ITcon
www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

THE IFC STANDARD - A REVIEW OF HISTORY, DEVELOPMENT, AND STANDARDIZATION

PUBLISHED: May 2012, http://www.itcon.org/2012/9
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SUMMARY: *IFC (Industry Foundation Classes) is an open and standardized data model intended to enable interoperability between building information modeling software applications in the AEC/FM industry. IFC has been in development by an industry consortium since 1994, and since the start of the effort, the evolving industry context, standardization organization, resource availability, and technology development have exposed the standardization process to a dynamic environment. While the overarching mission of IFC standardization has always been to enable interoperability between AEC/FM software applications, the approach for how best to operationalize that mission has changed over the years. Through a literature review supported by the general theory on IT standardization, this study follows the development process of the IFC standard from its origins in the early 1990s to its latest activities in 2012. The end result is both a descriptive review of the history of IFC standardization and the establishment of an initial connection to IT standardization research for the IFC standard by profiling the effort in accordance with existing IT standardization theories and typologies. The review highlights the evolution of IFC standardization through several distinct phases, and its gradual movement from emphasizing technical architecture development towards growing involvement in specifying the processes facilitating its use. The organization behind the standard has also seen changes in its modus operandi, from initially being a closed and loosely coupled alliance to evolving into a consortium incorporating open hybrid standardization, where a formal standards body publishes the standards prepared by the consortium. The consortium has faced many challenges compiling an ambitious interoperability standard with few resources, and were it not for the growing demand for the standard provided by public actors, momentum and enthusiasm for the effort might have petered out due to slow market uptake and low use of the data standard in actual construction projects thus far. While this paper does not investigate the adoption phenomenon in-depth, the moderate uptake of the standard can perhaps be explained to be a symptom of the slow adoption of collaborative model-based construction processes and industry reluctance to switch over to new IT tools, which in turn are prerequisites for the existence of demand for an open interoperability standard.*

KEYWORDS: *IFC, interoperability, standardization, BIM, review, construction industry*

REFERENCE: *Laakso M, Kiviniemi A (2012) The IFC standard - a review of history, development, and standardization, Journal of Information Technology in Construction (ITcon), Vol. 17, pg. 134 - 161, http://www.itcon.org/2012/9*

1. INTRODUCTION

1.1 Background

In the construction industry, where several organizations collaborate intensively on one-of-a-kind projects in temporary groupings, having compatible tools and assets within projects is vital. Widely accepted and mature technical platforms, preferably based on open standards, are required to enable communication and collaboration among project participants without requiring them to have specific proprietary applications. The advanced features of building information modeling (BIM) software have contributed to a shift in the way IT can be used in the construction industry, going beyond simple visual representation of the building to an integrated semantic product and process model. In 1994, development of the Industry Foundation Classes (IFC) formally initiated work on an open data model standard to serve the BIM interoperability needs of the industry. While certified implementations of major IFC releases have been present in leading BIM software for more than ten years, real-world use of the format as an enabler of interoperability between project actors has remained low (Kiviniemi et al. 2008; Young et al. 2007). The exchange of BIM data is dominated by proprietary solutions, meaning most integrated construction projects are based on a solution in which all collaborators have software from the same or compatible vendors despite the fact that the industry began working on specifications for an open data format relatively early with regard to the technological maturity of BIM software. IFC could potentially bridge the connections between stakeholders and project phases in a fragmented project environment typical of the construction industry.

IFC-supported model-based construction has the potential to transform the core fundamentals of construction processes. The potential for greater productivity is substantial: open interoperability for building information modeling would enable the seamless flow of design, cost, project, production and maintenance information, thereby reducing redundancy and increasing efficiency throughout the lifecycle of the building. As such, the IFC effort can be considered one of the most ambitious IT standardization efforts in any industry. Based on the initial findings of an ongoing systematic literature review by the first author, the majority of the research related to IFC has not really approached it from a standardization perspective and can coarsely be categorized as applied research; documenting implementations of the standard in software, technical performance evaluations, and functionality or scope extensions to the baseline standard being among the most common. This paper takes a different approach and suggests looking at the socio-technical process of IFC standardization in itself instead of only focusing on the output of the process. Of particular interest is the longitudinal development (i.e. changes that have happened as time has progressed) with regards to the standard, the organization behind it, and the industry environment for BIM software.

This paper is structured as follows: the next sub-section provides a brief introduction to the context of information interoperability in the construction industry, followed by a sub-section reviewing relevant parts of the standards and standardization theory and literature. Section two discusses the methodology, and section three presents the primary analysis of IFC standardization from past to present, spread across four time periods, with corresponding sub-sections. Section four discusses the major findings of the standardization effort. The paper concludes with section five, containing the main conclusions of the review and suggestions for future research.

1.2 The context of building information interoperability

Two commonly reported interdependent hurdles for achieving the interoperability of integrated building information within the construction industry have been the fragmented industry actor landscape and the heterogeneous adoption of IT among these actors.

EU industry sector statistics indicate that over 90% of the construction industry workforce is employed in companies with fewer than ten employees (ECTP 2005). The dominance of small actors is also common on the project level where the work of numerous sub-contractors must be coordinated. To bridge the gaps created by this challenging environment, new types of software and electronic services have been introduced in an attempt to unify core processes in construction projects. While only a minority of innovations stick and become integral parts of the construction process, those that do can disrupt otherwise cemented stakeholder patterns (Taylor and Levitt 2004). Technological advances in BIM technology have gradually led to a disconnect from time and space at the actual work site, where more and more tasks can be planned and produced further ahead in time, thereby reducing the uncertainty related to construction projects. The distinct industry structure is challenging, particularly for software that is not fully leveraged when used in isolation. BIM data is intended to be readable, editable, and shared between various systems throughout the stages of the construction project and the entire lifecycle of the building.

The past decade has been one of constantly progressing but uneven adoption of IT for the construction industry (Young et al. 2007, 2008, 2009; Bernstein et al. 2009; Samuleson 2010). The introduction of affordable technology largely initiated a transition to adopt new and improved tools for supporting existing processes. Drafting moved from pen and paper to Computer-Aided Design (CAD) software, document storage from physical folders and archive cabinets to document management systems, and project communication transitioned from memos and landlines to e-mail and mobile phones. Beyond this point of technological advancement, where technology is largely a replacement for traditional manual processes, adoption varies heavily between companies (Samuelson 2010). This heterogeneous adoption of IT is presumably influenced by the fragmented industry structure, with a traditionally high national and regional character where a vast majority of the industry workforce is divided among small companies which have few to no development resources or capabilities.

The problem of interoperability and using software in isolation rather than networked is a problem for which a remedy could foster a construction process with less redundancy and fewer disconnects. Although individuals and companies may choose to keep their data at arm's length for reasons other than a lack of technological interoperability (e.g. reluctance to share business intelligence, intellectual property protection, contractual and other legal matters), investigating such aspects in-depth is not a main focus in this paper. Challenges related to product data interoperability have existed in the construction industry for as long as computers have been involved (Bloor & Owen 1995), and data exchanges have become increasingly complex as technology has advanced. While few studies have attempted to produce cost estimations for interoperability within the industry, the evidence available thus far suggests a monetary incentive for improvement. The United States National Institute of Standards (NIST) estimates that, based on the results of a multi-method study conducted in 2002, insufficient interoperability among information technology tools costs the US capital facilities industry USD 15.8 billion annually, which is equivalent to 1-2% of the industry's annual revenue (Gallaher et al. 2004). The majority of this cost was attributed to redundant data entry, redundant IT systems and IT staff, inefficient business processes, and delays indirectly resulting from these inefficiencies. Another recent US survey suggested that software non-interoperability costs on average 3.1% of total project budgets (Young, Jones and Bernstein, 2007). These studies suggest the notion that interoperability between information systems offers potential for considerable savings and financial gain.

1.3 IT standards and standardization

Standards enable the seamless use of information technology, and constitute the most basic building block for electronic communication within and between computers. However, most end-users rarely consciously concern themselves with network protocols, data encoding formats, and hardware interfaces to perform everyday computing tasks even though these are crucial for any interconnected functionality to exist at all. While low-level interoperability standards, such as the examples noted above, usually go through an accelerated selection and exclusion process, whether an a-priori agreement among implementing manufacturers or a task left to competitive market forces, higher-level standards with several competing options on the market often see a more drawn-out process.

Research focusing on standards is commonly considered to have originated in the economics of standards literature of the 1980s. Research during this time almost exclusively used instrumentalist means of analysis to determine the effects of network externalities, vendor lock-in, tipping-points, and switching costs on market coordination (David & Greenstein 1990). During the 1990s, the subject began to draw multi-disciplinary attention, the most prominent new interest coming from sociology, political economics, and organization studies, all of which cultivated a healthy mix of perspectives. The wide breadth of scholarly interest in standards may partly stem from the concurrent rapid adoption of information technology and the demand for technical standards that seamless electronic communication requires. Another reason for the growth in research interest may also be the desire to understand the implications that standards carry for technology development and use.

1.3.1 Definitions

The term *standard* has been used with slightly different meanings in the past, which is likely a result of the diversity in standards research, as almost any subject matter can be discussed in the context of standards. Researchers have launched initiatives to establish a common typology for IT standards research to reduce the ambiguity of constructs and to strengthen internal communication in the research area (Cargill 1989; de Vries 2005). The following inclusive definition is used throughout this paper to support the notion of constructing a more cohesive typology:

> *"A standard is an approved specification of a limited set of solutions to actual or potential matching problems, prepared for the benefits of the party or parties involved, balancing their needs, and intended and expected to be used repeatedly or continuously, during a certain period, by a substantial number of the parties for whom they are meant." (de Vries 2005:15)*

As part of the typology, de Vries (2005) also provides a classification of different types of IT standards and a review which emphasizes the breadth of the subject. Because the topic of IT standards is so diverse, it is useful to limit and define the scope explicitly before proceeding further. This paper focuses on a standard that provides indirect horizontal compatibility (de Vries 2005) between software applications, thereby creating data interoperability between different types of construction industry software through the use of an intermediate neutral data structure.

Interoperability based on an open standard, whether a file-based exchange or a server-based data exchange, has many theoretical benefits. If no common open standard exists, each individual software application must develop and implement direct translators back and forth for all other pieces of software which it seeks to communicate with in order to convert the mappings from the internal application format to the target formats. If an open standard can be used instead, the mappings only need be translated back and forth from that single format in order to be compatible with all other applications supporting that same standard. A visualization of the two conceptual scenarios appears in Figure 1.

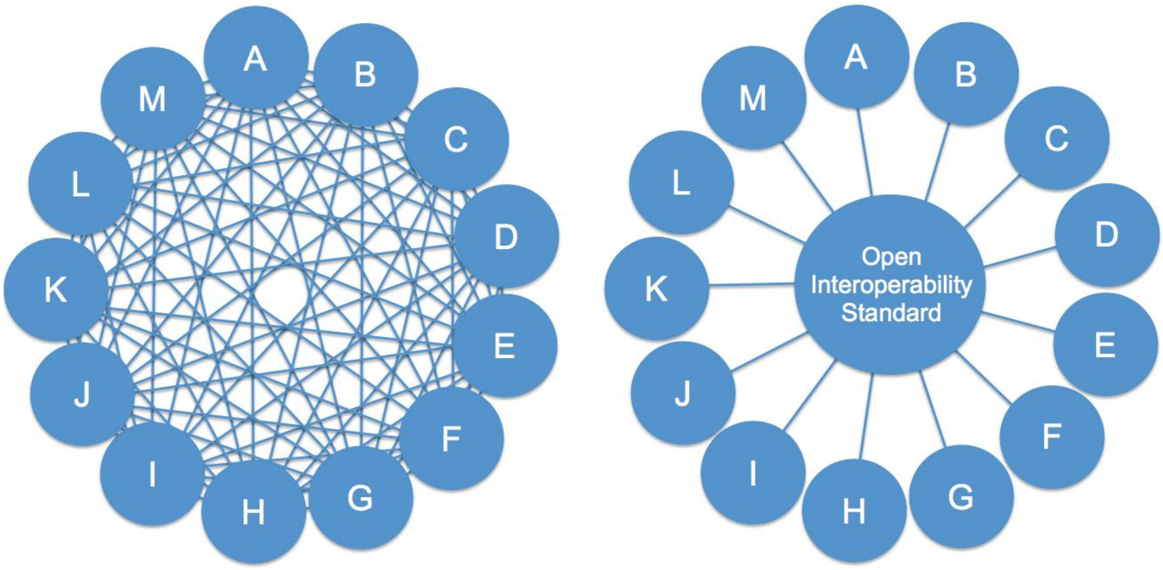

FIG. 1: Interoperability: direct translators vs. an open interoperability standard (author reproduction based on sources: Bloor & Owen 1995:18; Gielingh 2008:755)

Although the scenario of everyone communicating with everyone directly is excessive and not representative of the actual data exchange needs of the construction industry, where some larger actor usually assumes the role of a central aggregating node hosting the master building information data, the data conversion-reducing benefits of a common open standard nevertheless remain. The direct translator model is based upon the notion that specifications for target formats are made available for a complete translator network to be realized even in theory, although they are often proprietary and guarded by commercial interests (Dreverman 2005). Other challenges with the direct translator model include concerns about handling software versions, future access to data stored in proprietary formats, responsibility for errors in translation, as well as mechanisms for translator testing and certification (Bloor & Owen 1995; Gielingh 2008). Bearing in mind the theoretical compatibility benefits of an open format versus a proprietary format (assuming technical features for each are equal), it might seem natural for users to adopt an open alternative. However, for a simplistic anecdotal example one can look to the file-format situation in the field of word processing software, a traditionally popular area among standardization researchers. Free, open alternatives have been available for a number of years yet most users continue to perceive vendor-specific proprietary formats as the de-facto standard format.

Standards are the end-result of a process referred to as *standardization*. Standardization, here defined as the process of producing a standard, is not limited to any number or type of activities. Theoretical accounts identifying the common key stages of the standardization process have been suggested, and over time the process models have evolved from linear to cyclical lifecycle models. Figure 2 presents a generalized standards lifecycle based on a number of published studies suggesting frameworks for representing the key phases of the process (Söderström 2004). Söderström (2004) has also added some key extensions based on findings from supplementary standards literature. Gravitation towards a cyclical model is largely due to an expanding research focus; the initial phases of standardization gained interest among researchers early on, whereas aspects related to continuous development and maintenance have only more recently been acknowledged and explored in the context of standardization.

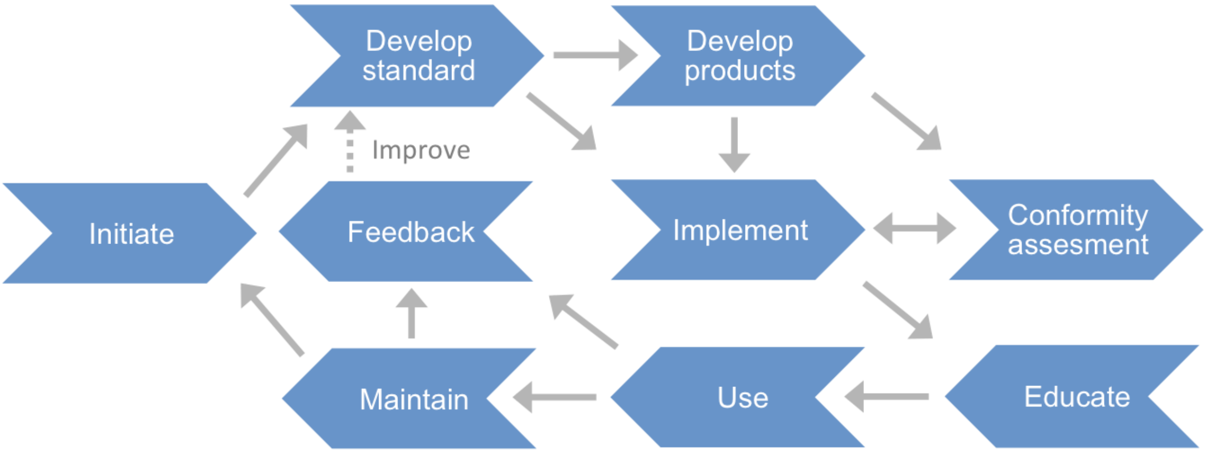

FIG. 2: Extended generalized standards lifecycle model (author reproduction based on source: Söderström 2004:272)

Standardization in the technology context must acknowledge that standards are not created in isolation from the technology; studies have been conducted on the implications of standardization either early or late in relation to technology maturity and on how such factors impact the development of both standards and technology. Cargill (1989) argues that early standardization influences product properties as standards and products are co-created in parallel, whereas late standardization is more restricted to already existing industry interests. Egyedi (1996) suggests that instead of separating technology development and standards development into two separate factors, standardization should be treated as a regular environment of technology development. The notion that technology and standardization development might overlap at different stages of their respective processes is evident in de Vries (2005) standards typology, which classifies standards as either anticipatory, concurrent, or retrospective in relation to technology development. Another important classification related to the connection between technology and standards is the distinction between designing and selecting standardization: Are technical solutions designed and developed as part of the standardization process or is the process based on the selection and formalization of existing alternatives?

The common distinction between different types of standardization processes in the literature is based on the forum and institutional context for standard development: the standard developing organization (SDO), or industry consortium.

The SDO is the traditional forum for conducting standardization, where a persistent organization provides a process framework for supporting the development of standards. The scope and reach of SDOs vary both geographically and topically. Within the construction industry, national standardization through local organizations has traditionally been prominent. The International Organization for Standardization (ISO) was founded in 1947 and remains the world's largest SDO and publisher of international standards, with 160 countries in its network of national standards institutes (ISO.org 2011a). Common advantages of SDO standardization over a process supported by an industry consortium reportedly include responsibility to one or more nations, existing people and resources, the cultivation of broad consensus, and better brand recognition (Krechmer 2005).

Industry consortia in the context of standards development became an increasingly common form of standards development during the latter half of the 1980s, and by the early 1990s, classifications for different consortium sub-types had already emerged (Cargill 1989; Weiss & Cargill 1992). While classification is practical for contrasting and polarizing different attributes, consortia are not stagnant forms of organization. Indeed, later publications have observed the much more fluid behavior of consortia as forums for standardization. *"...[standards] consortia tend to mutate over time, assuming the various forms as they age. [...] sometimes by changing their focus, sometimes by expanding their focus, and sometimes by becoming something different" (Cargill 1998:21).* The notion of a responsive and dynamic standardization process is an underlying assumption for this study as well. Hawkins (1999:161) defines a consortium as *"…an informal alliance of firms, organisations, and (sometimes) individuals that is financed by membership fees for the purpose of co-ordinating technological and market development activities."* The notions of *informal* and *market development activities* are important to note. Consortia are informal in the sense that they commonly function outside of the formal business network, which includes arrangements such as sub-contracting and joint ventures (Hawkins 1999). Market development activities and orientation around business goals have also traditionally remained outside the explicit scope of SDO standardization, although the latter has gradually expanded outside the realm of consortia standardization, as many SDOs have changed their strategy in order to remain relevant to industry needs. The ISO formulates its purpose as providing *"...solutions that meet both the requirements of business and the broader needs of society"* (ISO.org 2011a). Common benefits of consortia standardization compared to an SDO commonly include focused funding, one-stop international standardization, better marketing opportunities, and the possibility to negotiate matters related to intellectual property (Krechmer 2005).

Traditionally SDOs have been viewed as inclusive, open, slow moving, due-process-enforcing, consensus-and-democracy-supporting environments, whereas industry consortia have often upheld the notion of a faster, exclusive, functionality-oriented alternative. While the two major types of standardization might seem to be in direct competition, some have argued that interplay between SDOs and industry consortia can be largely complementary and that both can perform specific tasks in the development of a standard without engaging in redundant work (Lowell 1999). The line between the two institutional contexts has become increasingly blurred, however. A distinct example of this is hybrid standardization, which combines the processes of SDOs and consortia (Schoechle 2009) (e.g. an SDO formalizes and publishes a consortia-developed standard). ISO offers this service through the ISO PAS (Publicly Available Specification) process (ISO.org 2011b). While acknowledgement by an SDO can add to the perceived legitimacy of a consortia standard, history has shown that such an acknowledgement does not on its own make or break the proliferation of a given technology in the industry. Many formal standards have lost momentum and faded away during the standardization process (Gielingh, 2008). Consortia standardization processes can also be more formally organized or open than some SDOs, and vice versa. As such, the organizational form supporting such standardization should not be seen to directly imply much about a given standard or process. Differences in general approach standardization in different parts of the world have also emerged Europe and Asia have traditionally adopted a top-down approach which aims for complete and exhaustive standards, whereas the US has a tendency to rely on a more market-driven, sectorally divided, bottom-up approach to standardization (Egyedi 1996; Hawkins 1999). This difference has implications for international efforts where opinions may vary regarding what fundamental approach to standardization should be adopted.

In research relating to IT standards and data exchange, the concepts of *minimalist* and *structuralist* (sometimes also referred to as *explicit*) methodologies have served as descriptors for two polarizing approaches to reaching data-exchange interoperability (de Vries 1991; Tarandi 1998; Behrman 2002). This paper aims to extend the foundations that these earlier studies set in place and which have motivated our use of similar analytical concepts.

The following definitions, which draw upon and combine definitions provided by Tarandi (1998) and Behrman (2002), serve to describe the core ideologies of the two approaches:

> *"An explicit model can be defined as a type of model where there are concepts corresponding to almost all information types in the products which are to be included in the information exchange. The drawback is the great effort to define the concepts and also to write applications. An obvious advantage is the ease of interpretation for the receiver of the model"* (Tarandi 1998:55). *"The structuralist approach values comprehensive and complete standards. It is a top-down approach. The development process starts with a high-level model and then proceeds with the elaboration of more and more detail. The process is often daunting and time-consuming"* (Behrman 2002:3).

> *"A minimal model can be defined as having very few concepts in its conceptual schema, making it relatively easy to understand. It can also be called generic. The drawback of minimal models is the effort with the interpretation at the receiving end of the data transferred"* (Tarandi 1998;55). *"The minimalist approach values simple standards and rapid adoption by the user community. It is a bottom-up approach in which standards start small. The development process places heavy emphasis on experimentation, testing, and iterative improvement of proposed standards in applications before adoption. Once such standards are adopted and gain acceptance, they are further developed as needed"* (Behrman 2002:3).

These concepts touch upon both the underlying design ideology and composition of the standard, as well as lay out assumptions for the wider standardization process. Tarandi (1998) further identified *layered models* as a third approach, where influences from both the minimal and structural models are utilized in different layers of the data model. We will return to these and the other concepts introduced in this section when we review the standardization approach of IFC in Section 3.

2. METHODOLOGY

2.1 Research motivation

While some studies have contributed at least partial retrospective analytical perspectives on the development of IFC, either alone or in parallel to other standards based on collected empirical material or existing written sources (primarily Tarandi 1998; Eastman 1999; Liebich & Wix 1999; Kiviniemi 1999; Tolman 1999; Behrman 2002; Gielingh 2008; Howard & Björk 2008; Kiviniemi 2008; Björk & Laakso 2010; Liebich 2010), no study has reviewed the standardization process as a dedicated whole.

2.2 Aim of the study

The aim of this retrospective study is to review the history of the IFC standard, as well as to identify and describe the origins and major shifts in its standardization process. We used and referenced relevant literature, both scholarly and professional, to support our analysis. We also used publicly available documentation in the form of technical manuals and meeting minutes. It is important to draw upon what has already been reported in various contexts in order to present informed suggestions for future action for both industry and research. At the same time, this approach potentially enhances our knowledge of the intricacies of the standardization of open specifications in the forum of a distributed global industry consortium. To guide the focus of this paper, we have emphasized chronological completeness in order to encompass the standardization process as comprehensively as possible with regards to timeline coverage. The option is then open for complementary studies to review individual time periods or specific aspects of the standardization more exhaustively.

The main contribution of this study is directed at the construction IT literature, mainly related to aspects of building information interoperability and standardization. However, a secondary audience for this study also exists, as the construction industry is a highly attractive case industry for studying IT standardization; its project-based, multiple-stakeholder environment is well suited for that purpose. Because projects are relatively short term, the environment is dynamic, and the tools used to communicate are evaluated on at least some level for each project. Standards research is a fairly young area of scientific interest, although many of the same technologies have been studied in a large part of the available literature. Some of the most popular case technologies in the field of IT standardization have been telecommunication (e.g. Egyedi 1996; Fomin 2001), Internet standards (e.g. Crocker 1993; Hovav et al. 2004), and supply chain communication standards such as EDI and e-business services (e.g. Damsgaard & Truex 2000; Zhao et al. 2005). This study should provide an accessible resource for individuals outside of the construction IT research area to obtain an overview of the developments thus far. As such, this study contributes to the diversity of research within the standardization area with one of the most interesting cases of IT standardization currently in progress. Connecting the lessons learned from the standardization of IFC to the growing literature and theory of standardization can be mutually beneficial. However, enabling such an interchange to take place requires a descriptive review of what is known and has been explored thus far.

3. IFC PAST TO PRESENT

This part of the paper analyzes the history of the IFC standard, which spans the origins of the standard and initial planning stages in the early 1990s through the current situation in 2012

3.1 Pre 1994 "Stepping out"

Advances in product data exchange from the early days of CAD through the release of STEP (Standard for the Exchange of Product Model Data) can be divided into three distinct generations of data exchange methods: ad-hoc solutions, which have been used since the 1950s; neutral CAD standards, which emerged in the 1980s; and STEP standards, which have been released since the 1990s (Bloor & Owen 1995). Not only is each generation distinct in its level of technological advancement, but the industry context and demands for product data exchange within it have undergone radical change during each time period as well.

During the first generation of product data exchange methods from the 1950s to the 1970s, closed and proprietary solutions were used exclusively. This was not only due to the rapid pace of technological development, but also because the actual needs for data exchange during this initial period can be considered limited. Computers of that time were workstations used for narrow and specific tasks, mainly speeding up and automating tasks that could otherwise be done manually, such as calculations.

The second generation of exchange standards, which emerged in the late 1970s and endured to the mid 1980s, is identified as a stage when open formats for the representation of basic geometry began to emerge. Such exchange standards developed in the late 1970s gained support by being incorporated within national standards in many parts of the world, of which perhaps the most notable is IGES (Initial Graphics Exchange Specification), a neutral exchange standard for CAD models. In 1979, a consortium of heavy industry CAD users penned an agreement with the leading CAD vendors to jointly develop an open exchange mechanism. Open exchange standards were a new concept at the time and were initially considered a threatening proposition for CAD vendors, who feared they would have to disclose a major competitive advantage. However, after some short-lived initial resistance, vendors began to see support for open standards as something attractive from a marketing point of view as well as a means to increase one's chances of obtaining government contracts (Kemmerer 1999). The first version of IGES was published in 1980. Despite the fast standardization cycle of about a year (from committee formation to publication of the first draft standard), IGES struggled to stay relevant in a time when 3D modeling began to prove viable for design drawings; IGES for CAD use outside of limited contexts remained primarily based on more feature-rich and well-supported vendor-specific formats (Gallaher 2002). Nevertheless, the standardization of IGES suggests some interesting notions; a limited technical scope, which includes only parts proven as implementable, and a high level of dedicated buy-in among a limited group of vendors and customers, can facilitate the standardization process (Kemmerer 1999).

Marking the beginning of the third generation of exchange formats, in 1984 the TC184/SC4 subcommittee of ISO declared that none of the existing formats could on their own be extended to serve the needs of an open computer modeling standard for multiple industrial and manufacturing industries (Bloor & Owen 1995). That point marks the beginning of the development of STEP. The AEC/FM industry was just one of several industries included for standardization within STEP. The STEP specification formalized a long line of development in national and industry consortia standards, of which the U.S. developed PDES (Product Data Exchange Standard) specifically for general technical architecture, GARM (General AEC Reference Model) and the Building Systems Model (Turner 1990) for the AEC/FM industry-specific concepts, which themselves were a combination and integration of previously developed models (Gielingh 1988; Bloor & Owen 1995: Kemmerer 1999). When work on STEP started its objectives were beyond what technologies could offer at the time, so for a long time standardization had to be conducted in anticipation or in parallel with features being implemented commercially available software (Wix & Bloomfeld 1995; Kemmerer 1999). SC4 recognized that robust data modeling was central to supporting the complexity of STEP, and after some evaluation, existing modeling languages were deemed incomplete or unsuitable for the requirements of STEP. Thus began an effort to develop a language that later became known as EXPRESS (Kemmerer 1999). The EXPRESS information-modeling language was initially developed in conjunction with STEP to define STEP data models as well as the standard itself. Relationships, attributes, constraints, and inheritance are core concepts of EXPRESS. The information models are both machine and human readable, and in addition can be rendered graphically through the EXPRESS-G notation standard, or as an instance through EXPRESS-I (Schenck & Wilson 1994). Before the need for separate Application Protocols (AP) for different industries became apparent, attempts to integrate information models from different disciplines were made. This integration was problematic and progressed slowly, because existing models were on different levels of abstraction. The purposes of the APs became to explicitly define information needs within a particular domain or application, to unambiguously specify which information needs to be exchanged, and to provide a foundation for conformance verification. The concept of APs is largely built upon the basic architecture developed within the PDES effort, an information model that the STEP committee had voted against two years earlier (Kemmerer 1999). In December 1994, the initial release of STEP became an international standard: ISO10303:1994, *Industrial Automation Systems and Integration - Product data representation and exchange* (ISO.org 1994). As work on the AEC/FM industry-specific components of STEP progressed, the Building Construction Core Model (BCCM) became the central data model for AEC/FM related concepts. BCCM was an ambitious effort to aggregate and harmonize the most important aspects of existing work and develop a high-level data model and universal concepts across the major AEC/FM disciplines, active between 1994 and 1997 (Wix & Bloomfield 1995).

For over 20 years construction IT researchers have studied aspects related to the representation and interoperability of product model data for construction, an area of technology that is now commonly referred to as BIM. As examples of some early work, Björk & Penttilä (1989) proposed five requirements for an open building product model standard that should: 1) encompass all building information, 2) meet the information needs of all stakeholders, 3) be non-redundant, 4) be software independent, and 4) be format independent. Eastman et al. (1991) suggested similar criteria in a later study: 1) represent function and form, 2) support the product lifecycle and multiple levels of abstraction, 3) provide general semantic representation, 4) and provide extensible semantics. Although these requirements are both abstract and defined without consideration of implementation-related practical issues and limitations, they nevertheless embody much of what, only a few years later, was incorporated into the IFC standard. IFC is in many ways the culmination of this area of research; these are only some examples showcasing the largely cumulative foundation of IFC. For an extensive retrospective review of the research on early building product model data readers are recommended to look up Eastman (1999).

3.2 1994-1999 "From IFC 1.0 to IFC 2.0"

While the STEP ideology of having common universal resources at the core of a comprehensive standard intended to cover a diverse range of industries was an attractive prospect, thereby reducing any redundant standardization work and enabling easier future cross-industry collaboration, the motivation to launch a separate standardization effort began to grow among actors in the AEC/FM industry. The massive ISO STEP effort, with the promising BCCM data model tied into it, was as a whole considered too slow and unresponsive to meet upcoming market demand for the construction industry in the near future (Tolman 1999). In August 1994, 12 US-based companies joined together to examine the possibility of developing an open standard for increased interoperability of emerging building information modeling software. The initial group of companies included AT&T, Archibus, Autodesk, Carrier, HOK, Honeywell, Jaros Baum & Bolles, LBNL, Primavera, Softdesk, Timberline, and Tishman (Kiviniemi 2006). After development of initial prototypes showcasing the possibilities, in September of 1995 the IAI (Industry Alliance for Interoperability, changed to International Alliance for Interoperability in 1996) was formally founded and the consortium opened up for other companies to join (IAI 1999).

In his influential building product modeling textbook published at the time, Eastman (1999:314) described the IAI's actions as follows "*Technically the IFC is not a standards effort, but rather an industry-led undertaking to develop practical user capabilities for data exchange."* During these early days, the IAI could hardly have been referred to as a consortium due to its loose informal couplings with the organizations involved and the lack of a formally registered organization representing it. In addition to the two major types of standardization processes, SDO and consortia, Cargill (1998) further identified the standardization form of alliance. Cargill (1998:19) writes *"This type of activity is usually a preliminary step to becoming a consortium, unless the activity is to be very short-lived and reasonably simple."* The early days of the IAI effort fits this description well, although IAI's adoption of more traditional consortium characteristics increased as time went on.

IAI had established seven chapters in 1996, each a separate organization representing an international region: the French-speaking, German-speaking, Japan, Nordic, North America, Singapore, and UK chapters (IAI 1999). Due to its heterogeneous division into chapters, with some chapters spanning multiple countries and others being based on spoken languages, the administrative hierarchy below the chapter level is not uniform on a global level; each chapter includes representatives from either several national forums or representatives directly from member companies. The national forums exist as additional layers aggregating country-level activities, autonomously regulating and collecting membership fees from their member companies. A diagram demonstrating the two different forms of administrative structure appears in Figure 3. In 1999, the IAI encompassed over 20 countries and 600 member companies. In 1997, estimates for the annual budget of the International IAI Organization were around 200 000 USD (Nordic IAI Chapter Board Meeting 1/1997).

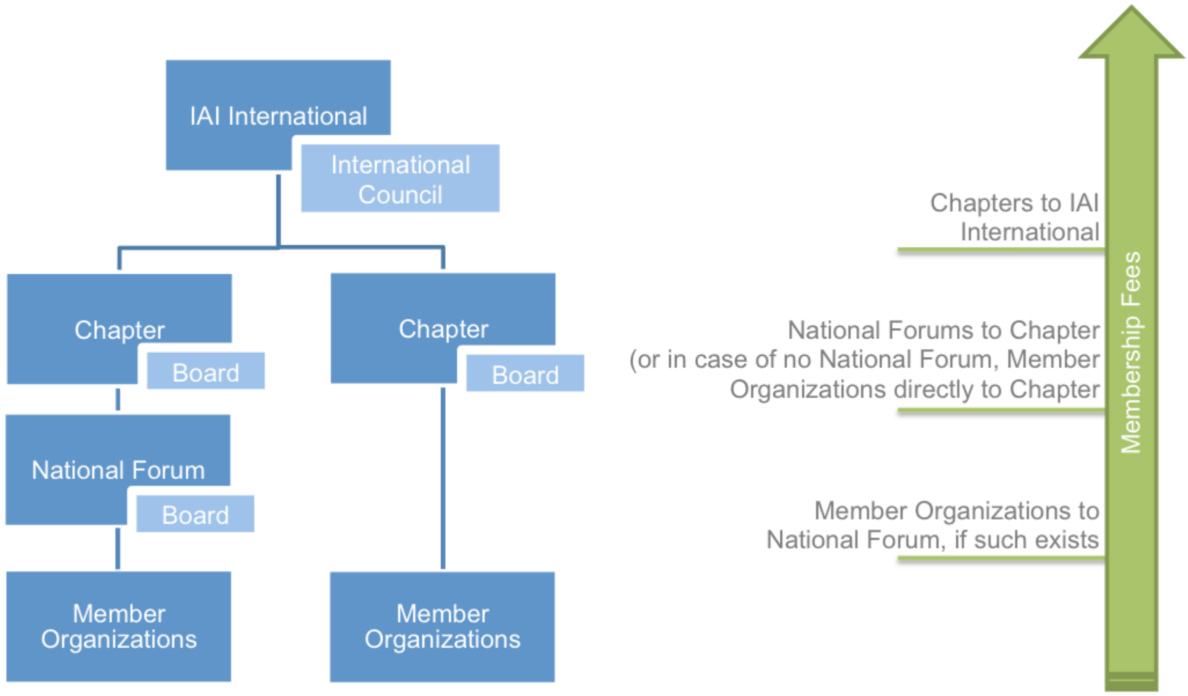

FIG. 3: Relationship between members, national forums, chapters, and IAI International

The IAI expressed its vision as "*To enable software interoperability in the AEC/FM industry*" and its mission as "*To define, promote and publish a specification for sharing data throughout the project life cycle, globally, across disciplines and across technical applications*" (IAI 1999:3).

The IAI was founded on the following values (IAI 1999:4):

"
- *Not-for-profit industry organization*
- *Membership open to any company working in the AEC/FM industry*
- *Action oriented: Alliance vs. Association*
- *Consensus based decision making*
- *Incremental delivery rather than prolonged study*
- *Global solution*
- *AEC/FM industry professionals working with software professionals to define standard specification*
- *Specification to be open for implementation and use by all software vendors*
- *Design for specification to be extensible*
- *Specification will evolve over time*

"

The major roles within the development cycle as identified by the IAI were: project groups for defining the requirements, technical experts for specification and integration, and software vendors for implementation (Liebich & Wix 1999). A basic outline of the IAI's internal structure, based fundamentally on these roles, appears in Figure 4.

FIG. 4: Outline of the IAI's internal organizational structure and division of main responsibilities (author reproduction based on source: Kiviniemi 1999a)

3.2.1 Fundamental technical aspects and structure of the IFC data model

Using existing parts from the ISO STEP standard, most notably incorporating concepts from the BCCM model, EXPRESS modeling language, definitions for geometric representation, technical development did not begin from an empty slate (IAI 2000). Eastman (1999:314) estimates that about half of the objects and types present in the first IFC releases were adopted from the integrated resources of STEP. Nevertheless, the task of composing a strict but flexible data model capable of containing and representing product and process data fulfilling the requirements of an entire industry is no small task. Information modeling involves the extraction and subjective interpretation of reality, defining concepts and attributes considered relevant and creating semantic relationships between them. Thus creating an unambiguous internationally accepted generic data structure is an extremely challenging task. IFC was always intended to be a high-level data model, like STEP, which exists above software implementations to remain truly neutral and future-proof. It provides a standardized data structure for the storage of building information, but does not itself enforce, or even enable, any specific way of implementing it into software. Almost anything is possible; it is up to the software developers to decide. EXPRESS schemas containing IFC data can be encapsulated into files for physical file-based exchange, or the IFC data structure can be represented in an object-oriented database and be updated remotely over the Internet In practical terms, most BIM software end-users interface with the IFC in the 'Save As' or 'Export' dialogue of the software where the IFC standard might be listed as one of the options for storing the model data, in parallel with proprietary data formats. However, the IFC standard itself is not an API (Application Programming Interface), though some have argued that it is (Tolman 1999). Rather, the IFC standard is a generic implementation-independent data model along which APIs can, and have been, designed to implement the data model in different application environments and programming languages.

The structure of the IFC data model was divided into four layers: domain, interoperability, core, and resource layers. Relationships between these layers appear in Figure 5. The layers have strict referencing hierarchies, the main rule of thumb being that referencing can only occur downwards in the hierarchy. This means that data in the resource layer must be independent and reference no classes above it. The other layers, however, can all reference data from the resource layer as well as all other layers below them. References within the same layer are allowed only for the resource layer. The *resource layer* holds the resource schema that contains basic definitions intended for describing objects in the above layers. The *core layer* consists of the kernel and extension modules. The kernel determines the model structure and decomposition, providing basic concepts regarding objects, relationships, type definitions, attributes and roles. Core extensions are specializations of classes defined in the Kernel. The *interoperability layer* provides the interface for domain models, thus providing an exchange mechanism for enabling interoperability across domains. The *domain layer* contains domain models for processes in specific AEC domains or types of applications, such as architecture, structural engineering, and HVAC, among others. (IAI 1999a;IAI 1999b:IAI 2000)

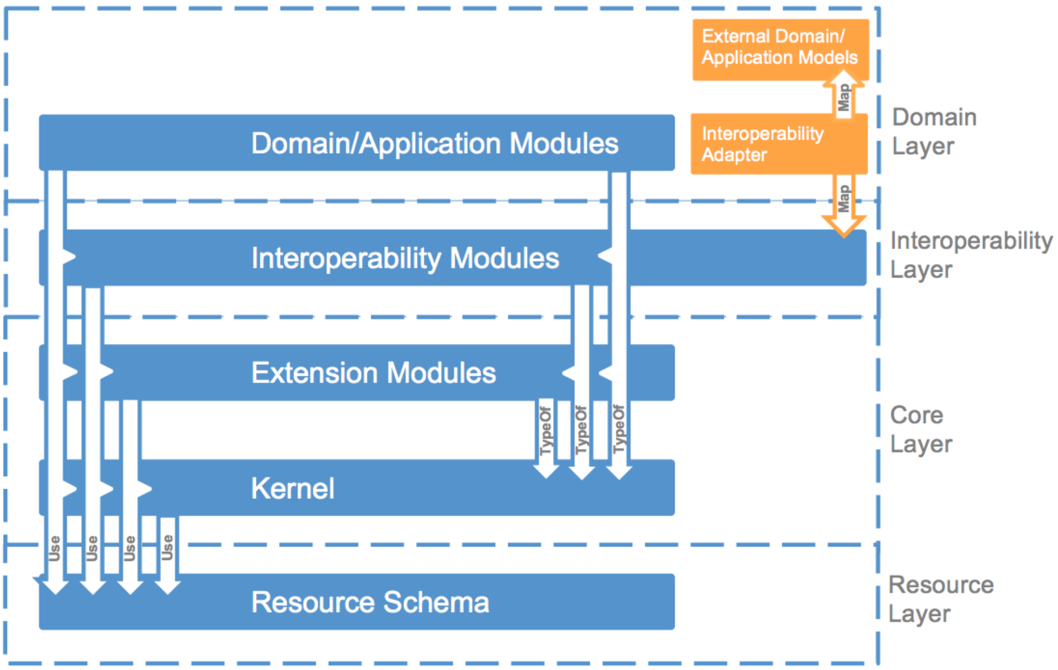

FIG. 5: Structure of the IFC data model (author reproduction based on source: IAI 1999b:IAI 2000)

Only a short while after the general structure of the IFC data model had been finalized Tarandi (1998) included IFC in a comparison of eleven different AEC/FM product data model standards, taking a closer look at the general data relationship structures and whether they are dominantly minimal or explicit (structural) in how they support data exchange. Most standards were identified as either minimal (EPISTLE, GARM, EDM, OOCAD, The Minimal Approach) or explicit (AP225, AP230, AEC Building Systems Model, COMBINE), while the IFC data model and the ISO STEP Building Construction Core Model were classified as layered models, i.e combining traits from both minimal and explicit approaches. Tarandi (1998) argued that the low-level resource and core layers of the IFC data model were minimal in the sense that they hold the high level concepts from which the other levels draw on to construct specific explicit (structural) data definitions which might or might not draw upon external data tables and classifications. While this is true when looking at the IFC data model on the micro-level, layer-by-layer and the relationships between the layers, we argue that the IFC data model as a whole is dominantly structuralist when considering how it is assumed to used and implemented; this notion is shared by Behrman (2002), which will be discussed more extensively in Section four.

As a demonstration for how IFC data can be interfaced with in practice, Figure 6 depicts excerpt IFC source data from a STEP physical file (ISO 10303-21) containing information about a building, and Figure 7 visualizes what the same, complete file, looks like instantiated in BIM software. While each line of syntax is assigned a unique sequential number, the contents within STEP physical files is not structured in any specific order nor are the boundaries of the data subsets obvious by looking at the data despite being human-readable; i.e. it is not possible to partially exchange data across STEP files simply by cutting and pasting lines of code (Yang & Eastman 2007). Instance data has to be created where the content of the file is parsed into object structures and semantic structures are constructed.

```
#14290= IFCQUANTITYAREA('GrossSideArea',$,$,13.5);
#14292= IFCQUANTITYAREA('NetSideArea',$,$,13.5);
#14294= IFCQUANTITYVOLUME('GrossVolume',$,$,2.376);
#14296= IFCQUANTITYVOLUME('NetVolume',$,$,2.376);
#14298= IFCQUANTITYAREA('GrossFootprintArea',$,$,0.88);
#14300= IFCELEMENTQUANTITY('39WRngk_9CBgT2CyujQGwI',#29,'BaseQuantities',$,'',
(#14284,#14286,#14288,#14290,#14292,#14294,#14296,#14298));
#14305= IFCRELDEFINESBYPROPERTIES('3pBHU4_rT0HfoLp_Fbra9j',#29,$,$,(#14122),#14300);
#14307= IFCMATERIALLAYERSETUSAGE(#14105,.AXIS2.,.NEGATIVE.,0.1);
#14308= IFCDIRECTION((0.,-1.,0.));
#14312= IFCCARTESIANPOINT((12.,7.,0.));
#14316= IFCAXIS2PLACEMENT3D(#14312,#52,#14308);
#14320= IFCLOCALPLACEMENT(#2946,#14316);
#14323= IFCWALLSTANDARDCASE('2JXm8iNNv7LfVrBi4zO_Vd',#29,'Wand-019',$,
$,#14320,#14393,'35C73C96-4BA7-4334-A6-A1-102EFD27E980');
#14342= IFCCARTESIANPOINT((0.,0.));
```

FIG. 6: Excerpt data from an IFC BIM model stored in STEP physical file format. (AC11-Institute-Var-2-IFC model courtesy of the Open IFC Model Repository 2012)

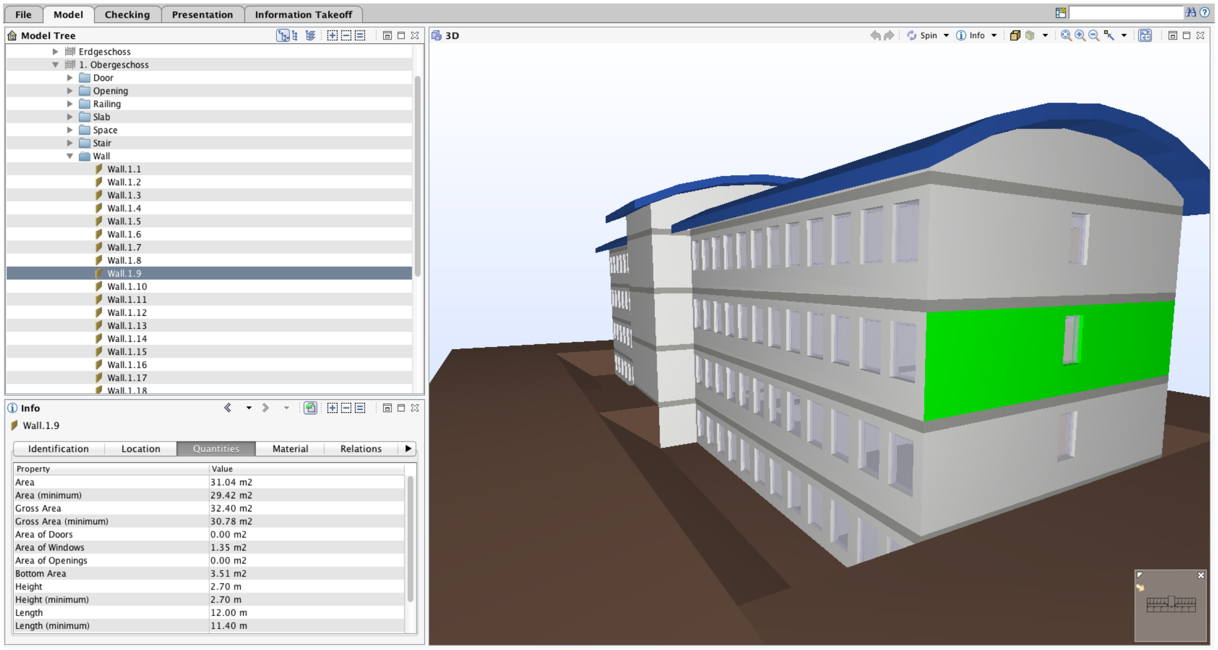

FIG. 7: IFC BIM model instantiated and visualized in software (Solibri Model Viewer, AC11-Institute-Var-2-IFC model courtesy of the Open IFC Model Repository 2012).

Because the class and entity structure of the IFC standard was based on no pre-existing ontology within the construction industry, an aspect that has become relevant for discussion, as international classification systems for building parts have become increasingly standardized. The purpose of ISO 12006-2 *"Organization of information about construction works – Part 2: Framework for classification of information"* is to coordinate several regional and national classifications systems which has been evaluated in terms of retrospective harmonization with the IFC standard (Ekholm 1999, Ekholm, 2005). According to Ekholm (2005), integrating IFC with ISO 12006-2 would help facilitate the adoption of object-based information management, even though the starting point for IFC development was explicitly to reject the influence of existing classifications in its technical framework due to their constraining influence on information modeling concepts. Research has focused on this issue since before the dawn of IFC (Ekholm 2005); in fact, Björk (1992) identified possible harmonization between building classifications and product modeling within the "Unified Approach Model". Although harmonization is possible in theory, it would be difficult; integrating ISO 12006-2 classification using the initiation methodology suggested by Ekholm (2005) would first require a move towards conventional and strict object-oriented definition practices in the underlying IFC data model to replace some of the adopted ad-hoc solutions, which in turn would require a major commitment to the effort by the consortium.

Even though the scope of STEP and IFC overlap, the relationship between the two efforts began on good terms. In 1997, a liaison agreement and something referred to as a 'Memorandum of Understanding between ISO

TC184/SC4 and the IAI' aimed to strengthen knowledge sharing between the two organizations and standardization efforts (IAI 1999:20). The two efforts differed over the forum of standardization and core mission, formulated succinctly in a paper from that time as "STEP *must* take as much time as necessary; the IAI *must* act quickly" (Bazjanac & Crawley 1997:209).

3.2.2 IFC 1.0 – IFC 1.5.1

With development formally launched in September 1995, IFC 1.0 was published in January 1997. The release, having a very limited scope, focused primarily on the architectural part of the building model, incorporating five processes for architecture, two for HVAC design, two for construction management, and one for facilities management. This first release was only used for prototypes; a total of 17 companies developed implementations based on IFC 1.0, which was carried out in order to create some initial experience of using the format and to increase stability for IFC 1.5 (Kiviniemi 1999). The development cycle for IFC 1.5 was fairly short: work on the update was initiated in February 1997 and released in November 1997 (Kiviniemi 1999). When the time came to implement IFC 1.5 into software, problems arose with the model, which led to the development and subsequent release of IFC 1.5.1. The first implementations in commercial BIM software came out around July 1998, with several commercial modeling suites supporting IFC 1.5.1. In conjunction with the release of IFC 1.5.1, the first version of the IFC Object Model Architecture Guide (IAI 1999b) and the Specification Development Guide (IAI 1999a) were released to the public to enhance the potential for collaborative development of the standard (Liebich & Wix 1999). At this point, the objective of the IAI was to issue a major release of the IFC data model annually (IAI 1999). According to figures and estimates published at the time, the actual hard development costs for IFC 1.0 and IFC 1.5 were only USD 60 000 and USD 225 000, respectively. However, the fact that the contributor effort was valued respectively at USD 1.6 million and 250 000 USD for the two releases (Kiviniemi 1999) highlighted the important resource input mechanism on which the IFC development work depended: externally funded research projects. As we will elaborate on further, national and international research efforts have played a key role in either directly or indirectly driving IFC development forward, a mechanism which is of great importance when observing IFC standardization to better understand its unique development context.

3.2.3 IFC 2.0

As the first truly international IFC release, the scope of IFC 2.0 was primarily to incorporate schemas for building services, cost estimation, and construction planning (Liebich 2010). The development of IFC 2.0 began in December 1996, and the final release was delivered largely on schedule 29 months later in April 1999. The IAI hard costs for the release – under USD 400 000 – were again low, although the contributor labor effort cost an estimated USD 2.5 million (Kiviniemi 2006). These numbers highlight a continued reliance on contributed effort in the development effort. Although the organization managed to firmly establish a sustainable funding model despite having so few resources, new member companies were joining at an unexpectedly slow rate, and some old members grew frustrated with the slow pace of progress, since the scope of functionality was still fairly limited (Kiviniemi 2006).

Since responsibility for figuring out practical implementations of the standard fell squarely on the software developers the Building Lifecycle Interoperable Software Group (BLIS) group was founded in 1999 to accelerate and coordinate implementation efforts and narrow the gap between publication of the standard and its implementation in software (BLIS-project.org). This was a separate organization from the IAI and offered its own optional membership. The organization aimed to give software vendors an opportunity to collaborate and get an early start on developing implementations (Karstila & Serén 2001). A vision for BLIS was also to develop BLIS-specific use-cases of the IFC model (i.e. restricted but well-supported subsets of information to be exchanged in a specific workflow).

In a review paper from this period, the STEP and IFC standardization processes, the AEC/FM industry's efforts to standardize product modeling generated fairly pessimistic outlooks: STEP, for being fragmented and burdened by democracy and lacking real drive behind it, and IFC, for generating weak support among industry actors and having few resources available to make substantial progress (Tolman 1999).

3.3 2000-2005 "ISO PAS and IFC 2x"

This time period marked several important shifts in the standardization process. Initial enthusiasm for the standardization effort came up against some harsh realities: the industry's reception of IFC 1.0, 1.5.1, and 2.0 was lukewarm, and IFC usability in real-world projects was considered poor. Coupled with its dwindling resources and lack of long-term plans for future development, this period was clearly one of the major low points in the standardization process; larger changes had to be made in order to maintain momentum. Prior to the year 2000, road maps for future development were largely absent, partly due to the lack of common vision concerning the content and purpose of the standard. An excerpt from meeting minutes of the Nordic IAI Chapter Board Meeting in October 2000 (p.2) effectively expresses the general atmosphere of the time: *"The main problem is lack of international resources. Also the lack of participation of some chapters on international level is causing problems in decision making process, because it is very difficult to get the majority."*

The focus of the work within IAI was initially oriented towards specification development, leaving it to the industry to determine feasible use-cases and implementations of the resultant specification into software. Since developing the standard was a huge effort in itself, both technically and administratively, it is understandable that limited consortium resources made it impossible to establish robust in-house implementation support processes early on. No one was paid to support or monitor implementations; general implementation and certification meetings were the main and only activities (Kiviniemi 2006). One effect of the liberal approach to implementations presented problems for establishing a unified robust certification process. The time around the release of IFC 1.0 and 1.5.1 saw an urgent push to get IFC certified products into the marketplace, which, combined with the limited resources, led to the establishment of simple certification tests. Although the official certification guide is not a public document and was available only to IAI members, the main parts of the process, however, appear in other publications (e.g. IAI 2000, Karstila & Serén 2001, Steinmann 2010). The end result of the certification processes was that implementation quality of certified products was insufficient for reliable data exchange between software applications in real projects (Kiviniemi 2008). Despite problems with fundamental interoperability, future releases of the standard were marketed with an emphasis on new features and domains covered by the standard, even though only a small fraction of the existing features had been implemented in the commercial software. Together, these problems contributed to the persistent notion that IFC interoperability as a whole is unusable.

For the sake of simplicity, this paper has until now described the IFC simply as an ‘open’ standard; its degree of ‘openness’ (West 2004; Krechmer 2005), however, saw an important shift during this time period. Initially, the intention was to limit access to the IFC standard and only make it available to members of IAI chapters (Nordic IAI Chapter Meeting Minutes, Strategy Meeting 6/1996); not until the IAI summit in Munich in October 1999 was the notion of an openly available IFC standard and documentation proposed for formal discussion within the consortium. The open publishing and free use of the IFC standard were formally approved during the next international IAI summit in Melbourne, February 2000 (Nordic IAI Chapter Meeting Minutes, Board Meeting 3/2000). Attempts to commercialize the IFC standardization process were also made; at one point, some software vendors had initial plans to sell IFC test files necessary for certification to potential adopters of the standard for USD 2000 (Nordic IAI Chapter Meeting Minutes, Board Meeting 6/2000). In addition to opening up the IFC specification, the Melbourne meeting in 2000 was an important turning point in the standardization process, giving *"... new hope for the future of IAI"* (Nordic IAI Chapter Meeting Minutes, Board Meeting 3/2000:3). Not only did the consortium decide to open up the standard for implementation by anyone for free, and adopt a more transparent standardization process, but at the same time, the consortium also initiated partial SDO standardization known as the ISO PAS process. In order to increase the legitimacy of the standard, getting the ISO to publish the standard became a priority within the consortium (IAI Nordic Meeting Minutes). During this time, the consortium also became increasingly global with five new chapters joining the consortium between 1997 and 2006: Australasia, China, Iberia, Italia, and Korea (Kiviniemi 2006). In 2005 the stable core of IFC 2x attained ISO/PAS16739 status; and since 2008 the status of this specification has remained “*International Standard to be revised*” (ISO.org 2008).

While it may seem odd that the ISO became involved in publishing two separate standards with overlapping purposes, IFC and STEP, the situation is not unique for the case of product modeling in the construction industry. Intending to provide interoperability to word processing files, the ISO standardized both the Microsoft-supported OOXML format and the Sun Microsystems-supported Open Document Format (ODF), which are not cross-compatible with each other even though both are XML-based. While some argue that competing formal standards are a good thing because they encourage innovation in the standardization process and let the market make the ultimate choice (Blind 2008), others have argued that overlapping standardization causes confusion in addition to unnecessary societal and economic costs, and that innovation and competition should be limited to the products that implement the standard rather than at the level of standards (Egyedi & Koppenhol 2009).

3.3.1 IFC 2x and IFC 2x2

Because IFC 2.0 had aggressively increased the scope of information supported by the standard, IFC 2x was primarily a stability release, which included a considerable rework of some of the underlying technical architecture (Liebich 2010). IFC 2.0 was the stable core of IFC 2x that was submitted to the ISO PAS process. The schedule for the IFC 2x release was 30 months, with work on the release being underway from January 1998 to July 2000; the final version was published in October 2000. Again, the IAI's hard costs for the release were lower than the cost of the contributed effort; members contributed around the equivalent of USD 5 million, whereas the hard costs of IAI were only USD 500 000 (Kiviniemi 2006). IFC 2x2 was released in May 2003 and was a release that brought with it a considerable increase in scope, featuring 2D model space geometry, presentation, extension of the building service component breakdown, structural analysis structural detailing, support for building code verification and facility management (Liebich 2010).

The development of ifcXML, an official XML representation of IFC, began in 2001 and was released later that same year. ifcXML provides XML language bindings to the IFC EXPRESS schema. However, simply translating the language does not bring with it any instant fix to conceptual challenges in information modeling. Because of the inherently different structures of the STEP-File and XML modeling language, translation of native IFC STEP-File to ifcXML result in needlessly large, lossy, and unoptimized files which compromise the strengths of XML modeling (Behrman 2002).

During this time, a significant push for IFC-based BIM was initiated in Finland in the form of the ProIT project, a Finnish national effort that ran between 2002 and 2005. ProIT was a broad joint project between public sector stakeholders and construction industry companies coordinated by the Confederation of Finnish Construction Industries with the intention to facilitate the use of product model data in the construction process. In addition to the important role of increasing market awareness and coordination on the topic by disseminating up-to-date information about the use of BIM technology in projects, modeling guidelines were developed for both architectural and structural design (ProIT 2004 & ProIT 2005). In addition to signaling some of the first formal public sector interest in BIM and IFC, the project contributed directly to IFC standardization by developing an 'IFC Aspect Card Library', which provided pre-defined subsets of the IFC data model to support the implementation of IFC data exchange by providing specific use-cases as a base for the exchange (Karstila & Serén 2005). While the data exchange use-cases were primarily intended to support modeling guidelines for the Finnish construction industry developed within the ProIT project, the effort invested into the development of the aspect card methodology was a direct contribution to facilitating implementation and use of the IFC standard.

3.4 2006- "Emergence of buildingSMART and the useful minimum"

The year 2006 saw a re-naming and re-branding of the IAI consortium to buildingSMART, a change which brought with it greater emphasis on the business benefits of an interoperable integrated design and construction process. Central to this refresh was a reformulation of the consortium's vision. As noted earlier, the old vision was formulated as "*To enable software interoperability in the AEC/FM industry*." The new vision goes beyond technical aspects to emphasize what interoperability means for users and business: *"Improving communication, productivity, delivery time, cost, and quality throughout the whole building life cycle"* (Stangeland 2009:1). This marked a change mostly in approach and methods, with little to no influence to the form of organization within the consortium. Currently, buildingSMART has 13 chapters around the world, all of which are represented by two delegates in an international council that meets twice annually to coordinate business and technical strategies (buildingSMART.com 2011).

In its overall standardization approach, this time period marked a change from the past by increasing the focus on minimalistic/bottom-up methods of narrowing down IFC data exchanges into manageable, predictable, and implementable specifications. Hietanen & Lehtinen's (2006:1) report "The useful minimum" communicates this general emergent climate well by defining the concept of the useful minimum as "*The minimum scope for data exchange, which makes IFC based exchange a better solution than any other available format*." Reducing the scope of information exchange from dealing with the whole IFC data model to well-supported and predictable workflows is considered a gateway for the industry and implementers to increase their support for the standard, after which incrementally increasing the number and scope of the supported exchanges would be easier when use of the standard increases. While in-depth technical description and documentation are beyond the scope of this paper, and since they already exist in the publicly available documentation of buildingSMART, a brief overview of the functionality, purpose, and scope of these technologies should prove beneficial for understanding the direction in which the standardization has shifted.

One outcome of the emergent minimalistic approach to standardization is the concept of Information Delivery Manuals (IDM), for which specification was introduced in 2007 as an official element of IFC standardization. IDMs aim both to serve the technical implementation needs of software developers and to provide role-based process workflows for end-users, thereby supporting an integrated construction process. While buildingSMART could in theory release and endorse generic applied IDMs, buildingSMART's primary purpose is to provide a toolset and specification for how IDMs should be created for the purpose of industry actors creating their own. An IDM is intended to be an integrated reference for processes and data required by BIM and should specify *where* a process fits; *why* it is relevant; *who* are the actors creating, consuming and benefitting from the information; *what* is the information; and *how* should software solutions support this information (Wix 2007).

Another outcome of the minimalist standardization approach is the IFC Model View Definition Format (MVD), of which the stated goal was "*finding a useful balance between the wishes of users/customers and the possibilities of software developers, and documenting the outcome clearly*" (Hietanen 2006:2). Proposed by BLIS in early 2005 and introduced as an official element of IFC standardization in 2006, MVDs narrow down the complete IFC model specification, documenting how data exchanges are applied between different application types; as such it mostly directly benefits the implementers of IFC software. One software application can implement one or several MVDs depending on the scope of its domain. The MVD format is largely a harmonization of the BLIS and ProIT efforts.

The major parts of an IDM, in descending order of technical abstraction, are: process maps, exchange requirements, functional parts, and concepts. The *process maps* should provide an understanding of who the involved actors are, how the activities are configured , and what information is required, consumed and produced at different stages of the process. An *exchange requirement* describes in non-technical terms, the information that must be exchanged in order to support a particular business requirement at a particular stage of a project, with the principal audience being the end-users, but is something software vendors must also be aware of in order to provide them support. *Functional parts* are individual units of information which software vendors use to support exchange requirements, describing the information by taking into account the requirements of the IFC data model. *Concepts* are connected directly to the IFC model and are implemented in functional parts. Concepts are capable of, but are not limited to, capturing the basic functionalities of a model, such as naming and classification, and can be flexibly assigned to individual or whole entities (Wix 2007). The IDM methodology and format was published as ISO/DIS 29481-1 in April 2010 (ISO.org 2010).

How both the IDMs and MVDs relate to each other and to the wider context of the IFC data model appears in Figure 8. The IFC data model is the foundation from which specific MVDs are defined. Software applications then implement support for specific MVDs. IDMs provide documentation and guide the workflow of IFC-enabled exchanges, and are designed acknowledging the functionality of specific MVDs. These cross-referencing information exchange layers were designed to facilitate the deployment of IFC-supported interoperability.

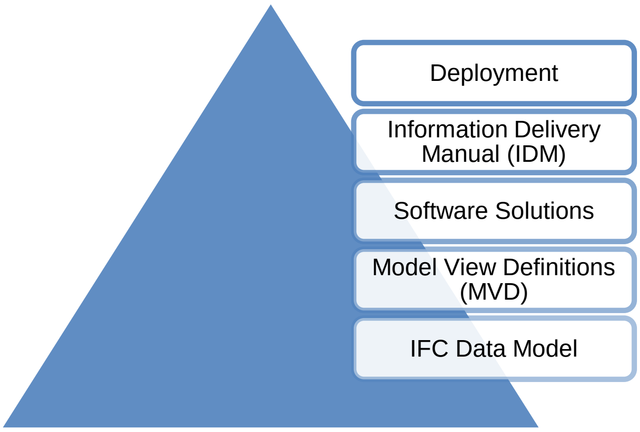

FIG. 8: Layers of the information exchange framework (author reproduction based on source: Wix & Karlshøj 2007:18)

In addition to IDM and MVD concepts to extend the scope of standardization of IFC-based exchanges beyond the IFC data model, the International Framework for Dictionaries (IFD) effort formally began at buildingSMART International in April 2008 during this same time frame (ifd-library.org). Referred to as the third pillar of IFC data exchange, together with IDM and MVD, IFD describes *what* is exchanged by providing a mechanism that allows the creation of dictionaries or ontologies, to connect information from existing databases to IFC data models (Bell & Bjorkhaug 2006). IFD goes beyond the limits of error-prone language-restricted text descriptions while still offering human-readable and understandable descriptions. IFD information in IFC models, like information related to materials of structures or other supplemental descriptions, are tagged with Global Unique IDs (GUID) which, coupled with a reference to a locally or remotely stored library, can produce human-readable text strings in virtually any language. The largest benefits of this approach would become available as unified libraries with open application interfaces grow, with the optimal scenario of having a single global library which would cater to the needs of producers to enter information about their product catalogues. Initial work on a standard to fulfill similar purposes began in 2006 as a collaboration effort between the BARBi project in Norway and the Lexikon project in the Netherlands; the work then continued within buildingSMART International (ifd-library.org).

The IFD standard is an example of how standardization dynamics influence the choice of forum for development of the standard. Even though the IFD standard is very similar to the ISO 15926 standard, a standard commonly referred to as EPISTLE (which the oil industry uses), the owners of different IFD libraries decided to keep the content completely free and open, and avoid some of the complexities of appending work to an existing standard (Bell & Björkhaug 2006). Different types of standards place different demands on their standardization processes, as the end result is meant to fill different needs and purposes. The decision not to extend the work of the EPISTLE standard to accommodate construction, even though the dictionaries would have much in common, can be considered something similar with regard to the decision to develop IFC as a separate effort instead of working on the STEP standard within ISO. Notably, the IFD standard was developed according to the principles of the ISO 12006-3:2007 framework standard for object-oriented building information, which we discussed earlier in relation to the architecture of the IFC data model (ifd-library.org). So while the IFC data model is neither built exactly according to the ISO data model, nor retrospectively harmonized to it, the IFD standard provides support for information structured according to that framework of classification.

A holistic diagram depicting all three of the buildingSMART standards appears in Figure 9.

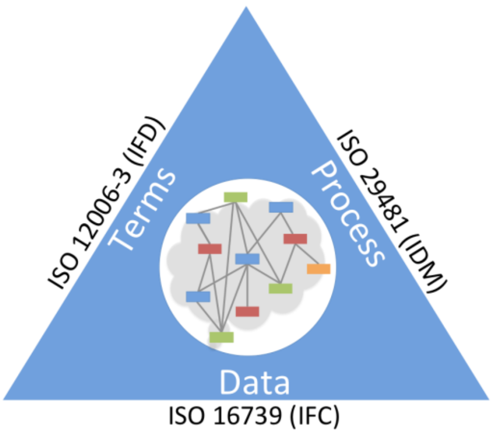

FIG 9: The buildingSMART standards (author reproduction based on source: http://www.buildingsmart-tech.org 2011)

In August 2009, in an effort to collect feedback from different user groups, the Modeling Support Group of buildingSMART distributed a survey by e-mail to the registered members of the official iai-tech.org website – over 3650 members as of April 2010 – and circulated it on the mailing lists of local chapters (MSG Survey 2009). The survey resulted in over 200 responses and represents one of the rare public efforts by buildingSMART to collect opinions from active users, software developers, and researchers interested in the IFC standard. buildingSMART describes the purpose of the survey as to *"help MSG understand the participants' roles and interest in IFC [....] understand how to better help users take advantage of the IFC specification" [...]* and also to see *"if users where interested in contributing to IFC- related work, and if so, in what way they could be willing to participate"*. While most of the results elicited a neutral response, the highest amount of disagreement (30% disagreed or disagreed strongly) was attached to the claims of both *"I find it easy to understand how to use the IFC documentation in order to meet my requirements"* and *"I find it easy to* *understand Model View Definitions (MVDs) and how it they represents a subset of the IFC model"*. In their comments, users expressed desire for more practitioner-oriented resources on buildingSMART websites (e.g. how-to's, user manuals, clearer MVD instructions) in addition to the IFC release specifications.

3.4.1 IFC 2x3 and IFC4

IFC 2x3, released in February 2006, was primarily a stability release to enable implementers catch up with the many additions to IFC 2x2 (Liebich 2010). During development of IFC 2x3 in 2007, the quality of the IFC certification process underwent closer scrutiny; the current process of certifying the quality of implementation proved to be both too simple to ensure real-world usability, was inconsistent in its methods, and only covered IFC data export (Kiviniemi 2009). Following scrutiny of the existing process, work began on a new certification process for IFC implementations. In 2010, buildingSMART adopted a new process, dubbed "IFC Certification 2.0", which brought major improvements to the issuance of certification. Developed with MVDs in mind, emphasis fell on quality control of the IFC interfaces and involved narrower, more explicitly defined testing procedures than in the past (Groome 2010). With the new process, software vendors can obtain a two-year certificate for supporting already defined or newly defined MVDs based on the underlying IFC 2x3 data model. As such, software cannot be universally certified "IFC compatible", and instead obtains certification for supporting specific MVDs. Whereas the old process required Excel sheets and lots of traveling, an advanced web-platform was developed to automate much of the process and to provide centralized testing, support and documentation (Steinmann 2010). Involvement of the ISG and MSG parts of buildingSMART International facilitate the process to ensure high-quality interfaces.

A paper that brings up IFC certification head on and takes a critical look outside the box at how other industries have solved similar problems is Amor (2008). Amor (2008) takes a comparative look at how data interoperability challenges are dealt with within healthcare, shipbuilding, and STEP-related industrial sectors. Based on the practices found in the other industries, the main suggestions of the paper are; 1) to establish an independent body to handle certification and conformance testing since buildingSMART is already responsible for both development and publication of the standard, 2) reduce the barriers to conformance testing by having free tools available for use and download, 3) conformance testing tools used within the ISO-STEP community could be repurposed and modified for use with IFC, particularly geometry comparison applications, 4) data interoperability labs could be set up in the major regions of the world where vendors can meet, have expertise and the latest software available, and conformance tests could be conducted at any time of the year.

While IFC 2x3 was conservative in providing new features, IFC 4 focuses on providing just that. As this paper puts focus on history rather than future events there it is not advisable to go into too much detail regarding the circumstances of this next major release, however, some things are critical to mention. In addition to its many improvements and extensions to the standard, two objectives were central to the development of IFC4: *"to put quality over speed"* and to obtain full ISO international standard status with the final version scheduled for release in 2012. (Liebich 2010:4)

3.4.2 Public sector initiatives

Public sector property owners around the world have been among the most influential supporters of IFC-based interoperability in connection to issuing requirements and guidelines for the increased use of BIM technology, where IFC plays an integral part in keeping the information open and non-proprietary. On January 17th 2008, AEC/FM sector government client organizations from the US (GSA), Denmark (DECA), Finland (Senate Properties), Norway (Statsbygg), Rijksgebouwendienst (Netherlands) issued a commonly signed "Statement of Intention to Support Building Information Modeling with Open Standards" (Winstead et al 2008), making the commitment to facilitate the use of the IFC standard very explicit. Among the most central information contained in the statement is *"We will support, to the extent legally and practically possible, the use of IFC-related BIM solutions in public construction works."* and *"Within established budget limits, quality goals, and defined project progress, we will initiate and participate in open BIM-related research, development, and collaboration efforts, including making accessible our own building construction projects for piloting, thus contributing to the gradual proliferation and use of open digital building information models with IFCs throughout the lifespan of building structures."* (Winstead et al 2008). The document ends with an open invitation for other governmental client organizations to sign the statement.

The Scandinavian countries have long been among the pioneers regarding demand for BIM with IFC deliverables (Kiviniemi et al. 2008; Lê et al. 2006). One of the first substantial official commitments to IFC came from Finland when Senate Properties, the public property owner in Finland, published their BIM requirements in 2007, guidelines which included requirements for product model deliverables to conform to IFC format (Kiviniemi et al 2007). A recent high-profile example highlighting Norway's high level of commitment to IFC occurred in 2009 when Statsbygg, the national public property owner, organized the world's first international architectural competition for the National Museum in Oslo, where design submissions were accepted only in IFC format. The competition was a success, and Statsbygg received 237 submissions in IFC format (Statsbygg 2010).

While not every public commitment towards IFC can be listed here, other notable public actor actions include Australia publishing their own BIM guidelines in 2009 (CRC 2009), and the strong support for IFC given by the Singapore government, not least through the development and use of the CORENET e-submission system, which is a highly-automated construction conformance portal based on IFC used by local regulatory authorities to verify the conformance of incoming building plans (Khemlani 2005). Several public sector organizations are also members of buildingSMART and directly contribute to the consortium through project funding, technical development, and valuable end-user feedback, most of which is integrated upstream into the core buildingSMART standards. Furthermore, as noted earlier, national research and development projects have served as important standardization resources by indirectly funding organizations and individuals active in IFC-related projects.

4. DISCUSSION

A summary of the IFC release timeline appears in Figure 10. buildingSMART currently aims to release major new versions of the standard at about three-year intervals in the hope that it will strike a balance between the need for stability to facilitate implementations and responsiveness in incorporating new features into the standard (Liebich 2007).

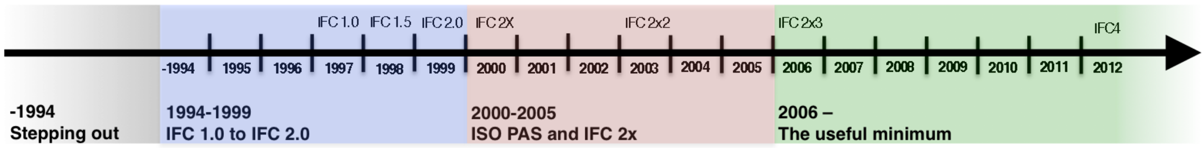

FIG. 10: IFC timeline

Returning to Söderström's (2004) generalized and extended standards lifecycle (Figure 2) and applying it to the findings from the IFC standardization process presented throughout this paper, one can contrast the process to the generalized theoretical model for IT standardization. On a general level, one can see that the lifecycle of the IFC standardization process has been iterated many times over, and feedback on these iterations has influenced the trajectory of standardization as development has progressed. Because major versions and modular parts of the standard have often been developed in parallel, it is more natural to interpret iterations as having taken place around the identified time periods rather than with each individual release of the standard. As we saw in the previous section, the changes in direction between iterations can often be traced back to feedback from industry and scholars: 1) the lack of progress in STEP for AEC/FM product models motivating the IFC effort, 2) increased openness and ISO publishing the standard, 3) a much improved certification process and an overall deeper focus on implementations with 'the useful minimum', and, ultimately, 4) a change of image for buildingSMART, and a more holistic business emphasis on interoperability. While this is only one possible interpretation (and mostly from the perspective of an external observer), this type of feedback may have facilitated new iterations of the standardization process and infused a distinctive profile for each time period.

4.1 Market coordination problems

In the general standards literature, consortia standardization has seldom been reported to suffer from underfunding; on the contrary, SDO standardization has typically been considered the standardization forum which must make an effort to encourage participants to contribute. For the IFC standard, the resource problem might stem from a combination of three factors: *producing a free common good* (which is not always the case in consortia development), *focusing on the standardization of AEC/FM universal concepts* (rather than, until only recently, more readily-implementable solutions), and *the lack of business motivation for some software vendors* (to relinquish proprietary formats).

Resources may have been scarce during the development process, but the effort never came to a complete stop and has constantly made progress. Considering its ambitious scope and technical complexity, the consortium has made remarkable progress with an annual budget of only around USD 100,000-150,000. At this point, it is important to reiterate that the formal international budget constitutes only a part of the resources used to develop the standard. National and international research programs as well as companies have indirectly funded a considerable part of the development work by paying the time and travel expenses of individuals involved in consortium activities. While providing only official protocol, the well-maintained and publicly available meeting minutes of the IAI Nordic Chapter offer insight into some of the developments that have occurred over time through the proxy of a chapter perspective. One general observation is that funding issues have been a frequent topic of discussion at almost every meeting. When the effort began, all four national forums received project-based government funding from their respective countries and secured continued funding from both new research projects; frequent agenda entries included collecting membership fees. With only one administrative person and some technical people working part time, only a small number of people have been intensively involved in the development of the IFC standard. Approximately 30% of the technical work has been paid for, and 70% has been contributed. With such a high dependency on project-based funding, the focus and direction of standardization has been fairly ad-hoc; the development focus is determined by whoever can provide the core group with funding. At times, the lack of a clear roadmap or list of priorities has sometimes led to overlapping definitions. (Kiviniemi 2006)

When the International Alliance for Interoperability was formed, IFC could be classified as an anticipatory standard, meaning that development of the standard was initiated in anticipation of future demand for compatibility. BIM software, as we know it today, was very much in its infancy back then, and the aim was to develop a neutral standard before proprietary solutions could take over the market. Observing the situation in 2012, however, the standardization work could now be labeled concurrent with or responsive to the development of BIM software. While it is hard, or almost impossible, to prepare and predict the distant future, research has shown that aligning 'time-to-standard' with 'time-to-market' goals is of great importance to the widespread adoption of standards (Gielingh 2008). Because IFC has to be implemented in software in order to be useful, the adoption of IFC fully depends on the adoption of BIM software. Thereafter, the standard faces a two-stage adoption process: first, software vendors must implement IFC interoperability to a satisfactory level before end-users are even able to evaluate the decision to adopt IFC-based exchange. The lack of generalizable measured benefits for integrated BIM, however, has put a damper on market demand and thus also on the priority for software vendors to develop and improve IFC interfaces. These interdependent relationships raise their own challenges to obtaining feedback from actual end-users of IFC-based interoperability. The BIM market coordination problem appears in Figure 11, which visualizes the relationships in a paradoxical loop.

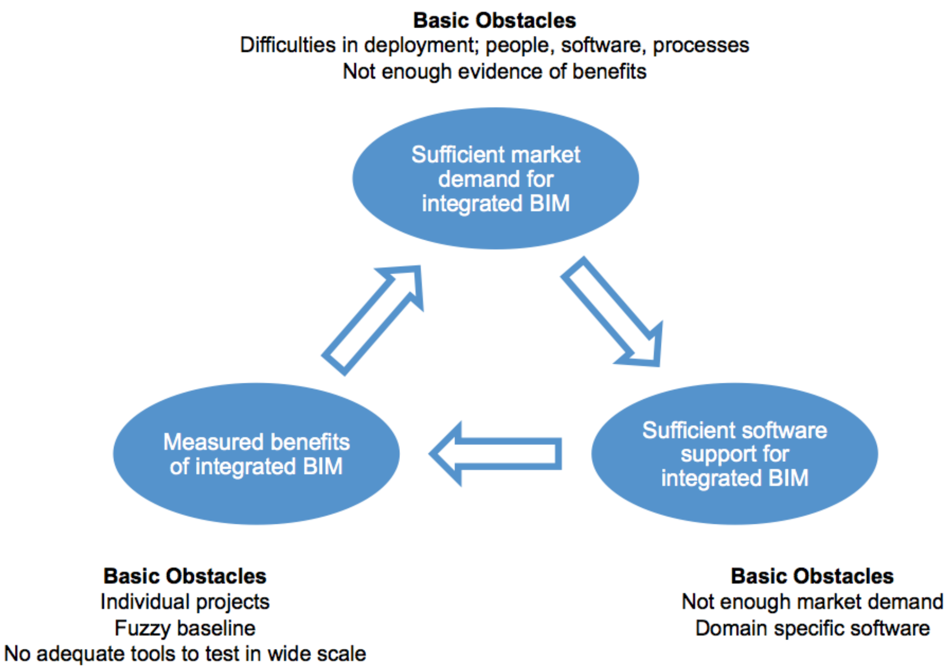

FIG. 11: Paradoxical loop of integrated BIM (author reproduction based on source: Arto Kiviniemi, VTT 2007)

As noted briefly in the introduction, a significant portion of the literature on the economics of standards has discussed similar market coordination problems. BIM as a technology does not fit into the concept or definition of a standard and can be regarded more as a technological innovation. Market coordination in the early economics of standards literature was largely oriented around a macro-perspective in order to analyze the dynamics of the whole marketplace, whereas the diffusion of complex technological innovations benefits from an adopter-centric micro-level grounding of analysis, and in so doing to accounts for the relationship between innovation and population. The diffusion of innovations requiring coordinated action among multiple actors in project networks has been an area of research in which BIM technology has served in theory-building case studies. Taylor & Levitt (2005 & 2007) studied the diffusion of three different BIM applications in construction project networks in Finland and the United States, with many of their findings emerging from a polarizing analysis of construction industry practice between the two countries. They suggest that systemic innovations are adopted more easily in networks with strong relational stability, network-level interests, fluid boundaries, and in the presence of an agent for network-level change. In their analysis, the Finnish construction network environment was seen as tending towards support for all these facilitating constructs, and the US was viewed as lacking relational stability, firm-level interests, rigid boundary strengths, and a prominent agent for network-level change (Taylor & Levitt 2005). These findings provide no quick fix for the paradoxical loop of BIM adoption, but nonetheless shed valuable light on what kind of environment provides support for the adoption of systemic innovations.

While the IFC standard has no immediate direct competition with regards to open standards in development, software vendors' attempts to control proprietary formats are something that can influence market demand for an open alternative purely for purposes of interoperability. One example of such action is the announcement by Autodesk and Bentley to improve the interoperability of their BIM software (Autodesk 2008). In the long run, it remains to be seen what impact this and possible expanded agreements will have on the IFC standard. One can assume that software companies with dominant market share lack the business motivation to lower barriers to competition. Chen & Forman (2006) studied the degree of influence vendors have on switching costs in an environment with open standards; if one were to generalize the results of this study to a hypothetical future market in which BIM software vendors have implemented IFC support in sufficient quality and quantity, dominant actors could still maintain high switching costs for buyers. This would be due to proprietary extensions to the standard and the bundling of services and other software packages with the main product. Chen & Forman 2006 also mention that judging whether actors engage in such actions to improve buyer satisfaction or to pose obstacles to more open competition is difficult to assess. Dominant vendors could therefore also influence the adoption speed of new technologies, as existing customers wait for upgrades from their current vendor so as to avoid high switching costs. However, a more extensive discussion of this topic is beyond the scope of this paper.

4.2 IFC and STEP - separate, but sharing similar challenges

What influence the foundation of STEP and EXPRESS information modeling has had is difficult to assess. When IFC standardization began, the concepts of IDM, MVD, and IFD were not explicitly planned or defined; their need has emerged during the process. Initially the purpose was simply to create a definition framework for the core objects and concepts used in the AEC/FM industry. Generally, one could state that it began with the standardization of a technical specification which over time expanded to include and standardize the processes of its use as well. The STEP standard has seen a similar evolution over the years beginning with the initial split of the core model into APs with common universal resources, which for implementation viability were divided into Application Interpreted Models (AIM) and Application Reference Models (ARM). While harmonized core model definitions are the foundation for these implementable parts of the standard, fragmentation of the standard into such data-exchange use-cases mitigates some of the ambitious original cross-domain interoperability goals of STEP development.

Gielingh (2008) reviewed the development, industry uptake, and usability of product data technologies from within and related to the STEP project, including the IFC standard. Gielingh (2008) framed the discussion of the causes of poor industrial uptake of open product data standards around three main factors: business motivation, legal aspects, and industrial readiness. The uptake of open data exchange formats for product data were generally found to be lacking, a result which spurred Gielingh (2008) to more fundamentally question the viability of the underlying principles and concepts of STEP-originated open product data standards. Gielingh (2008) argued that the poor performance of neutral product data exchange standards stems from inconsistent translations between the internal software data structures and the neutral format, the ambiguity in how data structures can be defined while still conforming to standards, and the variations in domain scope between software applications. *"Only if applications have the same scope and the same view on a Domain of Discourse, and if scope and view equal that of the standard, the risk of information loss will be minimal. This is the reason why using applications of one and the same CA-vendor gives the best performance in practice"* (Gielingh 2008: 757).

4.3 Reflection on previously published research on standardization

4.3.1 IFC-related research

In a study reviewing the standardization processes of CAD standards in the construction industry, Björk and Laakso (2010) came to the conclusion that the construction industry has seen standards come into wide use through very different standardization processes. The authors suggested a multi-level process model for analyzing and interpreting the different processes of CAD standardization, a process that incorporates in its flow both technology development and standardization. Despite the IFC standard's much broader scope than purely visual information, the general outline of IFC standardization was briefly contrasted to the processes of past CAD standards. The main conclusions of this comparison was that, given its relatively transparent development process and the standard's free availability on the internet for implementation and use, IFC standardization is considerably more open than past CAD efforts. Furthermore, IFC standardization has proved more anticipatory than previous CAD standards, which have generally been developed for use in already existing technological solutions.

Behrman (2002) contextualized and compared the IFC standardization process to efforts in other areas of IT. The main standards covered in Behrman's analysis were OSI (Open Systems Interchange), Internet standards (in particular TCP/IP), and RosettaNET. Founding his analysis on the notion that standardization can be either minimalist or structuralist in its general approach, Behrman concluded that IFC has followed a structuralist approach much like the OSI and STEP standards. Behrman notes that IFC has experienced problems acquiring functional software implementations largely due to insufficiently involving software vendors in the standardization process. The structuralist approach, the lack of resources, the lack of industry involvement and commitment, and the EXPRESS modeling language were identified as obstacles to successful standardization. In conclusion to the analysis of the standardization cases, Behrman argued heavily for a bottom-up minimalist standardization methodology in favor of a top-down structuralist one. Behrman based his view on the degree of success that the industry standardization projects have had, which he defined as whether: 1) the standard solved the problem it was intended to solve, 2) it was developed in a timely manner, 3) it achieved widespread adoption and use, and 4) it anticipates and allows for future technological change, constraining future development as little as possible.

Although Behrman's (2002) notion that early IFC standardization followed a structuralist approach enjoys the support of the analysis in this paper, one should not judge its rate of success in the industry simply based on this one characteristic. Such a perspective implicitly adopts a limited view of the dynamics involved in standardization. Suggesting that minimalist development approaches would be recommendable best practice for standardization purposes universally fails to adequately address issues such as openness in the process or product (Krechmer 2005), reaching broad consensus, or standardizing a necessary initial definition of concepts, all of which are major reasons for adopting processes more in line with a structuralist approach. Many more variables, such as the degree of technology or market maturity, influence the approach and outcome of standardization than merely polarizing structuralist versus minimalist. The IFC standard was originally intended to be a minimalist effort: a neutral data exchange format developed outside of STEP, designed and used by members of its industry alliance comprising of several key software vendors. Choosing the STEP file format and EXPRESS as the modeling language should further support the initial minimalist intentions, as existing work was chosen for use as much as possible. Only after failing to find a viable minimal approach did the IFC effort follow a structuralist path; developing a complex implementation-independent model for mapping definitions of AEC/FM concepts and objects as well as their interrelations is a task which by design is arguably best suited for top-down structuralist development.

Though it generally holds true that releases of the IFC standard have usually first been published, and only after the fact are implementations attempted; this is an issue involving more a methodological development process than one stemming from a lack of participation of software vendors in consortium activities, as Behrman (2002) suggested. Software vendors comprise a considerable share of the stakeholders who founded the consortium and have been key funders, participants, and influencers within IAI and buildingSMART from the beginning. Regarding the use of EXPRESS as the information modeling language and as an obstacle to standardization, as we described earlier, translating to another modeling language such as XML Schema does not necessarily bring with it any instant fix to the conceptual challenges inherent to information modeling and interoperability. Of course, more people are familiar with the widely adopted XML syntax than with EXPRESS, which could pose an additional barrier for software developers' involvement in IFC development. However, the EXPRESS modeling language in itself does not strictly dictate how concepts are defined, nor has it become technically obsolete even though it is not in as widespread and general a use as XML.

4.3.2 Non-IFC-related standardization research

Despite being unrelated to IT in the construction industry specifically, interesting parallels to the IFC standard can be found in Henning's (2008) paper on the rise and fall of the CORBA (Common Object Request Broker Architecture and Specification) middleware standard. The author, who was heavily involved in the standardization effort, noted that many of the problems with the standardization of CORBA were rooted in the 'design by committee' symptom of developing an anticipatory standard. Based on lessons learned from CORBA, Henning (2008:57) suggested, among other guidelines, the following to improve industry consortia standardization processes.

- Consortia should enforce strict rules to ensure that existing best practice is standardized.
- No standard should be approved without a reference implementation, and without implementation in projects of realistic complexity.
- When creating software, the ability to say *no* is usually more important than the ability to say *yes*.

One of Henning's main implicit messages is the cautious use of the word standard when referring to something still in development, as reliability and performance expectations are set high for anything proclaiming to be a standard. Henning divided the analysis of consortia standardization into technical issues and procedural issues, noting, however, that *"[...] the technical problems are a symptom rather than a cause"* (Henning 2008:56). These points resonate with the findings of Behrman (2002), but also with findings related to IFC standardization since then.

As noted earlier, project-based funding from companies and governments around the world have been important resources in IFC standardization by directly and indirectly funding organizations and individuals active in IFC-related projects. However, the goals of tangential projects and the immediate optimal tasks of standard development may not always be aligned. With the consortium operating with few fixed resources, one can speculate that projects contributing to IFC development are unlikely to be turned down, even if they fail to comply with the immediate development priorities and vision of the consortium.

One of the IFC's main problems with simply standardizing best practice rather than figuring out and developing something new is that BIM software has evolved at a rapid pace, making IFC attempts at standardization tantamount to shooting at a moving target. The IFC standard has developed as it has been standardized – also known as designing standardization – since no complete modules exist from which one can simply pick and choose. This type of anticipatory designing standardization is at high risk to fall into the trap of 'design by committee' if goal orientation does not remain a high priority (Purao et al 2008). While it is hard to prepare for and predict the distant future, research has shown that aligning 'time-to-standard' with 'time-to-market' goals is of great importance to the widespread adoption of standards (Gielingh 2008).

5. CONCLUSIONS

The main purpose of this paper was to provide a comprehensive review of the major stages of the IFC standardization process and to connect the findings of that review to the broader scholarly literature on IT standardization. Drawing on de Vries' (2005) IT standards typology, one can conclude that IFC is an *open, formal, international, consortium standard* currently involved in a *hybrid standardization process* designed to enable *indirect horizontal compatibility* between AEC/FM software applications. This standardization effort has largely been *anticipatory* in relation to the overall maturity in the standardization of target software and the industry; only more recently could one label the standardization effort as answering to immediate needs and describe it as *concurrent* standardization. Development of the standard has primarily involved *designing* in nature, as it has not simply been a matter of selecting and agreeing on features from existing technological alternatives, even though the project began that way with STEP definitions as a base. In order to cater to the AEC/FM sector's needs for data representation, new technical solutions have been formally designed and developed as part of the standardization process. Tying into this, the IFC data model has been developed using a *structural* approach, whereas supplementary MVD, IDM, and IFD standards have developed with more *minimalistic* influences, which also influences the more minimalistic use of the IFC information model in conjunction with these supplementary standards.

Within this short description of the core characteristics of the IFC standardization effort lie factors which help to explain the IFC standard's slow but steadily increasing use in actual construction projects. Although the industry's near future data exchange needs were envisioned fairly well in the mid 1990s and formalized in the IFC data model, in retrospect it was probably too early to anticipate wider market uptake during a technological generation shift from purely visual geometric CAD to semantic object-based BIM. Although the idea of having an open data specification available for implementation as commercial software enters the marketplace can arguably contribute towards preventing proprietary solutions from gaining dominance, a lesson learned from the CAD generation of AEC/FM design software suggests that cementing the cornerstones of a technology early when market demand is still lagging can also have drawbacks of its own. As noted in the chronological review, IFC standardization has faced challenges in acquiring sufficient resources to manage the development of the standard, something which is probably due to weak coordinated market demand for the standard.

It will be interesting to see how increasing public sector support for the standard, in particular by requiring its use in public procurement tenders, will influence IFC implementation quality and overall software support in the coming years. This demand-inducing phenomenon, together with the release of the official IFC4 ISO standard, will most likely facilitate the implementation and use of the standard, which in turn should generate valuable project reports demonstrating the potential benefits of IFC-based interoperability, thus helping the standard to break free from the 'vicious circle' described earlier where the lack of demonstrable benefits arguably reduced demand for the standard, causing BIM software developers not to prioritize IFC-related features in their products.

This paper, despite its broad scope, has only briefly mentioned but a few of the many important and interesting key developments in the IFC standardization process. Hopefully, such discussions that we were unable to address in this paper will spur future research interest in both applied and non-applied research related to the standard.

ACKNOWLEDGEMENTS

This research was funded by the Finnish Doctoral Programme of the Built Environment (RYM-TK). This paper was written while the first author was on a researcher exchange at the School of the Built Environment at the University of Salford; the hospitality and facilities generously made available for the duration of the visit are deeply appreciated.

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