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Review

Exploring the Relationship between Research and BIM Standardization: A Systematic Mapping of Early Studies on the IFC Standard (1997–2007)

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Academic Editor: Tanyel Bulbul

Received: 2 January 2016; Accepted: 4 February 2016; Published: 6 February 2016

Abstract: It has long been argued that the Industry Foundation Classes (IFC) data model standard is the key to unlocking the potential of interoperable Building Information Modeling (BIM). Despite a wealth of published research literature incorporating IFC, there have been no attempts at systematically summarizing the literature related to the standard. Targeting both summation and analysis of thematic developments over time, we performed a comprehensive systematic literature review of IFC-related research published between 1997 and 2007: the first 11 years of research on the standard. Through a systematic web-retrieval process, 170 unique publications were collected, read, and mapped to a custom framework. The results reveal that journals and conferences have been an integral part of the technical evaluation and development of the standard. The full classification data is provided as an appendix to facilitate future research on IFC and other standards.

Keywords: IFC; interoperability; open; standardization; data exchange; BIM; review

1. Introduction

The origins of research in the area of data exchange and the interoperability of building information can be traced back several decades. Research within the area began with studies on issues related to the representation and interoperability of product and process data for construction, a technology that is now commonly referred to as building information modeling (BIM) [1,2]. As in many other industries, the introduction of increasingly affordable technology in the construction industry initiated the adoption of new and improved tools for supporting existing processes. Drafting moved from pen and paper to computer-aided design (CAD) software, document storage moved 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 mainly replaces traditional manual processes, adoption varies heavily between companies [3]. One can assume this heterogeneous IT adoption landscape to be influenced by a fragmented industry structure, where a vast majority of the industry workforce is split into small companies. With several organizations collaborating intensively in temporary project constellations, having compatible electronic assets within the project has always been of critical importance. Open standards for representing and exchanging product model data have been in development and use since the 1970s when simple 2D and 3D CAD were prevalent, with the Initial Graphics Exchange Specification (IGES) being a good example of an open standard that gained traction in many industries for visual modeling [4]. This study uses the following widely used definition for what is meant by a standard:

> "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." [5]

1.1. The IFC Data Model Standard

In 1994, development was initiated on an open data model standard to serve the BIM interoperability needs of the construction industry. The standard was named the Industry Foundation Classes (IFC). Twelve US-based companies joined together to examine the possibility of developing an open standard for enabling interoperability in emerging building information modeling software. In September of 1995, after the development of initial prototypes showcasing the possibilities, the IAI (Industry Alliance for Interoperability, changed to International Alliance for Interoperability in 1996, and further to buildingSMART in 2006) was formally founded and the initial consortium made it possible for other companies to join [6]. Development was formally launched in September 1995, and IFC 1.0 was published in January 1997. For a chronological summary of the IAI organization and a historical overview of IFC standardization efforts, see [7]. In our view, the development and release of the openly specified IFC data exchange standard for BIM data initiated a new era of building information interoperability research.

Technological advances have gradually enabled a disconnect of time and space from the actual work site. An increasing number of tasks can be planned and produced further ahead in time, reducing the large amounts of uncertainty related to construction projects. A fragmented industry structure is challenging, particularly for software that is not leveraged when used in isolation, and where the data output of a design process is meant to be readable, editable, and further shared between the systems of various collaborators throughout the whole lifecycle of the building. IFC-supported construction based on modeling has the potential to transform the core fundamentals of construction processes. The potential for greater productivity is substantial: open interoperability for BIM 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 of any industry.

Lacking interoperability and running software in isolation rather than networked is a problem that, if remedied, could enable a construction process with less redundancy and fewer disconnects. There may be reasons other than a lack of interoperability that explain why individuals or companies run software in isolation—e.g., a reluctance to share business intelligence, protection of intellectual property rights, and other legal matters—but incompatible data formats place functional barriers that even those inclined to exchange data cannot overcome. Although few studies have attempted to put a price tag on interoperability within the construction industry, we assume that a financial incentive exists. For example, a U.S. industry survey suggested that software non-interoperability on average makes up 3.1% of total project costs [8]. The IFC standardization effort was initiated to reduce such inefficiencies, thus potentially benefitting all major construction stakeholders.

Ever since initiation of its development and release in the late 1990s, the IFC standard has attracted interest from both academia and industry. As a result, it has played both major and minor parts in academic research on a variety of contexts within the construction IT literature. Despite the sustained research interest up until this day, and a constantly increasing commitment and uptake of the standard in the industry, there have been no attempts at summarizing research related to the IFC standard.

1.2. Aim of the Study

BIM is very complex; as a technology, it ultimately aims to incorporate the main construction domains with their own processes and products under a singular umbrella. As if that were not challenging enough, there is the temporal aspect to consider: that BIM should cover the complete lifecycle of a building, from supporting the early iterative design processes to facilitating routine maintenance and management. Given that every aspect of BIM cannot be given maximum priority simultaneously, it is interesting to explore which areas of BIM technology were the first to attract interest among academic researchers. Also of interest is the degree to which research on the IFC standard can be observed to support the act of standardization through the evaluation of technical solutions and by contributing with potential extensions to the practical application of the standard. Inspired by these questions, the aim of the study can be summarized as follows.

The research aim is to comprehensively profile early academic research related to the IFC standard in an attempt to improve the understanding of its past and present research activities, as well as to facilitate a better understanding of academic research during the initial stages of technical standardization.

To frame this study, Figure 1 depicts the perspective adopted to distinguish the major stages of knowledge evolution around emerging technologies.

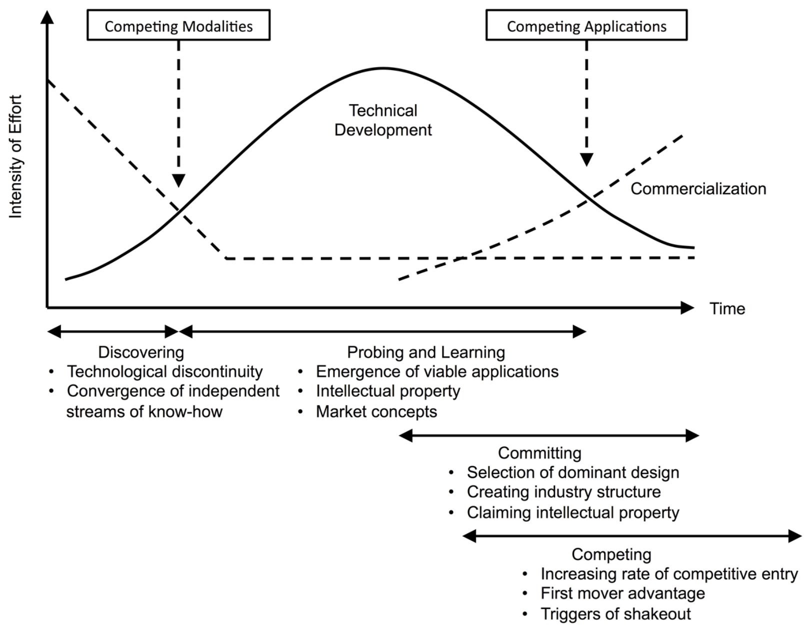

Figure 1. How emerging knowledge evolves (redrawn from [9]).

Given that this study focuses on early technology development, IFC-enabled BIM technology during the timespan 1997–2007, the majority of the evolutionary curve is of relevance to the literature reviewed in this study. Notably, BIM and IFC have matured very much in parallel, with IFC being a standardization effort initiated early in the development of BIM technology [7]. Standardization in a technology context must acknowledge that standards are not created in isolation from 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. It has been argued 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 [10]. We argue that both BIM as a technology, and IFC as a particular data-model standard for exchanging BIM data, experienced their own individual but interrelated paths through the model depicted in Figure 1. We will return to this model later in the article when presenting the major findings of the study.

This article is structured into four main sections. After this introduction, the second section describes the methodology used to collect the relevant literature for review. The third section presents an analysis of the results. The fourth section presents a discussion based on the findings, drawing conclusions for both research and practice.

1.3. Related Work

There is scant research available on the relationships between research, standardization, and technology development—particularly not on research focusing on the construction industry. A substantial share of this small pool of existing research has been funded by the European Union, as part of the 6th Framework Programme, through several large research initiatives related to exploring and improving the dialogue between research and standardization, both in general and also specifically in the context of BIM and IFC for the construction industry. Most of the research in this domain focuses on exploring ways to incorporate research into the standardization processes of standard-setting organizations [11] and, vice versa, ways of incorporating standards, either established or still under development, into research initiatives [12].

One of the rare academic studies that directly relates to researcher participation in standardization asked why researchers participate in standardization activities, a very important line of research that would warrant more attention in future research [13]. Based on an in-depth case study of one research institution, Zi and Blind discovered a negative relationship between productivity—in terms of publishing *high-quality scientific publications*—and participation in standardization committees, and they found a positive relationship between productivity—in terms of publishing *technical and industry-oriented publications*—and standardization activities. Researcher seniority was positively correlated with participation in standardization activities, suggesting that non-tenured academics have a lower degree of participation in standardization work.

Earlier Mappings of the Construction-Informatics Research Literature

Even though no summaries of research related to the IFC standard have been published, there have been a handful of notable systematic literature reviews that have explored the construction informatics literature. Understanding the larger trends and shifts in construction informatics research is important for interpreting the IFC research subset of this larger body of literature.

Amor, Betts, Coetzee, and Sexton provide a systematic review of all research articles published in the annual conference proceedings of the International Council for Research and Innovation in Building and Construction—Working Commission W78 Information Technology for Construction (CIB W78) between the years 1992 and 2002, longitudinally identifying trends and research themes [14]. Research on the theme of computer-integrated construction was found to be dominant under the observation period, with runner-up themes being construction process and decision support. Furthermore, standards-related research was identified as being cyclical, with the proposed explanation being that such research is sensitive to ongoing national strategies and research programs. Drilling down to the technical themes, it was revealed that, while product modeling was consistently the most frequently researched theme, process modeling had emerged from no representation to almost equaling the popularity of product modeling during the latter half of the observation period.

Similar to Amor, Betts, Coetzee, and Sexton [14], Turk and Cerovsek also utilized the CIB W078 proceedings body of literature to conduct a longitudinal bibliometric analysis [15]. The authors included all available proceedings in their analysis, spanning the years 1988–2002 (689 articles), in order to create a construction informatics topic map. Two different degrees of automated data mining were used to thematically map out the literature based on keywords in titles and abstracts. Regarding topic map evolution over time, the results were fairly inconclusive, with two-way fluctuations happening within most thematic areas. The experiment highlighted that manual reviewing literature is still a valuable and needed effort for anything requiring a more in-depth understanding of the research conducted, despite the element of subjectivity introduced when compared to using automated data mining processes. In a further journal article, Turk continued to iterate on automated bottom-up mapping of the construction informatics literature [16]; however, the outcome was primarily aimed at facilitating the storage of articles in hierarchical structures rather than providing a deeper review of the content.

Abudayyeh, Dibert-DeYoung, and Jaselskis analyzed the trends present in construction research published between the years 1985 and 2002 by reviewing articles published in the *Journal of Construction Engineering and Management* (JCEM) [17]. The authors found that scheduling, productivity, constructability, simulation, cost control, planning, safety, and computer systems were among the top research areas. A further major finding was the need to increase research collaboration between industry, academia, and government. Two years later, Abudayyeh, Dibert-DeYoung, Rasdorf, and Melhem published a similar study, where the focus of analysis was on articles published in the *Journal of Civil Engineering* from 1987 through 2003 [18]. Modeling was found to be the top research topic among articles in the observation period, with a clear peak in popularity during 1992–1996. An analysis of author affiliations revealed that the share of authors with an academic affiliation had doubled relative to the shares of authors with government and industry affiliations when comparing the first five observation years to the last seven. A possible explanation for this finding could be that academic publishing has become increasingly closed off from direct industry input with an increasing degree of academic co-authors collaborating on articles by industry professionals. Other reasons could be a lack of a growth accelerator for academic publishing among government and industry authors, whereas there is an increased pressure for academics to "publish or perish".

Based on this review of existing literature, it is possible to see that many different approaches have been employed to tackle the analysis of large volumes of construction informatics literature. However, no template was found that would have supported the direct research aims of this study. In the following section, the methodological design of this study is outlined; it is informed by previous studies, but is not based on an existing template.

2. Material and Methods

Based on the aim of the study, systematic mapping [19] was deemed the best method of surveying a substantial body of literature sharing a well-defined common element. While sharing some similarities, this type of study should not be confused with a systematic literature review, which by traditional definition is used to aggregate empirical data from individual primary studies—for example, clinical trial data within medicine—in order to generate new insight and findings [19]. That type of approach usually centers around one well-defined research question, and it requires that the researchers carefully evaluate the sampled literature for methodological soundness and quality, and that they formulate objective exclusion criteria [19]. A different approach is needed to fulfil the aim of this study, where there are multiple research questions, empirical data from the publications is not extracted for meta-analysis, and studies that fulfill the initial relevance criteria are not later excluded based on either methodological or other grounds. Systematic mapping studies are often a pre-stage to narrower, in-depth systematic literature reviews [19].

Although systematic approaches to literature mapping and review offer benefits in scope and objectivity regarding the sample selection when compared to selective qualitative reviews, the very nature of selecting literature and formulating an efficient mapping protocol *a priori* has spurred discussion regarding some of the weaknesses of the approach. Systematic reviews, in their rigorous methodical approach, have been questioned for being strict to the point of being harmfully unresponsive to new insights and perspectives that emerge after the mapping protocol has been formulated and the review has been initiated [20]. To reduce the influence of this potential weakness, two important aspects differentiate the methodological approach adopted in this study from a typical systematic mapping study: a pre-existing familiarity with the literature and a flexible mapping protocol. An outgoing mapping protocol could be composed based on the authors' familiarity with the general profile of the literature related to the IFC standard. This familiarity has come as a result of conducting non-systematic literature reviews in earlier research efforts focused both on standardization in general and on IFC more specifically. The flexibility to add mapping categories was allowed, should any piece of research not be adequately described by any of the existing categories. Although this flexible approach required that all previously mapped publications be revisited each time something was added to the protocol, the additional effort was crucial in order to make the study responsive to the needs of the standard studied, as well as to the research related to it.

2.1. Research Questions and Classification Framework

It has been suggested that research questions for systematic mapping studies should be formulated in parallel with the design of the classification framework that is used for the mapping of the individual publications in the planning stages of the research process, because that instrument dictates what data is produced as output for analysis [21]. Consequently, the primary research questions lend themselves to being stated in conjunction with the composition of the mapping protocol.

What is the longitudinal distribution of IFC research with regards to:

Q1: the role the IFC standard plays in the studies?

Q2: applied and non-applied modes of research?

Q3: research evaluating the standard?

Q4: research extending the standard?

Q5: responsiveness to different releases of the standard?

The review process was started with a very basic applied/non-applied research split, with subcategories for evaluation and extension studies for each group. Upon completion of the review, the framework had evolved into something more detailed and complex, as can be seen from Table 1. Important to note is that publications were not artificially limited to only one main research contribution, *i.e.*, one study could be mapped with findings that relate to both applied research and non-applied research.

Table 1. Literature mapping framework.

Label	Criteria	Description	Coding
1. Mode of research		Differentiates between research presenting new data/empirical material and research that builds upon previously published research	
	1.1 Primary	Research presenting new experiment/case/data/empirical material *etc*.	YES/NO
	1.2 Secondary	Builds only upon previously published research, findings or data	YES/NO
2. Role of IFC in the study			
	2.1 Primary	IFC is the main focus of the research	YES/NO
	2.2 Secondary	IFC is in secondary focus, the research is focused on some other main contribution	YES/NO
	2.3 Tertiary	IFC is not a significant component of the research	YES/NO
3. Supplementary information			
	3.1 IFC version	Documents the exact IFC version used or discussed in the study	IFC version number
	3.2 Public policy	The relationship between IFC and public policy is brought up (e.g., public procurement, building code checking)	YES/NO
	3.3 Primary construction domain/Context of research	Classifies the main construction domain or research context	Free text description, category clustering
	3.4 Representation syntax	The programming or data modeling language through which IFC is represented in software (applied research only)	Free text description
4. Applied research		Publications that describe an implementation of IFC in software	
4.1–4.5 Evaluating		Incorporates evaluation of quality or usability of IFC (multiple YES codlings possible per study)	
	4.1 IFC data exchange	IFC data is imported or exported	YES/NO
	4.2 Construction process	Support of the IFC standard is evaluated against construction processes	YES/NO

Table 1. *Cont.*

Label	Criteria	Description	Coding
	4.3 IFC use in simulations	IFC is used in the context of simulations	YES/NO
	4.4 Single-case study	Contains a single real-world project case study	YES/NO
	4.5 Multiple-case study	Contains multiple real-world project case studies	YES/NO
4.6–4.9 Extending		Involves extending the usability of IFC functionality in practice (multiple YES codlings possible per study)	
	4.6 Construction domain coverage	Construction domain coverage is extended	YES/NO
	4.7 IFC information model	The IFC information model itself is extended	YES/NO
	4.8 Functionality	Functionality of IFC is extended in some way, e.g., by prototyping the standard in a new software setting or workflow, or by describing how the standard can be used in conjunction with other data models	YES/NO
	4.9 Relevance to integrated construction environments or model servers	IFC is used in the context of integrated construction environments, *i.e.*, not just 1-to-1 data exchanges	YES/NO
5. Non-applied research		IFC is not implemented in software (multiple YES codlings possible per study)	
5.1–5.3 Evaluating		Provides evaluation of quality or usability of IFC	
	5.1 Quality/usability of IFC	Incorporates evaluation of quality or usability of IFC	YES/NO
	5.2 IFC standardization process	Incorporates some level of evaluation on the IFC standardization process	YES/NO
	5.3 Industry survey/opinions	Opinions of industry members are present	YES/NO
5.4–5.6 Descriptive		Provides descriptive information about IFC (multiple YES codlings possible per study)	
	5.4 Status report	The publication reports on the status of IFC development	YES/NO
	5.5 Roadmap	The publication presents a roadmap for IFC development	YES/NO
	5.6 Documentation	The publication can be considered official IFC documentation	YES/NO

2.2. Literature Selection and Retrieval

2.2.1. Direct Queries

A systematic literature review was initiated in 2011 and was completed in 2014. The long timespan was largely due to the very time-consuming manual review process requiring meticulous reading and interpretation of the studies. Scientific journals known to frequently publish IFC-related research were targeted directly for relevant research published between 1997 and 2007. Through their respective websites, the following journals were exhaustively harvested for articles containing the term "IFC" or "industry foundation classes" in their title, abstract, or keywords: *Automation in Construction* (10 articles), *Journal of Information Technology in Construction—ITcon* (20 articles), *Advanced Engineering Informatics* (1 article), and the *Journal of Computing in Civil Engineering* (3 articles). Based on the authors' familiarity with the subject matter, it was known that an important body of relevant literature is not limited to journals, but comes in the form of conference proceedings. Identical criteria to the journal search were used to query the complete CIB W078 conference proceedings from 1984 to 2007 (62 articles). The ITC Digital Library, which is a subject-based repository for construction IT research, was also queried for additional literature fulfilling the search criteria stated earlier (1 doctoral dissertation). In total, the direct queries garnered 97 unique and relevant publications.

2.2.2. Publication Databases

To collect relevant publications outside of these known outlets, both the comprehensive Scopus and Google Scholar publication indexing services were queried. Scopus was queried for publications within the two broad categories of Physical Sciences as well as Social Sciences and Humanities, with "IFC" or "industry foundation classes" in the title abstract or keywords, and published after 1990. From the 715 results this search garnered, only 209 results referred to the IFC abbreviation of interest here. After removing publications in trade magazines, non-English language journals, false positive hits, and editorials, 162 entries remained. Thirty-five of these 162 entries, which predominantly were conference proceedings, could not be retrieved, either because they never had an online version, because they had been taken offline, or because access was restricted due to the outlets being outside of the authors' universities content subscriptions. Of the 127 publications that could be retrieved, only 37 had not been identified through any of the search methods already used. Google Scholar was queried for entries with "IFC" or "industry foundation classes" in the title within the category of engineering, computer science, and mathematics. The more limited search approach employed was due to the lack of a robust abstract and keyword search ability. Seventy-seven relevant publications were identified, including reports and documentation as well as research articles, of which 37 entries had not previously been collected through direct queries. In total, these two publication indexes garnered 73 additional unique and relevant publications.

2.2.3. The Retrieved Literature

After merging all of the search results, the whole search process had resulted in 170 unique publications. Although there are IFC-related publications relevant to the scope of this review that were not caught by the queries and sources used, broadening the scope by loosening the search criteria or expanding the source coverage would have expanded the mass of literature to the extent of becoming unfeasible to manage by a two-person research team. In support of the methods used, it should be emphasized that the sample of publications was not artificially limited in any way, for instance by excluding specific types of research or outlets. Any research-type bias possibly introduced by querying certain sources directly should be balanced by the fact that two inclusive publication-indexing services were used to complement the direct queries, enabling relevant publications from any source to be included. Tables 2–5 summarize the retrieved literature: Table 2 presents the full publication source title list, Table 3 an overview of publication type per year, Table 4 the most frequently appearing authors, and Table 5 a publication keyword-frequency ranking list.

Table 2. Frequency ranking of publication outlets.

Publication Source Title	Publication Count
Journal of Information Technology in Construction—ITcon	20
Proceedings of the 2005 CIB W78 Conference	12
Proceedings of the 2006 Joint CIB W78, W102, ICCCBE, ICCC, and DMUCE International Conference	12
Automation in Construction	10
Proceedings of the 2002 CIB W78 Conference	9
Proceedings of the 2007 CIB W78 Conference	9
Proceedings of the 2000 CIB W78 Conference	7
Proceedings of the 1999 CIB W78 Conference	6
Proceedings of the 2003 CIB W78 Conference	6
Computer-Aided Civil and Infrastructure Engineering	5
Proceedings of the 2002 Annual Conference of the Canadian Society for Civil Engineering	5
Energy and Buildings	4
Proceedings of the 1998 CIB W78 Conference	4
Proceedings of the 2006 ECPPM Conference	4
Journal of Computing in Civil Engineering	3
Advances in Engineering Software	2
Building and Environment	2
Proceedings of the 2002 ECPPM Conference	2
Advanced Engineering Informatics	1
Artificial Intelligence in Engineering	1
ASHRAE Winter Meetings CD, Technical and Symposium Papers	1
Building Simulation	1
CAD Computer Aided Design	1
CIFE Technical Report	1
Construction Research Congress, Winds of Change: Integration and Innovation in Construction, Proceedings of the Congress	1
Earthquake Engineering and Structural Dynamics	1
IAI Documentation	1
International Journal of Project Management	1
International Journal on Engineering Performance-Based Fire Codes	1
Journal of Architectural Engineering	1
Journal of Construction Engineering and Management	1
Journal of the Chinese Institute of Engineers, Transactions of the Chinese Institute of Engineers,Series A/Chung-kuo Kung Ch'eng Hsuch K'an	1
Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)	1
M.Sc. Thesis—School of Engineering, University of Canterbury, New Zealand	1
NIST Special Publication	1

Table 2. *Cont.*

Publication Source Title	Publication Count
PhD Thesis—The Royal Institute of Technology, Construction Management and Economics	1
Proceedings of the 2005 CSCE Specialty Conference on Infrastructure Technologies	1
Proceedings of the 2003 ISPE International Conference on Concurrent Engineering Research and Application, Enhanced Interoperable Systems	1
Proceedings of the 1997 CIB W78 Conference	1
Proceedings of the 1997 International Building Simulation Conference	1
Proceedings of the 1999 International Building Simulation Conference	1
Proceedings of the 2000 ICCCBE Conference	1
Proceedings of the 2000 International ASCE Conference on Computing and Building Engineering	1
Proceedings of the 2000 Product Data Technology Europe Symposium	1
Proceedings of the 2001 CIB W78 Conference	1
Proceedings of the 2002 International Conference on Systems Simulation of Buildings	1
Proceedings of the 2002 Systems Simulation in Buildings Conference	1
Proceedings of the 2003 International Building Simulation Conference	1
Proceedings of the 2003 International Conference on Building Fire Safety	1
Proceedings of the 2003 International Conference on Information and Knowledge Management	1
Proceedings of the 2004 ICCCBE Conference	1
Proceedings of the 2004 SimBuild Conference	1
Proceedings of the 2005 ASCE International Conference on Computing in Civil Engineering	1
Proceedings of the 2005 International Conference on Information Visualisation	1
Proceedings of the 2005 National Symposium of The Irish Research Council for Science, Engineering and Technology	1
Proceedings of the 2007 IEEE International Conference on Automation Science and Engineering	1
Proceedings of the 2007 International Congress on Modelling and Simulation	1
Proceedings of the 2007 International Crimean Conference on Microwave and Telecommunication Technology	1
Proceedings of the First International Conference on Semantics, Knowledge and Grid	1
Proceedings of the International Conference on Information and Knowledge Engineering , IKE '04	1
Proceedings of the Twelfth International Conference on 3D Web Technology 2007, Web3D 2007	1
Report prepared for the U.S. Army Corps of Engineers Washington, DC	1
Technical Report—Dresden University of Technology	1
Technical Report from the BLIS Project	1
Technical Report from the Pro-IT Project	1
VTT Symposium	1
Total	**170**

Table 3. Publication types by year.

Year	Journal Articles	Conference Proceedings	Other Publications	Total
1997	0	2	0	**2**
1998	1	4	1	**6**
1999	2	7	0	**9**
2000	2	10	0	**12**
2001	2	1	2	**5**
2002	4	15	1	**20**
2003	10	12	1	**23**
2004	9	4	0	**13**
2005	5	20	2	**27**
2006	6	16	0	**22**
2007	16	13	2	**31**
Total	**57**	**104**	**9**	**170**

Table 4. Frequency ranking of authors (Top 30).

Author	Number of Publications
Froese, T	11
Bazjanac, V	10
Fischer, M	8
Aouad, G	7
Katranuschkov, P	7
Scherer, R J	5
Spearpoint, M J	5
Turk, Z	5
Amor, R	4
Faraj, I	4
Halfawy, M	4
Hammad, A	4
Keane, M	4
Underwood, J	4
Wix, J	4
Yu, K	4
Alshawi, M	3
Anumba, C	3
Beetz, J	3
Child, T	3
Ekholm, A	3
Gehre, A	3
Karstila, K	3
Kiviniemi, A	3
Liebich, T	3
Nour, M	3
van Leeuwen, J	3
Wan, C	3
Weise, M	3
Yabuki, N	3

Table 5. Frequency ranking of all keywords that appeared in at least three publications.

Keywords	Frequency
IFC	58
interoperability	21
BIM	11
IAI	11
integration	9
CAD	6
construction	5
data exchange	5
ontology	5
product model	5
data standards	4
facility management	4
project management	4
semantic web	4
STEP	4
construction industry	3
data exchange and sharing	3
design process	3
information technology	3
process modeling	3
product data technology	3
scheduling	3
standards	3
virtual organization	3
virtual reality	3
VRML	3

3. Results

After all full-text publications had been collected, they were sorted according to publication date, and reading was initiated from the oldest to the most recent. This approach was evaluated to be the most natural and offered the benefit of understanding progression over time.

The contents of each publication needed to be read with great attention to detail because of the comprehensive classification framework and the need to produce a short freeform abstract to support the chosen classifications and strengthen the validity of the study. Although this approach was time consuming, it was deemed worth the investment in time in order to avoid limitations to either the scope of the reviewed literature or the level of detail in its classification. To enhance the understanding of the results and how they relate to the individual pieces of literature, the quantitative bibliometric results are extended with brief commentary and references to notable examples from the studied literature.

A broad overview summarizing the general mode of research in the reviewed literature is presented in Table 6.

Table 6. Frequency ranking of research modes.

Label	Number of Publications
Identified as primary research	148
Identified as secondary research	20
Identified as official documentation, technical guides, *etc.*; not research documents	2

The results suggests that the vast majority of early research on the IFC standard broke new ground by basing the studies on new empirical data or new technical circumstances (primary) rather than using previously published research or data (secondary). From this perspective, our understanding of the body of literature can further be elaborated as being dominantly explorative, experimental, and forward facing. Continuing with the high-level summary of the research, Table 7 presents a summary of the role of the IFC standard itself in the individual pieces of research.

Table 7. Frequency ranking of publications by IFC focus.

Numner of Publications	Label
135	IFC in primary focus of research
28	IFC in secondary focus of research
5	IFC in tertiary focus
2	N/A, *i.e.*, not research

Perhaps as expected, given that IFC is in the title, abstract, or keywords of the reviewed research, the focus of the reviewed research is heavily on the IFC data model and on facilitation of its use (135 publications). Only a small portion of the reviewed research focused on other primary outputs while still incorporating IFC to some smaller degree (28 publications), and only a handful included it to an almost unrelated and distanced degree (5 publications).

Furthermore, the following individual literature mappings could be made:

- 91 publications implement IFC as part of the research, indicating that over half of the reviewed publications relate to software implementations in a very direct manner.
- 31 publications could be identified as reporting information about the active development of the IFC standard itself, often by a researcher involved in the development activities of the standard.
- Only seven publications incorporate aspects of public policy, all of which were published in the latter half of the observation period (2003–2007). This finding indicates that such aspects received little scholarly attention in the early days of IFC research and only garnered marginal research attention later on.

Figure 2 provides a longitudinal overview of the primary construction domains, or if not applicable the research context, of the studied publications. Each individual publication was assigned one descriptive classification each as part of the reading and mapping process. Throughout the years, there seems to have been a continual balance between product and process studies, independent of overall publication volume for a specific year.

Prior to the time period 1997–2001, representation of the IFC information model in software implementations were a mixture of Java and C++, as native classes in object-oriented programming languages. From 2001 onwards, XML-based data representation syntaxes such as OWL and ifcXML became the dominant method for representing IFC data structures, with few exceptions. This transition is likely due to the widespread growth in applications based around web technologies which happened at the time. Use of the IFCs original EXPRESS-based syntax within software was only identified in one publication. Table 8 provides an overview of syntax frequency over time.

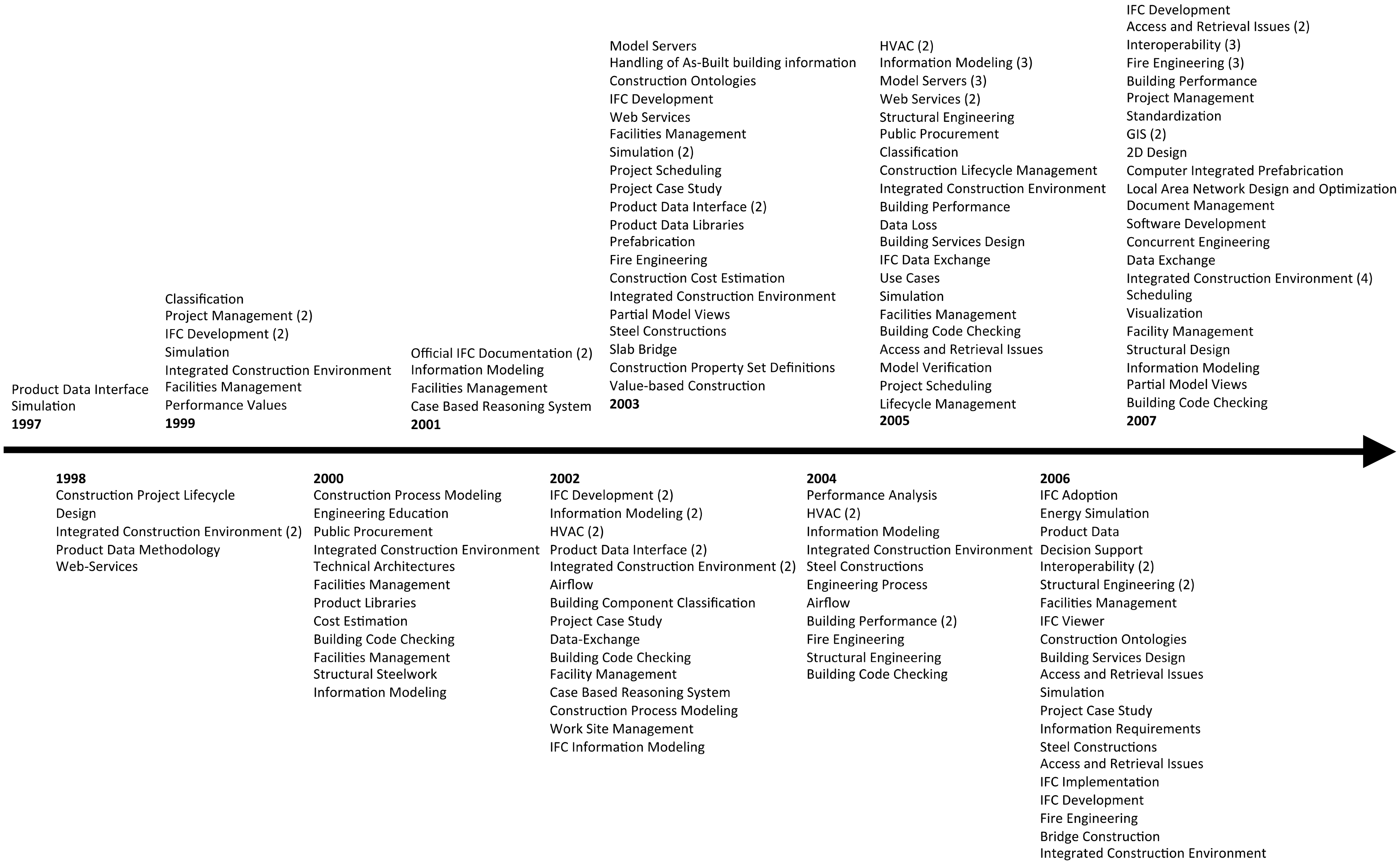

Figure 2. Primary construction domain or research context of each included publication.

Table 8. Representation of IFC when implementing the IFC information model in software.

1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Java	Java	Java	Java	XML	XML	XML	XML	OWL	OWL	XML
Java	C++		Java		XML	XML	XML	OWL	OWL	XML
			Java		C++	XML	XML	OWL	XML	XML
						XML	Java	Java	XML	XML
						XML		XML	NET	XML
						XML		EXPRESS		XML
						XML				XML
						C++				XML
										OWL
										OWL
										OWL

Insight into the timespans over which new versions of standards are adopted in research is crucial in order to gain a better understanding of the relationship between research and standardization. Figure 3 provides a visual representation of how the timing of the publication of the 152 publications that had a discernible IFC version relates to timing of official releases of the standard. The timeline reveals that the publication of the first research into new versions of the standard often appeared prior to official releases of those standards, suggesting that some researchers worked on pre-release data models as part of their research. Particularly when taking into account that published research takes time in the peer-review process and publishing pipeline, which is usually shorter for conference proceedings and longer for journal articles, it would appear that research into new versions of the standard was picked up very rapidly. Old versions of the standard were also dropped from research as new versions became available. Overall, the relationship between version releases and research adoption can be described as highly responsive.

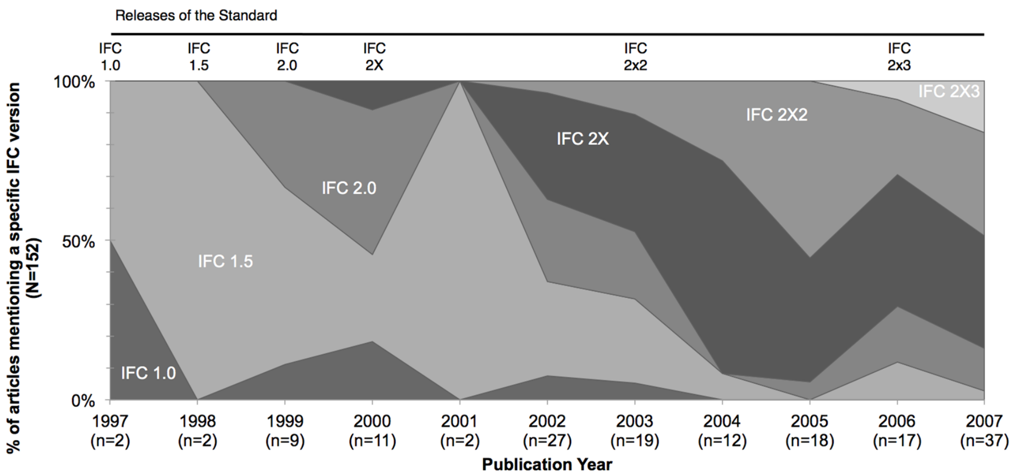

Figure 3. Publication year contrasted with version of IFC standard mentioned or applied in the article.

As the timeline depicts, there were several versions of the standard released between 1997 and 2000. For software vendors who wanted to keep up with the major or minor releases of new IFC versions, there was no documentation available that would have provided a detailed change log for each modified entity and class from the previous version. This lack of official migration support as new versions of the standard were released led to experimentation at automatic mapping between different IFC schema versions. In mapping differences between IFC 1.5.1, 2.0, and 2X, with evaluations done both in EXPRESS and XML-based IFC schema, it was suggested that about 65% of all mappings could be automatically generated, while the remainder would have to be conducted by a human operator [22].

Figures 4 and 5 take a closer look at the longitudinal development of applied research on the standard. During the late 1990s, applied research on the standard was less focused on researching data-exchange scenarios using the standard, instead focusing to a larger extent on the basic readiness and capabilities of the IFC information model to support both product information as well as the construction process.

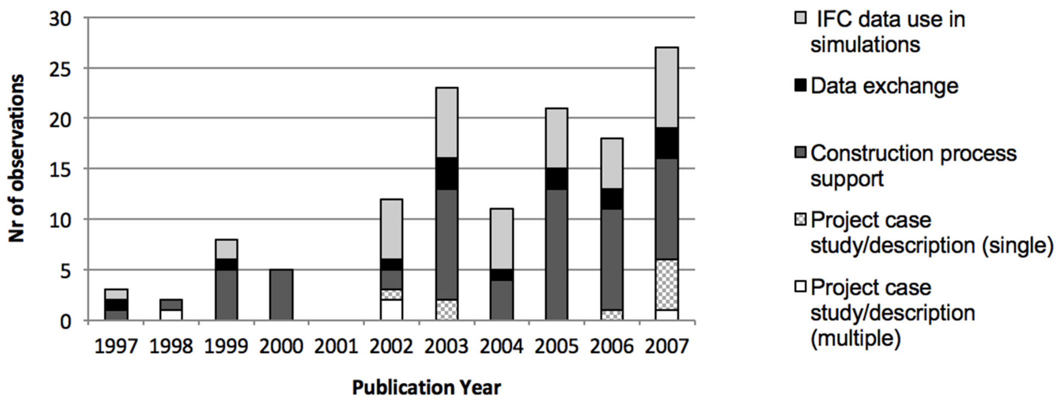

Figure 4. Applied Research: Evaluating the quality and usability of the IFC standard.

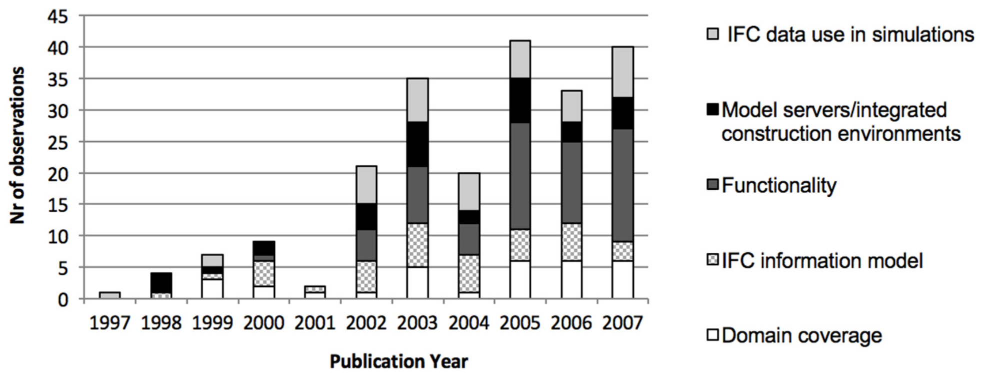

Figure 5. Applied research: extending the usability of the IFC standard.

Figure 4 presents the thematic distribution of applied evaluative research, showcasing that this type of research was minimal during the timespan 1997–2001. However, beginning in 2002, there was a total shift, and more publications focused on evaluating the quality and usability of the standard, with key thematic areas being IFC data use in simulations, and enhancing the alignment between the use of IFC and construction processes. Evaluation of data exchange quality has had a persistent but low representation. IFC evaluation studies have been a popular type of research since the first releases of the standard. In a test of interoperability of IFC 2x for architectural domain data, Pazlar and Turk conducted IFC file-based exchange evaluations within and between three widely used IFC 2x certified software applications [23]. Based on both visual and semantic analysis of the exchanged data, the main result was that IFC-based exchange could not be blindly trusted due to the loss of data between the exchanges. Although interoperability had progressed from what had been reported in earlier evaluations, the authors suggested monitoring the exchange process and using model-checker software to minimize the loss of information in exchanges.

In a direct evaluation of the standard itself, Amor, Jiang, and Chen conducted a meta-level analysis of the structure of the IFC data model and its development through version 1.5.0 to 2x3 [24]. They expressed concern regarding unnecessary complexity in the model, more specifically the number of associations and dependencies between classes. A reduction through refactoring techniques could make implementation maintenance easier. Amor *et al.* also tested the functionality of IFC translators available in commercial CAD systems, importing valid IFC files and directly exporting them back. They concluded that the exported IFC files contained errors of varying severity, indicating a need to both address the issues in the IFC certification process as well as improve the accuracy of existing translators, to retain semantic integrity on both import and export.

Although there has been a lack of real-world case studies, in summarizing some early lessons learned from the deployment of IFC-compatible software in three high-profile pilot projects, Baznajac evaluated the state of the standard from both a technical and a methodological perspective [25]. One of the most notable findings was that the industry is largely unprepared to work on integrated projects, with workflows not leveraging the benefits of BIM, thus weakening the end-user demand for an open standard. Regarding technical aspects, Baznajac concluded that there were problems related to incompatible data as well as limitations regarding what data could be successfully transferred [25]. However, Baznajac remained optimistic that these technical problems would be resolved in the near future by developing the IFC data model further and specifying more limited views for data exchange, in addition to having dedicated modeling and data integration experts oversee population and exchange of data in projects.

One of the most comprehensive publicly documented IFC pilot projects even to date is the "HUT-600" project, which ran between 2000 and 2002. Its scope was to design and construct an auditorium extension to the main building of the Helsinki University of Technology, since 2010 called Aalto University. Together with the Finnish public-property owner Senate Properties, the tightly scheduled project aimed to utilize IFC interoperability to as extensively as possible support an integrated design and construction process. Benefits of IFC data exchange were reaped, particularly in the design and evaluation phases, where IFC data could be exported for simulations on different design alternatives. Major barriers to reaping the full benefits of IFC in the project were: a lack of two-way exchanges, revision management, lack of robustness in IFC-compliant software, and complex data mapping [26]. Because the exchange in the project was file-based, there were also challenges with versioning, large file sizes, and model data loss during translation between applications. More generally, the project highlighted the need for guidelines to direct the population of data and workflows in an integrated construction process, something that has been addressed by, among others, Senate Properties themselves.

Applied research extending the usability of the standard follows a similar overall longitudinal activity pattern, with only a low quantity of such research published from 1999 to 2001 but soon thereafter quickly rising to become a very active research area. Most topics have persistently had a fairly equal relative representation from year to year, with the exception of functionality extending research, research that often provides documentation of useful extensions to the IFC data model, usually through augmentation of IFC data outside of the core data model itself. Of particular relevance to the relationship between research and standardization is that direct extension suggestions to the IFC model have been published in academic literature almost throughout the observation period, suggesting that such literature is an important forum for discussing and disseminating potential new elements of the standard.

Research and development efforts for software that extends the use of the IFC standard beyond basic one-to-one physical file-based exchange increased during this time period, as the surrounding technology infrastructure matured and the limitations that a file-based approach have on an integrated asynchronous model-based construction process became practical problems for efficient collaboration. IFC model servers have been in development at least since 2001. Although potential candidates for underlying technology protocols for IFC data sharing have already been available for some time, managing the semantic integration of concurrent changes to the master model(s) was long an open question, which was explored intensively. Weise and Katranuschkov suggested a 3-step state-based model (selection, modification, reintegration) of a single master model based on the creation of a change vocabulary for each revised state, an approach which maintains full discrete design step revision history of changes to the model [27]. Another methodology suggested to deal with the integration problem is the separation of instantiated models, with links between them to form a combined merged model based on several sub-models [28]. Even some open source multi-model solutions emerged [29], as well as studies presenting implementation of the IFC standard for specific purposes, for example, serving as an integrated project management model [30].

Extending the reach of the standard beyond software applications with implemented native IFC support has garnered interest among both industry and academia. IFC parsers of different varieties and levels of advancement were a popular area of research. Vanlande, Cruz and Nicole developed an IAI certified web-based IFC parser, ACTIVe3D BUILD SERVER, which extracts a semantic geometry model from the IFC source and displays the information in either the form of a hierarchical tree or as an interconnected visual 3D model [31]. Conceptual solutions founded on parsing IFC files have been developed for: online construction product libraries [32], IFC database version handling [33], and an inexpensive workflow for IFC information model reading and updating [34].

Ambitious wide-scope parser-based technologies were also developed. One is the BSPro Com-Server, a piece of software which acts as a middleware layer, extracting geometry information from IFC files to be used in non-IFC supporting software for electrical and HVAC simulation purposes [35]. Another solution with substantial scope was developed in the SABLE project, which aimed to standardize client APIs for several domains based on BLIS views, essentially creating a multi-domain IFC model server [36]. What all these solutions have in common is that, by introducing an additional layer of translation into the data exchange, they necessitate software translators to be developed between the target software application and the IFC source. However, such solutions are potentially friendlier for implementers because the scope is limited to implementing an API instead of dealing first-hand with the wider and more complex full IFC information model.

Figure 6 provides a look at the non-applied research published related to the standard. From the outset, it is evident that non-applied research is not a dominant trait of IFC standards research; most research conducts first-hand experiments by applying the standard in software. Non-applied research consisted predominantly of theoretical accounts based on data models, descriptions of construction practices, or often a combination of these approaches. The longitudinal distribution of non-applied research is more even than that of applied research. Because the years 1997–2001 were early in the standardization of IFC, with initial software implementations being available on the market in mid-1998, most of the scholarly publications were authored by individuals involved in the standardization process, communicating progress, and generating awareness about the effort within academia and the industry [37–40]. Since the early public releases of the IFC standard, the dialogue between the developers of the standard and its researchers has always been an important feedback mechanism.

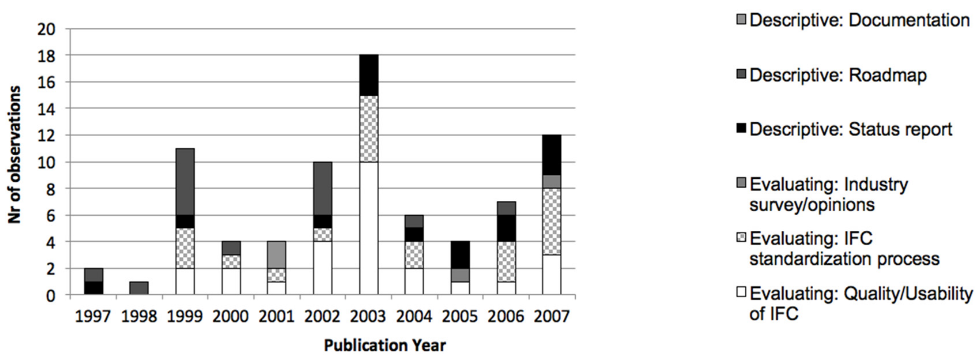

Figure 6. Non-applied research: Descriptive and evaluating research.

One of the first IFC evaluation studies was published in 1999; in a workshop setting, the goal was to evaluate how well IFC 2.0 models supported the real-world project management tasks of estimating and scheduling in a range of different scenarios, ending up with fairly positive results [41]. IFC 2.0 was seen to adequately support the sampled project management tasks, and in some cases offer potential benefits for estimation and scheduling integration beyond the software alternatives available at the time.

The class and entity structure of the IFC standard was not based on any 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" was to coordinate several regional and national classifications systems, whose retrospective harmonization to the IFC standard has been evaluated [42,43]. According to Ekholm, integrating IFC with ISO 12006-2 would facilitate the adoption of object-based information management. However, 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 [43]. Research around this question has been around since before the dawn of IFC. As Ekholm notes [43], harmonization between building classifications and product modeling was suggested by Björk (1992) within the "Unified Approach Model" [44]. Although harmonization is possible in theory, it would not come easily: integrating ISO 12006-2 classification through the initiation methodology suggested by Ekholm would first require a move towards conventional and strict object-oriented definition practices in the underlying IFC information model to replace some of the adopted ad hoc solutions, which in turn would require major commitment to the effort by the consortia [43].

Enhancing the semantic extensions of modeled objects by increasing the support for behavioral and knowledge-based information in IFC models has also been suggested. This approach would reduce the need for complementary systems as well as provide advanced features such as detailed object revision history, cross-dependency relationships between objects, and value-calculation derivation founded on strict modeling methodology [45,46].

Either parts or the whole of the IFC standardization process itself have been the focus of several publications; however, few extensive studies have been published related to this aspect. In a 1999 review paper of the product modeling standardization efforts of the AEC/FM industry, the STEP and IFC standardization processes were given fairly pessimistic outlooks: STEP for being fragmented and burdened by democracy and having no real drive behind it, and IFC for being weakly supported by the industry actors and low on resources to make substantial progress [47].

To conclude the literature analysis, Appendix 2 presents an image and associated data table that visualizes the publication keywords that have received the most citations up until April 2015 according to Google Scholar, thus giving some insight into what topics and what kinds of publications have been the most cumulative or popular when researchers have cited previous research. The full source of keyword and citation data can be found in Appendix 1. Based on the citation analysis it can be concluded that publications containing "IFC", "IAI" or "interoperability" among their keywords have been among the most frequently cited, a result that is perhaps not surprising considering the selection criteria for the literature sample. However, following these keywords two less predictable entries appear, "project management" and "scheduling", making these areas of IFC-related research measurably stand out from the rest. Without an in-depth investigation of the content citing these publications, it is impossible to conclude exactly why this is. A potential explanation could be that publications which have included project management aspects have gained cross-disciplinary attention and thus also been of relevance outside of the construction IT domain.

4. Discussion

Research related to the IFC standard has been oriented towards design science and applied science, with individuals involved in the standardization effort being among the most frequent contributors to the academic literature. This overlap between official documentation and research articles makes the general profile of available literature unique compared to many other standardization efforts. The overall balance between product and process studies, independent of overall publication volume for a specific year, came as a surprise since the outgoing assumption was that most research would be applied product studies based on the technology/standard-focused literature search criteria. This balanced output can only be seen as beneficial for supporting any standardization effort that evaluations and improvement suggestions are made both on the technical level as well as on the level of how well the standard actually caters to the needs and processes of actual work.

A general observation that can be made related to the IFC research stream as a whole is the issue of overlapping research and technology development. There would seem to have been minimal sharing of both IFC models and prototype software between researchers, which makes cumulative knowledge building less than optimal. This aspect of fragmentation and duplication of work in IFC research has also been acknowledged in literature outside of the observation period by researchers at the University of Auckland, where an initiative for creating a more unified research environment has been started through the Open IFC Model Repository [48–50].

This study has given a bottom-up, external perspective on the relationship between research and standardization, drawing conclusions based on the activity patterns in academic publications. In previous research, focus in this context has often been top-down, on creating formal collaboration channels and workflows between standard-setting organizations and researchers. It could be argued that the approaches are largely complementary, given that neither approach by itself enables holistic insight into the relationship between the process of standardization and in what way research interacts with the standard as it matures. In light of the findings of this study, it would be a logical extension to conduct interviews with individuals involved in the IFC standardization process, including both prolific academic researchers as well as representatives from the major organizations currently involved in the standard's development, namely buildingSMART and ISO.

Returning to the outgoing perspective on the longitudinal knowledge development around emerging technologies presented in Figure 1 (Day, Shoemaker, and Gunther 2000), there are several aspects that ring true to the insights garnered from this study into the early stages of IFC and BIM development. The whole decade of research showcases a highly fluctuating foundation where knowledge streams have converged, different competing modalities have fought for their place among the dominant designs, and commercialization pressures have shaped the landscape of available BIM technology. The idea that sufficient common ground (*i.e.*, standards) should be created before software solutions are put up to compete against each other through different application offerings is something that has not happened as neatly as Figure 1 suggests. Tough competition among BIM software vendors was initiated even before the IFC initiative was started, making it hard to retrospectively standardize heterogeneous software applications with different internal data structures and market positions.

This article contributes to both by offering a methodology to understand IT standardization, particularly in the context of construction IT and BIM, as well as by suggesting a methodological literature framework for similar studies within or outside the construction IT domain to build upon. The complete annotated literature list can be found in Appendix 1 as part of the full literature dataset, Appendix 3 contains the same list presented as an academic reference list. Classifying research into detailed categories is always a subjective task with margin for interpretation. Thus, open dissemination of the full dataset is important for research transparency, validation, and potential future re-use or extension by other researchers.

In comparison with the use of ad hoc solutions or proprietary standards, the common open artifact has provided a vehicle for research to contribute towards a common body of knowledge and technological development. This observed effect can be related back to how the core purpose of standards has been formulated as "agents of change" (Cargill 1989). It is evident that IFC ushered product and process model research into a new era where there was a clear common ground amongst researchers, a fact that has also benefitted the testing and further development of the IFC standard itself.

Suggestions for Future Research

Through this study, we discovered that research concerning an IT standard lends itself well to systematic mapping of the literature. Where other areas of research might have to consider ambiguity in definitions and variations in natural language expression, standards and technical terms offer relatively unambiguous search terms and keywords for identifying and retrieving relevant literature. However, despite the fairly natural fit of methodology and subject matter, no typology for classification frameworks regarding review of technical standards research exists. It would likely be fruitful to further explore the usefulness of systematic reviews in the context of standards research in general, potentially resulting in some baseline classification framework for different types of IT standards within and outside of construction IT.

Acknowledgments: This research was supported in part by funding from the Finnish Doctoral Programme of the Built Environment (RYM-TO).

Author Contributions: M.L. conceived and designed the experiments; M.L. & L.N. performed the experiments; M.L. analyzed the data; M.L. & L.N. wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BIM	Building Information Modeling
CAD	Computer-Aided Design
IAI	Industry Alliance for Interoperability, changed to International Alliance for Interoperability in 1996
IFC	Industry Foundation Classes
IGES	Initial Graphics Exchange Specification

Appendix

The following are available online at http://www.mdpi.com/2075-5309/6/1/7/s1.

Appendix 1, Literature list with review coding (XLSX spreadsheet format); Appendix 2, Citation analysis (PDF document format); Appendix 3, Chronological literature list (PDF document format).

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