Best Practices for Developing BrIM Standards

The methodology presented in Chapters 7 and 8 utilized current standards and method published in industry. By utilizing existing methods, modifications and improvements to the current limitations were able to be implemented. Additionally, the Information Exchange Standard and ontology development were tested and validated with the domain case study. Since this development was an iterative process, the best practices that were discovered are implemented in the final process. This process is a living and every iterative process, and thus best practices will continue to be modified.

9.3. Limitations

9.3.1. Validation of Software Implementation

Although this dissertation demonstrated the feasibility of linking an ontology to a software application, there still exist a need to implement with commercial software companies. Software implementers need to get involved with the ontology development for each use case and develop test case models for validation.

9.3.2. Scope Limitations

This dissertation was limited to the bridge domain. Moreover, within the bridge domain this dissertation focused on steel bridge erection, and thus more expansion to include other domains for validations is needed.

9.3.3. Time and Financial Incentives

The AASHTO/NSBA task groups were used as the industry group to validate the methods within this dissertation. This collaboration group has the means and structure to support research efforts. However, other domains may lack such organization bodies to support similar efforts. Additionally, the industry experts in this research put in great time and effort on a voluntary basis, which showed that the need for developing a method to achieve interoperability was a great time and financial incentive. Therefore, it is important that other domains find similar organizations and domain experts who understand the overarching needed to not be financially motivated.

9.4. Future Research

9.4.1. BrIM Organization

It is recommended that there is to be a governing body to continue the BrIM standardization process. As NIBS and buildingSMART is to the National BIM Standard, there needs to be an organization body to lead the National Information Exchange Standard. It is also recommended that a transportation organization, whether it be AASHTO or a subsidiary of the FHWA, needs to shepherd the BrIM standard. There are current parallel efforts to standardize BrIM interoperability, and thus there needs to be one central organizational body that can align the efforts and approve standards. This dissertation attempts to create the methods and processes for the alignment, but the continuation needs to be at a consensus level in order to become an official standard. In addition, rules and regulations need to be established to continue this alignment. For example, the BrIM process map for the lifecycle of a bridge needs to have a standardized format, such as BPMN. The current form deviates from the standards outlined by OMG (2015), and this dissertation remediated these issues. Although simple formatting discrepancies may seem trivial, having consensus standards involves every detail to be identical.

Linking the BrIM taxonomy to an official organization will promote reusability. One example is to implement into the buildingSMART data dictionary (bSdd). Having the taxonomy become a standard for bridge information modeling, the taxonomy will align various groups and committees throughout the U.S. Furthermore, the bSdd is translated into different languages, thus promoting the standard on an international level.

9.4.2. Taxonomy Editor Expansion

The Taxonomy Editor proved to be a useful tool in the automation of the taxonomy development. Additional features and functionalities can be implemented to improve the process. One example is the automated mapping from the taxonomy to an ontology, such as OWL. Other examples include mapping to other schemas, such as IFC. As the needs in industry are discovered, additional modifications will be made.

9.4.3. Ontology Development

An ontology has proven to be useful for information exchange. This dissertation provided the framework needed to develop ontologies for specific domains. It is important that the BrIM ontology continues to be developed and expanded to include all other aspects of the AEC industry. Additionally, it will be important to continue the development with the future in mind, such as incorporating with the Semantic Web.

9.4.4. Expansion of BrIM Information Delivery Manuals

This dissertation developed the steel erection information delivery manual (IDM), and future work is needed to incorporate the full taxonomy and ontology into it and be published as a standards. Moreover, additional work is needed to develop IDMs for other use cases and domains.

9.4.5. International Collaboration

Chapter 8 highlighted the current international efforts to achieve interoperability of infrastructure models (e.g. bridges, roads, etc.). There is promise that IFC can provide the neutral platform needed for the seamless exchange of information, but the practical costs and limitations to integrate infrastructure into IFC present the need for a more efficient, and cost effective approach. This is seen in the fact that there are only a few widely implemented building models that are capable of interoperability of information transfer. This dissertation addressed this issue at the abstract and fundament level of utilizing ontologies to provide the semantic and syntactic information needed to transfer information, in addition to extend to IFC. However, further research is needed to extend and validate the ontologies into the IFC schema for each of these efforts. Section 2.6.1 discussed the current research has of utilizing ifcOWL to convert OWL into IFC, which is shown to be the promising gap of linking ontologies to IFC.

APPENDICES

Appendix A. FHWA BrIM Workshop Notes

BrIM Workshop Questions/Comments/Discussion Notes

August 25-26, 2015

Note Taker: Kelley Rehm

<u>T19 AASHTO Perspectives (Scot)</u>

Comments – NSBA – fabricators. Abandoning shop drawings. Fab shops don't need drawings anymore because they can pull a data file. They only produce the drawings for DOT review cycle – so a good opportunity to get rid of them.

Liability always comes up when we talk about getting rid of 2D plan. Same issues in the building industry. We need to have an education plan to get people more comfortable with 3D. Case studies are the best way to educate. Has already been found that BriM allows a lot less mistakes (in fabrication, etc) and manages risk better.

Changes are required in contracting and procurement as well – can use building industry as an example.

Things that are relatively simple in the building world are not as easy in the bridge world (geospacial issues, coordinates such as state plane, etc)

Scot thinks it may not be as difficult to deal with as many think.

Uses of the model – what is actually being done now? Is there any data on cost savings / ROI? WI has some data now – showing less errors, etc. that are saving money.

What is different about bridge because it is government? Need to be able to prove investment – savings in not only funding but also in schedule

How do you establish and identify the ROI on this – how to make the case for moving to this technology?

Need qualitative examples and case studies to educate DOT in public sector – different than public sector/building

Using this technology for utilities – problem is getting data from utilities – how do we incorporate that data into the models. Could also include other stakeholders

How do we Coordinate external issues /geospacial issues / utilities/ROW, etc

What is the perception of further effort and spending compared to what we are already doing?

Goal is to put all the data into one place so that data only has to be "put in once" and can be added to

One other issue is the difference between doing a new bridge and doing a model of a rehab / addition – there are more questions when there is an addition (new lane, etc) than when it is just a new design.

Roger Grant – Modeling standards and procedures available

-Some questions are: how to make data available and how to separate data from software / how to incorporate into contracts?

If IFC and Building Smart have an advanced structure already – if we felt that would be a way to go for bridges, would Building smart be able to work with "us". Is it just an effort that needs to be done in the US – already established internationally

Things can be borrowed and used from the international effort to move the US effort forward. There are national chapters and working groups of this building smart organization. Most work done on infrastructure modeling has been international

Need to work with DOT's to find out what they are already doing or their directions

Is the Real value for an owner is the downstream – asset management, preservation, etc

How is this compatible with ProjectWise, Ebuilder, etc. that DOT use for design and contraction (exchange of documents)

If this will eventually tie into asset management then it needs to be compatible with programs that states are already using. IFC would have to be assessed for its abilities on the asset management exchanges in a future project

Are any DOT's already giving models to fabricators with IFC? Roger's group hasn't talked much with the DOT's to see what they are doing. NY is talking about using Bentley models be used for reinforcing, but not sure what other dot's are using. Using a proprietary tool but having a requirement to use it is an issue with DOT but it can be done. May also require an open format so anyone can use it

NY State XML has a way of defining bridges in an XML. Steel bridge fabricators want an XML but don't necessarily need a 3D model for fabrication. Really just want the data file. NSBA doesn't care about the format as long as its usable. Using something like IFC you could use a standardized XML to get the data.

Most fabricators work load is NOT model based. Some projects do need a model (ex. Truss bridges, etc) (when virtual assembly fitup is necessary, etc)

Possibly the fabricator can produce a model from the data as part of their deliverables

OpenBrIm – Mike B

Owners and designers convert existing standard detail to 3d digital model

Nsba fabricators develop and review std parameters for models

Pci precasters have similar goals

Contractors / software vendors

Open BrIM is not software – OpenBrim App is developed by Red Equation / independent of and not funded by FHWA – internet browser based – engineering on the cloud – free – no license agreement

Basic modeling too and basic validation tool

Not a high end photo realistic tool / clash detection or structural analysis

Meant to just be an interoperability tool

(form of XML)

When any key parameter changes the entire model updates / model is tied to alignment

Geometric alignment objects – circular / spiral / horizontal /parabolic vertical/cross slope/ etc

Whats next? – what's really needed is a champion. Promote industry collaboration and maintain data structure

Questions – can you export to a CADD format? CADD format is inside the app – but yes, any application can connect and bring in the information off of the model – you can get 3d and 2d and finite element off of the model of OpenBrim

Who owns openbrim? Red Equation developed – but it is open so there is technically no owner – community driven

Anyone can connect and contribute

However, it requires stewardship – two committees proposed –" objects" committee oversight and "technology" (makes sure it stays open system and useable for all systems)

One of the challenges – someone created a girder objects in open Bridge represented by single line finite element / someone else develops a cross frame in a different way – how will those two models work together?

Have to make sure the objects are defined are compatible. Objects are extendable in openbrim. Ex. Someone defines an object in finite element but you don't like it – you can extend and modify according to your preferences.

Version control – owner will have their own library that cant be changed – so you could copy another's and then make your own with modifications that can't be changed by anyone else

Everyone has to invest their time to develop their own library

There will need to be oversight and QA/QC.

Creating a warehouse (example "sketchup") of objects. How do I validate an object? You can see it in 3D. every XML should have a schema file. Schema is defined for basic things that rarely change There are schema for "primitives" but no scheme for "objects"

How do you certify / validate an object before it goes to a library for use? Who is defining the set of parameters that an object has to have for each user to have all the data they need to do their job? Anyone can define objects but there is a tag on it that will show what level of development the object is in

There is a section in the library for discussions. Objects go through a development phase that includes a discussion phase.

In the final phase – the owner can change until it becomes a "standard"

If it is changed after the standard phase, then it goes back to a development phase.

Development of an object is overseen by a committee

We haven't put a stewardship management system in place yet for open brim – we still need to define that policy and process

Bridge Process Map

Program – Design – Construct – Deploy

We are in the Program phase now

In the bridge industry – we need to define what we want for each component. What do we need / want for an Ibeam? What do we need for a box girder? Etc.

Need to have structural engineers "boots on the ground" to help develop a program

There needs to be a central authority on issues. With IFC Building Smart international has a certification program and set of rules / policing that software companies can get (a symbol on their software package)

Constant effort needed to have some sort of organization that can police and validate data quality

If a software is certified by that organization, then errors should be small

What on the process map is "in scope" for this project – no – we are only trying to prove one exchange (design to construction) – this is a LONG TERM future plan

We need to look at the existing shapes (such as abutment being three walls, or a girder being and Ibeam)in IFC to see if it really serves the purpose of the bridge designer. Then if not then it can be developed.

Critical question is "WHAT ARE the IFC elements" – we need to look closer at these elements. Question is does IFC have the correct elements for the bridge assemblies.

The purpose is not to have instance library – it is to have elements that can be used for the bridge element purposes

What is the use case, what is the exchange and what data is needed for that exchange? It will be different for each exchange – designers may want different data than constructors and fabricators.

Structural idealized theoretical version of a beam may be different than the physical representation of the beam.

Wednesday

IFC overview

IFC is typically only for final deliverables…not necessarily how you got there

Listing of all the top level objects

Alignment in IFC – there isn't really that many inputs for alignment. IFC is just the way the data is stored (XML, etc). is there an easy way to report out the alignment data? Depends on software used

IFC components can have a time component (task related in connection with objects – example temporary structures, construction sequencing…) or "scheduling event", data could be stored with object – haven't been traditionally used on the building side in software. Is this valuable for bridges?

It will not be able to translate back and forth during design phase. IFC is for final design – only intended for results. This will be a different project to exchange info during the design phase.

DOT owners want an ability to work across disciplines for design phase and not just put together a rendering of 2d plans (final plans). Need to look at how this fits into the design workflow.

We still aren't sure how much information is really needed by fabricators. In order for steel fabricators to participate – NSBA as an industry – wants to publish a document of what information is really needed.

In the end we need to be able to exchange 3d information – we need to be doing more in "real time" to do true clash detection.

We want to define a complete set of information. Software will need to be able to just identify the information needed for that phase – example – design software will take what information it needs from the IFC files for analysis and just store what isn't needed to pass on later. But information will be corrupted if the design is changed? Similar to the shop drawing process now – there will need to be a business process developed for version control, etc. there is version control in IFC but most people don't use it.

On OWNER needs to be saying "this is what we need" and come together to with software companies. Software companies can say "we can't do this, or we can do this" but there needs to be an owner that will direct the needs.

IFC is a "mediation" file. If you decide what the methodologies are it can be embodied into the MVD – MVD will need to be "tight"

GAPS in IFC – there are ways to use what his "already there" in IFC for objects. There may still be more of a growing process for "workhorse" bridges. IFC objects can be "adapted" to be used for bridges. There is still some work to be done. There are some questions about alignment issues.

MVD outlines (creates a standard) for what data is needed for input and what is needed for output exchange. There has to be governance/stewardship to develop these.

There are many many MVD's – hundreds of MVD's are needed.

OpenBrim

Parametic model – is it more efficient? Is model too big?

Doesn't matter because computers can handle. It is essential to have parametic information involved in the model

It is available in the design analysis software

Do the owners have a desire to create a library of their own digital definition of their objects? Every structural analysis vendor has done this.

States want to leverage what other industries are doing.

Software tools would have to make and effort for OpenBrim to work with these objects

What is standard to one state is not common to other states.

Most state libraries are cadd details

Do we really need to have an "open" library. More openness requires more governance

Who is governing both IFC or OpenBrim?

IFC is established – as a file format – IFC may already have everything needed

T19 – wants to develop a roadmap on the decision making process and we have a 20-07 to help do that

Need more buy in in our industry? What do the states want?

Where should we keep these objects? Cloud? Each state host their own library?

What can we do to incorporate Open Brim and IFC – are they compatible?

<u>Owners Breakout Session</u>

T19 took on strategic planning for how to move forward on modeling / 3d

T19 had a mid year meeting in Scottsdale – did a modeling 101 – what is out there? How can we work with FHWA? What types of things should we do to make this transformation in our business?

What are some of the items we want to do and what is our roadmap.

1) education process

2) owners do know some what they want

3) TRB / other committes / cross functional work / aashtoware tie in's

Scott sees weaknesses in both areas

Scott wants to see time, resources and schedules – ROI discussion

What are our next steps?

In BrIM area – it is not widely used. Not being widely used in any state.

States are doing some "bits and pieces" to structurally locate the bridge but its not a "Brim" effort

20-07

T19 put in a proposal to find proof of concepts (in addition to FHWA efforts) / roadmap suggestion / recommendation of next steps and who to talk with - synthesis study

Precast concrete has been working with IFC for seven years in BIM. Has there been an evaluation of if there is a primary objection of doing this. (return on investment)

What is the prime objective for doing this? – make design processes better, make fabrication work flow better, make asset management easier?

(circular process – birth to death of bridge)

There may be solutions that work for one area and not for another area. A ROI analysis needs to be done to find potential benefits and costs of doing business this way in each area.

It may also help determine what processes on the map we should work on first.

Objective – overall purpose - may be to have a ONE depository for all 3d model information that can be pulled out to use for different phases.

We need to have a full understanding of current workflow and how we can improve current workflow.

Huge benefit for the future is in inspection and asset management area

We need to make sure what we communicate to software vendors is what owners want.

Ultimately the data that supports the business (not necessarily the software) – how its kept and how its maintained / information modeling and how we can use it in the future

This is the need for design, this is the need for fabrication, this is the need for asset management…define these now to move forward.

governance and stewardship: what kind of role do states want to have?

AASHTO committee?
Vetting committee (certification process for Open Brim) – who would be vetting? No volunteer would be able to have the time to monitor

AASHTOware has tired to do this with Vertis/Opis/Pontis (having a data file from design, load rating, inspection)

3D is part of bridge information modeling – bridges are behind roadway in terms of using 3d modeling, haven't taken advantage of all the tools

Contractors have driven the conservative decisions – you need to show an ROI to contractors / designers to change the attitudes on the change to using available tools

What is FHWA's view on governance? They don't have a good answer right now

An industry group (AASHTO) has to put together workgroups (precast, steel, etc)

AASHTO could provide a standard "guide" – possibly a new standing or sub committee within AASHTO

Bridges could take a lead to work with other subcommittees (highway, construction, etc) that have their own efforts – work with AASHTOWare

Short term next steps:

Outcome of this meeting – something that is of value to AASHTO

MVD written by states/AASHTO that can be used for contracting

We would want the industry to be on board as well. They would be part of the process. Want common terminology, process model, etc.

How do we get endorsement from industry?

AASHTO will come out and say what they need – after discussing with industry / practitioners – have a workshop

How much 3d modeling are we going to do for standard bridges? What level of detail is an engineering going to produce in the production phase? Biggest cost is maintenance – not necessarily data that a design engineer would provide?

Whats the next priority for exchanges?

Next steps?

Bridge management system (Pontis) has a terminology definition (dictionary) already. Is it compatible with IFC? Building smart is also working on the terminology . Will be sent to AASHTOWare / Scot for review

Intend to produce a draft MVD based on steel and concrete girder bridges that we analyzed and document the case studies from these contracts.

We have to have the process model fully defined first. – add process maps of each process to further define

If we don't have an overall roadmap how do we get the software companies to work with us?

We need to pick a schema / standard so we aren't developing a bunch of different standards

Need to know what other industries are doing in order to relate to those industries (fabricators may be working with building and bridge data, so it would be good to have similar standards)

Its not wise for us to ignore our "customers"

What form does our "deliverable" take – in the past the deliverable has been a "piece of paper" (plans). What is our deliverable now?

Liability? When we have modeling as your final document (sign and seal) – need to have a process to "seal" those plans – document management. There may be a third party model checker – sign and seal a model. Digitally sign a document?

Another workshop focus around the process map?

20-07 will have a workshop – more focused on governance / process and prioritization

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Software/technology breakout recap

Vendors need to "step back" to listen to the owners / practitioners

Main want (of fabricators) – just want to be able to exchange data in a file

Want to do things one time with one model and transfer between software efficiently

Some issues were discussed that validation was extremely important

Fabricators may want to see same system between buildings and bridges

IFC has only been used internationally and not in US

Need to develop a way to sell a system to aashto and users / what is the best way to educate (case studies)

We are still trying to understand the way to integrate IFC and OpenBrim

Openbrim is a great platform to test and determine data requirements

Openbrim is a way of conceptualizing and could be used to develop objects that then become IFC?

What problems are we trying to solve with Openbrim? Are those problems already solved in other areas?

Rebar issue: what are the IFC capabilities? We really need "standard bends" etc. they are in proprietory software, but it is up to the designer to send that to IFC…

Models are often incomplete between design and construction (designers ofter just model one and then say "4 at X spacing;) something that needs to be addressed? In Bridges we often do more modeling – but may only model one facia beam and one interior beam – so how do decide level of detail we need?

Can have a digital signature / certificate.

Produce 2d documents from the model and still sign and seal and then have a note of either the 2d or model controls in the event of a discrepancy. There is a BIM standard that addresses this issue – depends on level of development of the model and authorized uses. Uses date stamping. Need a way to "lock down" the model once approved.

A "federated model" is a collection of files – each with different signatures

Other discussion

Still have missing gaps – need a structural analysis exchange – need input for analytical model for analysis?

Appendix B. AASHTO/NSBA Denver Meeting Minutes

TG15 Denver Minutes
Thursday 10am-12pm, 11/19/15
Note Taker- Aaron Costin

- Welcome, Introduction, Web and Conference connection
- Rob, HDR
    - Design to Construction Data Exchange
        - Issues
        - Fixes
        - Lessons Learned
            - Need for standard taxonomy for bridge elements
    - Discussion
        - What information is being stored in data collection?
            - Location, coordinates, reports, fabrication, etc. per piece
                - Data structure is in QA software
                - Limited to this software
            - Separate DB is being built to take in in QA data
                - Labor intensive
        - What is long term use of model?
            - Owner will use for asset management
        - What are some examples?
            - Steel girders
            - Non steel substructure had to be named (pile 1, pile 2, etc.)
        - ID needs to be universal to identify that specific piece
        - TG4 needs to be brought in for data exchange
        - Taxonomy and piece mark do not have to be the same, but they need to be linked to make connection
- Old business
    - Stuart did not have connection to talk about it
    - Feel we (in US) are disconnected from international efforts
        - Need to align with them
        - Need to put in effort
        - Reasons
            - Software developers or over seas
- Brian Kozy, FHWA
    - FHWA is very involved in BrIM
    - Moving from 2D based to 3D modeling to BrIM
    - Contracts to work on interoperability
        - Built upon this work
        - Ch2m Hill
            - OpenBrIM (openbrim.org)
                - Concept phase
            - Community can describe bridge components
                - Standard definitions

        - NIBS (National Institute of Building Sciences)
            - Roger Grant is program manager
            - Focus on standardization
            - Review Standards currently used
                - Industry Foundation Classes(IFC)
                - Investigated how can bridges be modeled in IFC
                    - Case studies
        - Every Day Counts (EDC)
            - 3D modeling for transportation
            - Roadshows to demonstrate
        - 20-07
            - Michael Baker and AASHTO SCOBS T19
            - Highlight implementation of digital project delivery across states
                - Contracts and legal issues
    - How does this fit in with current BIM tools?
        - Buildings are different than bridges
        - BIM is ahead 10 years
        - Using lessons learned
        - What are the limitations and where can we fill in the gaps?
        - Current efforts are going on
- Aaron Costin, Georgia Tech
    - Overview of FHWA/NIBS project
        - Draft publication is out for review and feedback
        - We have copies to distribute
    - Overview of Process Map
    - Overview of Data Dictionary
    - All topics will be discussed in more detail this afternoon and Friday
- Steve Walsh
    - TG1/TG15
        - Design to Detailer exchange
            - Compilation of data that is already produced
        - Plate Girder Bill of Material
        - Cross frame Bill of material
- Jason Stith
    - TG10/TG15
    - Contractor to Erection Engineer Exchange
    - Identify full process
    - Looking through data dictionary to identify information needed
- Comment from Brian Kozy
    - Define data requirements based on levels
        1. pieces of information needed
        2. what data is needed for each piece information
    - Help reduce effort for each piece (i.e. don't have to spend time discussing each piece at once)
    - Different people may want to describe data differently at the lowest level

- New Business
    - Spillover effects to collaboration TGs that has not yet dealt formally with interoperability and data exchanges
        - TG 4/TG15 – handoff involving inspection model data
        - TG12/TG14 – address and streamline design exchanges
        - NSBA Task force/TG 15
            - Plate girder bill of tomorrow
- Assignments pushed until tomorrow
- Discussion
    - When will we have an example showing this?
        - Aaron Costin's thesis is developing the case study with TG10/TG15
            - Hope to have case study by the end of this year

Appendix C: Outline of Typical Processes for Steel Erectors

TG10-TG15 Work Group for Steel Erection Analysis Modeling

Final Draft version incorporating previous comments (11-2-2015)

Author: Ron Crockett

OUTLINE OF TYPICAL PROCESSES FOR STEEL ERECTORS

DESIGN-BID-BUILD PROJECTS ARE ASSUMED! (For P3 and Design/Build Projects the designer/contractor/erector typically collaborate during the Preliminary Design Phase).

Some definitions:

The Construction Engineer includes the Erection Engineer, and for purposes of steel bridge superstructure construction, these terms can be used interchangeably. The Construction Engineer may also have roles for engineering the means and methods for other phases of construction including foundations, substructures, piers, superstructure deck and other bridge features.

The Contractor (also referred to as General Contractor) is the party contracting with the Owner.

The Erector is the entity that erects the steel superstructure. In some cases this may be performed by the Contractor, and in other cases this may be performed by an Erection Specialty Subcontractor employed by the Contractor.

The Designer (engineer of record) is an agent of the Owner in traditional design-bid-build construction.

Design-build projects are not specifically considered herein, and the steel erection processes described below must be modified. A key difference is that a schematic design is provided by the Owner and the Contractor employs the Engineer of Record who further develops the schematic design following the Owner's guidelines during the bidding phase. The bidding and letting phase is much longer, and bidding is based on conceptual instead of final designs.

<u>Bidding and Letting Phase</u>

The Contract Documents provide the basic information needed to determine how a bridge can be erected before the work can be priced. These need to include the following information to the maximum extent feasible (amount of information depends on project complexity including interface with existing structures and facilities):

1. Topographic information for right of way and Owner provided access to the right of way.

2. Bathymetry or waterway/stream bottom profile information (if over or adjacent to a waterway/stream); current ranges, hydrographs, normal and 100 year flood levels, tidal ranges, etc.

3. Right of way boundaries

4. Work area restrictions inside right of way

5. Location of existing structures, facilities, roads, utilities (above and below ground), railroad tracks, etc. within or immediately adjacent to right of way. Dimensional layouts must be shown on drawings and should be drawn to scale within a specified accuracy relative to control points and right-of-way boundaries.

6. Horizontal and vertical alignment of new bridge roadway and approaches (showing how they tie into the bridge structure and control points on the plans).

7. Location of new piers and other structures to be constructed within the right-of-way (showing how they tie into control points on the plans).

8. Girder dimensions and approximate weights (weights cannot be finalized until shop drawings are approved).

9. Designated splice locations and possible flexibility to relocate splices.

10. Plans and specifications, including special provisions and all pertinent Contract Documents, Reference Documents and Information Handouts.

11. Provide plans in microstation or autocad format for Items 1-7 and associated elements of Item 13 above (preferably prior to bid, but definitely after award to the successful contractor, this should be a requirement, not an option, for BrIM to be an effective scheme).

12. Copies of permits and approvals from railroads, Coast Guard, US Army Corps of Engineers, property owners for off right-of-way storage areas provided by Owner, etc. Include specific information on any navigation channel restrictions or minimum clearance restrictions to railroads or other traffic.

13. Environmental Permits and Work Restrictions:

    a. Storm Water Collection or Runoff

    b. Noise restrictions (above ground, underground and underwater)

c. Protection of fish, mammals, birds, plants, sea grasses, etc., including times of year when work is prohibited or restricted due to nesting or spawning.

14. Bridge structural model information:

a. Bridge geometry for the total dead load condition of the bridge (horizontal and vertical curves, skews as applicable) tied to common control points referenced under Items 1 – 7 above.

b. Member properties (area, I, S, r, J, C_w, etc.)

c. Material properties (density, Fy, E, G, etc.)

d. Stress sheets (at a minimum steel dead load, total dead load, wind load variations/ranges, live load variations/ranges for the final condition)

e. Camber diagrams or charts (showing no load, steel dead load and total dead load camber).

f. Member weights (especially main girders including shop welded connection plates, weight of splice plates, typical lateral bracing and typical pier and intermediate cross frames).

g. Main girder splice locations

h. Wind reports and site specific wind speed data (if available); otherwise, design wind pressures for the bridge.

i. Owner/designer should specify reduced construction wind pressures and load factors or allow the erection engineer to apply ASCE/SEI 7 and ASCE/SEI 37 to develop reduced construction wind pressures and load factors depending on the activity and duration (e.g., NHI training manual calls for "erecting a beam with a crane" to cease for critical lifts (over 75% of crane capacity) if wind is blowing more than 25 mph, whereas a much higher design wind pressure based on 75% to 80% of the final design windspeed is appropriate for evaluating the partially erected bridge and falsework stability and strength over longer periods of time).

j. COMMENTARY: For BrIM to be a workable and useful tool for bidders and contractors, the Owner should provide a complete 3D bridge digital model to bidders indicating all design details such as bolts, splice plates, connection plates, connection details, bracing, bearings and other features of the bridge. This digital model should be directly importable to customary software used for structural analysis or structural steel detailing, as well as viewing software to see graphical 2D and 3D representations of the design. If owners/designers are unwilling to embrace BrIM by providing this 3D digital model to bidders, then BrIM may not accomplish its intended objective to provide better overall construction economy, accuracy and time savings unless a detailed dialogue with the industry is conducted to confirm that there are better ways to develop this information without the Owner/Designer providing it.

15. If owner/designer require a specific type of erection analysis to reduce locked-in stresses for the final total dead load profile and deflections, consistent with specified fit under Item 16 below (see NCHRP Report 725 and AASHTO/NSBA S10.1-2014), then they must specify:

    a. 1D line girder model (adequate for straight girders with up to 20 degree skew)

    b. 2D grid analysis model (when required by the designer)

    c. 3D FEA model (best for highly curved girders and should be specified by the designer if necessary to achieve design objectives)

16. If owner/designer require a specific fit for detailing depending on type of bridge, skew and curvature (if needed to achieve the desired final dead load vertical profile and horizontal deflections), then they must specify. Otherwise fabricator and erector are free to choose (see NCHRP Report 725 and NSBA Fit Detailing paper):

    a. no load fit (NLF)

    b. steel dead load fit (SDLF)
    c. total dead load fit (TDLF)

17. If owner/designer require a specific final vertical alignment of webs over bearings at a defined standard temperature for the total dead load condition, they must specify the fit and type of erection analysis necessary to achieve it – see NSBA Fit Detailing paper. Otherwise erector and fabricator are free to choose and no specific tolerances shall apply.

18. If owner/designer require a specific pour sequence for deck concrete, they must specify and identify major issues that could arise from failure to follow the specified pour sequence (in case the Contractor desires to deviate and assume responsibility for evaluating and submitting its own pour sequence for approval by the designer).

19. If owner/designer require a particular type of splice bolt hole, they must specify; otherwise fabricator and erector free to choose (sub punch and ream, drill from solid, CNC, virtual assembly)

20. If owner/designer require a specific bolt tensioning method, they must specify; otherwise fabricator and erector free to choose.

21. Specific bearing information (fixed, expansion, etc., capacity, allowable directional movement and rotation)

22. Boring logs and geotechnical reports

The General Contractor, the Erector and the Construction Engineer coordinate the exchange of the above information during the bidding period. Most information should be provided in the Contract Documents or Information Handouts/Reference Information provided to Bidders, and remaining information can generally be secured upon request to the Owner prior to bidding.

Other items for Erector and Contractor (and potential fabricators) to coordinate prior to bidding when possible, or shortly after award and prior to executing an erection contract:

1. Other access to right-of-way and storage/staging areas not provided by Owner (for storing and moving materials and equipment into and out of the jobsite).

2. General method of shipping girders to site and unloading (truck, rail, barge, etc.)

3. Who performs the unloading, and where is unloading performed?

4. If not delivered under hook for the erector when needed for erection, who is responsible for moving girders from temporary storage to the erection hook?

5. Does erector need to unload girders in the horizontal or vertical position?

6. General sequence of erection (which end of the bridge to start and which to end) unless this is a requirement of the Contract Documents. Occasionally a bridge will be designed specifically to be erected in a certain way, and this should be specified in the Contract Documents.

Items 1-6 immediately above should be coordinated directly between the General Contractor and the Erector during the pre-bid phase after consultation with potential fabricators. This is not always done, especially if the General Contractor is not soliciting erection pricing prior to bid, and in that case these issues should be discussed and agreed prior to finalizing an erection or erection engineering contract.

Unless specifically addressed in the Contract Documents, Erector, Fabricator and General Contractor may also coordinate Item 19 above (especially methods to verify accuracy of hole locations and assembly). More typically this is addressed in the Contract Documents and any mutually agreed changes occur during the post award/planning and detailing phase.

Post Award/Pre-Construction Planning/Detailing Phase

Owner provides more extensive information regarding plans, specifications and background information upon request by Contractor and Construction Engineer (to the extent not already provided in the Pre-Bid Contract Documents as outlined above). In particular this may be the time to deliver autocad and microstation files for specific contract plans needed by the Contractor, Construction Engineer and Erector.

Preconstruction meeting with the Contractor, Construction Engineer, Fabricator and Owner/Designer to review initial design questions, problem design details and standard practices to be followed. For more complex projects this can involve multiple meetings or web meetings/teleconferences.

Prior to commencing shop detailing agree among the Owner/Designer, General Contractor, Erector, Construction Engineer, Fabricator and Shop Detailer on the following:

1. RFI submittal and response protocols (responses are generally needed within 5 working days after submittal).

2. Expected timing to submit erection plans and procedures. Erection plans and procedures cannot be finalized for submission until after shop drawings for steel fabrication have been approved by Owner. Erection plans and procedures are generally submitted at least 15 working days prior to commencing affected work, providing ample time for Owner to review and comment if desired without delaying erection, unless other longer timeframes are specified in the Contract Documents.

3. Girder splice locations.

4. General phasing and sequence of fabrication and erection.

5. Type of erection analysis (1D, 2D grid or 3D FEA).

6. Detailing fit (NLF, SDLF, TDLF).

7. Vertical alignment of girder webs over bearings for total dead load condition.

8. Bolt hole fabrication methods and methods to verify all components and pieces will fit properly during erection (CNC/virtually assembly methods versus physical progressive trial assembly methods, etc.)

9. How to resolve difficult access details for field bolting and/or field welding.

10. How to resolve field hole fit issues for bottom laterals (oversized, slotted or field ream/drill).

11. If field welding is required, secure initial erector input regarding likely weld processes and suitable field weld details. Establish mutually agreed deadlines for final erector input/decisions.

12. Reinforcement, temporary lifting lugs, etc. to be included in final fabrication to accommodate handling and erection requirements. Agree on a deadline for erector/construction engineer to provide such information if shop detailer and fabricator can accommodate.

13. Interface between piers and bearings – who is responsible for location and placement of field surveys, elevations and anchor bolt placement or drilling/installation?

14. Interfaces between bridge steel or concrete abutments and expansion joints – who is responsible for location, placement and final horizontal and vertical alignment/shimming/grouting, etc.?

15. When erection plans and procedures are to be submitted. Time for review and response from Owner, if required.

Prior to commencing Construction Engineering, the Erector and Construction Engineer need to meet with the General Contractor to finalize the following:

1. Who is responsible for:

    a. Storage areas.
    b. Access roads to site.
    c. Preparation of erection areas (grading, drainage, gravel if needed, compliance with storm water runoff and drainage, etc.)
    d. Delivery of girders and other components from storage area to erection point.
    e. Field surveys of completed substructures and bearing locations.

2. Overall preliminary erection schedule and timing, including the starting and ending points for erection.

3. Preliminary locations for erector's falsework/shoring towers.

4. Consider any environmental restrictions (noise, nesting and spawning seasons for birds, fish and wildlife, etc.).

5. Timing and phases for areas that will be available to the erector for erection and any work area restrictions imposed by the General Contractor that may impact how the erector can perform his work.

During Construction Engineering (erection analysis, erection plans and procedures):

1. Erector and Construction Engineer collaborate on means and methods.

2. Construction Engineer performs preliminary analysis based on means and methods preferred by Erector. Also clarifies with Owner through RFI process any ambiguities or proposed adjustments in erection design criteria.

3. Construction Engineer and Erector confer on the preliminary analysis and make adjustments as required.

4. Erector begins selection of equipment, temporary supports (falsework) and other temporary works (bracing and lifting lugs) needed to perform the erection. Erector exchanges information with the Construction Engineer. Necessary to interface any special modifications to fabrication to permit erection.

5. After shop drawings are approved, Construction Engineer finalizes the erection analysis and erection plans and procedures.

6. Construction Engineer prepares erection plans and procedures to address all elements required by the Contract Documents. The Submittals required by AASHTO/NSBA S10.1-14, Steel Bridge Erection Guide Specification or the NHI Training Course, Engineering for Structural Stability in Bridge Construction, describe useful particulars to include that may not be required by the Contract Documents.

    Erection analysis calculations may not be required for submittal unless required by the Contract Dcouments or specifically requested by the Owner.

7. Construction Engineer and Erector review plans before submitting to Contractor and Owner. Owner approval may not be required, but generally the Owner will review and provide comments or request additional information. Generally the complete package of erection calculations, plans and procedures must be submitted 3 weeks prior to commencement of erection and any comments from Contractor or Owner must be provided in time to avoid delays to the Erector. If longer timeframes are required for more complex project reviews, then the Owner shall specify in the Contract Documents.

<u>During Construction</u>

1. Erector follows the submitted Erection Plans and Procedures. If any changes are required, he must consult with the Construction Engineer and inform the Contractor and Owner. Depending on Owner requirements, a revised submittal may be required.

2. Changes to the as-fabricated structure (due to fabrication errors, changes in erection procedures, repairs, mislocations, major misfits, etc.) are recorded on NCR's or RFI's, depending on the situation. These NCR's and RFI's are later incorporated into the final "as-built" drawings. Physically placing this information onto "as-built" drawings is essential for future reference during the lifetime of the bridge, especially for future bridge renovations or expansions. The lack of sufficient and accurate "as-

built" information is frequently a major issue for bridge renovations and expansions that causes claims and extras from future contractors at the Owner's expense.

Appendix D: Notes and Comments section from the TG10-TG15 Subcommittee "Process Model Development for Erection"

- The "Neutral File" = Exchange Model and contains all the data to be passed from one model to the next. To the point of Ronnie, under present circumstances a 3D model generally cannot be passed unless everybody has the same software. Exchange Models will be used by software vendors to create a neutral file (e.g. IFC) to "pass" the 3D model from one software to the next. Therefore it is important that we create these Exchange Models to make sure all the correct data needed is passed. Neutral File = Exchange Model = Data Exchange (as contrasted with Document Exchange, which is another part of the overall Information Exchange)
- Owner is the Designer or hires the Designer. Designer is the Engineer of Record (not an architect). The Owner completes the final design and issues it as part of the plans and specifications (later included as part of the Contract Documents) to be used by the Contractor, Erection Engineer and Erector to prepare a Bid Proposal.
- The Contractor, the Erector and the Erection Engineer are three different actors. The Erector is the party constructing the steel portions of the bridge. The Erection Engineer performs the analysis and calculations to prepare the sealed erection plan and erection procedures, with input from the Contractor and the Erector. Sometimes the Erection Engineer is an employee of the Contractor. Few few Erection Engineers are employees of the Erector unless the Erector is also the Contractor. The more complex the bridge, the more likely that the Erection Engineer is an independent consulting engineer instead of an employee of the Contractor or Erector.
- Post Award Preconstruction Planning is a phase that commences after bidding and contract award and continues until Steel Erection commences.

- “Preconstruction meeting” is an event that occurs after bidding and contract award on Design-Bid-Build projects
- “Prior to commencing shop detailing” is a new subphase that occurs between contract award and the start of shop detailing. This may result in exchanges among the Contractor/Owner/Erector/Fabricator/Erection Engineer as the result of the Preconstruction Meeting and separate early meetings or communications among these parties.
- “Prior to commencing Erection Engineering” is a new subphase that occurs between contract award and the start of Erection Engineering. Exchanges generally occur among the Contractor/Owner/Erector/Fabricator/Erection Engineer to determine splice locations, fit methods, shoring locations, sequence of erection and other important details that may deviate from or complement what was shown on the bid plans. Once these basic issues that affect Erection Engineering are decided, then Erection Engineering can commence in earnest.
- “During Construction Engineering (erection analysis, erection plans and procedures)” is a new subphase of Preconstruction Planning that commences after the above early post award preconstruction phases are essentially concluded. This phase continues until the start of Steel Erection.

- Construction
  - “During Construction” This should be in another phase and not under “Post Award/Pre-Construction Planning/Detailing Phase”
- Substantial Completion occurs after the Owner can start using the project or particular phases of the project are turned over for use by the Owner. Traffic can run but there are still minor issues that have to be fixed or completed. Generally

this triggers the Owner's responsibility to start maintaining the portions of the project that can be used.

- Final Completion occurs after the Owner finally accepts the project as conforming to plans and specifications. All quality records and as-built drawings have been turned over to the Owner, and any remaining punchlist work is completed by the Contractor and accepted by the Owner. All responsibility for the care, custody, control and maintenance is transferred from the Contractor to the Owner.

Feb. 21, 2016

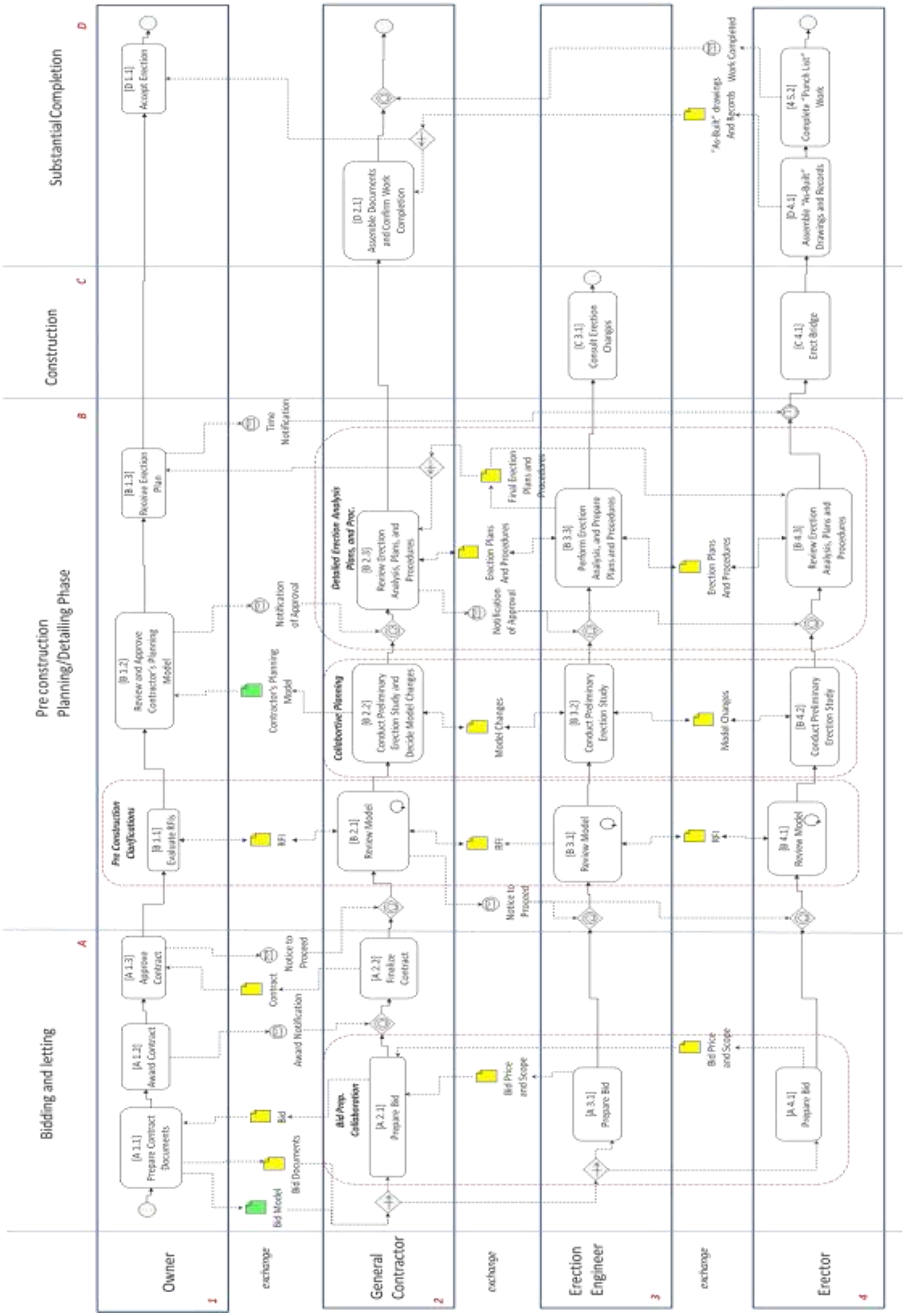
1. I suggest renaming the General Contractor bidding and letting activity "Append Contract Documents" to "Prepare Bid". In my opinion the Group Activity name "Bid Prep Collaboration" is adequate to generally describe what occurs during the bidding phase.
2. Upon further reflection, the Owner activity "Award Bid" should be shown as occurring during the bidding and letting phase because "Let Contract" = "Award Contract."
   a. Ronnie: "I'm not sure about this; I think if you move it then we don't have a trigger for the pre-construction column of activities.
   b. This also causes me to wonder if we should add "advertise" in 1.a; in fact, is "Advertise job" better than "Prepare Request for Proposal"?
   c. At I high level, I think that the owner
      - Advertises the contract,
      - Receives and opens the bids, then
      - Awards the Bid
3. RFI's from the Erector should go to both the General Contractor and the Erection Engineer. RFI's from the Erection Engineer should go to both the Erector and the General Contractor. Should this be incorporated into the logic arrows? A

similar principle applies for RFI's from the fabricator and detailer than might in any way affect the Erector or the Erection Engineer.

4. RFI's that go to the Owner must have a response from the Owner to all actors in any way affected by the response. The new Owner/Designer Activity might be named "Develop Response to Model Review/RFI's"
5. Should the Owner, Fabricator and Detailer be included within the red box for "Preconstruction Meeting"? I realize that we are focused on Steel Erection, but that joint collaboration is an essential part of the process and should not be overlooked. Also would a better title for the red box be "Preconstruction Clarifications"? This applies to pre-detailing issues during the first couple of months after contract award.
    a. Ronnie: Yes
6. Should the Fabricator and Detailer be included in the red box for "Collaboration Meeting"? Also, flow of information is not exactly as shown and instead more circular/matrix-like. Should "Meeting" be dropped from the red box name or a more descriptive name such as "Collaborative Planning" be applied? This red box occurs after "Preconstruction Clarifications" and before proceeding with detailed erection analysis, erection plans and erection procedures.
    a. Ronnie: "*I'm not sure; I'm not up to speed with what we're trying to do at the Collaboration Meeting; is this intended to get the GC, Erection Eng, and Erector to the same meeting to refine and finish the model?*"
7. The Erector needs to review the Erection Plans and Procedures developed by the Erection Engineer before they are submitted by the Contractor to the Owner. Perhaps there should be a red box/subphase including the General Contractor, Erection Engineer and Erector called "Detailed Erection Analysis, Plans and Procedures" to indicate this interaction. The output of the red box is "Final

Erection Plans and Procedures” submitted by the General Contractor to the Owner.

Appendix E: Final Draft Process Map for Steel Bridge Erection



Appendix F: The AASHTO/NSBA Steel Bridge Collaboration Operations Manual

****** Draft ******

This manual describes the operations of the AASHTO/NSBA Steel Bridge Collaboration. The Collaboration is a forum of public and private professionals who work together to improve the quality and value of steel bridges. The Collaboration is a jointly sponsored by ASHTO and the National Steel Bridge Alliance (NSBA). Representatives are from state and local DOTs, the Federal Highway Administration, academia, and various industries related to steel bridge design, fabrication and erection.

1 Introduction

In the United States, steel bridges are generally designed and built in accordance with AASHTO specifications, but much of the actual design and construction are governed by specifications, codes, standards, and practices that are prepared at the state level. Therefore, there are as many as fifty different ways engineers must follow to design bridges and fabricators and contractors must follow to build bridges, resulting in costly inefficiency and the demand upon each state to maintain expertise to ensure their specifications, practices, and designs reflect the state of the art.

The collaboration was formed to develop national standards that reflect the state of the art in steel bridge design and construction. By using these standards, DOTs can improve their processes and help minimize the differences and the associated costs.

2 Mission

The mission of the collaboration is to achieve quality and value in steel bridges by standardizing design, fabrication, and erection processes and by advancing the state of the art.

3 Sponsorship

The Collaboration is jointly sponsored by the public and private sectors. The public sponsor is AASHTO, through the Standing Committee on Highways, the Subcommittee for Bridges and Structures, and the Technical Committee for Steel Design, T-14. The private sponsor is the NSBA, through the Executive Committee.

Background

Considerations for a national collaboration began in spring 1997. An informal poll of steel fabrication professionals from both the public and private sector revealed that there was broad support for a steel bridge collaboration. Consultations with the Subcommittee for Economic Fabrication (SCEF) and the Texas Quality Council revealed the same.

It was important for the Collaboration to be supported by AASHTO to ensure proper owner representation and to ensure credibility with bridge owners. In June, 1997, support was sought from the AASHTO Subcommittee for Bridges and Structures, and the subcommittee agreed to provide its support. The Subcommittee directed the Collaboration to associate with the Subcommittee as a liaison committee to the Technical Committee for Steel Design, T-14.

Sponsorship by industry was important to ensure proper industry representation and to ensure credibility with industry. The NSBA was also approached in June, 1997, and the NSBA also agreed to support the Collaboration.

The Collaboration held its first meeting in Cincinnati in September 1997. The meeting was attended by over 40 steel bridge professionals, including representatives from seven fabricators and twelve DOT's. Representatives identified areas that needed attention and task groups to tackle the highest priorities.

4 Goals

The collaboration's goals are to achieve higher quality and value in steel bridges through standardization of design, fabrication, and erection requirements, through exchange of expertise, and by advancing the state of the art.

4.1 Standardization

State highway authorities are responsible for design of structures and for quality assurance through construction and fabrication oversight. However, each DOT has its own details, its own way of designing bridges, its own format for design presentation, its own fabrication requirements, and its own way of conducting inspection. Besides the burden to the state of maintaining each of these dynamics, the disparity between the states results in variation in the shop, and variation lowers quality, increases costs, and creates avoidable problems for both the fabricator and the states. Though states will always have a few special requirements based on their own needs and experiences, steel bridge professionals can agree on a best way to achieve a structure of high quality and value, and that is the first goal of the collaboration. Such standardization may seem extraordinary, but it is not unprecedented. Since 1980 the SCEF has worked to standardize various aspects of steel bridgework within the states of FHWA Region 3, and they have agreed on a number of standards and details; the collaboration will build on their work at the national level. Further, 49 of 50 states have all now adopted the same welding code, AASHTO/AWS D1.5. Though some states have their own particular additions and exceptions to this document, it has provided a common benchmark for bridge welding throughout the nation and beyond.

4.2 Advancing the State of the Art

The collaboration seeks to improve quality and value in steel bridges by advancing the state of the art through ready exchange of engineering knowledge and facilitation in technology development and implementation. Collaboration participants exchange knowledge through Collaboration sponsored meetings and through the Collaboration list server. The Collaboration facilitates technology development by helping develop research problem statements and by providing guidance and comments to entities that develop technology.

5 Participation

The collaboration is a volunteer organization formed from state DOT's, the FHWA, academia, consultants, and a variety of industry professionals. Participation is open to anyone who would like to contribute in any fashion.

6 Structure

The collaboration is divided into three distinct parts: steering committee, main committee, and task groups.

6.1 Steering Committee

The steering committee is comprised of task group chairs and selected leaders. Duties include:

- schedule and organize meetings
- monitor developments and participation
- provide liaison to T–14
- handle ballots

The chair of the steering committee serves 3-year terms. The number of terms is not limited. The steering committee chair also acts as main committee chair.

A vice-chair serves in support of the chair. The vice-chair automatically takes avoid when the chair steps down.

6.2 Main Committee

The main committee is comprised of any steel bridge professionals who would like to participate and serves these functions:

- approval of task group and task force formation and scopes
- through ballot, approval of standards, practices, and details for design, fabrication and erection of steel bridges

- facilitation of the exchange of information and technology among its participants and other steel bridge professionals

6.3 Task Groups

Task groups are initiated by the main committee to conduct the work of the Collaboration. Task groups are provided the opportunity to meet during the semiannual Collaboration meetings, but having such meeting is not required. Task group work is also performed outside of meetings by individual members by conference calls, videoconference, email, fax, etc.

The task group chair is appointed by the steering committee and serves these functions:

- appoints task group members
- lead the work of the task group
- serve on the Collaboration steering committee
- provide updates on task group activity at main committee meetings

There is no maximum limit to the task group's size. However, the task group must include at least three each industry and owner representatives.

Task groups are empowered to develop standards for ultimate consideration by the main committee and subsequent submittal to AASHTO and NSBA for approval.

6.4 Task Forces

Task forces are initiated by the main committee to advise the main committee on items related to the work of the main committee. Task group work is generally performed outside of meetings by individual members by conference calls, videoconference, email, fax, etc. However, meeting time may be provided during Collaboration meeting by request.

The task force chair is appointed by the steering committee. The task force chair appoints other task force members at will. There is no maximum or minimum limit to the task group's size, and there are no representation requirements.

6.5 Quality Groups

To facilitate implementation of Collaboration standards and further facilitate national uniformity, the Collaboration associates with other regional and state quality groups whose purpose is to improve steel bridges.

7 Funding

The Collaboration is a non-funded volunteer organization. However, the NSBA provides meeting space and coffee breaks, with contributions from other industry participants.

8 Communications

8.1 Website

The Collaboration's business is conducted through the Collaboration website at www.steelbridge.org. The website is hosted and maintained by the NSBA.

8.2 List Server

News about Collaboration events, notification of ballots, and questions related to steel bridge technology are handled through the Collaboration list server. Advertisements are not allowed.

9 Meetings

Collaboration meetings are held twice a year. A main committee meeting is held, and time is made available for task group meetings.

The main committee meeting serves the following functions:

- presentation of task group standards for acceptance
- consideration and assignment of new work
- presentation of technology advancements
- discussion of critical issues of the day
- coordination with other industry activities

Scheduling is handled by the NSBA. Meeting locations are chosen by the steering committee. The agenda is developed by the chair.

10 Adoption of Documents

The Collaboration develops standards that are submitted to AASHTO and to the NSBA for approval. Adoption of documents by the Collaboration is as follows below.

Development

1. Each document originates in a task group. The task group works until it achieves a consensus. As the document is developed, the task group keeps the rest of the Collaboration up to date as follows:

a. The task group chair or designee provides updates at the Collaboration meetings. As progress is made, the Collaboration confirms the scope of the task group work.

b. Task group members that are a part of a regional or local Quality Group keep the Quality Group up to date and collect input as needed.

2. Once the task group reaches a consensus, the document is forwarded to the larger Collaboration for review through the steering committee as follows:

a. The steering committee chair sends the document to the chair of each Quality Group that is aligned with the Collaboration. Each Quality Group chair shares it within the Quality Group, facilitates discussion of the document, and assimilates comments. This may or may not take place at a meeting. Participants in the Quality Group who are a part of the task group that created the document also facilitate discussion of the document within the Quality Group. The Quality Group chair then forwards the collective comments of the quality group back to the task group chair.

b. Concurrently, the steering committee chair sends the document directly to Collaboration participants who are not a part of a quality group that is associated with the Collaboration. Individuals are instructed to send their comments directly to the chair of the task group that created the document.

The Quality Groups and individuals have one month to respond.

3. The task group reviews the comments received from the Quality Groups and other individuals. Then, the task group modifies the document as they see fit based on the comments received. The task group responds to any technical comments that are not incorporated into the work.

4. At any time during the development of the document, the task group may ask some representative parties to beta-test the document. The results may be considered for incorporation in the final draft of the document that includes comments from balloting.

5. If the Collaboration would like confirmation of the document by another organization (such as SSPC), the task group works with such organizations through development of the document.

Acceptance by the Collaboration

6. The task group sends the final draft of the document to the larger Collaboration for acceptance through the steering committee chair. The steering committee chair sends an individual copy of the document directly to all individuals associated with the Collaboration along with a ballot. The ballot shows four options:

a. Accept and approve as-is with no comments.

b. Accept with comments and will still accept if comments are not incorporated into the final document.

c. Unacceptable. For an unacceptable vote to count, an explanation must be provided about why the document is unacceptable.

d. No comment because the individual does not feel qualified to respond.

Only the “a”, “b”, and valid “c” ballots are counted.

7. The ballots are returned to the steering committee and compiled. If greater than 75% of the counted ballots are cast with an “a” or “b”, the measure passes. If 75% or less of the counted ballots are cast with an “a” or “b”, the measure fails.

8. The ballot results are returned to the task group.

a. The task group responds to all negative comments received on passing measures. If the task group makes a technical change the document to incorporate the comments, the document is re-balloted.

b. On failing measures, the task group considers comments and reworks the document. When the document is ready, it is re-balloted as described in step 5.

The steering committee also examines the ballot results and may direct the task group to action, regardless of the outcome of the measure.

9. The task group submits their responses to negative ballots on passing measures to the steering committee. If the task group confirms that it does not wish to revise the document based on ballot comments, the document stands as an official Collaboration document.

Acceptance beyond the Collaboration

10. The steering committee chair submits official Collaboration documents with ballot results to Technical Committee T-14 and to the NSBA Advisory Committee for review and approval. Advanced copies are sent to both committees, and the steering committee chair presents the document at their meetings. Documents carry forward in each organization as normal business.

11. Prior to formal adoption by AASHTO and/or NSBA, the document stands as a Collaboration approved and recommended document which may be applied as the user sees fit.

12. The document may also be submitted for acceptance to other organizations for confirmation/adoption (such as SSPC). Comments from such organizations are considered on their merit.

13. If the either T-14 or the Advisory Committee or subsequent committees of AASHTO or NSBA have comments or questions, these are handled by the task group chair. If either AASHTO or NSBA cannot accept the document, it is returned to the task group for rework based upon comments received, and the document then returns to step 4 above.

14. If AASHTO and/or NSBA do accept the documents but still have comments, these comments will be considered for future editions of the document

Appendix G. Unique Words and Usage in the BrIM Data Dictionary

Word	#	Word (cont.)	#	Word (cont.)	#	Word (cont.)	#	Word (cont.)	#
of	287	wall	34	layout	20	right	13	CL	9
number	127	beam	32	modulus	20	tendon	13	construction	9
length	105	cross	32	on	20	Washer	13	date	9
type	103	vertical	32	slab	20	additional	12	fatigue	9
at	94	shape	31	used	20	connection	12	gap	9
material	93	steel	31	clip	19	connector	12	Ixx	9
flange	84	surface	31	thread	19	curve	12	left	9
name	82	weight	31	between	18	profile	12	no	9
to	80	duct	30	in	18	void	12	notch	9
top	78	elevation	30	line	18	y	12	pedestal	9
bottom	77	from	30	support	18	begin	11	process	9
property	74	hole	30	bridge	17	CVN	11	Screw	9
location	73	nominal	30	cover	17	fillet	11	set	9
width	68	span	30	field	17	final	11	Transverse	9
end	65	station	30	grade	17	frame	11	value	9
bolt	60	the	28	head	17	grout	11	Volume	9
distance	59	height	27	ratio	17	member	11	with	9
thickness	59	shear	27	stress	17	offset	11	work	9
plate	58	spacing	27	testing	17	side	11	abutment	8
dimension	57	edge	26	unit	17	time	11	analysis	8
girder	52	haunch	26	data	16	total	11	capacity	8
depth	49	mark	26	splice	16	zone	11	Elastomeric	8
indicator	48	mass	26	strength	16	coating	10	Fill	8
radius	48	point	26	design	15	cut	10	flexure	8
area	47	horizontal	25	footing	15	dead	10	Gusset	8
angle	46	column	23	loss	15	direction	10	Half	8
load	46	drilled	23	strand	15	each	10	hammer	8
section	45	for	23	centerline	14	effective	10	Nail	8
bearing	44	or	23	condition	14	Fracture	10	per	8
weld	44	pile	23	Crane	14	identification	10	plane	8
GUID	43	shaft	23	longitudinal	14	minimum	10	rigid	8
web	42	Skew	23	Project	14	quantity	10	Slot	8
and	41	start	23	slope	14	stiffener	10	status	8
description	37	cap	22	chamfer	13	Sxx	10	stem	8
bar	36	deck	22	critical	13	system	10	upper	8
designation	36	specification	22	finish	13	temperature	10	x	8
diameter	36	hook	21	inside	13	WP	10	1	7
pier	36	method	21	maximum	13	2	9	Actual	7
information	35	paint	21	nut	13	assembly	9	axis	7
size	34	concrete	20	piece	13	bill	9	cg	7

Word	#	Word (cont.)	#	Word (cont.)	#	Word (cont.)	#	Word (cont.)	#
elastic	7	stud	6	row	5	Metal	4	available	3
I	7	tension	6	Secant	5	Other	4	before	3
Lump	7	torsional	6	step	5	percent	4	boundary	3
measured	7	tower	6	Supply	5	permits	4	box	3
negative	7	ultimate	6	sustainability	5	Pin	4	Calculations	3
Note	7	Wind	6	tangent	5	placement	4	center	3
Page	7	across	5	tee	5	polyethylene	4	chair	3
positive	7	along	5	ties	5	position	4	check	3
preparation	7	Anchorage	5	topography	5	post	4	Common	3
restriction	7	approach	5	transfer	5	pour	4	controlling	3
roadway	7	Average	5	transition	5	primer	4	cost	3
sequence	7	back	5	alignment	4	product	4	cutoff	3
shim	7	bending	5	blasting	4	reference	4	Delivery	3
shop	7	chain	5	bound	4	region	4	Deterioration	3
Sliding	7	channel	5	by	4	reinforcement	4	directional	3
space	7	chord	5	circular	4	respect	4	Dispatch	3
spiral	7	class	5	component	4	Rolled	4	elongation	3
stirrup	7	classification	5	compressive	4	Shore	4	Environmental	3
sum	7	clearance	5	control	4	shoulder	4	Fabricator	3
timber	7	code	5	corner	4	splicing	4	Facility	3
wedge	7	coefficient	5	couplers	4	St	4	factor	3
Azimuth	6	Connecting	5	existing	4	State	4	fit	3
camber	6	contract	5	exterior	4	Stations	4	Full	3
Castellation	6	coordinate	5	faying	4	strut	4	H	3
coats	6	curvature	5	feature	4	tensile	4	highway	3
constant	6	definition	5	fixity	4	tensioning	4	impact	3
cutting	6	Initial	5	force	4	test	4	interior	3
erection	6	item	5	geometry	4	theoretical	4	jacking	3
fabrication	6	lane	5	grouting	4	Venant	4	key	3
HCL	6	lower	5	H.C.L	4	water	4	Kx	3
Layer	6	Miscellaneous	5	harped	4	year	4	Ky	3
out	6	outside	5	if	4	yield	4	Kz	3
place	6	Overall	5	inertia	4	a	3	Lap	3
Prestressed	6	pad	5	inlet	4	AASHTO	3	lifting	3
prestressing	6	PCI	5	inner	4	after	3	Noise	3
reinforcing	6	Poisson's	5	Iyy	4	AISC	3	order	3
requirement	6	priming	5	joint	4	Allowable	3	orientation	3
road	6	prismatic	5	K	4	application	3	over	3
segment	6	root	5	lifted	4	approval	3	overhang	3
shipping	6	rotation	5	LL	4	Associated	3	parallel	3

Word	#	Word (cont.)	#	Word (cont.)	#	Word (cont.)	#	Word (cont.)	#
Pattern	3	Admixtures	2	Diagonal	2	Library	2	see	2
perpendicular	3	ADTT	2	difference	2	limits	2	self	2
pitch	3	Advance	2	DL	2	live	2	semi	2
price	3	allowance	2	double	2	Local	2	sheet	2
procedure	3	alternative	2	drawings	2	logs	2	should	2
Reduced	3	amount	2	drilling	2	manual	2	single	2
report	3	Anchor	2	drive	2	Manufacture	2	Site	2
Rotational	3	applicable	2	dynamic	2	maturity	2	skewed	2
Rx	3	applied	2	Easting	2	measurement	2	Sloping	2
Ry	3	Backfill	2	EIEB	2	Moment	2	solid	2
Rz	3	Bathymetry	2	Electrode	2	movement	2	speed	2
safety	3	be	2	elements	2	non	2	Storm	2
sealant	3	Bolting	2	Energy	2	Northing	2	strain	2
shank	3	Boring	2	Engineer	2	ordinate	2	Stressing	2
stage	3	cantiliver	2	Erector	2	OSHA	2	Structural	2
stakeholder	3	category	2	expansion	2	outlet	2	superstructure	2
standard	3	cement	2	Extension	2	Owner	2	T	2
taper	3	certification	2	External	2	parties	2	tag	2
tapered	3	change	2	film	2	path	2	tangency	2
TGL	3	Chemical	2	fittings	2	pavement	2	temporary	2
Truck	3	Cleaning	2	flats	2	Pilot	2	term	2
Utility	3	clear	2	Functional	2	Plain	2	Thermal	2
valves	3	color	2	galvanized	2	plan	2	tip	2
way	3	composite	2	General	2	plugs	2	treatment	2
weathering	3	Composition	2	geotechnical	2	port	2	variation	2
when	3	Compound	2	grading	2	Pre	2	vertices	2
wing	3	Concentrated	2	hardening	2	preliminary	2	W	2
Ybottom	3	Connected	2	Holding	2	Prestress	2	wire	2
15%	2	continuous	2	identifier	2	Production	2	Z	2
21	2	Contractor	2	identities	2	purpose	2	10th	1
28	2	count	2	include	2	Rebar	2	1st	1
3	2	Countersink	2	included	2	Rectangular	2	2nd	1
6mm	2	creep	2	including	2	Relative	2	3rd	1
AADT	2	Curing	2	Input	2	Required	2	Abrupt	1
above	2	D1	2	intent	2	Resulting	2	Absolute	1
access	2	D2	2	Internal	2	Review	2	Accessories	1
achieve	2	days	2	intersection	2	rounding	2	achieving	1
acting	2	deflection	2	Jacks	2	Route	2	Age	1
address	2	depending	2	Ledge	2	sacrificial	2	agency	1
adjacent	2	developed	2	less	2	sectional	2	Ahead	1

Word	#	Word (cont.)	#	Word (cont.)	#	Word (cont.)	#	Word (cont.)	#
allow	1	Bolted	1	cycle	1	Equality	1	Hw	1
alpha	1	Bonded	1	D3	1	equipments	1	Imperial	1
Altered	1	book	1	D4	1	Erected	1	inch	1
another	1	boom	1	D5	1	Estimation	1	Incoming	1
approved	1	both	1	D6	1	etc.	1	index	1
Approximate	1	Buckling	1	DC0	1	Exclude	1	Indication	1
Arbitrary	1	built	1	DC1	1	extra	1	intersected	1
Arc	1	bulb	1	DC2	1	Fall	1	Inverted	1
arrangement	1	C	1	DD	1	falsework	1	irregularity	1
as	1	C.C.	1	deformation	1	far	1	is	1
ASBI	1	C.S.	1	delivers	1	fastener	1	Issues	1
Assemble	1	calculated	1	Demolition	1	Fastening	1	Ix	1
attachments	1	Calendar	1	Designer	1	FCW	1	Joined	1
author	1	carried	1	destructive	1	File	1	Joining	1
Authority	1	cases	1	detail	1	Finished	1	Kn	1
automatic	1	casting	1	Detailer	1	Foreman	1	L	1
awarded	1	cells	1	detailing	1	Formwork	1	L1	1
AWS	1	centroid	1	Determination	1	foundation	1	L2	1
B1	1	charge	1	developer	1	Frequency	1	lateral	1
B2	1	Charpy	1	Development	1	Future	1	Latitude	1
B3	1	City	1	diaphragm	1	G1	1	Lbs	1
B4	1	Client	1	dimensional	1	G2	1	Lc	1
B5	1	CNC	1	Direct	1	gauge	1	LD	1
B6	1	coated	1	director	1	Globally	1	LE	1
Barrier	1	collection	1	District	1	Governing	1	Leg	1
based	1	commercial	1	done	1	grantor	1	letting	1
Baseline	1	completed	1	DOR	1	Grind	1	Life	1
Basic	1	Conduit	1	Drafter	1	Grip	1	Lift	1
basis	1	configuration	1	Drill	1	ground	1	loading	1
Batter	1	Constituent	1	drop	1	gyration	1	locked	1
Bay	1	Construct	1	Dry	1	handed	1	long	1
BBL	1	Consultant	1	due	1	handrails	1	Longitude	1
BBR	1	contact	1	during	1	Hard	1	low	1
below	1	contours	1	DW	1	Hardness	1	Ls	1
bid	1	Cope	1	E	1	Hardware	1	M	1
bidders	1	counterweight	1	Eccentricity	1	Heat	1	Maintenance	1
BIN	1	County	1	elasticity	1	hex	1	manager	1
binding	1	Crown	1	entering	1	hollow	1	Manufacturer	1
BL	1	Ctc	1	eo	1	house	1	measure	1
block	1	current	1	Epoxy	1	humidity	1	measuring	1

Word	#	Word (cont.)	#	Word (cont.)	#	Word (cont.)	#	Word (cont.)	#
mechanical	1	PI	1	removal	1	staging	1	USGS	1
mechanism	1	placing	1	resistance	1	stamp	1	using	1
Median	1	Plastic	1	restricted	1	Standees	1	V	1
Mesh	1	POR	1	Reviewer	1	started	1	Vendors	1
Message	1	possible	1	revised	1	Stepped	1	verification	1
Meta	1	prefab.	1	rigging	1	Stopping	1	version	1
Metric	1	preload	1	River	1	storage	1	Village	1
mid	1	Prepared	1	Rounded	1	strap	1	voided	1
mill	1	pressure	1	rule	1	structure	1	Warping	1
minor	1	prior	1	runoff	1	sub	1	WD1	1
mist	1	Processed	1	Runs	1	Subcontractor	1	wearing	1
Monitoring	1	Procure	1	rupture	1	substructure	1	Welders	1
Move	1	prohibited	1	rzz	1	Superimposed	1	Welding	1
Mpf	1	proof	1	S.C.	1	Superintendent	1	Wet	1
MTR	1	protection	1	S.D.L.	1	Survey	1	while	1
National	1	Protective	1	S.S.D.	1	symbol	1	Who	1
near	1	provide	1	S.T.	1	T.S.	1	WX1	1
necessary	1	PT	1	Sales	1	Tan	1	xyy	1
NEPA	1	pull	1	same	1	tapping	1	yes	1
nesting	1	punch	1	Sawn	1	TBL	1	Yt	1
occurrence	1	Purchase	1	scenario	1	TBR	1	yxx	1
Opening	1	Purchased	1	Scheduled	1	Template	1	zx	1
operator	1	Purchaser	1	Sector	1	termination	1	zy	1
Original	1	PVC	1	select	1	third	1		
outer	1	PVI	1	SEQR	1	Threaded	1		
Outgoing	1	PVT	1	shrink	1	Three	1		
Overlapping	1	quadrangle	1	shrinkage	1	Through	1		
P.C.	1	quarter	1	Sidewalk	1	TL	1		
P.C.C.	1	Railing	1	Sight	1	Town	1		
P.T.	1	railroad	1	Situation	1	Traffic	1		
Painting	1	Rate	1	slip	1	Transported	1		
Parabolic	1	RE	1	Slotted	1	u	1		
parameter	1	ream	1	smooth	1	unbonded	1		
Parapet	1	Recent	1	spawning	1	Under	1		
Parent	1	record	1	Special	1	underground	1		
Pay	1	reduce	1	species	1	underwater	1		
Pcs	1	reducing	1	Specific	1	unified	1		
Penny	1	Regional	1	Spliced	1	Uniform	1		
Percentage	1	Relaxation	1	spot	1	unloading	1		
PGL	1	Release	1	spread	1	unloads	1		

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