

## NRC Publications Archive Archives des publications du CNRC

### **Systems integration and collaboration in construction: a review**

Shen, W.; Hao, Q.; Mak, H.; Neelamkavil, J.; Xie, H.; Dickinson, J. K.

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. /  
La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version  
acceptée du manuscrit ou la version de l'éditeur.

#### **Publisher's version / Version de l'éditeur:**

*The 12th International Conference on Computer Supported Cooperative Work in Design (CSCWD 2008) [Proceedings], pp. 11-22, 2008-04-16*

#### **NRC Publications Archive Record / Notice des Archives des publications du CNRC :**

<https://nrc-publications.canada.ca/eng/view/object/?id=c987e7db-423b-4743-83c9-21f2b9d999c0>

<https://publications-cnrc.canada.ca/fra/voir/objet/?id=c987e7db-423b-4743-83c9-21f2b9d999c0>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

**Questions?** Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

**Vous avez des questions?** Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.



## Systems integration and collaboration in construction: a review

---

### **NRCC-50289**

Shen, W.; Hao, Q.; Mak, H.; Neelamkavil, J.;  
Xie, H.

A version of this document is published in / Une version de ce document se trouve dans:  
Proceedings of the 12<sup>th</sup> International Conference on Computer Supported Cooperative  
Work in Design (CSCWD 2008), Xi'an, P.R. China, April 16-18, 2008, pp. 11-22

The material in this document is covered by the provisions of the Copyright Act, by Canadian laws, policies, regulations and international agreements. Such provisions serve to identify the information source and, in specific instances, to prohibit reproduction of materials without written permission. For more information visit <http://laws.justice.gc.ca/en/showtdm/cs/C-42>

Les renseignements dans ce document sont protégés par la Loi sur le droit d'auteur, par les lois, les politiques et les règlements du Canada et des accords internationaux. Ces dispositions permettent d'identifier la source de l'information et, dans certains cas, d'interdire la copie de documents sans permission écrite. Pour obtenir de plus amples renseignements : <http://lois.justice.gc.ca/fr/showtdm/cs/C-42>



National Research  
Council Canada

Conseil national  
de recherches Canada

Canada 

# Systems Integration and Collaboration in Construction: A Review

Weiming Shen, Qi Hao, Helium Mak, Joseph Neelamkavil, Helen Xie, John Dickinson  
*Institute for Research in Construction, National Research Council Canada,*

*London, Ontario, Canada*

*[weiming.shen, qi.hao, helium.mak, joseph.neelamkavil, Helen.xie, john.dickinson]@nrc.gc.ca*

## Abstract

Rapid advancement of information and communication technologies has brought both challenges and opportunities to the construction industry. There have been significant research and development efforts on the application of systems integration and collaboration technologies in construction. This paper presents a research literature review on systems integration and collaboration in architecture, engineering, construction, and facility management (AEC/FM), and discusses challenging research issues and future research opportunities.

**Keywords:** Systems Integration, Collaboration, Interoperability, Construction, Facility Management.

## 1. Introduction

Due to deep changes in technology, demographics, business, the economy, and the world, we are entering a new age where people participate in the economy like never before. A new business rule for competitiveness is to “collaborate or perish” [51]. This applies to all societies and industries including the construction industry.

According to an industrial survey on the Canadian construction IT industry [16], “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%).

Because of the complexity of the construction industry, the multiple phases of the construction project life-cycle, and the involvement of multidisciplinary teams (including owners, architects, consultants, engineers, contractors, sub-contractors, and suppliers) using various heterogeneous systems, systems integration becomes an important and imperative step 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 [17].

Systems integration and collaboration are not new research topics. 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 facility management (AEC/FM). After many years of R&D, the AEC industry has now started to embrace and adopt software systems that support and promote the concepts of integration and interoperability [20].

However, due to the unique nature of the construction sector, the development and deployment of systems integration and collaboration technologies in AEC/FM are somewhat behind other sectors (e.g., manufacturing sector). This paper provides a research literature review on systems integration and collaboration in AEC/FM, and discusses challenging research issues and future research opportunities. 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 current 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 brief concluding remarks.

## **2. Current Problems and Requirements**

The US National Institute of Standards and Technology (NIST) published a study [17] that identified and estimated the efficiency losses 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, which incur these costs predominantly during ongoing facility operation and maintenance.

According to FIATECH [64], some major problems on systems interoperability in the construction industry include (paraphased based on [64]):

- It is difficult to access to 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 a project's information assets does not exist.
- Program plans and designs are optimized for a limited set of parameters in a limited domain. The capability to make fully supported “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 functionality for any kind of project 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 and end-of-life needs are given limited consideration in the project planning equation.
- The ability to assess uncertainties, risks, and impacts of failures is not mature, partly due to the lack of knowledge to support 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 risks and alternatives.

In order to address these problems, FIATECH has created a roadmap (particularly its Element 6) to integrate all functions of a project/facility planning and management system and all required information in a unified project/facility management environment [64]. 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.

### **3. Challenging Research Issues and State-of-the-Art**

The very basic 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 the systems interoperability from two different perspectives: data interoperability and frameworks interoperability. Then we review some challenging research issues and related state-of-the-art 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 optimization. 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., to create the design and structural frame of the building, or the analysis of the structural strength of the building, etc., the demand to share data/information among the project parties has increased. Sharing data in such a multi-party heterogeneous environment requires all parties to have a common data model so that each party knows how to generate and interpret the data created by any party among them. A common neutral model enables data sharing or integration in heterogeneous applications. Then it is possible for building information to be created once and used many times. This reduces project time by eliminating the need to recreate the same information repeatedly and increases project quality by eliminating errors introduced during the data recreation process. The development of several such competing neutral models or standards has been done by various appropriate international standard organizations (e.g., ISO) or industrial consortia (e.g., IAI - International Alliance for Interoperability).

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 application, the constraints the data within that application should obey (e.g. there should be one and only one wall at any one physical space) and the relationship between application objects (e.g. the wall is a part structure of a building). In older standards, e.g. IGES, the data models are implicit and the standards concentrate on defining the format the data should be packed in the 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 project 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 element (e.g. walls), building structures, (e.g. the cluster of walls forming the storey), equipment, (e.g. HVAC), plumbing and electrical wiring, material, etc. In order to reuse any common information, later BIMs employ the object-oriented approach with inheritances from an extensive parent-child hierarchy.

The major interoperability problem facing today's data sharing using one data model is the existence of different exchange flavors. A flavor of a standard is a fact that two different vendors can 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. [5] have done a comprehensive review of the research literature on data interoperability or "integration through product sharing and exchange". We would like to refer the readers to [5] for a detailed review of the major research efforts on the development of standard building data models and model mapping languages.

### *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; when two or more software systems being used in a construction project need to work together, they must be able to communicate using the same protocols and languages in order to inter-operate.

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. So 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 details in the following subsections.

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, when a highly distributed and loosely-coupled integration approach is used, the interoperability is usually achieved through common communication languages and protocols while allowing different systems or sub-systems to be integrated to use different data models and formats.

## **3.2 Systems integration approaches**

### *3.2.1 Web-based systems*

The World Wide Web was originally developed to allow information sharing within internationally dispersed teams and the dissemination of information by support groups. It uses a centralized information integration approach through a shared Web server or a database behind the

Web server. It is currently the most advanced information system deployed on the Internet [73]. According to the industrial survey on the Canadian construction IT industry [16], about half (49%) of the construction IT tools developed in Canada use Web-based systems as their implementation technology.

With simple client-server system architecture and mature Web development tools, it is easy 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. There is no need for doing advanced research in this area. While there were many publications on Web-based collaboration systems in the 1990s, a paper reporting Web-based system development is not publishable these days.

A simple Web-based system may be adequate for daily construction project management, but it is not sufficient to meet the requirements described above 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. To the degree that Web servers are not mere repositories of information but engage users in active dialogue while providing such remote services in order to solve complex engineering problems, such servers may be implemented as intelligent software agents detailed in Section 3.2.3.

### *3.2.2 Distributed objects / components*

An 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 [13] 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 integrated a number of commercial software packages including AutoCAD/AEC (for design), World Tool Kit (for visualization in virtual reality), and Super Project Expert (for planning) as well as several other applications developed in-house. A centralized (modularized) project model is used to connect all these applications.
- Halfawy and Froese [19] proposed to build integrated AEC systems using smart objects. In the proposed approach, smart objects are 3D parametric entities that combine 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 proposed approach was implemented to support the integrated design of a falsework system.

- Halfawy and Froese [20] extended the model-based approach (using smart objects) into a component-based approach with widely used three-tier system architecture. Components are usually considered to be a higher level of abstraction than objects and they do not share state? but communicate by exchanging messages carrying data. This extension makes it easier to integrate various applications, particularly legacy applications. A prototype system has been implemented using COM/DCOM. In fact, this component-based approach can be easily extended to a service-oriented approach and implemented using Web services technology and related standards. A similar component-based approach was also proposed by Anwar et al. [2].
- Similar approaches using distributed object technologies (particularly CORBA) can also be found in [9, 33, 56]. However, Lu and Issa [33] emphasize loosely-coupled integration, compared with standards-based approaches like IFC-based integration [14, 15, 19, 20]. This kind of loosely-coupled integration is particularly suitable for distributed systems integration and collaboration. Similar approaches can be found in [36, 37, 42]. 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. [10] presented a model-based integration approach with semi-automatic methods for the classification, retrieval and 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 [47]. Parunak [38] 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, allows them to handle ill-structured or rapidly changing situations in a more economical way [47]. This section provides a brief review of recent projects on the application of agent technology for systems integration in AEC/FM.

- Bilek and Hartmann [6] presented an agent-based approach to support complex structural design processes in AEC. The proposed workbench aims at assisting design experts according to their specific tasks during project work 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 agent-based collaboration model, the agent-based engineering software integration model, and the agent-based 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 [54] 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 necessary action 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 presently of RFID adoption in the wider construction sector, the paper concludes that a breakthrough will result from applications that emphasize the management of the building or facility, in particular energy consumption.

- Reffat [40] proposed an approach for architectural design to be carried out collaboratively and synchronously inside real-time 3D virtual environments within which 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 [18] and virtual reality technology to meet the requirements of architectural design. However, so far no implementation has been reported to support the proposed approach.
- Rueppel and Lange [44] 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 agent migration and the agent interaction. A prototype system was implemented using JADE and validated through a case study of fire protection planning.
- Aziz et al. [4] 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 have not been implemented.
- Alda et al. [1] proposed and developed an integrated multi-agent and peer-to-peer 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 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. Neither do they cooperate or 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 [46]. By their definitions, a Web Server is “a software system designed to support interoperable machine-to-machine interaction over a network” [74] 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” [74].

Even though Web Services and Semantic Web 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, though we strongly believe there will be widespread application of the technology in AEC/FM in the foreseeable future.

- Schevers et al. [45] 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 Sydney Opera House.
- El-Diraby et al. [12] 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. [31] proposed a Meta-Data-Based (MDB) approach that extracts information from the original Web-based documents and re-organizes 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 rapid location of information.
- Kosovac [28] 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. [53] 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. Note that this work focuses only on the integration of building automation systems, rather than over the building project lifecycle. However, the proposed approach makes it easy to integrate other systems (from design, construction, to supply chain) with the proposed system because of its service-oriented architecture and its use of Web services standards.
- Based on an excellent literature review on computer-integrated construction, Boddy et al. [8] proposed a process driven approach by integrating software agents and Web services technologies. It is very similar to the Cooperative Workflow concept presented in [23].

### *3.2.5 Integration of RFID and wireless sensor networks*

The radio frequency identification (RFID) is a wireless technology and it 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) technologies. 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 construction industry, either during the construction process for improving real time decision making processes, or during the operation and maintenance of built environments for monitoring and intelligent control.

There have been some research and development and efforts on the application of WSN, particularly RFID, in the construction industry, but most are pilots and have not been widely accepted by the stakeholders. The US National Institute of Standards and Technology [71] 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 allows sensors to be placed in spaces that may see changing configurations.

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 so as to improve productivity and efficiency.

### ***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 [41] 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 [55], organizations [47], and hardware systems.

- Lee and Bernold [30] proposed agent-mediated communication to overcome the problem of information overload during a construction project.
- Menzel et al. [34] have shown how agent technology can assist the users of mobile devices in the construction field to support their individual requirements in specific working situations.
- Bletzinger and Lähr [7] proposed an agent-based collaborative environment for dynamic workflow management.
- Zhang and Hammad [57] presented an interesting approach based on software agents to coordinate crane operations where two cranes are working together, where 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*

Rosenman et al. [43] presented a framework for collaborating in a virtual environment including a database, based on IFCs, containing the various models and relationships between them; a virtual world environment for collaboration and an agent-based society for handling the communication between the users, the virtual world and the database.

Aspin [3] proposed an interaction mechanism that enables a group of co-located users sharing a common visualization to collaboratively interact with the visual environment through the use of light-weight personal computing devices operating as bidirectional remote interfaces. Applying an object-based distributed shared memory (DSM) system enables the description of the active session 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. [21] used a socio-technical theory as a framework to explore differences in engineering design team decision making as a function of various media of communication. 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.

### *3.3.4 Virtual organization as a collaboration medium*

According to Camarinha-Matos [11], “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. [22] 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. [34] presented an integrated, holistic framework for context-sensitive, mobile applications based on the concept of Virtual Organization.

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 an entire construction 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. A general construction project starts from planning, cost estimation, bidding, contracting, to architect, detail design and engineering, down to the actual building construction phases and the final project delivery stage. During a construction project, many decisions often have to be made based on incomplete information, assumptions and personal experience 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, U.K.) report [49], it states that “the clients’ dissatisfaction is due to the fact that over 50% of construction projects suffer from delays and over-spending, 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 [35]. Most researchers distinguish two kinds of changes: rework and change order [24]. 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, and 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 disciplining and coordinating 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 [52]. A generic change management model consists of five stages in a sequence: identification, evaluation, proposal, approval, implementation and roll-up. Small reworks with minor impacts do not need to go through a formal change process. However, changes with noticeable impacts, either reworks or change orders, all require following a formal process in change management. The impact of changes to a construction project needs to be evaluated case by case in order to assist with the decision making process. In general, upper-stream changes have larger impacts. Lu and Issa [33] believe that the most frequent and most costly changes are often related to design, such as design changes and design errors.

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. [50] designed a change management toolkit for construction projects that includes a change dependency framework, a change prediction tool, a workflow tool, and a knowledge management guide.
- Ipek and Omer [25] investigate requirement-design relationships and enable traceable requirement in architectural design. They developed a prototype system called *DesignTrack* and used LEED requirements as a case study.
- Lee and Peña-Mora [29] proposed using system dynamics to build dynamic project models to assist 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. [35] 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 (DPM). These models were previously developed by the same group to evaluate the negative impacts of changes on construction performance. Their work also provides a good literature review on construction change management.

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 3D geometry models. In this way, changes can not only be controlled in the design and engineering stages in the whole construction process, but also be controlled in the built environment life-cycle to some extent. Jongeling and Olofsson [26] suggest that location-based scheduling provides a promising alternative to activity-based planning approaches for planning of work-flow 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 [65], 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 working directly on the design model in any project view – be it the plans, sections or even element schedules. All you need to do is perform one change in the design model at one place at one time and all the integrated project views will be updated automatically.

- Data sharing and interoperation. Bakis et al. [5] 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. They also suggest that the development of standard building models is substantial to enable data sharing, exchange and change management at the design stage.
- Web-based integration and collaboration approaches. Lottaz et al. [32] proposed using constraint satisfaction techniques to express possibly large families of acceptable solutions in order to facilitate and abbreviate the collaboration and negotiation processes, ultimately to improve the change management and the productivity during phases of design and construction. 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 [23].

## 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 the interoperability between a specific industry with the AEC 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, Standard for the Exchange of Product Model Data (STEP). This section provides an overview of the three major standards in this area.

#### *The Industry Foundation Class (IFC)*

The IFC has been developed by the International Alliance for Interoperability (IAI) since 1994. Its latest release is IFC 2x3. The IFC 2x release has also 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 mainly used by architects to communicate the conceptual and detail design of a building to various partners. The key contents of the current IFC 2x3 include:

- The conceptual model and space utilization of a building so that the architect can capture the requirement of the building from the owner.
- Information about the site where the building is constructed such as the location and dimension of the site, build up areas, etc.
- The product structure and detail 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, floor, etc.
- The structural elements (footing, reinforcement, etc.) and structural analysis of a building.
- The specification of equipments and the information of the actual units (serial number, model, etc.) installed in a facility, such as the HVAC, fan, humidifier, filter, tanks, pump, etc.
- The details of electrical wiring and plumbing.

Implementations of IFC have been reported in various construction IT system integration projects [7, 19, 20, 39, 45, 48].

### *CIMSteel Integration Standards (CIS/2)*

CIS/2 is a multi-part industrial standard for the exchange of engineering information of a steel framed building. 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 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 parts can be represented in simple 2D (plates and sheets) form or complex 3D non-planar form. It can contain features such as notch, chamfer, holes etc. It can be manufactured by rolling, welding casting or cold-formed. The joints can be held by bolts or welding.
- The structural analysis of the steel frame using combinations of rigid, plastic and elastic analysis models.

### *ISO 15926*

ISO 15926 (integration of life-cycle data for process plants including oil and gas production facilities) was originally developed for the oil and gas industries. This standard is intended to support the complete life-cycle 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 become an independent standard subsequently. Some parts of this multi-part standard have become International Standards and some are still in active development. One characteristic of this standard is to 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 roll up these extensions into the standard periodically. 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 exchange file format and a data base interface for database function.

### ***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:

- *ST-Developer*: 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*: 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, the most widely used one is JADE (Java Agent Development Framework) [68].

- *Web services development tools*: A wide range of tools available for Web services development and deployment from powerful tool packages like Rational 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<sup>TM</sup>* [65] and *Autodesk Buzzsaw<sup>TM</sup>* [58].

## 5. Major Efforts / Programs / Projects

There have been some major international initiatives / programs / projects in the subject matters. We will provide an overview of two major initiatives: FIATECH in North America and ECTP in Europe. We will also briefly review the Lean Construction initiative which is considered to be relevant to the scope of this paper.

Large-scale initiatives / programs / projects have also been carried out by research organizations and universities in several other countries such as Australia [61], UK [70], France [62], and Finland [72].

### 5.1 Construction Industry Institute (CII) and FIATECH

The Construction Industry Institute (CII) [59], 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 together 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 U.S. 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) [64] 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 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 at least ten years to be fully realized.

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, policies 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” [63].

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 focussed on the innovation of construction process technologies. In fact, the majority of the 8 items proposed under the ECTP Priority H are highly related to the scope of this survey, particularly interoperability and collaboration support.

## ***5.3 Lean Construction Institute***

The Lean Construction Institute (LCI) [69] 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.

According to Koskela et al. [27], 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 multiple wired and wireless sensor networks for real time information collection in order to support decision making processes in construction sites for real time project management (including dynamic scheduling) and during the operation and maintenance of built facilities for intelligent real time facility management.
- Development of a systems integration and collaboration framework for the AEC/FM industry with emerging implementation technologies like software agents and Web services and

leading industrial standards like IFC, ISO 15926, and CIS/2, with further extension of ontology-based integration (including Semantic Web).

- nD modeling as an extension of building information modeling by incorporating all the building information (including 3D building model, material, time, cost, accessibility, sustainability, maintainability, acoustics, and thermal etc.) required at each stage of the lifecycle of a building facility.
- Global optimization over the entire project lifecycle, particularly considering all direct costs (design, materials, pre-fabrication and transportation, labor, equipment, etc.) and indirect costs (overheads, financial loss caused by delayed completion, facility operation and maintenance after completion, etc.). It may be particularly interesting to apply global optimization to Green building projects.
- 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.
- Proactive project information systems in order to efficiently disseminate the information from planning and analysis to project managers and users in the field.
- Computer-supported human-centered collaboration including user modeling, intelligent user interfaces and assistance.
- Project information access control, information security and privacy.

## 7. Concluding Remarks

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

According to Bakis et al. [5], “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 most promising. 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. The 2D AutoCAD drawings are still extensively used in every aspect of a building during its life-cycle. There is a strong movement, lead by the architects to migrate the whole process into 3D models. Many pilot projects have demonstrated great savings in time and cost for construction projects. It will take time for this approach to become universal. 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 its domain industry. The ISO 15926 standard, still being developed, has not been extensively pilot 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 [16], 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 [51], and mentioned earlier, a new

business rule in the 21<sup>st</sup> century is to “collaborate or perish”. In order to remain competitive and to survive in the increasingly competitive global market, many companies must change the way they do business, adopt new technologies and collaborate with others.

FIATECH-CPTR and ECTP provide a great vision and comprehensive roadmaps for the future of the construction IT industry. Even though it is believed 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 way to success.

## References

- [1] S. Alda, J. Bilek, A.B. Cremers, D. Hartmann, “Awareness and workflow based coordination of networked co-operations in structural design”, *ITcon*, 2006, Vol. 11, 489-507.
- [2] N. Anwar; W. Kanok-Nukulchai; D.N. Batanov, “Component-Based, Information Oriented Structural Engineering Applications”, *Journal of Computing in Civil Engineering*, ASCE, 2005, 19(1), pp.45-57.
- [3] R. Aspin, “Supporting Collaboration, in Colocated 3D Visualization, through the Use of Remote Personal Interfaces,” *Journal of Computing in Civil Engineering*, 2007, 21(6), 393-401.
- [4] Z. Aziz, C. Anumba, D. Ruikar, P. Carrillo, D. Bouchlaghem, “Semantic web based services for intelligent mobile construction collaboration”, *ITcon*, 2004, Vol. 9, 367-379
- [5] N. Bakis, G. Aouad, M. Kagioglou, “Towards distributed product data sharing environments – progress so far and future challenges”, *Automation in Construction*, 2007, 16(6), 586-595.
- [6] J. Bilek, D. Hartmann D, “Development of an agent-based workbench supporting collaborative structural design.” *Proceedings of the CIB W78's 20th International Conference on IT in Construction*, April 2003, Waiheke Island, New Zealand, <http://itc.scix.net/data/works/att/w78-2003-39.content.pdf>
- [7] K-U. Bletzinger, A. Lähr, “Prediction of interdisciplinary consequences for decisions in AEC design processes”, *ITcon*, 2006, Vol. 11, 529-545.
- [8] S. Boddy, Y. Rezgui, G. Cooper, M. Wetherill, “Computer integrated construction: a review and proposals for future direction”, *Advances in Engineering Software*, 2007, 38(10), 677-687.
- [9] A. Brown, Y. Rezgui, G. Cooper, J. Yip, P. Brandon, “Promoting Computer Integrated Construction Through the Use of Distribution Technology”, *ITcon*, 1996, Vol. 1, 51-67.
- [10] C.H. Caldas, L. Soibelman, L. Gasser, “Methodology for the Integration of Project Documents in Model-Based Information Systems”, *Journal of Computing in Civil Engineering*, ASCE, 2005, 19(1), pp.25-33.
- [11] L. Camarinha-Matos, “The Virtual Enterprise Concept”, L.M. Camarinha-Matos, H. Afsarmanesh (Eds.) *Infrastructures for the Virtual Enterprise –Networking Industrial Enterprises*, IFIP Vol. 153, Kluwer Academic Publishers, 1999.
- [12] T.A. El-Diraby; C. Lima; B. Feis, “Domain Taxonomy for Construction Concepts: Toward a Formal Ontology for Construction Knowledge”, *Journal of Computing in Civil Engineering*, ASCE, 2005, 19(4), pp.395-406.
- [13] I. Faraj, M. Alshawi, “A Modularised Integrated Computer Environment for the Construction Industry: SPACE”, *ITcon*, 1999, Vol. 4, 37-52.
- [14] T. Froese, M. Fischer, F. Grobler, J. Ritzenthaler, K. Yu, S. Sutherland, S. Staub, B. Akinci, R. Akbas, B. Koo, A. Barron, J. Kunz, “Industry foundation classes for project management—A trial implementation”, *ITcon*, 1999, Vol. 4, 17–36.
- [15] T. Froese, “Future directions for IFC-based interoperability”, *ITcon*, 2003, Vol. 8, 231-246.
- [16] T. Froese, Z. Han, M. Alldritt, “Study of information technology development for the Canadian construction industry,” *Canadian Journal of Civil Engineering*, 2007, 34(7), 817-829.
- [17] M.P. Gallaher, A.C. O’Connor, J.L. Dettbarn, Jr., and L.T. Gilday, “Cost analysis of inadequate interoperability in the U.S. capital facilities industry.” U.S. Department of Commerce Technology Administration, National Institute of Standards and Technology, NIST Report No. GCR 04-867, 2004.
- [18] J. Gero, U. Kannengiesser, “The situated Function-Behaviour-Structure framework”, *Design Studies*, 2004, 25 (4), 373-391.
- [19] M. Halfawy, T. Froese, “Building Integrated Architecture/Engineering/Construction Systems Using Smart Objects: A Methodology and Implementation”, *Journal of Computing in Civil Engineering*, 2005, 19(2), 172-181.
- [20] M. Halfawy, T. Froese, “Component-Based Framework for Implementing Integrated Architectural/ Engineering/ Construction Project Systems”, *Journal of Computing in Civil Engineering*, 2007, 21(6), 441-452.

- [21] J.M. Hammond, C.M. Harvey, R.J. Koubek, W.D. Compton, A. Darisipudi, "Distributed Collaborative Design Teams: Media Effects on Design Processes", *International Journal of Human-Computer Interaction*, 2005, 18(2), 145–165.
- [22] S.H. Han, K.H. Chin, M.J. Chae, "Evaluation of CITIS as a collaborative virtual organization for construction project management", *Automation in Construction*, 2007, 16(2), 199-211.
- [23] Q. Hao, W. Shen, "Collaborative Workflow Technology for Design and Manufacturing Coordination", *Proceedings of ASME MSEC 2007*, MSEC2007-31179, Oct. 15-18, 2007, Atlanta, GA.
- [24] T. Huang, C.W. Kong, H.L. Guo, A. Baldwin, H. Li, "A virtual prototyping system for simulating construction processes", *Automation in Construction*, 2007, 16(5), 576-85.
- [25] O. Ipek, A.Ömer, "Tool support for computer-aided requirement traceability in architectural design: the case of DesignTrack", *Automation in Construction*, 2007, 16(5), 674-684.
- [26] R. Jongeling, T. Olofsson, "A method for planning of work-flow by combined use of location-based scheduling and 4DCAD", *Automation in Construction*, 2007, 16(2), 189-198.
- [27] L. Koskela, G. Howell, G. Ballard, I. Tommelein, "The Foundations of Lean Construction." *Design and Construction: Building in Value*, R. Best, and G. de Valence, (eds.), Elsevier, Oxford, UK, 2002.
- [28] B. Kosovac, *A Framework for Managing Information from heterogeneous, Distributed, and Autonomous Sources in the Architecture, Engineering, Construction, and Facilities Management Domain*, PhD Thesis, Dept. of Civil Engineering, University of British Columbia, Canada, 2007.
- [29] S.H. Lee, F. Peña-Mora, "System dynamics approach for error and change management in concurrent design and construction," *Proceedings of the 2005 Winter Simulation Conference*, Orlando, FL, 2005, pp. 1508-1514.
- [30] J. Lee, L.E. Bernold, "Ubiquitous Agent-Based Communication in Construction", *Journal of Computing in Civil Engineering*, 2008, 22(1), 31-39.
- [31] N.N. Leung, S.L. Chan, R.R.A. Issa, "Meta-Data-Based Collaboration in Construction Project Management", *Proceedings of the 4th Symposium of IT in construction*. ASCE. Nashville, Tennessee, November 15-16, 2003.
- [32] C. Lottaz, D.E. Clement, B.V. Faltings, I.F.C. Smith, "Constraint-Based Support for Collaboration in Design and Construction", *Journal of Computing in Civil Engineering*, 1999, 13(1), 23-35.
- [33] H. Lu, R.R.A. Issa, "Extended Production Integration for Construction: A Loosely Coupled Project Model for Building Construction", *Journal of Computing in Civil Engineering*, ASCE, 2005, 19(1), 58-68.
- [34] K. Menzel, M. Keller, K. Eisenblätter, "Context sensitive mobile devices in architecture, engineering and construction", *ITcon*, 2004, Vol. 9, 389-407.
- [35] I.A. Motawa, C.J. Anumba, S. Lee, F. Peña-Mora, "An integrated system for change management in construction", *Automation in Construction*, 2007, 16(3), 368-377.
- [36] W. O'Brien, J. Hammer, "Robust mediation of construction supply chain information." *Proceedings of the ASCE Specialty Conference on Fully Integrated and Automated Project Processes (FIAPP) in Civil Engineering*, Blacksburg, VA, ASCE, September 2001, [http://www.cise.ufl.edu/~jhammer/publications/FIAPP/FIAPP\\_2001.pdf](http://www.cise.ufl.edu/~jhammer/publications/FIAPP/FIAPP_2001.pdf)
- [37] W. O'Brien, R.R.A. Issa, J. Hammer, M.S. Schmalz, J. Geunes, S.X. Bai, "SEEK: Accomplishing enterprise information integration across heterogeneous sources", *ITcon*, 2002, Vol. 7, 101-124.
- [38] H.V.D. Parunak, "What can agents do in industry, and why? An overview of industrially-oriented R&D at CEC", *Cooperative information agents II*, Klusch, M. and Weiss, G. (ed.), Paris, France, Springer, 1998, pp. 1-18
- [39] J. Plume, J. Mitchell, "Collaborative design using a shared IFC building model—Learning from experience", *Automation in Construction*, 2007, 16(1), 28-36.
- [40] R.M. Reffat, "Computing in architectural design: reflections and an approach to new generations of CAAD", *ITcon*, 2006, Vol. 11, 655-668.
- [41] Y. Rezgui, G. Cooper, A Proposed Open Infrastructure for Construction Project Document Sharing, *ITcon*, 1998, Vol. 3, 11-25.
- [42] Y. Rezgui, G. Cooper, P. Brandon, "Information management in a collaborative multiactor environment: The COMMIT approach." *Journal of Computing in Civil Engineering*, 1998, 12(3), 136–144
- [43] M.A. Rosenman, G. Smith, M.L. Maher, L. Ding, D. Marchant, (2007) Multidisciplinary collaborative design in virtual environments, *Automation in Construction*, 16(1), 37-44.
- [44] U. Rueppel, M. Lange, "An integrative process model for cooperation support in civil engineering", *ITcon*, 2006, Vol. 11, 509-528.
- [45] H. Schevers, J. Mitchell, P. Akhurst, D. Marchant, S. Bull, K. McDonald, R. Drogemuller, C. Linning, "Towards digital facility modelling for Sydney opera house using IFC and semantic web technology", *ITcon*, 2007, Vol. 12, 347-362.
- [46] W. Shen, "Web-Based Infrastructure for Collaborative Product Design: An Overview", *Proc. of CSCWD2000*, Hong Kong, 2000, pp. 239-244
- [47] W. Shen W., D.H., Norrie, J.P. Barthes, *Multi-Agent Systems for Concurrent Intelligent Design and Manufacturing*, Taylor and Francis, London, UK, 2001.

- [48] Y. Song A. Hamilton, H. Wang, “Built environment data integration using nD modeling”, *ITcon*, 2007, Vol. 12, 429-442,
- [49] M. Sun, M. Sexton, G. Aouad, A. Fleming, S. Senaratne, C. Anumba, P. Chung, A. El-Hamalawi, I. Motawa, M.L. Yeoh, “Managing Changes in Construction Projects,” EPSRC Industrial Report, 2004, <http://www.built-environment.uwe.ac.uk/research/cprc/publications/mcd.pdf>
- [50] M. Sun, S. Senaratne, A. Fleming, I. Motowa, M. Lin Yeoh, “A change management toolkit for construction projects”, *Architectural Engineering and Design Management*, 2006, 2(4), 261-271.
- [51] D. Tapscott, A.D. Williams, *Wikinomics: How Mass Collaboration Changes Everything*. Penguin Group, New York, NY, 2007.
- [52] V. Voropajev, “Change management – a key integrative function of PM in transition economies”, *International Journal of Project Management*, 1998, 16(1), 15-19.
- [53] S. Wang, Z. Xu, J. Cao, J. Zhang, “A middleware for web service-enabled integration and interoperation of intelligent building systems”, *Automation in Construction*, 2007, 16(1), 12-121.
- [54] R. Wing R “RFID applications in construction and Facilities Management”, *ITcon*, 2006, Vol. 11, 711-721.
- [55] S. Wu, H. Ghenniwa, W. Shen, Y. Zhang, “Personal Assistant Agents for Collaborative Design Environments”, *Computers in Industry*, 2006, 57(8/9), 732-739.
- [56] A. Zarli, O. Richaud, “Requirements and Technology Integration for IT-Based Business-Oriented Frameworks in Building and Construction”, *ITcon*, 1999, Vol. 4, 53-75.
- [57] C. Zhang, A. Hammad, “Agent-Based Simulation for Collaborative Cranes,” *Proceedings of the 2007 Winter Simulation Conference*, Washington DC, Dec. 9-12, 2007
- [58] Autodesk, <http://saarc.autodesk.com/buzzsaw/>
- [59] CII, <http://www.construction-institute.org/>
- [60] CIMSteel Integration Standards (CIS/2) <http://www.cis2.org/>
- [61] CRC Construction Innovation, 2006, Construction 2020: A Vision for Australia’s Property and Construction Industry, [http://www.construction-innovation.info/images/pdfs/Construction\\_2020.pdf](http://www.construction-innovation.info/images/pdfs/Construction_2020.pdf)
- [62] CSTB, <http://www.cstb.fr/>
- [63] ECTP, <http://www.ectp.org/>
- [64] FIATECH, <http://www.fiatech.org/>
- [65] Graphisoft (2008) <http://www.graphisoft.com/products/archicad/teamwork/>
- [66] International Alliance for Interoperability (IAI) [http://www.iai-international.org/Model/R2x3\\_final/index.htm](http://www.iai-international.org/Model/R2x3_final/index.htm)
- [67] ISO 15926: <http://15926.org/>
- [68] JADE, <http://jade.tilab.com/>
- [69] LCI, <http://www.leanconstruction.org/>
- [70] NCCTP, <http://ncctp.constructingexcellence.org.uk/>
- [71] National Institute of Standards and Technology (NIST), <http://www.bfrl.nist.gov/WirelessSensor/index.htm>
- [72] VTT Construction IT, <http://cic.vtt.fi/>
- [73] W3C, <http://www.w3c.org/>
- [74] Wikipedia, <http://www.wikipedia.org/>