Systems integration and collaboration in architecture, engineering, construction, and facilities management: A review

Weiming Shen *, Qi Hao, Helium Mak, Joseph Neelamkavil, Helen Xie, John Dickinson, Russ Thomas, Ajit Pardasani, Henry Xue

Institute for Research in Construction, National Research Council Canada, London, Ont., Canada N6G 4X8

ABSTRACT

With the rapid advancement of information and communication technologies, particularly Internet and Web-based technologies during the past 15 years, various systems integration and collaboration technologies have been developed and deployed to different application domains, including architecture, engineering, construction, and facilities management (AEC/FM). These technologies provide a consistent set of solutions to support the collaborative creation, management, dissemination, and use of information through the entire product and project lifecycle, and further to integrate people, processes, business systems, and information more effectively. This paper presents a comprehensive review of research literature on systems integration and collaboration in AEC/FM, and discusses challenging research issues and future research opportunities.

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1. Introduction

Due to rapid changes in technology, demographics, business, the economy, and the world, we are entering a new era where people participate in the economy like never before. A new business rule for competitiveness is to "collaborate or perish" [71]. This applies to all societies and industries including the construction industry, or the AEC/FM (architecture, engineering, construction, and facilities management) industry.

According to an industrial survey on the Canadian construction IT industry [20], "the most frequently identified issue is related to collaboration (including communications, document management, and interoperability)". It is considered to be the most important "opportunity for improvement to the Canadian construction industry". From the same survey on a question related to "the trends in information technology that will be important for the construction industry over the next 10 years", the strongest response was for "Web-based collaboration and project management systems" (67%) followed by "integration of software tools across the project lifecycle" (43%). Surveys conducted in other countries showed similar results [16,29,60,89,92].

Because of the complexity of the construction industry, the multiple phases of the construction project lifecycle, the involvement of multidisciplinary teams (including owners, architects, consultants, engineers, contractors, sub-contractors, and suppliers), and the use of heterogeneous software and hardware systems/tools, systems integration becomes an important prerequisite to achieve efficient and effective collaboration. In fact, systems integration is all about interoperability. Under the context of this paper, interoperability refers to the ability of diverse software and hardware systems to manage and communicate electronic product and project data smoothly. Interoperability problems in the capital facilities industry stem from the highly fragmented nature of the industry and are further compounded by the large number of small companies that have not yet adopted advanced information technologies [21].

Systems integration and collaboration are not new research topics. With the rapid advancement of information and communication technologies, particularly Internet and Web-based technologies in the past 15 years, various systems integration and collaboration technologies have been developed and deployed to different application domains, including architecture, engineering, construction, and facility management (AEC/FM). After many years of R&D, the AEC/FM industry has now started to embrace and adopt software systems that support and promote the concepts of integration and interoperability [25].

However, due to the unique nature of the construction sector, the development and deployment of systems integration and collaboration technologies are behind other sectors (e.g., manufacturing). This paper provides a literature review on systems integration and collaboration in AEC/FM, and discusses challenging research issues and future research opportunities. We would like to refer the readers to some other recent literature review or overview papers in the related areas. Boddy et al. [10] provided a review of the construction IT literature in general and drawn an excellent research landscape of the computer-integrated construction. They proposed a process

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* Corresponding author. Tel.: +1 519 430 7134; fax: +1 519 430 7064.
E-mail address: wshen@ieee.org (W. Shen).

driven vision for the integration of construction processes. Isikdag et al. [35] presented some historical background of building information modeling (BIM) and particularly reviewed the storage and exchange mechanisms for building information models. Bakis et al. [7] conducted a comprehensive literature review on the development of standard building data models and model mapping languages. O'Brien et al. [52] discussed key challenges and approaches for distributed construction process integration and particularly presented the SEEK – Scalable Extraction of Enterprise Knowledge toolkit [51] as a mechanism to discover semantically heterogeneous source data. Being complementary to all these review and overview papers, this paper is to present a critical review of the state-of-the-art systems integration and collaboration technologies, standards and tools in the AEC/FM industry.

The rest of the paper is organized as follows: Section 2 briefly describes the current problems and requirements on systems integration and collaboration in AEC/FM; Section 3 discusses challenging research issues and the state-of-the-art; Section 4 reviews related standards and commercial tools; Section 5 presents major international initiatives, programs, and projects; Section 6 identifies future research opportunities; Section 7 provides some concluding remarks.

2. Current problems and requirements

The US National Institute of Standards and Technology (NIST) published a study [21] that identified and estimated the efficiency loss of $15.8 billion in 2002 in the US capital facilities industry resulting from inadequate interoperability among computer-aided design, engineering, and software systems. Of these costs, two-thirds are borne by owners and operators, who incur these costs predominantly during ongoing facility operation and maintenance.

According to FIATECH [92], some major problems on systems interoperability in the construction industry include (paraphased based on [92]):

– It is difficult to access accurate data, information, and knowledge in a timely manner in every phase of the construction project lifecycle.
– There is a lack of interoperability between systems, with several standards competing for managing data. A common methodology for managing construction projects' information assets does not exist.
– Program plans and designs are optimized for a limited set of parameters in a limited domain. The capability to support "total best value" decisions does not exist.
– Tools for project planning and enterprise management are maturing, but an integrated and scaleable solution that delivers all needed functionalities for any kind of projects is not available.
– Lifecycle issues are not well understood and therefore modeling and planning do not effectively take all lifecycle aspects into account. Operation, maintenance, environmental impact, and end-of-life disposal issues are given limited consideration in the project planning equation.
– The ability to assess uncertainties, risks, and the impact of failures is not mature, partly due to the lack of knowledge to support these evaluations, and partly due to the limitations of available tools.
– The business foundation for addressing increased security concerns does not exist, and the ability to address these issues is limited by the lack of understanding of the risks and alternatives.

In order to address these problems, FIATECH has created a roadmap (particularly its Element 6) to integrate all functions of project/facility planning and management systems and all required information in a unified project/facility management environment [92]. The Roadmap presents a vision for the capital projects industry and a strategy and plan for achieving that vision: "a highly automated project and facility management environment integrated across all phases of the facility lifecycle". Information is available on demand, wherever and whenever it is needed to all interested stakeholders. This integrated environment will enable all project partners and project functions to instantly and securely 'plug together' their operations and systems. Interconnected automated systems, processes, and equipment will drastically reduce the time and cost of planning, design, and construction. Scenario-based planning systems and modeling tools will enable rapid, accurate evaluation of all options, resulting in the selection of the best balance of capability and cost-effectiveness". This statement clearly describes the requirements for future construction IT systems integration and collaboration technologies. While FIATECH presents the North American perspectives on current problems and requirements of the construction industry, the ROADCON project [60] provides the European perspectives on ICT in construction. In particular, the ROADCON project identified some specific requirements/barriers (e.g., short-term and temporary relationships between business partners, and special needs of mobile and wireless solutions for the site-based work) and priority R&D areas including the legal and contractual aspects management and the human aspects management. Moum et al. [49] presented some perspectives of construction ICT applications in Denmark.

3. Challenging research issues and state-of-the-art

The very fundamental idea for integrating two or more software systems is to enable them to communicate, share or exchange information, and then to inter-operate in order to achieve a common objective. In this section, we first discuss systems interoperability from two different perspectives: data interoperability and frameworks interoperability. Then a comprehensive state-of-the-art review is provided for challenging research issues and technologies in this area.

3.1. Interoperability

3.1.1. Data interoperability: data modeling and integration

Data interoperability is the ability that data generated by any one party can be properly interpreted by all other parties. It is the first step towards any systems integration and collaboration. The enabling technology for data interoperability is data modeling. In the construction industry, data models are called building information models (BIMs). Various data models can be classified as either proprietary, developed and controlled by individual vendors, or neutral (open), developed by a consortium of efforts and available to all.

As a building project typically involves a number of software tools from different vendors to carry out specific tasks by individual parties, e.g., design, structural analysis, project management and control, the demand to share data/information among the project parties during the project lifecycle has increased. Sharing data in such a heterogeneous environment requires all parties to have a common data model so that each party knows how to generate and interpret the data within the community. A common neutral model is the most feasible solution in AEC/FM to enable data sharing or integration in heterogeneous applications. With a common data model, it is possible for building information to be created once, re-used and enriched in the rest building lifecycle. This reduces project duration by eliminating the need to recreate data models repeatedly and increases project quality by eliminating errors

and inconsistencies introduced during the data recreation process. The development of several such competing neutral models or standards has been done by a number of international standard organizations (e.g., ISO) or industrial consortia (e.g., IAI – International Alliance for Interoperability which has been evolved into the buildingSMART International organized as regional alliances) [84]. Some of these standards and tools are described in more detail in Section 4.

A data model organizes the data of a certain domain of interest (application) in a manageable manner. It should contain the definitions of all application objects (e.g. wall, floor) within that domain, as well as constraints and relationships between objects (e.g. there should be one and only one wall at any one physical space). In older standards, e.g. IGES, the data models are implicit and they tend to concentrate on defining the format of the data and how the data should be presented in an exchange file. In newer standards, e.g. those described in Section 4.1, data modeling languages are used. IDEFx are used by the US Air Force to define projects and project data. EXPRESS is used by all the standards discussed in Section 4.1. Recently XML schema is used to facilitate the Web-based applications.

In order to describe the multi-facets of a building, the BIMs are usually organized in clusters with a certain hierarchy. Each cluster corresponds to an aspect of building information, e.g. building elements (e.g. walls), building structures, (e.g. the cluster of walls forming the storey), equipment, (e.g. HVAC), plumbing and electrical wiring, and material. In order to reuse any common information, later BIMs employ the object-oriented approach with inheritances from an extensive parent-child hierarchy.

The major problem facing today's data interoperation solutions is the existence of different exchange flavors. A flavor of a standard is evidenced when two different vendors interpret the same standard in two different ways in encoding the same piece of information. The problem was especially serious in early IGES models and remains an issue in many new standards. Since BIMs are highly complex, it is unavoidable. Standards need good user feedback, vigorous pre-release cross-platform testing and time to mature to weed out these flavors.

Bakis et al. [7] have done a comprehensive review of the research literature on data interoperability or "integration through product sharing and exchange". ITcon recently published a special issue on Case Studies of BIM Use to show the benefits and challenges of using building information modeling for stakeholders in the building process [53]. According to Young et al. [78], "BIM has now evolved from a focused tool set for design to a more comprehensive platform for design and construction integration, driving major changes in the ways all the players interact", which may represent the North America's industrial perspectives on BIM. Howard and Bjork [31] pointed out that "BIM solutions appear too complex for many and may need to be applied in limited areas initially", which indicates the European industrial perspective on BIM. On the practical side, Borrmann and Rank [11] proposed possible implementations of directional operators in a 3D spatial query language for building information models.

As indicated by Soibelman et al. [66], another challenging issue on data modeling and integration is the various types of unstructured data sources in the construction industry, including text-based project documents, site images, web pages, and project schedules. They reported some recent developments of data mining on text-based, web-based, image-based, and network-based construction databases [66].

3.1.2. Frameworks interoperability: communication protocols and languages

While most people consider that interoperability is all about data interoperability, frameworks interoperability is also critical in systems integration. For example, when two different sensor networks need to work together, we need to deal with not only data interoperability but also frameworks interoperability including communication protocols and languages.

On the other hand, while data interoperability is preferable to achieve efficient systems integration and effective collaboration, it is not practical for the integration of legacy software applications which were initially developed by different vendors and were not expected to work together. Therefore, incorporating legacy systems and achieving platforms interoperability at a higher level is a challenge currently faced by the construction industry. In order to achieve frameworks interoperability, various technologies have been proposed, developed and deployed. We will review these technologies in detail in Sections 3.2 and 3.3.

In summary, data interoperability focuses on common data models or formats, while frameworks interoperability depends on common communication languages and protocols. When a centralized integration approach is used, data interoperability is more important. However, in a highly distributed and loosely-coupled integration approach, the interoperability is usually achieved through common communication languages and protocols while allowing different systems or sub-systems to use different data models and formats. These systems/sub-systems may have their own perspectives on the problem being solved and they do not have direct knowledge of other systems/sub-systems.

3.2. Systems integration approaches

3.2.1. Web-based systems

The World Wide Web was originally developed to allow information sharing within global teams and the dissemination of information by support groups. A Web-based system uses a centralized information integration approach through a shared Web server or a central database behind the Web server. Web-based systems are currently the most advanced information systems deployed on the Internet [101]. According to the industrial survey on the Canadian construction IT industry [20], about half (49%) of the construction IT tools developed in Canada use Web-based systems as their implementation technology. Similar results are found in other countries, e.g., in UK/Europe [60] and UAE [16].

With simple client-server system architecture and mature Web development tools, it is possible to develop and deploy a Web-based system within a very short timeframe for daily construction project management. In fact, a number of commercial Web-based software systems have been made available and used by many construction companies.

A simple Web-based system may be adequate for daily construction project management, but it is not sufficient to meet the requirements described in Section 2. For example, in order to support a collaborative design project involving owners, architects/designers, and engineers, Web servers must also engage users in a dialog-like interaction that encompasses a range of activities, such as geometric and semantic product modeling, design representation, user-interaction, and design browsing and retrieval. The basic Web technology itself cannot meet these requirements. In other words, information access is not the only major outstanding problem. In order to collaborate on a complex project, remote engineers and designers need active assistance to coordinate their efforts. This coordination involves translation of terminology among disciplines, locating/providing generic analysis services, prototyping services, and project management. As these Web servers are not only acting as repositories of information but also systems to engage users in active dialogs while providing such remote services in order to solve complex engineering problems, they can be implemented as intelligent software agents as detailed in Section 3.2.3.

3.2.2. Distributed objects/components

The Object-oriented programming paradigm can be traced back to the 1960s and has been popular for about two decades. It emphasizes programming efficiency by stressing modularity of data structures and code sharing. It also uses a centralized integration approach. It has been widely used for the implementation of integrated systems, particularly after the development and deployment of three major Distributed Objects standards: CORBA by the Object Management Group (OMG), COM/DCOM by Microsoft and Java RMI. In fact, most of the so-called agent-based systems (see Section 3.2.3) are implemented using Distributed Object technologies. This section provides a review of some recent projects on the application of distributed object technologies in AEC/FM.

- Faraj and Alshawi [17] presented an object-oriented implementation of a rapid prototyping environment called SPACE (Simultaneous Prototyping for an Integrated Construction Environment) which supports a subset of a construction project lifecycle. It integrates a number of commercial software packages including AutoCAD/AEC (for design), World Tool Kit (for visualization), and Super Project Expert (for planning) as well as several other applications developed in-house. A centralized project model is used to connect all these applications.
- Halfawy and Froese [24] proposed to build integrated AEC systems using smart objects. In the proposed approach, smart objects are 3D parametric entities that are combined with the capability to represent various aspects of project information required to support multidisciplinary views of the objects, and the capability to encapsulate "intelligence" by representing behavioral aspects, design constraints, and lifecycle data management features into the objects. In fact, the smart object concept is similar to the software agent concept discussed in the next subsection (Section 3.2.3). A prototype system of the proposed approach was implemented to support the integrated design process of a false work system. The smart object approach was then extended into a component-based approach using a three-tier system architecture [25]. Components are usually considered to be a higher level of abstraction than objects and they do not share a state but communicate by exchanging messages carrying data. This extension makes it easier to integrate various applications, particularly legacy applications. A prototype system was implemented using COM/DCOM. In fact, this component-based approach can be easily extended to a service-oriented approach and implemented using the Web services technology and related standards [43]. Similar component-based approaches were proposed by Anwar et al. [3] for structural engineering applications and by Geyer [23] for building design optimization combing Multidisciplinary Design Optimization (MDO) and Building Information Modeling.
- Similar approaches using distributed object technologies (particularly CORBA) can also be found in [12,45,80]. However, Lu and Issa [45] emphasize loosely-coupled integration, compared with standard-based approaches like IFC [18,19,24,25,72,79]. This kind of loosely-coupled integration is particularly suitable for distributed systems integration and collaboration. Similar approaches can be found in [50,51,59]. In our opinion, such loosely-coupled integration is more easily achieved using software agents and Web services technologies.
- As a special case, Caldas et al. [13] presented a model-based integration approach with semi-automatic mechanisms for the classification, retrieval, ranking, and association of text-based project documents. It addressed another important issue, usually in the area of knowledge management, which is not the focus of this paper.

3.2.3. Software agents

Software agent technology was applied to systems integration and collaboration before the Web became available [65]. Parunak [54] has analyzed where agent technology can be best used in industrial applications: "agents are best suited for applications that are modular, decentralized, changeable, ill-structured, and complex". The reasons often given for adopting an agent approach are linked to their being proactive object systems and to the simplification of the architecture of the software systems. The real gain obtained from an agent-based approach, however, often comes from a better description of the real world by focusing on objects rather than functions. When used appropriately, this leads to the desired modularity, allowing flexible simulations, and to better response and improved software reusability. In addition, agents can cope with a dynamically changing world by performing dynamic linking, allowing them to handle ill-structured or rapidly changing situations in a more economical way [65]. This section provides a brief review of recent projects on the application of agent technology for systems integration in AEC/FM.

- Bilek and Hartmann [8] presented an agent-based workbench to support complex structural design processes in AEC. The proposed workbench aims at assisting design experts according to their expertise and assigned tasks and furthermore detecting typical deficiencies and conflicts that may occur in collaboration, cooperation and coordination between different structural designers. The workbench consists of a set of software agents that are designed and modeled to integrate typical organizational characteristics of a project, engineering software and data structures in terms of product models. Three agent-based models were proposed: the collaboration model, the engineering software integration model, and the product model, which are connected by an agent-based process model. The proposed approach was validated through the analysis of the design process of an arched bridge which was already built.
- Wing [75] presented some recent research on the application of software agents together with RFID (Radio Frequency IDentification) technology in construction. Wing argued that, since software agents need to make autonomous decisions and take actions when required, they are totally dependent upon sensors (rather than human intervention) to provide real-time information on parameters such as location, condition and timing. RFID tags are seen as an appropriate sensor type for providing this kind of information. Although there is little evidence indicating RFID adoption in the construction sector, the paper concludes that a breakthrough will result from applications that emphasize the management of the building or facility, in particular in the area of energy consumption.
- Reffat [57] proposed an approach for architectural design to be carried out collaboratively and synchronously inside real-time 3D virtual environments where architects design with intelligent agents based on the view of situated digital architectural design. The interesting side of this approach is on its integration of intelligent agents with situated digital design [22] and virtual reality technology. However, so far no implementation has been reported to support the proposed approach.
- Rueppel and Lange [62] applied intelligent agents and Petri-Nets to support cooperation and coordination in distributed planning processes in civil engineering. Petri-Nets are used to model the processes and to support the coordination between the participants during the planning process, while intelligent software agents are used to integrate models and knowledge-based services. Petri-Nets are also used to model the migration and inter-

action of agents. A prototype system was implemented using JADE and validated through a case study of fire protection planning.

– Aziz et al. [6] presented a mobile collaboration support infrastructure by integrating the Semantic Web (to provide a framework for shared definitions of terms, resources and relationships), Web Services (to provide dynamic discovery and integration) and intelligent software agents (to help mobile workers accomplish particular tasks). Several interesting application scenarios are discussed, but implementations were not reported.

– Alda et al. [2] proposed and developed an integrated multi-agent and P2P software architecture for supporting collaborative structural design processes. Based on this integrated platform, both human experts and software agents are capable of emitting and perceiving awareness events that correspond to planned activities, so that users can be informed and enabled to detect potential inconsistencies at an early stage of modeling activities.

There are several other projects/efforts reported in the literature which cannot be covered in this paper due to space limitations. The approaches briefly mentioned above are all quite unique and show a spectrum of applications of software agents for systems integration in AEC/FM.

3.2.4. Web services and a Semantic Web

The basic Web servers are passive, i.e., they only reply to requests from users, rather than actively or proactively send data/ information to users or other servers. They neither cooperate nor coordinate. The Web service technology officially proposed by W3C in 2002 is meant to address these shortcomings. In fact, it is very similar to the concept of Active and Proactive Web Servers that we proposed in 2000 [64]. By their definitions, a Web service is "a software system designed to support interoperable machine-to-machine interaction over a network" [102] and a Semantic Web is "an evolving extension of the Web in which Web content can be expressed not only in natural language, but also in a format that can be read and used by software agents" [102].

Even though Web Services and Semantic Web technologies have been widely used in systems integration and collaboration in other domains (particularly in e-business applications), very few reported results have been found in AEC/FM. However, we strongly believe there will be widespread applications of these technologies in AEC/FM in the foreseeable future.

– Schevers et al. [63] reported the application of the Semantic Web technology, particularly the Resource Description Framework (RDF) and the Web Ontology Language (OWL) to the implementation of a digital facility model for the Sydney Opera House.

– El-Diraby et al. [15] presented a domain specific taxonomy for construction management. The taxonomy is based on the IFC and several other classification systems. It classifies construction concepts in six main classes: Project, Process, Product, Actor, Resource, Technical Topics, and Systems. A prototype ontology was developed using OWL for the construction domain based on a taxonomy of relationships and a set of axioms.

– Leung et al. [42] proposed a Meta-Data-Based (MDB) approach that extracts information from the original Web-based documents and reorganizes them in an integrated Web page according to specific users or tasks, with XML as the core technology which serves as a common language that facilitates data exchange and the rapid location of information.

– Kosovac [39] presented a Web services based framework for managing information from heterogeneous, distributed, and autonomous sources in AEC/FM with a pilot implementation.

– Wang et al. [74] presented a middleware framework for integrating heterogeneous building automation systems on the Internet. The proposed framework combines OPC (OLE for Process Control) and Web services to integrate data and services. Although this work focuses only on the integration of building automation systems, rather than over the building project lifecycle, the proposed approach makes it easy to integrate with other systems (from design, construction, to supply chain) because of its service-oriented architecture and its use of Web service standards.

– Based on an excellent literature review on computer-integrated construction, Boddy et al. [10] proposed a process driven approach by integrating software agents and Web services technologies. It is very similar to the Cooperative Workflow concept presented in [28].

– Akinci et al. [1] developed a semantic web-based approach to enable interoperability between two existing CAD and GIS platforms. Similar approach was also reported in [36].

3.2.5. Integration of RFID and wireless sensor networks

Radio Frequency IDentification (RFID) is a wireless technology that enables one to automatically identify and track assets in almost any organization. It offers wireless communication between RFID tags and readers with non line-of-sight readability. This reduces or eliminates the need for manual data entry and introduces the potential for automated processes to increase productivity, safety and efficiency.

RFID is just one kind of wireless sensor network (WSN) technology. A wide range of wireless sensors have been developed and applied to cooperatively monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants. It is evident that these technologies can be well applied to the AEC/FM industry, either during the construction process for improving real-time decision-making processes, or during the operation and maintenance of built environments for condition monitoring and intelligent control.

There have been some research and development efforts on the application of wireless sensor network technologies, particularly RFID, in the construction industry, but most are pilots and have not been widely accepted by stakeholders. The US National Institute of Standards and Technology [99] is currently exploring novel technologies for sensing in buildings using WSN. This will enable a building operator to place sensors without disrupting existing construction and which allows sensors to be placed in spaces that may see changing configurations. A detailed review of the related literature can be found [77].

One major challenge, among others, such as communication and energy efficiency, is to integrate a wireless sensor system (as a real-time data collection system) into real-time decision support systems to help construction engineers and facility managers to make the right decisions in a timely manner thereby improving productivity and efficiency. Rebolj et al. [56] proposed a combined method of capturing real-time information during the construction process, consisting of three components: an automated activity tracking subsystem based on image recognition, an automated material tracking subsystem, and a mobile computing supported communication environment. Ibrahim et al. [33] reported the use of computer vision technology for the collection of real-time construction work packages in the job site. By comparing with the ex-

pected state of construction, the monitoring and analysis results provide progress feedback on the work packages, allowing a project to be monitored more effectively.

3.3. Collaboration technologies

3.3.1. Web-based collaboration

As mentioned above in Section 3.2.1, the Web was originally designed for information sharing and collaboration. It is natural to develop and use Web-based tools to facilitate collaboration in AEC/FM. The Web-based systems mentioned in Section 3.2.1 are mostly for construction project documents sharing [58] and collaborative project management.

3.3.2. Agent-based collaboration

Software agents are usually used to facilitate collaboration or interoperation among software systems, but they can also be applied to facilitate communication and collaboration among software system users [76], organizations [65], and hardware systems.

- Lee and Bernold [41] proposed an agent-mediated communication approach to overcome the problem of information overload during a construction project.
- Menzel et al. [46] have shown how agent technology can support mobile device users in the construction field to fulfill their individual requirements in specific working situations.
- Bletzinger and Lähr [9] proposed an agent-based collaborative environment for dynamic workflow management.
- Zhang and Hammad [81] presented an interesting approach based on software agents to coordinate crane operations where two cranes are working together. Software agents are used to dynamically control the kinematical actions of the two cranes respecting the functional constraints for safety and efficiency of operations.

3.3.3. Collaborative virtual environments

With the integration of virtual reality, software agents, and Internet/Web-based technologies, collaborative virtual environments are being widely applied in almost all e-business and engineering domains for collaboration among distributed teams. There will be no exception for the AEC/FM industry.

Rosenman et al. [61] presented a framework for collaborating in a virtual environment including a database (based on IFCs) containing the various models and relationships, a virtual world environment for collaboration, and an agent-based society for handling communication between the users.

Aspin [5] proposed an interaction mechanism that enables a group of co-located users to collaboratively interact with a common visual environment through the use of lightweight remote computing devices. Applying an object-based distributed shared memory (DSM) system enables the description of the active sessions to be distributed to both the collection of services, forming the design/review session configuration, and the remote interface applications that support individual user-interaction. This distributed system then forms a synchronized, distributed description of the session content that both informs services of the session content and provides a centralized system for managing user-interaction.

In an interesting experimental work, Hammond et al. [26] used a socio-technical theory as a framework to explore differences in engineering design team decision-making as a function of various communication media. Their results indicate that design teams communicating via an electronic medium perceive an increase in mental workload and interact less frequently, but for a greater total amount of time. These results brought interesting implications and suggestions for the management of distributed design teams or the human aspects management [30,60].

3.3.4. Virtual organization as a collaboration medium

According to Camarinha-Matos [14], "a Virtual Organization (VO) is an identifiable group of actors that make substantially more use of information and communication technologies than physical presence to interact, conduct business and operate together, in order to achieve common, project-centred business objectives. The aim of the VO is to gather complementing competencies of different actors in order to enhance efficiency and productivity while decreasing overheads".

There have been a few reported research projects on the application of the concept of Virtual Enterprise (VE)/Virtual Organization (VO) to the AEC/FM industry. Han et al. [27] presented a VO-based approach to support electronic information exchange between project participants through the implementation of a CITIS (Contractor Integrated Technical Information Service) system for the Korean construction industry. Menzel et al. [46] presented an integrated, holistic framework for context-sensitive, mobile applications based on the VO concept.

Based on our knowledge and research experience on VE/VO in the manufacturing industry, we believe that the VE/VO concept can be well applied to the construction industry for facilitating the cooperation and coordination of multiple partners (owners, architects, designers, contractors, and suppliers) during the entire project lifecycle, particularly for bidding, partner selection, subcontracting, and change management.

3.4. Change management

The common operational practice of the construction industry is project-based. During a construction project, many decisions often have to be made based on incomplete information, assumptions and the personal experiences of the construction professionals. Currently, project changes or adjustments are a fact of life at all stages of design and construction. In an EPSRC (Engineering and Physical Sciences Research Council, UK) report [69], it states that "the clients' dissatisfaction is due to the fact that over 50% of construction projects suffer from delays and overspending, while more than 30% of the completed projects have quality defects. Furthermore, some 30% of construction is rework".

Changes in construction projects are very common and likely to occur from different sources, by various causes, at any stage of a project, and may have considerable negative impacts [48]. Most researchers distinguish two kinds of changes: rework and change order [32]. Rework refers to re-doing a process or activity that was incorrectly implemented in the first place and is generally caused by quality defects, variance, negligence, poor design and on-site management. Rework is usually pure waste and can be improved by an effective change management practice. Change order refers to changes that are generated by unanticipated sources, for example, scope changes from the owner, design/technological changes from the architect, and cost and/or time changes caused by supplier problems or by unsatisfactory site conditions. In some sense, since change orders cannot be avoided in any construction project, the requirements for change management becomes the disciplining and coordinating of all aspects that relate to change orders, for example, document, drawing, process, flow, information, cost, schedule and personnel.

Change management seeks to forecast possible changes; identify changes that have already occurred; plan preventive measures; and coordinate changes across the entire project [73]. A generic change management model consists of five stages in a sequence: identification, evaluation, proposal, approval, implementation and roll-up. Small reworks with only minor impact do not need to go through a formal change process. However, changes with noticeable impact, either reworks or change orders, require following a formal process in change management. In general, upper-

stream changes have a bigger impact. Lu and Issa [45] believe that the most frequent and most costly changes are often related to design, such as design changes and design errors. The distribution of costs to different players in the process is also a critical issue in this area. Arain [4] argues that the information technology can be effectively used for providing an excellent opportunity for the professionals to learn from similar past projects and to better control project variations.

A large quantity of research work in change management is carried out in the generic project management domain. However, there is some limited research work addressing change management issues specifically in the construction project management context.

- Sun et al. [70] designed a change management toolkit for construction projects, which includes a change dependency framework, a change prediction tool, a workflow tool, and a knowledge management guide.
- Ipek and Omer [34] investigated requirement-design relationships and traceable requirements in architectural design. They developed a prototype system called *DesignTrack* and used LEED requirements as a case study.
- Lee and Peña-Mora [40] proposed using system dynamics to build dynamic project models to assist in the planning and control of construction projects. This dynamic project model captures several non-value adding change iterations (rework cycles and managerial change cycles). The simulation is demonstrated using a case study in Road Bridge Construction and many change option/policy implications are summarized based on this case study.
- Motawa et al. [48] presented some preliminary results on proactive change management through an integrated change management system composed of a fuzzy logic-based change prediction model and a system dynamics model based on the dynamic planning and control methodology. These models were previously developed by the same group to evaluate the negative impact of changes on construction performance. Their work also provides a good literature review on construction change management.
- Arain [4] reported a knowledge-based decision support system (KBDSS) for the management of variations in educational building projects in Singapore. The KBDSS consists of two main components: a knowledge-base and a controls selection shell for selecting appropriate controls. It can assist project managers by providing accurate and timely information for decision-making, rather than making decisions for them. It is supposed to be applied in the early stages (design stages) of the construction projects.

Apart from the project management domain, some other researchers have been trying to address change management issues in different ways:

- 4D or 5D integration which integrates time and cost models in addition to the 3D geometry models. In this way, changes cannot only be controlled in the design and engineering stages, but also can be controlled to some extent in the built environment lifecycle. Jongeling and Olofsson [37] suggest that location-based scheduling provides a promising alternative to activity-based planning approaches for planning of workflow with 4D CAD. In this approach, work schedules are integrated with design models so that changes in design or during construction can be better coordinated. In the latest 5D technologies of Graphisoft [93], automation does not stop at design changes. ArchiCAD also automates and coordinates the creation of documents, schedules, bills of materials, and quantities estimates through its integrated "virtual building" model based on IFC's BIM models.

Working with Building Information Modeling means any change in the design model can propagate to other project views automatically.
- Data sharing and interoperation. Bakis et al. [7] proposed an approach to model the complex interrelations of the different parts of the various aspects of the design and the different versions of each part in order to maintain consistency in architectural design. When changes happen, the interrelation models help notification/propagation of version changes.
- Web-based integration and collaboration approaches. Lottaz et al. [44] proposed using constraint satisfaction techniques to express possibly large families of acceptable solutions in order to facilitate and abbreviate the collaboration and negotiation processes. By combining Web services and intelligent agents, collaborative workflow technologies can be used to handle dynamic and complex business processes on the Web and can be applied to construction project management systems for effective and flexible change management. We have done a comprehensive literature review of collaborative workflows in design and manufacturing integration [28].

4. Standards and commercial tools

4.1. Standards for interoperability

In the past 15 years, due to the large number of multidisciplinary partners involved in a building project, the AEC industry has been actively developing international and industrial standards. Some of the standards developed are for the design and specification of buildings. Some are for interoperability within a specific industry, such as the structural steel industry and the pre-cast concrete industry. Many of these standards share a common technology base with the international standard ISO 10303, known as Standard for the Exchange of Product Model Data (STEP). This section provides an overview of three major standards in this area.

4.1.1. The Industry Foundation Class (IFC)

The IFC has been developed by the International Alliance for Interoperability (IAI) (which has been evolved into building-SMART) since 1994 [84]. Its latest release is IFC 2×3. The IFC 2× release has introduced the ifcXML specification by using XML schema to define the IFC models in parallel with EXPRESS. The target application of this standard is to provide a comprehensive description of the building and the construction site. It will be used mainly by architects to communicate the conceptual and detail design of a building to various partners. The key contents of the current IFC 2×3 include:

- The conceptual model and space utilization of the building to allow the architect to capture the building requirements from the owner.
- Information about the construction site such as the location and dimension of the site, built-up areas, etc.
- The product structure and detailed model of the building, so that one can capture various building elements and the relationship between them. For example the number of stories, shape and properties of each wall, door, and floor.
- The structural elements (footings, reinforcements, etc.) and structural analysis of a building.
- The equipment specifications and the information on the actual units (serial number, model, etc.) installed in a facility, such as the HVAC, fan, humidifier, filter, tanks, and pump.
- The electrical wiring and plumbing details.

Implementation of IFC has been reported in various construction IT system integration projects for design and construction

[9,24,25,55,67] and for facilities management [63,68,72,79]. The IFCs have now had 10 years of development, but with insufficient resources and dependence on a small number of experts [31]. According to Howard and Bjork [31], "there could be a new surge of enthusiasm," but "there are complexities that need to be hidden within good software implementations".

4.1.2. CIMSteel Integration Standards (CIS/2)

CIS/2 is a multi-part industrial standard for the exchange of engineering information for a steel-framed building [88]. It supports the analysis, design and detailing of the steel frame as well as the transfer of the resulting design information to the shop fabrication. Its latest release, CIS/2.1, was released in 2003. The data model of CIS/2 is called the Logical Product Model (LPM). The latest release of this model is LPM/6 which has achieved full harmonization with STEP. LPM/6 is defined in EXPRESS. It aligns with the STEP Generic Resources and the STEP AP225: building elements using explicit shape representation. The exchange file is in STEP Part 21 format. The key feature of this standard is the capability to capture:

- The detail design of the main structural steelwork and the secondary steelwork such as purlins, side rails, cleats and cladding.
- The full manufacturing assembly of the frame composed of parts and joint systems.
- The structural analysis of the steel frame using combinations of rigid, plastic and elastic analysis models.

4.1.3. Iso 15926

ISO 15926 (integration of lifecycle data for process plants including oil and gas production facilities) was originally developed for the oil and gas industries [95]. This standard is intended to support the complete lifecycle activities and processes of a capital facility including the conceptual design, detail design, analysis, construction, operation, maintenance and final decommissioning of the facility. In theory, this is a comprehensive standard for all types of facilities (industrial, commercial, institutional and residential) and for all aspects of a facility (equipment, structural, construction, O&M etc.). However, its suitability for all these applications still needs to be verified, especially for residential buildings. Like STEP, ISO 15926 is one of the ISO TC184 SC4 standards which started its development in 1992 initially as STEP Part AP221 but has subsequently become an independent standard. One characteristic of this standard is that it can employ a public work-in-progress repository to contain the latest reference library data for this standard. A registration process is established to allow users to add additional temporary reference data for their applications. There is a harvesting process to periodically roll-up these extensions into the standard. In this way, this standard is always extensible and agile. ISO 15926 uses EXPRESS to define its data models. For the sharing of information, it uses STEP P21 file as an exchange file format and a database interface for data management.

4.2. Tools for systems integration and collaboration

Various development and collaboration tools have been developed by research organizations, consortia and software vendors for systems integration and collaboration in AEC/FM:

- *IFC Toolboxes:* A good number of tools have been commercially available to support the development of IFC compliant applications [94]. As an example, *ST-Developer* is a commercial STEP SDK from STEP Tools Inc. that comes with pre-installed libraries for use with the AEC standards defined by STEP and others, including IFC, CIS/2, and STEP AP 225.

- *CORBA, COM/DCOM, and Java RMI:* Most integrated systems will still be implemented using these distributed object technologies.
- *Agent system development tools:* While a large number of academic, commercial, or open source agent system development tools are available [65], the most widely used one is JADE (Java Agent Development Framework) [96].
- *Web services development tools:* A wide range of tools available for Web services development and deployment from powerful tool packages like Rational Application Developer Tools to simple and practical tools like Eclipse.
- *Commercial collaboration tools:* Several commercial collaboration tools have been available for AEC/FM. The most popular ones include *ArchiCAD TeamWork*™ [93], *Autodesk Buzzsaw*™ [82], and *Bentley ProjectWise* [83].

5. Major initiatives/programs/projects

There have been some major international initiatives/programs/ projects in the subject matters. Apart from the three major initiatives – FIATECH in North America, ECTP in Europe, and CIB IDS (Integrated Design Solutions), large-scale initiatives/programs/projects have also been carried out by research organizations and universities in several other countries such as Australia [89], UK [98], France [90], and Finland [100]. We will provide an overview of three major initiatives; and also briefly review the Lean Construction initiative which is considered to be relevant to the scope of this paper.

5.1. Construction Industry Institute (CII) and FIATECH

The Construction Industry Institute (CII) [87], based at The University of Texas at Austin, is a consortium of more than 100 leading owner, engineering-contractor and supplier firms from both the public and private sectors in North America. These organizations have joined to enhance the business effectiveness and sustainability of the capital facility life cycle through joint research, related initiatives and industry alliances. Because of the strong involvement of more than 30 leading US universities in collaboration with industrial partners, CII R&D projects have made important contributions to academic research literature through a large amount of published reports and to the construction industry through best practices. At the time of writing this paper, CII members have completed about 120 joint projects and are working on 15 ongoing projects.

FIATECH (Fully Integrated and Automated TECHnology) [92] is a spin-off organization (or a subunit) of the Construction Industry Institute (CII). It was formed in 1998 based on a CII project called Fully Integrated and Automated Project Process (FIAPP). At the time of writing this paper, FIATECH members have completed 9 joint projects and are working on 9 active projects. The most important FIATECH project is the Capital Projects Technology Roadmap (CPTR) which is a cooperative effort of associations, consortia, government agencies, and industry.

The Roadmap presents a vision for the capital projects industry to develop "a highly automated project and facility management environment integrated across all phases of the facility lifecycle", as mentioned in Section 2. This vision is clearly captured in a guiding model as shown in Fig. 1. This model depicts a completely integrated structure composed of nine critical elements (including about 150 proposed projects) and can be thought of as a virtual enterprise of the construction industry for the future. It is a great vision for the construction industry. While some of the proposed features and functionalities may be implemented within the next 3–5 years, it is likely to take many years to be fully realized.
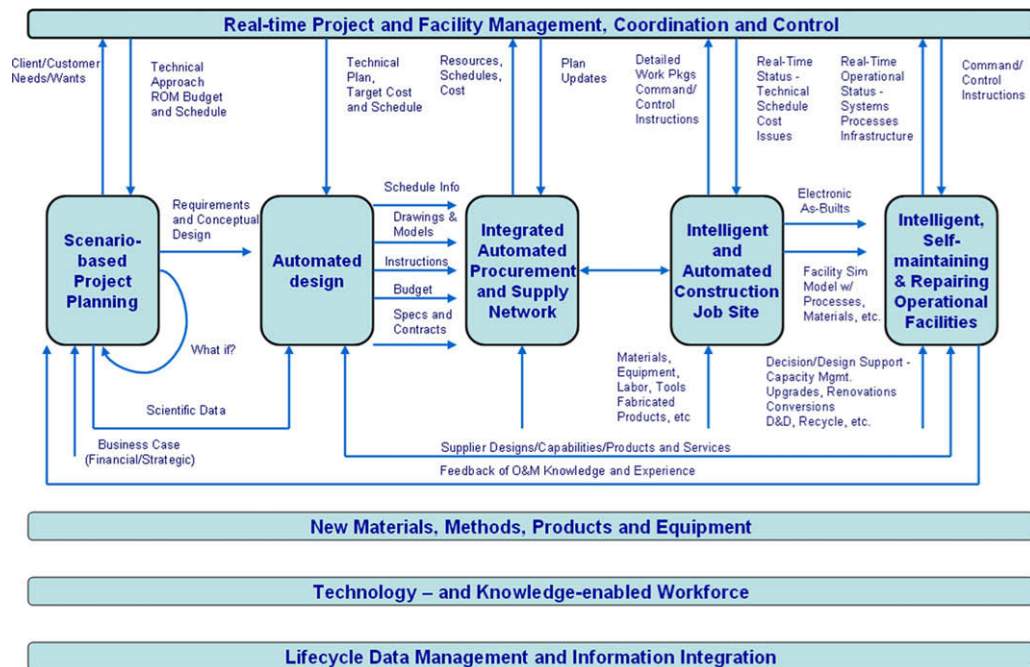
Fig. 1. FIATECH-CPTR Vision (http://ww.fiatech.org/).

Recently, we helped FIATECH to complete a mapping between CII projects and FIATECH elements/projects. We found that:

- There are a large of number of CII projects related to FIATECH Element 1 (Scenario-based Project Planning) and Element 6 (Real-time Project and Facility Management, Coordination & Control).
- While most early CII projects are related to Element 2 (Design) and Element 4 (Construction Job Site Management), more recent projects are related to Element 6 (Real-time Project and Facility Management, Coordination & Control) and Element 9 (Lifecycle Data Management & Information Integration).
- CII has more research projects led by academic researchers, while FIATECH has had more industry-led feasibility studies and technology evaluation projects.
- Most projects (both with CII and FIATECH) are related to evaluation, assessment, analysis, polices and standards, while only a few projects are on the development of new technologies.

5.2. European construction roadmap projects

There have been a number of construction technology roadmap projects within the European Union. The most recent one is ECTP – the European Construction Technology Platform project. It is "an initiative to mobilise the whole construction sector – contractors, authorities, architects and other designers, purchasing bodies, and the full range of suppliers, clients and users – to arrive at a clear set of common priorities" [91].

From its strategic research agenda, the Priority H on "New Integrated Processes for the Construction Sector" is specifically related to the scope of this survey. ECTP considers "process renewal, supported by ICT, as one of the main vehicles towards the vision of the ECTP". Our understanding of this "process renewal" is that it is focused on the innovation of construction process technologies. In fact, the majority of the 8 items proposed under the ECTP Priority H (Fig. 2) are highly related to the scope of this survey, particularly interoperability and collaboration support.

5.3. CIB Priority Theme – Integrated Design Solutions

CIB [85] was established in 1953 with the support of the United Nations, as an association whose objectives were to stimulate and facilitate international collaboration and information exchange between governmental research institutes in the building and construction sector. It stands for "Conseil International du Bâtiment" (in French) (i.e., "International Council for Building" in English). In 1998, its full name was changed to "International Council for Research and Innovation in Building and Construction" while its abbreviation has been kept.

Since early 2006, CIB has been developing a new Priority Theme called "Integrated Design Solutions" (IDS). According to the definition by the core group of the IDS Priority Theme, "Integrated Design Solutions use collaborative work processes and enhanced skills, and integrated data, information, and knowledge management to minimize structural and process inefficiencies and to enhance the value delivered during design, build, and operation, and across projects". The theme aims at bringing together the specialists of different sectors of the built environment to establish a smooth-functioning value network and to recognize the most acute business improvement opportunities within. In its recent meeting on October 2008 the core group agreed to start by identifying the current inefficiencies in construction as seen by different actors in the whole construction process. This will lead to prioritization of Process Improvement Opportunities (PIO's).

The first CIB IDS international conference was held on June 10–12, 2009 in Espoo, Finland [86].

5.4. Lean Construction Institute

The Lean Construction Institute (LCI) [97] was founded in August 1997 as a non-profit corporation. The objective was to apply the Lean Manufacturing or Lean Production concept to the construction industry. The idea is to maximize value delivered to the customer while minimizing waste.
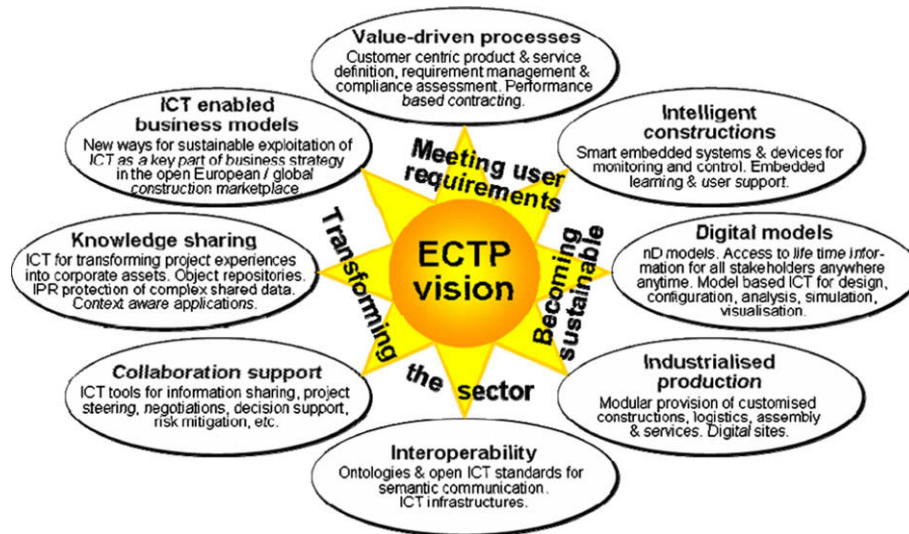
Fig. 2. 8 Items of ECTP Strategic Research Agenda Priority H (http://www.ectp.org/).

According to Koskela et al. [38], Lean Construction is a "way to design production systems to minimize waste of materials, time, and effort in order to generate the maximum possible amount of value". Achieving this vision is "only possible through the collaboration of all project participants at early stages of the project. This goes beyond the contractual arrangement of design/build or constructability reviews where constructors, and sometime facility managers, merely react to designs instead of informing and influencing the design".

6. Future research opportunities

Based on detailed analysis of the research literature and the current construction IT industry, as well as our experience on systems integration and collaboration in manufacturing, we believe research opportunities exist in the following areas:

– Integration of wired and wireless sensor networks for real-time data collection to support decision-making processes in construction job sites for real-time project management and during the operation and maintenance of built facilities for intelligent facility management. As significant amounts of data will still have to be entered manually for many years, this would have to include improved processes and work practices to ensure that entered data are of sufficient quality to serve in the decision-making processes.
– Development of a systems integration and collaboration methodology with a framework and toolboxes for the AEC/FM industry using emerging implementation technologies like software agents, Web services, and leading industrial standards like IFC, ISO 15926, and CIS/2, with further extension of ontology-based integration (including the Semantic Web).
– Integration of construction project lifecycle information (including design, procurement, construction, operation and maintenance) to support effective management and maintenance of built structures, facilities, and infrastructures. One example is the integration BIM and RFID (or WSN in a broader scope) [47].
– nD modeling – incorporating all the building information (including 3D geometric model, material, time, cost, accessibility, sustainability, maintainability, acoustics, and thermal) that is required at various stages of the lifecycle of a built environment.

– Global optimization over the entire project lifecycle, particularly considering all direct costs (pertaining to design, materials, prefabrication and transportation, labor, equipment, etc.) and indirect costs (like overheads, financial loss caused by delayed completion, and user costs if a facility is not properly maintained). It may be particularly interesting to apply global optimization to Green Building projects. The successful application of optimization hinges upon systems integration, information standards and the pervasive use of digital models in the design stages, as mentioned above.
– Change management during the construction phase, with a focus on change impact analysis, dynamic scheduling adjustment, collaboration and coordination among partners including owners, architects, engineers, contractors, and suppliers.
– Human factors and human aspects management [60]
– Proactive project information systems to efficiently disseminate the information from planning and analysis to project managers and users in the field.
– Project information access control, information security and privacy.

Please note that most of these topics are not new, as we mentioned early in the paper that Systems Integration and Collaboration are not new research topics. However, we believe that these topics are today's active research topics and will still be active within next 5–10 years.

7. Concluding Remarks

Systems integration and collaboration are believed to be the key enabling technologies that drive the construction industry in improving productivity and efficiency. This paper provides a state-of-the-art survey of key technologies and applications in this area. Based on a comprehensive literature review and industrial requirement analyses as well as our own experience in the related areas, research opportunities have been identified.

According to Bakis et al. [7], "in the construction industry, the use of a single central repository to store the design information is not usually a viable option due to the fragmented nature and adversarial behavior that characterizes the industry". Therefore, distributed loosely-coupled integration solutions using intelligent agents and Web services technologies would be the most promis-

ing. Industrial case studies and pilot implementations are needed to validate and showcase these emerging technologies.

Application of the Building Information Modeling (BIM) approach for the construction industry is still at an early stage, but will be booming in a short-term. However, "the formal standards on BIM, such as the IFCs are complex and have not had the resources for rapid development and promotion that their potential deserved [31]", and therefore there is still a long way to go. The 2D drawings are still extensively used in every aspect of a building project during its lifecycle. There is a strong movement, led by the architects, to migrate the whole process into 3D models. Many pilot projects have demonstrated great savings in time and cost. However, it will take some time for this approach to be widely adopted. Among all the pilot projects, the IFC is the most popular choice especially in the design and bidding process. The majority of the application of the 3D models is in the exchange of the design geometry of a building between various partners. The CIS/2 has also been demonstrated in the industry. The ISO 15926 standard, still being developed, has not been extensively tested yet. However, it may have the potential to become the most comprehensive standard for the construction industry.

According to the Canadian construction IT industrial survey [20], the biggest barrier for construction IT development is related to the acceptance of new technologies by the industry. On the other hand, as pointed out by Tapscott and Williams [71], and mentioned earlier, a new business rule in the 21st century is to "collaborate or perish". In order to remain competitive and to survive in the increasingly competitive global market, many companies have to adjust the way they do business, adopt new technologies and collaborate with others.

Both FIATECH-CPTR and ECTP provide a great vision and comprehensive roadmaps for the future of the construction IT industry. Although it is expected to be difficult, a collaborative network (or virtual organization) of the construction industry (including owners, operators, architects, design, engineering, constructors, and suppliers), academia (including universities and research organizations) and government agencies, may be the road ahead to success.

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