

CAD and GIS Integration

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CRC Press

Taylor & Francis Group

Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business
AN AUERBACH BOOK

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Chapter 4

Interoperable Methodologies and Techniques in CAD

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INTEROPERABLE METHODOLOGIES AND TECHNIQUES IN CAD

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ABSTRACT

It is estimated that the cost of inadequate interoperability in the U.S. capital facilities industry is approximately \$15.8 billion per year. Lack of or inadequate interoperability results in data and transfer problems and duplication of business transactions across multiple software applications used between architects, owners, engineers, suppliers and facility managers. Driven by the availability of multiple, incompatible information systems, various data standards and specifications are being developed for enabling interoperability within the architecture, engineering, construction and facility management (AEC/FM) industry. These data standards and specifications range from early efforts (e.g., DXF, IGES) developed to exchange geometry and topology information, to product model data exchange (e.g., STEP, CIS/2, gbXML), to semantically rich building information modeling exchange (e.g., IFC, IFD). This chapter is an overview of interoperable methodologies and techniques in computer-aided design (CAD). While interoperability between different software systems is still an issue, many existing efforts are pushing the front towards a more integrated modeling environment, enabling more effective collaboration and sharing of information between different stakeholders throughout the facility life-cycle.

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1. INTRODUCTION

Interoperability has been a long standing problem within the architecture, engineering, construction and facility management (AEC/FM) industry due to high fragmentation with tight dependency amongst project participants. Various parties, such as architects, engineers, contractors and suppliers, play a role in generating project data throughout the life cycle of a construction project. Each party utilizes task-specific software systems, and if interoperability between such systems is not maintained, this situation might result in non-value adding tasks, such as manually reentering data, utilizing duplicate systems and models, and version checking. Lack of or inadequate interoperability results in data and transfer problems and duplication of business transactions across multiple software applications used between architects, owners, engineers, suppliers and facility managers (Young et al. 2007). It has been claimed that such interoperability problems within the AEC/FM industry reached to \$15.8 billion in 2002 (NIST 2004) of which approximately \$500 million is for manually reentering data. In addition, it has also been identified that for each construction project, the interoperability issues cost, about 3.1% of a project's total cost on average (Young et al. 2007).

Many definitions of interoperability exist. It is defined as “a series of data exchanges between computer applications or other software components” by the International Alliance for Interoperability (2009); “exchange and management of electronic information, where individuals and systems are able to identify and access information seamlessly” by the National Institute of Standards and Technology (2004); and as “the ability to manage and communicate electric product and project data among collaborating firms, such as architects, engineers, contractors,

owners and building product manufactures” by Young et al. (2007). All these definitions of interoperability suggest that information amongst applications should be accessed and exchanged without reentering, reformatting or transforming.

Many data standards and specifications have been developed within the AEC/FM industry to reduce the problem of inadequate interoperability and to streamline exchange of information consistently. The idea behind these data exchange specifications and standards is to define a standard schema for a neutral file or data structure format so that task-specific applications can read data presented in this standard format and generate a similar format of data to be exchanged with other software systems. Having a standard data description and format relieves the software vendors and users from writing specific translators to transfer data among different software systems and hence streamlines the data exchange process and minimizes interoperability issues. Some of the efforts defined what should be represented and how they should be represented but did not pass a formal review process from a standards organization (e.g., ANSI, ISO). To make the differentiation between data schemas in terms of standardization, such efforts that have not passed a formal review are called as “specifications” and the ones that were standardized by an organization are called as “standards” throughout this chapter.

Initial efforts on developing a neutral file started around the late 1970s for exchanging geometry and topology information. Examples of early industry-accepted data formats are Drawing eXchange Format (DXF) initiated by Autodesk, and Initial Graphics Exchange Specification (IGES), which evolved from the U.S. Air Force Integrated Computer Automated Manufacturing Program (ICAM), and was led by large CAD users, such as Boeing and General Electric. These

data formats addressed some of the problems associated with interoperability among various engineering and design applications by enabling the exchange of predominantly geometric information (Eastman 1999). However, they also had several limitations, such as inadequate representations that incorporate various functionalities in engineering applications, sometimes subjective mappings of represented entities by data translators and insufficient conformance testing infrastructure (Bloor and Owen 1995). Standardization efforts continued in the 1980s with STEP (STandard for the Exchange of Product data model), which incorporates object-oriented modeling concepts and enables exchanging of computer interpretable product data. Incorporation of object-oriented modeling concepts has played an important role in capturing and exchanging semantic information (such as relationships, properties of products) related to represented products in a digital environment.

Building on STEP core representation models, many data exchange standards and specifications have bloomed targeting the exchange of data specific to a domain, such as steel and precast concrete, (which are also known as “aspect models”) or targeting the support of various domains and phases of a facility. Examples of aspect models are CIMSteel Integration Standards (CIS/2), Automating Equipment Information eXchange (AEX) and Building Information Model for Precast Concrete (BPC).

With the rising need to perform required AEC/FM related tasks in digital environments, studies continued for the development of semantically rich building information modeling standards, where semantics provide meaning to the geometric representations. These standards aim to have more semantics in a given model and enable cross-domain data exchange. One example of such

larger cross-domain data exchange standards is Industry Foundation Classes (IFC). There are also standards developed for exchanging domain specific information (other than product data) that are not specific to AEC/FM industry, but can be utilized within it. Examples of such standards include Sensor Model Language (sensorML) or Land eXtensible Markup Language (landXML).

The main purposes of this chapter are: (a) to briefly overview the history of computer-aided design, from 2D drawings to building information modeling (BIM) and semantics, (b) to give an overview of the main data exchange standards developed to support interoperability within the architecture, engineering, construction and facility management (AEC/FM) domain, (c) to evaluate and compare the overviewed data standards, and (d) to discuss the current status of interoperability in the AEC/FM domain and make a projection towards the future.

2. HISTORY OF CAD FROM DRAWINGS TO BUILDING INFORMATION MODELING AND THE ROLE OF SEMANTICS

Computer-aided design (CAD) has been an active research area for decades. Initial efforts are dated to the 1960's, with Sketchpad, developed by the MIT Lincoln Lab (Eastman 1999). Sketchpad was conceived as a drawing assistant for both technical and artistic purposes. The way the program organized its geometric data pioneered the use of "objects" and "instances" in computing (Sutherland 2003). During the 1970's and early 1980's, Charles Eastman, then Professor at the School of Architecture at Carnegie Mellon, was developing a database of several hundred thousand architectural elements, which could be assembled and drawn on screen into a complete design concept (Bozdoc 2004). The early work from Eastman's research group at

Carnegie Mellon was one of the first parametric modeling efforts, as they developed operations that included spatial transforms, spatial set operations and Euler operators, which were required for defining new parametric shape primitives (Eastman 1999).

The 1980's can be summarized by advances in parametric modeling (e.g. CATIA and ArchiCAD) as well as a wider distribution and adoption of computer-aided drafting and design technologies by the marketplace (e.g. AutoCAD). In the 1990's, 3D Studio was released (Bozdoc 2004), which is still one of the most widely used off the shelf 3D animation programs. Even though animations and renderings, created using 3D Studio, are photo realistic, modeled objects do not contain "domain" semantics, which is a key concept for the current drivers in building information modeling.

Semantics in building information modeling can be understood as objects with meaning. In other words, an object representing a metal stud wall will know that it is representing a metal stud wall, the dimensions of the wall, what materials the wall is made of, when and where it will be built, what other building elements that it is connected to, what other elements, such as windows, that it contains, which two spaces it separates, etc. Unlike the photo realistic (with no semantics) approach in which the wall would look like the intended wall type, a semantically-rich model will contain information about that object, such as its type and specifications. Such semantics are being used in Building Information Models (BIM), which is a term defined by the National Institute of Building Sciences (NIBS) Facilities Information Council (FIC) as "a computable representation of the physical and functional characteristics of a facility and its related project/lifecycle information using open industry standards to inform decision making for

realizing better value” (NIBS 2007). The National Building Information Model committee defines BIM as “a standard repository of information for the facility owner/operator to use and maintain throughout the life-cycle of a facility (NBIMS 2007).” The basic premise of BIM is collaboration by different stakeholders at different phases of the life cycle of a facility. Although this is a term widely used today, early notions of what is now understood as BIM date back to the 1970’s (Eastman 1975).

Several case studies are described by Eastman et al. (2008) in which BIM has played a significant role. These cases, along with many others, represent the pioneering experiences of professionals, such as owners, engineers, architects, contractors, fabricators and others in the application of BIM in construction projects. Another driver of BIM is the US General Services Administration (GSA), which according to GSA’s Office of Government-wide Policy (2006) is the largest lessee of building assets in the United States, with 169 million square feet leased. GSA has been requiring BIM for all major construction and modernization projects receiving design funding to be sufficient to support spatial program validation. GSA is developing guidelines for additional BIM capabilities in future projects.

One of the challenges related to BIM is pulling all the existing information together for the specific building being developed or used. In order to address this interoperability challenge, there have been several standardization efforts, such as the National CAD Standard guidelines, for uniformly organizing and presenting facility drawing information which streamlines the exchange of building design and construction data in drawings (buildingSmart Alliance 2008).

There are also efforts being developed for product modeling exchange, such as the Industry Foundations Classes (IFC), developed by the International Alliance for Interoperability (IAI 2009), now known as buildingSMART International, which provides a formalized representation of typical building components (i.e., wall, door), attributes (i.e., type, function, geometric description), relationships (i.e., physical relationships, such as supported-by, connected-to), and more abstract concepts, such as schedules, activities, spaces and construction costs, in the form of entities. IFC are the most notable and widely accepted data model for buildings and they aim at enabling information exchange in the AEC/FM industries. IFC specifications contain a digital information structure of the objects making up a building, capturing the form, behavior, and relation of the parts and assemblies within the building (IAI 2007). In contrast to exchanging plans via drawing files, such as DXF or DWG, IFC exchange is strictly model based. A wall is not a set of lines, but an object with specified attributes and relations (Clemen and Grundig 2006). Each entity is represented as a class, thus each can have a number of properties, such as name, geometry and materials, relationships, and constraints on the relationships. Such standard enables the use of semantics and parametric modeling, supports information exchange in the form of models as well as the use of these models to support more complex tasks, in computer-aided design and construction.

In summary, computer-aided design has been around since the 1960's with efforts varying from computer-aided drafting, mimicking a drafter's manual work, to parametric and object-oriented CAD, which added intelligence and automation to design tasks. For more than a decade, the notion of semantics is also being added on top of objects in Building Information Models, providing even more power to the term computer-aided design. It helps to perform complex

tasks, such as building energy performance simulations, schedule analysis through 4D simulations, and design coordination. Interoperability between different software systems is still an issue, but, as it is discussed in this chapter, there have been many efforts which are leading towards having a more integrated modeling environment, enabling more effective collaboration and sharing of information between different stakeholders throughout facilities life-cycle. The next section provides an overview of a wide variety of data standards developed for enabling exchanging information in early CAD applications to exchanging semantically rich building information.

3. OVERVIEW OF DATA STANDARDS AND SPECIFICATIONS UTILIZED WITHIN THE AEC/FM DOMAIN

Many data standards and specifications have been developed for seamless data exchange between multiple applications within the AEC/FM industry. Efforts to bring standardization into data exchange and transfer between parties can be grouped based on their coverage in representing and exchanging AEC/FM related information as: (a) early efforts targeting exchange of geometry and topology data only, (b) aspect model exchange standards and specifications, (c) building information model exchange standards and specifications, and (d) other standards or specifications that can assist in exchanging information needed in the AEC/FM industry.

The data standards and specifications introduced in this section are used to exchange information of products and processes within the AEC/FM domain at different stages of a project. Table 1 provides an overview of existing standards in terms of the agency leading the development effort, the year in which the development was initiated, the project phases for which the specific

data standard target to improve interoperability, semantics represented, the areas of use, typical file format used for data exchange and the possibility/mechanisms to extend the existing versions of the data standards.

3.1. EARLY STANDARDS AND SPECIFICATIONS TARGETING GEOMETRY AND TOPOLOGY INFORMATION/DATA ONLY

Initial efforts for maintaining interoperability within the AEC/FM industry were focused around developing neutral file formats, within which geometric and some topologic information are depicted. Utilization of neutral data formats required translators from specific software applications to neutral file formats. Drawing eXchange Format (DXF), Initial Graphics Exchange Specification (IGES) and STandard for the Exchange of Product model data (STEP) are three data exchange efforts that were developed in the 1980s and have been predominantly used within the AEC/FM industry.

3.1.1 Drawing eXchange Format (DXF)

DXF was initially developed by Autodesk for enabling interoperability between CAD applications (Eastman 1999). It was launched as part of AutoCAD 1.0 in 1982. It supports ASCII and binary formats, and is used especially to exchange 2D geometrical data (points, lines, arcs, polygons, text) of entities represented in various CAD packages developed by Autodesk. A “.dxf” file includes information about a drawing in various sections (Autodesk 2008): (a) *header section*, which provides information about variables associated with a drawing, (b) *classes section*, which provides information about application specific classes, whose instances appear in the other sections of the file, (c) *tables section*, which contains a set of tables each of which provides definitions of used terms, (d) *blocks section*, which contains information about entities

that are used to define each block, (e) *entities section*, which contains information about graphical objects, and (f) *objects section*, which contains information about entities that have no graphical or geometrical meaning. Advantages of DXF include small file sizes and efficient exchange of 2D graphical data.

Though DXF enables sharing 2D geometric information, there are limitations of DXF in terms of its capability in supporting semantically rich data exchange. DXF does not contain topology information, nor does it process all entity attributes. In addition, available DXF exchange processors are not generic in converting 2D entities (e.g., the same entities can be converted as polylines or line segments) and this results in trial-and-error of users to pick and use the translator that best serves their needs (Eastman 1999). These result in interoperability problems especially in sharing 3D geometric information.

3.1.2 Initial Graphics Exchange Specification (IGES)

IGES is another application-independent neutral file format developed for the exchange of CAD data. It was initiated in 1979 by Boeing and General Electric and then accepted as a standard (ANSI Y14.26M) by ANSI in 1981. IGES is capable of exchanging: (1) 2D/3D geometries, such as curves and surfaces, (2) topological relations, such as connectivity between geometric entities, and (3) some non-geometric data, such as properties of entities, dimensions and drafting notations (US PRO 1996). IGES uses ASCII file format and is composed of various sections as a DXF file. It starts with an optional *flag section*, which defines whether the file is in binary or compressed format. A *start section* follows the flag section and it provides a description of the contents of a file. Following that, a *global section* provides information needed for pre and post

processors. The rest of an IGES file contains a *directory entry section*, which keeps an index of the file and attribute information for each entry, a *parameter data section*, which contains entity type numbers, pointers to entities, pointers to attributes in tables, and finally a *terminate section* that shows the end of file (US PRO 1996).

Though IGES is an early vendor-neutral data exchange standard and is capable of exchanging geometric and topological information, it has certain limitations. IGES does not describe non-geometric information about a model. In addition, CAD systems require a translator to read the original file format. The utilization of translators might result in describing the same geometric entities in multiple ways (e.g., boundary representation vs. swept solid), incorrect mapping of data exported from a CAD system to IGES representation, resulting in unrecognized entities in the postprocessors; hence, might reduce the quality of the model. Also, IGES can result in large file sizes and require long processing times (Slansky 2005).

3.1.3 Standard for the Exchange of Product model data (STEP)

STEP is a data standard being developed since 1984 as an international standard (ISO 10303) for exchanging 3D product data, by ISO technical committee 184 subcommittee SC4. STEP can help storing product data archives throughout a product's lifecycle and exchange product data in a neutral format. In addition to 3D geometric representation of any type of product (e.g., a building, a steel structure), STEP supports exchanging topology (e.g., edge, vertex), tolerances, assemblies, configuration, and attributes (e.g., surface finishes, material properties) information. STEP also uses ASCII file format and the standard consists of several parts, including (Eastman 1999): (1) *description methods*, which provide information about which modeling language, such

as EXPRESS, is being used to model information in integrated resources and application protocols parts, (2) *integrated resources*, which provide information to represent single

Table 1. A summary of data standards utilized within the AEC/FM industry

Data spec/ standard	Development group & project starting year	Targeted project phases	Semantics	Usage	File format	Extensibility
Early standards targeting geometry and topology information/data						
IGES	Boeing/ General Electric (1979)	Design	2D/3D geometries, topological relations, non-geometric data	Exchange 2D/3D CAD data among various CAD applications	IGES based on ASCII	By development team
DXF	Autodesk (1982)	Design	2D geometry	Exchange CAD data among various CAD applications	DXF based on ASCII	By development team
STEP	ISO technical committee 184/SC4 (1984)	Design, Fabrication, Erection	2D/3D geometries, topological relations, non-geometric data	Exchange 2D/3D CAD product data throughout their life cycle	STEP Part 21	By development team
Product model exchange standards / Aspect models						
CIS/2	University of Leeds and AISC (1995) as STEP Application Protocol 230	Design, Analysis, Fabrication	Geometry, location, orientation, parts, assemblies, bolts, holes, welds, sequences, materials, surface treatment, connections, properties	Exchange of structural steel design, analysis, and fabrication information	STEP Part 21	Consensus amongst the software implementers and AISC
gbXML	Green Building Studio (2000)	Design	Geometry, spatial, geography (building coordinates)	Exchange building CAD model to building simulation models	XML	XML extension mechanisms
bcXML	eConstruct group (2000)	Design, Construction, Supply chain, Operations and maintenance	Products, properties, taxonomy of terms and language rules	Exchange of construction products, resources, work methods, regulations	XML	XML extension mechanisms
IFC-Bridge	IAI-France (2002) IAI-Bridge (2007)	Design, Construction	Bridge physical elements, geometry, parts, location, and property information	Exchange of bridge structure information	STEP Part 21, ifcXML	XML extension mechanisms
OBIX	OASIS (2003)	Facilities/OM	Sensor information (value, range, status) exchanged between building automation systems	Exchange of sensor information between building automation systems	XML and web services	XML extension mechanisms
AEX	FIATECH (2004)	Design, Supply chain, Facilities/OM	Product information of equipment, properties (e.g., material), document associated with equipment	Exchange engineered equipment information	XML	XML extension mechanisms
agcXML	NBIMS Committee (2006)	Design, Construction Supply chain, Operations and maintenance	Documents	Exchange of construction-related business-to-business documents	XML	XML extension mechanisms
BPC	FIATECH (2006)	Design, manufacturing, installation	Precast concrete members, parts, their geometry, location and connection information	Exchange of information for design, manufacturing and installation of precast concrete members	-	-

Data spec/ standard	Development group & Project start date*	Targeted project phases	Semantics	Usage	File format	Extensibility
Building information modeling standards						
IFD	International Construction Information Society (1995)	Design, Construction, Supply chain, Facilities/OM	Products as concepts, properties, units and values, relationships between these concepts	Exchange of language and application independent description of construction products	XML	Through defining new concepts
IFC	IAI, also known as BuildingSmart (1996)	Design, Construction Supply chain, Facilities/OM	Products and associated elements, geometry, properties, geography, topology, relationships, cost, schedule, people, organization, site, documents	Exchange project information (product, process, control)	STEP Part 21, XML	Formal extension mechanisms
NBIMS	NIBS (2005)	Design, Construction Supply chain, Facilities/OM	Information required about all aspects of a facility throughout its lifecycle	Exchange of information about facilities throughout their life cycle	Refers to other standards	Through model view definition diagrams
Other data standards						
Sensor ML	Open Geospatial Consortium and Sensor Web Enablement Working Group (1998)	Construction, Facilities/OM, Disaster management	Metadata for identification, classification, description, constraints, history, capabilities, and accuracies of sensors, physical objects and non-physical objects associated with sensor systems, lineage of observations, interconnections between sensors, post-processed data	Exchange of in-situ or remote sensor identification, location and observation data of sensors	SML	Major elements are fixed, but can be extended when needed
landXML	Industry consortium initiated by Autodesk (2000)	Surveying, Urban planning, Disaster management	Elements (address point, boundaries, daily traffic volume, parcel), complex types (point type, raw observation type) and simple types (angle, area, slope, speed, zone surface type)	Exchange of data created during the land planning and land surveying processes	XML	XML extension mechanisms
KML	Open Geospatial Consortium and Standards Working Group (2001)	Environmental Urban planning Disaster management	Geometry elements derived from GML 2.1.2, including point, line string, linear ring, and polygon	Exchange of geographic visualization information including annotation of maps and images	XML	XML extension mechanisms
cityGML	CityGML 1.0 Standards Working Group (2002)	Design, Construction Facilities/OM Urban planning, Disaster Management	Geometrical, spatial, topological, properties	Exchange of mainly spatial information for urban and landscape planning, disaster management, homeland security	XML	XML extension mechanisms
IFG	Norwegian Planning Authority (2003)	Design, Surveying, Construction	Geometrical (maps, contours, coordinate systems) , properties, spatial information (building storey and individual space)	Exchange of mainly geographical information	XML STEP21	XML extension mechanisms

*: project start year shows the year of initiation for developing the specifications.

definition of product information common as applications change, (3) *application protocols*, which specify scope and requirements of a domain-specific application for the data model, (4) *implementation methods*, which define resources for STEP implementation, such as STEP physical file and data access interface and (5) *conformance testing*, which assesses whether STEP languages and files, such as EXPRESS are used and implemented properly. STEP has advantages over IGES and DXF, as it focuses on a product data model for the domain semantics then specifies the data format. This data model includes data items related to topology, properties and assemblies, and targets incorporating data not only from the design phase, but also from later phases, such as operations and maintenance of a facility, depending on the application protocols.

Limitations of STEP exchange include large and complex documentation, time-consuming development of STEP translators, large file sizes due to a large number of objects represented from whole product life cycle (Ball et al. 2007, Slansky 2005). The limitations of early geometry and topology exchange standards led to continuous efforts for enabling interoperability within AEC/FM industry. The next section provides an overview of the exchange standards developed for exchanging domain specific information within the AEC/FM industry.

3.2. PRODUCT MODEL EXCHANGE STANDARDS AND SPECIFICATIONS/ ASPECT MODELS

Many data exchange specifications and standards/data models have been developed since the late 1990s for enabling the exchange of information items associated with a specific domain or phase of a project. These data standards, which were developed to address data

exchange requirements of specific domains or operational level departments, are also referred to as aspect models (Eastman 1999). These standards and specifications include:

- (a) CIMsteel Integration Standards (CIS/2): This specification was developed for enabling exchange of structural steel design, analysis, and fabrication information (Crowley and Watson 2000).
- (b) Green Building eXtensible Markup schema (gbXML): This specification aims at enabling exchange of design, certification, operation and maintenance information for resource efficient buildings (gbXML 2008).
- (c) Building Construction eXtensible Markup Language taxonomy (bcXML): This standard was developed for enabling exchange of construction terms, definitions, properties, units, names in different languages and alphabets (Rees et al. 2002).
- (d) Industry Foundation Classes for Bridges (IFC- Bridge): This standard was developed for enabling exchange of bridge engineering information as an extension to existing IFC standard (Yabuki and Li 2006).
- (e) Open Building Information eXchange (OBIX): This standard is being developed for enabling exchange of information for having intelligent buildings with the target of having integration for technologies utilized for security, HVAC, and building automation (OBIX 2008).
- (f) Automated Equipment Information eXchange (AEX): This set of XML schemas was developed as a specification for enabling exchange of equipment design, procurement, delivery, operation and maintenance information (FIATECH 2008).
- (g) Associated General Contractors of America XML (agcXML): This set of XML schemas was developed as a specification for enabling exchange of construction-

related business-to-business data that are currently exchanged on paper documents (Tardiff 2007), and

- (h) BIM for Precast Concrete (BPC): This specification was developed for enabling exchange of design information for precast concrete components (Eastman et al. 2008).

An overview for each data standard is provided in the following subsections.

3.2.1 CIMsteel Integration Standards (CIS/2)

CIS/2 is the product data model for structural steel that facilitates the exchange of information between steel design, analysis, detailing, and fabrication software (Crowley and Watson 2000). It was developed as a research project at the University of Leeds, as part of the Pan-European Eureka CIMsteel project (CIS 1997) and was adopted by the American Institute of Steel Construction (AISC) in 1998 as their data exchange format for interoperability between steel related software. CIS/2 has been widely implemented in many steel specific software packages and in some general purpose BIM software.

CIS/2 uses some of the STEP resource models and supports three different views or models of structural steel: design, analysis, and manufacturing. The manufacturing model is also known as a physical, detailed, or fabrication model. There is a logical relationship between the three models. For example, a beam that is subdivided into several elements for analysis is logically only one beam in a design or manufacturing model. A connection in a design model that only indicates that two parts are connected to each other is logically, in a manufacturing model, a fully detailed connection with bolts, holes, welds, and gusset plates.

The CIS/2 analysis model represents steel structures as analysis nodes, elements, loads, reactions, and boundary conditions. Prismatic parts in the design and manufacturing model are defined by a cross section designator, length, position, and orientation. Curved parts, flat and bent plates, and corrugated decking can also be modeled as can connection materials, such as bolts, holes, and welds. Parts can also be grouped into assemblies and sequences and assigned surface treatments, material grades, and functional characteristics.

A mapping has also been developed between CIS/2 and the Industry Foundation Classes (IFC) used in the general building industry for information exchange (Lipman 2009). In some cases, there is a direct one-to-one mapping between CIS/2 and IFC entities and concepts, while in other cases there is a one-to-many or one-to-none mapping. The mapping shows that while IFC can easily model, with multiple representations, the geometry of steel structures, some of the semantics in CIS/2 have no equivalent in IFC. For example, the geometry of bolts can be modeled in IFC; however, there is no concept that the bolts are in a specified pattern as there is in CIS/2. The mapping has pointed out other deficiencies for modeling structural steel in IFC. The mapping is implemented as a translator from CIS/2 files to IFC files.

3.2.2 Green Building Extensible Markup Language (gbXML)

gbXML specification is a data model developed for exchanging files or messages associated with exporting CAD model information of a facility to design and energy consumption simulation tools. It is an effort led by Green Building Studio with support of

the California Energy Commission Public Interest Energy Research (PIER) Program, and the California Utilities Companies since 2000. It is based on extensible markup language (XML) to enable sharing data with other applications.

Information, which can be represented with gbXML, include building information for space, surfaces and zones, surface types, space area and air volumes, building type, building geographic coordinates and information for light fixture elements. Table 1 provides an overview of this data standard.

gbXML was specifically designed for building energy simulation. In addition, information such as material U-values, space occupancy schedule and global building coordinates generated from building simulation tools cannot be imported back to original applications with the added information. gbXML is currently utilized for solving re-entering or reformatting spatial and geometric data used by building energy simulation tools.

3.2.3 Building and Construction Extensible Markup Language (bcXML)

Building and Construction Extensible Markup Language (bcXML) is a taxonomy of terms and language rules developed for enabling exchange of construction product, resource, work method and regulation information for e-business communication process (Rees et al. 2002). It was developed within the eConstruct project in 2000. bcXML can represent names, definitions of objects (concepts) and relationships between them, properties, measures of them that are related to building construction projects.

Similar efforts were seen to develop taxonomies for exchanging product information, such as LexiCON of the Netherlands, and Barbi of Norway (Lima et al. 2007). Mappings between these data models exist, such as translators between LexiCON and bcXML. These European based efforts have resulted in the development of an international standard (i.e., IFD).

3.2.4 Industry Foundation Classes for Bridges (IFC-Bridge)

IFC-Bridge data standard is being developed for enabling the exchange of bridge engineering information as an extension to the IFC standard. The roots of this data model come from two separate research studies from France and Japan. In 2002, these two groups were joined, with the support of IAI to develop the IFC-Bridge standard (Yabuki and Li 2006).

The IFC-Bridge data model includes information about the general structure of bridges, complete geometry information about bridge spatial elements, physical elements, and element parts, material properties, pre-stressing and process control (Arthaud and Lebegue 2007). This data model has been developed as an extension to the IFC schema similar to BIM for precast concrete, in order to detail information exchange for bridge components. The only limitation of this data model is the same limitation that comes with any domain specific data model. It can only enable exchanging bridge specific information items and need to be used hand in hand with industry wide data standards.

3.2.5 Open Building Information Exchange (OBIX)

OBIX data standard is being developed for enabling the exchange of information coming from embedded sensors that sense information for various tasks, such as security, utilities, access control, lighting and HVAC. It is being developed by the Organization for the Advancement of Structured Information Standards (OASIS) since 2003. It is based on XML and web-services. This data standard enables communication between mechanical and electrical building control systems and front end applications (OBIX 2008).

OBIX is currently capable of representing information items, such as objects (e.g., switches, lights), references to URIs of objects used to identify objects, status and values in its object model. The main advantage of using this data model will be having a standard for exchanging information shared between various building automation systems, which currently rely on binary protocols (e.g., BACnet, LonTalk) that may experience problems with routers, firewalls as they are used over TCP/IP networks (OBIX 2008).

3.2.6 Automating Equipment Information Exchange (AEX)

AEX is composed of a set of XML schemas developed for exchanging equipment information in design, procurement, delivery, operations and maintenance phases of a facility (FIATECH 2008). It is an effort that is led by FIATECH, equipment manufacturers, software suppliers, industry associations and NIST since 2004. Semantics represented within AEX include equipment information found on various equipment lists and bill of materials documents, process materials, associated properties, calculation methods and experimental property data.

This data specification targets streamlining the flow in the equipment supply chain by enabling information exchange from design to equipment delivery. AEX specification is continuously evolving, and currently covers centrifugal pumps, centrifugal fans, centrifugal compressors, reciprocating compressors, electric motors, air cooled heat exchangers, shell and tube heat exchangers, control valves, and numerous other types of valves (FIATECH 2008). Semantic mapping studies were conducted to map AEX information to and from IFCs and the American Society of Heating, Refrigerating and Air-conditioning Engineers' (ASHRAE) data models (Begley et al. 2005). The Hydraulic Institute (pump manufacturers and suppliers) adopted AEX as the basis for their data exchange standard HI 50.7 and advanced AEX as the recommended data exchange standard for ISO 15926.

3.2.7 The Associated General Contractors of America (AGC) Extensible Markup Language (agcXML)

agcXML was developed to enable the exchange of transactional information that parties, such as architects, engineers, suppliers within the building construction domain, exchange (Tardif 2007). This is an effort led by the Associated General Contractors of America (AGC) and National Institute of Building Sciences since 2006. It can be used to represent construction-related business-to-business data that is exchanged in documents, such as owner/prime contractor agreements, owner/construction manager agreements, contractor/subcontractor agreements, schedules of values and requests for information.

3.2.8 BIM for Precast Concrete (BPC)

BPC data schema is a data model developed for enabling the exchange of design information for precast concrete components. It is an outcome of a project initiated in 2006 by the Fully Integrated and Automated Technology (FIATECH) consortium and led by a research team composed of an architecture firm, 3D precast companies, academicians, NIBS and FIATECH.

Targeting interoperability between architects and precast contractors, BPC suggests extensions to IFC 2x3 by identifying information items that are exchanged specifically for precast elements. These information items include geometry of precast components, their details, and properties needed during design, fabrication and erection (Eastman et al. 2008). This data model focuses on information exchange for precast concrete domain and works hand in hand with IFCs.

3.3. SEMANTICALLY-RICH BUILDING INFORMATION MODEL EXCHANGE STANDARDS AND SPECIFICATIONS

While many of the domain-specific aspect models discussed above are useful and successful within the specific disciplines that they are targeting, there are still cross-domain and cross-discipline data exchange needs and interoperability issues that need to be addressed. The specifications described in this section target this need. Due to the fact that such specifications are more difficult to develop, there is a smaller number of standards of this type. Currently available standards include: (a) Industry Foundation Classes (IFC), developed for enabling the exchange of facility-related information throughout its life-cycle, (b) International Framework for Dictionaries (IFD), developed

for enabling the exchange of AEC/FM related products' definitions, properties, units, values and relationships between products, and (c) the new effort to develop the National Building Information Modeling Standard (NBIMS), aimed at developing an integrated life-cycle information model, based on existing open standards.

3.3.1 International Framework for Dictionaries (IFD)

IFD is an ontology that is being developed to exchange construction product information in multi languages (Bjorkhauk and Bell 2007). The International Construction Information Society and ISO TC 59/SC 13/WG 6 have been leading the effort since 1999. IFD can represent products as concepts, their properties, units and values, and relationships between these concepts. The IFD data model provides product specific information, such as what it is, what parts, properties, measures and values it has, which will be required at different phases of a project. IFD provides this ability by defining a controlled vocabulary of names of objects. With this ability, IFD provides a bridge between building information models (e.g., IFC-based) and databases that contain product specific information (buildingSMART 2008). Industry foundation classes can define to a level, the components, relations between components and properties, whereas IFD can provide information about what each component is about, such as its global ID, measuring units, material definitions, name and descriptions in a multiple languages.

3.3.2 Industry Foundation Classes (IFC)

IFC represent a specification for exchanging and sharing information throughout the life-cycle of facilities. This specification is being developed since 1996 by buildingSMART International (formerly known as the International Alliance of Interoperability - IAI). IFC-

based information can be exchanged using XML or STEP 21 file format. A STEP Part 21 file is an ASCII file and is composed of a header and data sections within which every entity is stated with a unique number. ifcXML uses XML to exchange information contained in IFC and involves a conversion of IFC schema from EXPRESS representation to one based on XML (Nisbet and Liebich, 2005). IFC began with IFC 1.0 and currently IFC 2x4 is under development.

IFC was developed to enable the exchange of information about all aspects of a facility for all phases of a project from design to operations. In order to claim IFC compliance, software vendors must undergo a certification process with buildingSMART's Implementer Support Group, who test and certify a vendor's IFC implementation. Currently, IFC compliant software cover a wide area of AEC/FM domains, such as: design, structural engineering, HVAC design, thermal analysis, code checking, quantity take-off, and cost estimation.

IFC can enable the exchange of product information, such as walls, columns with their geometric representations and properties. It also defines topology (element connectivity, schematic design), relations between component and spaces and spatial structures. Moreover, IFC incorporates non-product information, such as costs, schedules, resources and documents. Each entity is represented as a class, thus each can have a number of properties such as name, geometry, materials and relationships. Its latest release, IFC 2X3, has a total of 653 entity definitions. The capability of extension is provided by the IFC Property Sets. Shared product information can be from nine different domains, which are:

HVAC, building controls, electrical, plumbing and fire protection, architectural, structural elements, construction management, structural analysis, and facilities management.

The main architecture of the IFC model is illustrated in Figure 1. The model is divided into four layers: domain, interoperability, core and resource. Each layer comprises diverse categories, and it is within each category or schema that the individual entities are defined.

Currently, IFC is the data model that has the widest scope for enabling interoperability within the AEC/FM industry. With its extensible representation, IFC is growing as more specific data exchange is needed for new design, construction, manufacturing and operations tasks within the AEC/FM industry.

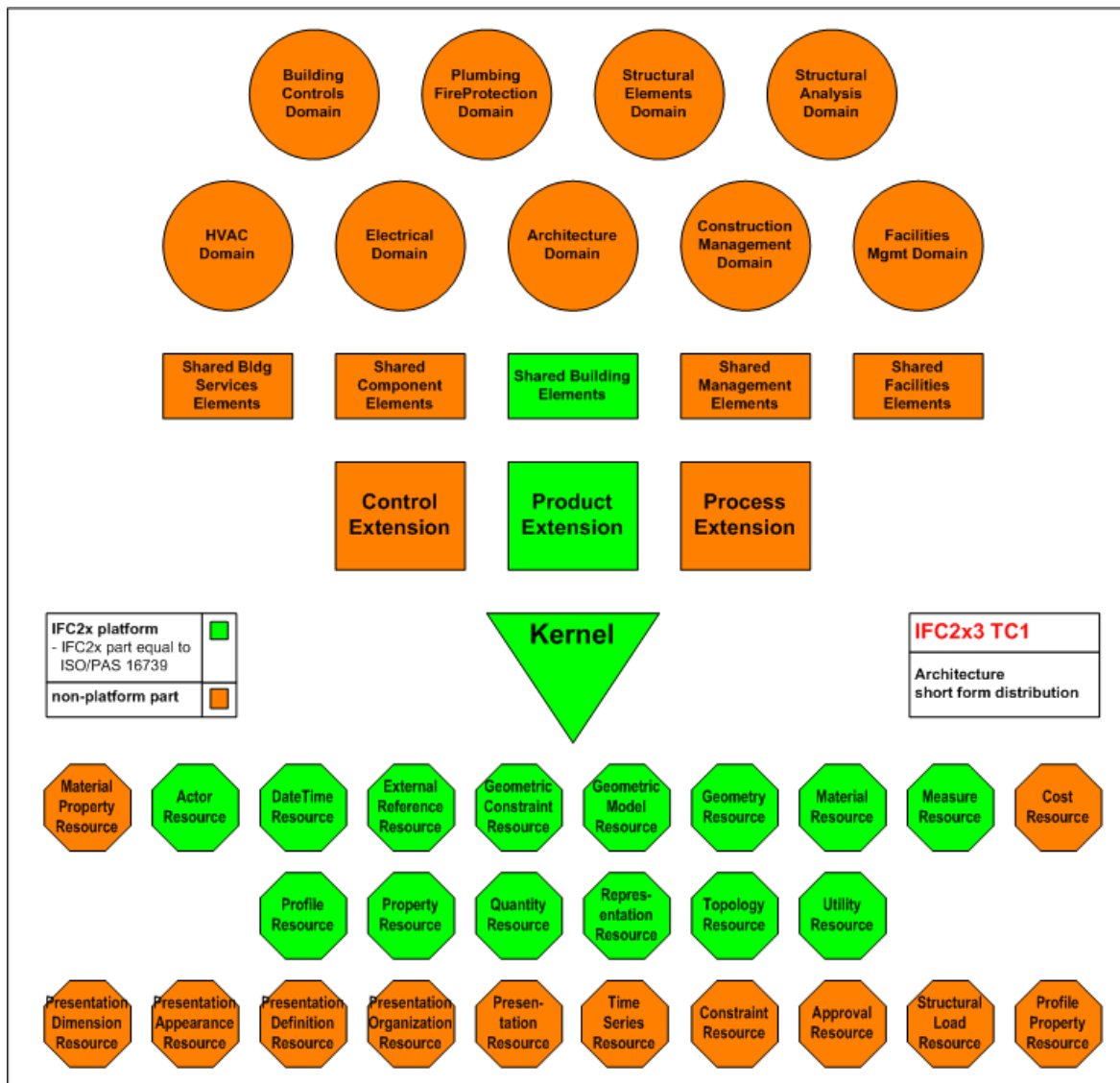


Figure 1. High-level architecture of the IFC model, with the four layers and diverse categories in each layer (figure is extracted from <http://www.iai-tech.org/ifc/IFC2x3/TC1/html/index.htm>)

3.3.3 National Building Information Modeling Standard (NBIMS)

NBIMS is being developed to enable an integrated life-cycle information model, based on existing open standards. It has been a project of the NIBS since 2005. With the objective of having integrated life-cycle information, this effort targets developing standards of

standards by defining NBIMS requirement for interoperability. The main objective of NBIMS is to have standardized information about a facility by defining how facility information exchange should be, what a building information model contains, and organizing facility life cycle information (NBIMS 2007).

For this purpose, NBIMS considers a shared building information model at the center, and works to define requirements for a model to be considered a building information model. While doing so, NIBS works in close collaboration with various parties, such as designers, contactors and software vendors to evaluate and extend existing industry wide data standards, such as IFC and IFD.

3.4. OTHER DATA STANDARDS AND SPECIFICATIONS

There are also data standards and specifications that facilitate the exchange of information and can be helpful within the AEC/FM industry even though they were not originally developed for and within that industry. These data standards are related to exchanging information with GIS-based applications, and include: (a) Sensor Model Manguage (SensorML) schema, which was developed for enabling the exchange of sensor-based information from different sensor applications, (b) Land eXtensible Markup Language (landXML), developed for enabling the exchange of data created during the land planning, civil engineering and land survey process, (c) Keyhole Markup Language (KML) schema, which was developed for enabling the exchange of geographic visualization information including annotation of maps and images, (d) city Geographic Markup Language (cityGML), developed for enabling the exchange of geometrical, spatial, topological data of water bodies, sites (currently building), transportation facilities, city furniture, generic

city objects and their properties, and (e) Industry Foundation Classes for GIS (IFG), developed for enabling the exchange of geographic information in GIS with the IFC schema. These data standards and specifications are overviewed in the following subsections.

3.4.1 Sensor Model Language (SensorML)

OpenGIS SensorML is a data model developed for providing a standard language to define sensor-systems and components that play a role in these systems associated with measurements, and post-processing of these measurements (OGC 2008). It was initiated by a group under a National Aeronautics and Space Administration (NASA) program in 1998, and continued its development under the oversight of Open Geospatial Consortium (OGC), since 2000.

SensorML includes modeling sensors as processes that convert observable phenomena into observed values. It provides information for locating sensors, sensor observations, processing information from observations and sensor properties (Botts 2002). Any discipline that needs sensor-based data/information can benefit from the utilization of the SensorML standard. Within the AEC/FM domain, SensorML can be used for exchanging information required during operations and maintenance (e.g., modeling different sensors for facility operations and management, navigation within facilities, security of facilities, maintaining occupancy comforts); or during construction for progress monitoring. Hence, SensorML is helpful in the construction and post-construction phases of a project.

3.4.2 Land Extensible Markup Language (landXML)

landXML was developed to enable the exchange of data created during land planning, development, transportation and land surveying processes (Cover 2004). It is a data schema under development since the beginning of 2000 by an industry consortium, initiated by Autodesk and now comprised of 190 companies, government agencies and universities. landXML can represent civil engineering and survey measurement data as elements (i.e., address point, boundaries, daily traffic volume, parcel), complex types (i.e., point type, raw observation type) and simple types (i.e., angle, area, slope, speed, zone surface type). It covers units, coordinate systems, design geometry data (including points, alignments, surfaces, lines, curves), roadways, pipe networks, plan features (e.g., fence lines, curbs), and survey observations.

Any discipline that needs exchanging of geospatial land information can use landXML. Within the AEC/FM domain, landXML can be used for exchanging information between civil/surveying, CAD and geospatial software applications, required during various tasks such as, site surveying, visualization during roadway design, road model generation, automated construction machine controlling, and infrastructure modeling (Crews 2006).

3.4.3 Keyhole Markup Language (KML)

KML is a data model developed for enabling exchanging geographic visualization information, including annotation of maps and images (OGC 2008). It is an effort initiated by Google and continued by Open Geospatial Consortium - Standards Working Group in 2001. It can be used to model and display geometric features (including points, line strings,

linear rings, polygons and regions), models, images, and additional geospatial data such as, coordinate systems, placemarks, and time stamps on 2D or 3D earth browsers, GIS applications or mobile applications (OGC 2008).

Any discipline that needs exchanging and displaying and visualization of geographical information can use KML. Within the AEC/FM domain, KML can be used to help facilitate information exchange and visualization in various applications, such as CAD and GIS applications, and overlay information exchanged between these applications on earth browsers. For example, KML can be used to locate and visualize groundwater levels, existing utilities, or project sites.

3.4.4 City Geography Markup Language (cityGML)

cityGML is a data model developed for enabling the exchange of virtual 3D urban objects, such as buildings, bridges, water bodies, and construct city models (Groger et al. 2007). A group called “Special Interest Group 3D” in Germany and CityGML 1.0 Standards Working Group have been working on the development of this data model since 2002. The cityGML data model can represent geometrical, spatial, topological, and appearance (surface characteristics texture, material) properties for buildings, and vegetation, water bodies, sites (currently only building), transportation facilities, city furniture, and generic city objects.

cityGML can be used in many application areas, such as, urban and landscape planning, architectural design, environmental simulations, and disaster management. This data standard can also be used to exchange data for applications within the AEC/FM industry.

Example application areas are disaster simulation and mitigation, site surveying, land development and planning.

3.4.5 Industry Foundation Classes for GIS (IFG)

Industry Foundation Classes for Geographic Information Systems (IFG) is a data model developed for enabling the exchange of geographic information in Geographic Information Systems (GIS) with the IFC schema (IFG 2008). Since 2003, the Norwegian Planning Authority is working on developing the IFG schema. It provides a bridge between IFC and standard geographic information exchange standards, such as geographic markup language (GML) (AEC3 2008). IFG can represent areas (land parcels), geometric representation of building elements, maps, contours, coordinate systems, networks, distribution systems (water, sewer, power), proximity, survey data, terrain, semantic identification of a building and building elements (building, wall, window, door, opening).

The aim of IFG schema was to use existing capabilities of IFC in representing data items that are related to GIS applications and extend it as needed. So, the basic idea was creating an overlap between the data models used within AEC/FM and GIS domains. For developing the IFG schema, developers explored the capabilities of IFC in representing (a) positioning of objects in coordinate systems (which IFC represents with `IfcCartesianPoint` entity), (b) building services, such as pipes and cables and their identification (which IFC enables with `IfcSystem` entity), (c) geographic features (where IFC was extended to have `IfcGeographicalElement` as a subtype of `IfcProduct` entity), (d) qualified geometry, where geometric information differentiation with unique identifiers is required in GIS applications (which IFC provides such differentiation with `IfcAnnotation` entity), (e) shape

of terrains (which IFC represents IfcSite entity as a grid or a triangulated irregular network (TIN), (f) proximity information (for which IFC was extended to include proximity relationship), and (g) spatial structure arrangements (which IFC represents with IfcBuilding, IfcSpace entities) (IFG 2008).

Applications of IFG in the AEC/FM domain are various. It is mainly used to exchange information between GIS and CAD applications. It can be used to store geographic and building information using a single data representation, used to facilitate zone and building plan submission processes by enabling sharing of location maps, utility services and zoning information. Other applications can be fire response management, disaster management, and integrating subsurface infrastructures with building information models.

4. AN EVALUATION AND COMPARISON OF OVERVIEWED DATA STANDARDS AND SPECIFICATIONS

This section provides a comparison of the data standards and specifications overviewed in the previous section in terms of their capability to represent and exchange information items shared within the AEC/FM domain. In order to perform this evaluation and comparison, a list of semantic information groups was created based on an exploration of work flows occurring between a set of disciplines within the AEC/FM industry. Based on this semantics list, the data standards and specifications were clustered over the disciplines that require identified semantic information groups to be exchanged among them. The disciplines whose workflows were examined for this study and the identified list of semantics are listed in Table 2.

The disciplines considered for the evaluation of standards and specifications were selected such that they are representative of all groups involved in a construction project from inception to operation/maintenance phases. Examples of these disciplines are design groups, suppliers, and urban planners, as detailed in Table 2. The identified groups of information items include (a) products and associated elements, (b) geometry, (c) spatial information, (d) properties, (e) geography, (f) topology, (g) relationships, (h) cost, (i) schedule, (j) people, organization and site, and (k) documents. These groups of information items were identified based on the explorations of the available data standards and specifications in terms of what they could represent and clustering the outcomes.

A comparison of different rows in Table 2 shows that most of the existing standards and specifications include information items related to “products and associated elements” and “properties” of these elements. This is not surprising since in order to exchange information about specific products (e.g., walls, columns, bridge elements), they first need to be defined and represented with their associated properties. “Geometry” information group follows these two semantics groups, as being the highly represented information group. In terms of the least represented groups of information items, even though a large number of disciplines needed to exchange information related to “people organization and site,” “cost” and “schedule” groups, only industry wide data standards, such as IFC, have incorporated those items in their specifications.

A comparison of different columns in Table 2 shows that the majority of the information items needed for designers, construction groups, and facility management groups was represented within a large number of data exchange standards. This is mainly due to the situation that these groups have been targeted early in the standardization efforts. As new

Table 2. Data standards and specifications that can represent semantics, by semantic information groups and AEC/FM disciplines

Semantics / Groups	Designer Groups	Surveyor Groups	Contractor Groups	Supplier Groups	Subcontractor Groups	Facilities / OM / Owner Groups	Environ-mental Groups	Urban / Disast er Man. Groups
Documents	AEX, AGCXML, IFC		AGCXML, IFC	AEX, AGCXML	AGCXML, IFC	AEX, AGCXML, IFC		
People / Org. / Site	IFC, IFG	IFG	IFC, IFG		IFC	IFC		
Schedule	IFC		IFC	IFC	IFC	IFC		
Cost	IFC		IFC		IFC	IFC		
Relation-ships	BPC, CIS/2, IFC, IFD		BPC, CIS/2, IFC IFD, SENSORML	BPC	BPC, CIS/2, IFC, IFD	BPC, IFC, IFD, SENSORML		
Topology	BPC, CIS/2, CITYGML, IFC, IFG	IFG	BPC, IFC, IFG	BPC, IFC, IFG	BPC, IFC, IFG	CITYGML, IFC	CITYGML	CITYGML
Geography	CITYGML, GBXML, IFC, IFG, LANDXML	CITYGML, IFG, LANDXML	CITYGML, IFG, LANDXML		CITYGML, IFC, IFG, LANDXML	CITYGML, IFC, IFG, LANDXML	CITYGML, IFG, KML, LANDXML	IFG, CITYGML, KML, LANDXML
Properties	AEX, BCXML, BPC, CIS/2, CITYGML, IFC, IFD, IFG	IFG, LANDXML	BCXML, CITYGML, IFC, IFD, IFG, SENSORML	AEX, BCXML, BPC, IFD	BCXML, IFC, IFD	AEX, BCXML, BPC, CITYGML, IFC, IFD, OBIX, SENSORML	CITYGML	CITYGML, KML, LANDXML
Spatial	CITYGML, GBXML, IFC, IFG, KML, LANDXML		CITYGML, GBXML, IFC, IFG, KML, LANDXML		GBXML, IFC, IFG, KML, LANDXML	GBXML, CITYGML, IFC, KML, LANDXML	CITYGML, IFG, KML, LANDXML	CITYGML, IFG, KML, LANDXML
Geometry	BPC, CIS/2, GBXML, IFC, IFG, IFC-BRIDGE	CITYGML, IFG, KML, LANDXML	BPC, CIS/2, IFC, IFC-BRIDGE, IFG	CIS/2, CITYGML, IFC, IFG, KML, LANDXML	BPC, CIS/2, IFC, IFC-BRIDGE	BPC, CITYGML, IFC, GBXML, KML, LANDXML	CITYGML, KML, LANDXML	CITYGML, KML, LANDXML
Products, associated parts, connections	AEX, BPC, CIS/2, IFC, IFD, IFC-BRIDGE, IFG	IFG, LANDXML	BCXML, BPC, CIS/2, CITYGML, IFC, IFC-BRIDGE, IFD, IFG, SENSORML	AEX, BCXML, CIS/2, IFD	BCXML, BPC, CIS/2, IFC, IFD, IFC-BRIDGE	AEX, BCXML, BPC, CITYGML, IFC, IFD, OBIX, SENSORML	CITYGML, KML	CITYGML, KML, LANDXML

aspect models are developed specifically targeting the information exchange needs of disciplines that are not widely represented, gaps will be filled.

A general observation about existing data exchange standards and specifications is that these deal with semantic information groups at different scales. For example, how a building site represented in IFC is different from how it is represented in IFG. Similarly, how a building is represented in IFC is different than how it is represented in cityGML. A question arises as to how these different scales can be integrated in standard representations or interoperability can be maintained between applications utilizing these different scaled representations. This issue will be more thoroughly discussed in other chapters in this book, where data standards integration issues, such as CAD/GIS integration issues, are discussed in detail.

5. A DISCUSSION ON THE CURRENT STATE OF INTEROPERABILITY AND A PROJECTION TOWARDS THE FUTURE

In an ideal world, exchanging information specified by a data standard between CAD applications would result in 100% of the expected information to be exchanged and accessible in the receiving CAD application 100% of the time. For some of the data exchange standards, it is known that this is not true for a variety of reasons. Some possible sources of the problems are: (1) issues with mapping to and from software internal representations of information to the data exchange standards; (2) incomplete or incorrect implementations of the data exchange standard; (3) the data standards does not meet all the requirements of the information needed to be exchanged for a particular domain; and (4)

inconsistent utilization of a software system, which results in information being mapped to the wrong data element in the exchange standard.

All data exchange standards should have some form of validation, conformance, and interoperability testing to be successful. Validation testing is the process to evaluate a standard whether it satisfies the information exchange requirements of a particular domain. Conformance testing is the assessment of a software implementation in terms of whether it meets the requirements of a standard, i.e., is the software generating the correct information in the data exchange files (Kindrick 1996). Interoperability testing is the assessment of the end-to-end functionality between two software implementations.

Conformance testing involves developing specifications of what information is to be modeled or exchanged, creating the model or information in the software application that is being tested, generating the data exchange file, analyzing the file for correctness, and reading the data exchange file. The analysis of the data exchange file can usually be done with various software tools. Interoperability testing extends the process by importing the data exchange file into another software application and evaluating the resulting model or information in the receiving application. The evaluation compares the original representation in the first application to the resulting representation in the second application. Successful conformance testing leads to better assurance that interoperability testing will also be successful. Interoperability testing without conformance testing can lead to software modifications compensating for non-conformance to the data exchange standard. This leads to implementations that do not universally interoperate with other similar applications.

Some data exchange standards have rigorous definitions of testing. For example, the STEP data exchange standard defines an entire framework for methodology and a framework for doing conformance testing (ISO 10303 Parts 31-35). For the STEP application protocol AP 227 for exchange of spatial configuration information of process plants, a validation report (Kline 1996) summarizes the validation, conformance, and interoperability testing program. The report is created in conjunction with the development of the exchange standard so that a methodology was in place with a test suite and implementation guidance to test software implementations while they are being developed. For the OpenGIS specification, software applications can validate their products through the Conformance and Interoperability Test and Evaluation Initiative (OGC 2002).

Leaders in the building industry are striving to use IFCs as a data exchange standard which is essential for the successful implementation of BIM. While some BIM projects can take place all within one suite of software products that do not require the exchange of information with other software applications, many projects need to exchange information between different CAD and BIM software and with applications, such as energy analysis, quantity takeoff, and facility management. However, there have been several studies that point out various problems with exchanging information with IFC.

An interoperability test was carried out by the Danish chapter of the IAI (IAI Denmark 2006) that modeled a simple structure in five CAD applications, exported the model as an IFC file, and imported the file to the other four applications. A set of evaluation criteria was applied to the exported IFC files and to the resulting model in the CAD application.

The testing and evaluation included aspects of conformance and interoperability testing. However, it was done on an ad-hoc basis without reference to any established testing procedure. The test showed some elements missing in the resulting IFC files and CAD application models.

A benchmark test for interoperability for precast concrete data was part of a project related to BIM for Precast Concrete (Kaner et al. 2008, Eastman et al. 2008). The test specified a structure with representative precast structural elements that was modeled in several CAD applications, exported to IFC files, which were then imported to a different CAD application. The exported IFC files and resulting CAD models in the receiving CAD application were evaluated. The IFC files generated by different CAD systems varied greatly. These variations were caused by how the precast concrete elements were modeled in the CAD systems and how those elements were mapped to the IFC file. There were also some significant differences between the original and resulting CAD models such as objects with the wrong placement, missing elements, and geometry errors.

The ATC-75 project (ATC), which is developing IFC for structural components, also performed some ad-hoc interoperability testing. The use case for the information exchange involved exchanging data from an architectural to a structural engineering model to do more detailed design. A benchmark test model of a section of a sports stadium was modeled in three CAD applications, exported to IFC, and imported to the other two CAD applications. The IFC files were evaluated by checking the file syntax and conformance to the IFC specification, and were visually inspected with IFC viewers. Discrepancies in the resulting CAD models were documented.

Several other projects have carried out testing through a comparison of IFC files (Palzar 2008, Ma 2006). The IFC files in those projects were generated in two ways. In the first scenario, given a representative model in a CAD system, an IFC file was exported and imported into a second CAD system. The second system then exported another IFC file which was compared to the original IFC. In the second scenario, the original IFC file was imported back into the original CAD application and a second IFC file was exported. This is commonly referred to as round-tripping. The original and the second IFC files are then compared. Each of the comparisons used different evaluation criteria. Comparing the IFC files to each other does give some measure of conformance and interoperability, but it does not take into account how the information might be modified when mapped multiple times to and from the CAD systems and IFC files. Comparing IFC files from different CAD systems is also not a representative workflow, particularly for round-tripping. The comparison of the CAD models is a more representative workflow.

All of the testing research projects described above have some aspects of conformance and interoperability testing. However, none of the testing was performed based on a rigorous methodology that: (1) defines how test models are specified to ensure coverage of the domain; (2) specifies how they are modeled in CAD applications; (3) ensures that a set of test models provides sufficient coverage for all data elements that need to be tested; (4) defines the verdict criteria that should be used to evaluate the resulting IFC file; and (5) specifies how the verdict criteria and testing process are used to evaluate the resulting CAD model and compare it to the original CAD model. The results of the tests are also only a snapshot in time of the state of interoperability. The tests were performed with

specific versions of CAD software and IFC interfaces that most likely have been modified and upgraded since those tests took place. Results of the tests cannot necessarily be extrapolated to CAD software and IFC interfaces that are currently available.

The observations about the testing projects indicate the need for more well-defined, reliable, and repeatable testing methods for data exchange standards, such as IFC. Such methods would be of great benefit to software developers for developing more dependable implementations of IFC information exchange and for end-users to perform their own testing projects without having to reinvent the wheel and do it on an ad-hoc basis.

6. CONCLUSIONS AND FUTURE DIRECTIONS

Various data standards and specifications are being developed continuously for enabling interoperability within the AEC/FM industry. These range from early efforts (e.g., DXF, IGES) developed to exchange geometry and topology information, to product model data exchange (e.g., CIS/2, gbXML, STEP) and semantically-rich building information modeling exchange standards and specifications (e.g., IFC, IFD). Data standards and specifications were compared in terms of their ability to represent a set of information groups, such as products, properties, geography, which were identified by combining and clustering the information items that could be represented by all standards. This comparison shows that the majority of the information items needed for various AEC/FM groups, such as designers, construction groups, and facility management groups are represented within a large number of data exchange standards. This is mainly due to the fact that these groups have been identified and hence targeted early in standardization

efforts. In addition, it was observed that most of the existing standards include information items related to “products and associated elements” and “properties” of these elements.

Though the capabilities of these data standards in representing required information items by different disciplines are satisfying, there are still issues that hinder interoperability between applications. These issues were identified as (1) issues with mapping to and from internal software representations of information to the data exchange standards; (2) incomplete or incorrect implementations of the data exchange standard; (3) the data standards not meeting all the requirements of the information needed to be exchanged for a particular domain; and (4) inconsistent utilization of a software system that results in information being mapped to the wrong data element in the exchange standard. The main reason for the existence of such issues is due to the lack of well-defined, reliable, and repeatable testing methods to test the conformance, interoperability and validation of the data standards and applications using these data standards.

As a future direction within the AEC/FM industry for solving the interoperability problems, there should be efforts to develop formalized, well-defined, reliable and repeatable testing methods for deploying the developed data standards and specifications. In addition, multiple fragmented efforts need to be integrated so as to bring a true interoperable environment for the AEC/FM domain. Initial efforts for such large scale integration of data standards are currently being performed. The National Building Information Modeling Standard (NBIMS), which is an ongoing effort led by National Institute of Building Sciences, is one of these efforts. Integration of data standards for enabling CAD and GIS integration is another example. Such efforts should incorporate a

standard methodology for having conformance, interoperability and validation tests for data standards. With that, true interoperable environments will be achieved within the AEC/FM domain without losing semantic integrity of information shared among applications and disciplines.

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