Information and Communication Technology Applications in Architecture, Engineering, and Construction Organizations: A 15-Year Review

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Abstract: Information and communication technology (ICT) has had enormous effects on the development of architecture, engineering, and construction (AEC) organizations in past decades. The effects have resonated in various disciplines, such as organizational efficiency, communication approach, and employee behavior. However, a comprehensive and in-depth review of the ICT applied in the AEC organization is missing from the current literature. To fill this gap, this paper presents an in-depth review of mainstream studies of ICT-supported AEC organizations published in last 15 years (1998–2012). A total of 145 articles from 12 construction and IT-related journals are identified and have been thoroughly reviewed. This review is divided into four parts: (1) synthesis and general trend of existing literature; (2) lessons learned from ICT practical implementation; (3) enabling technologies of ICT applications; and (4) ICT-induced organizational outcomes. Throughout this paper the authors summarize and categorize developments to date, discuss the advances and limitations of the use of ICT, and propose key areas for future research. This review can become a foundation for the classification and integration of the state of the art in ICT research on behalf of AEC organizations. **DOI: 10.1061/(ASCE)ME.1943-5479.0000319.**

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Introduction

Emerging information and communication technologies (ICT) introduce enormous opportunities for improving communication to enhance the effectiveness of construction processes and for creating business innovation (Peansupap and Walker 2005). Both technological and managerial advancements of ICT application in the architecture, engineering, and construction (AEC) industry and organizations have been significant. Distinctive features of the AEC industry make the task of managing construction projects particularly appropriate for applications of ICT tools (Ahmad 1999). The effect of ICT has shifted from the enhancement of traditional AEC work practices to an innovative approach that necessarily facilitates new and creative alternatives to organizing and operating AEC organizations.

Started in earnest in the last three decades of the 20th century, ICT attracted a considerable amount of attention by researchers in the AEC community attempting to address a spectrum of operational and managerial issues in an AEC organization, such as across-organizational collaborative design, enterprise-level data-driven decisions, ICT-enabled safety monitor and control, and global virtual working environment. However, in the large body of existing research, a comprehensive and rigorous review of ICT applied in the AEC organizations is missing. Deep and meaningful understanding of certain research questions have not been well achieved, especially those related to the general research trend in organizational ICT for AEC firms, methods and contributions of this search, ICT diffusion patterns in AEC organizations, emergence and popularity of technologies, and taxonomy of ICT effect on AEC organizational outcomes.

This study provides a state-of-the-art review of ICT application in the AEC organizations based on mainstream studies performed during 1998–2012 in select journals. A total of 145 papers have been reviewed and presented in the following format. The following section illustrates the research method of this study; the third section reviews the general trend in ICT application in terms of, e.g., time span, academic influence, end users, focused topics; the fourth section examines the top five most influencing categories for ICT implementation and diffusion in the AEC organizations; the fifth section concludes with emerging and adopted ICT technologies in project design, construction, and life-cycle phases. Additional sections discuss the taxonomy of ICT effect on an AEC organization into five dimensions: organizational decision making, organizational performance, organizational information efficiency, organizational collaboration, and organizational behavior. The concluding section presents a summary of this review and delineates the future direction of research. This study uses both qualitative and quantitative analysis to better interpret the existing studies in a holistic perspective.

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Research Approach

Because of a large amount of research fitting in ICT application in the construction organizations, this study develops a comprehensive and in-depth review using the following research method.

Step 1: Select Data Sources

To acquire as many papers as possible that deal with ICT in the AEC organizations, the selected journals are in a wide domain of the construction, engineering, design, management, and information technology (IT) journals. The journals are selected in two steps: (1) finding all well-known construction management journals through journal ranking results (Wing 1997) (Brochner and Bjork 2008), web-of-science indexed journals within categories of construction and building technology and civil engineering, and endorsed journals by globally acknowledged professional institutions such as the American Society of Civil Engineers (ASCE), the International Project Management Association, and the *Project Management Journal*; and (2) selecting journals that have close relations with ICT or construction organizations. After these two steps, a total of 12 international peer-reviewed journals in the AEC industry were identified and listed in Table 1.

Step 2: Perform Preliminary Search

The preliminary controlled searching criteria are defined with a focus on ICT or relevant terms as follows (to assure the search range of the review, this study also selected all plural forms of these search criteria):

Table 1. Review Sources of 12 Journals During 1998–2012

Journal	Number of articles (1998–2012)			
	Total articles	ICT	ICT application	ICT application in organization
Automation in Construction (AUTCON)	1,396	82	81	23
Journal of Management in Engineering (JME)	679	25	25	5
Journal of Construction Engineering and Management (JCEM)	1,820	70	70	27
Journal of Infrastructure System (JIS)	441	4	4	0
International Journal of Project Management (IJPM)	1,310	52	51	3
Project Management Journal (PMJ)	320	18	18	2
Construction Management and Economics (CME)	3,035	30	11	9
Journal of Information Technology in Construction (ITCON)	402	126	74	36
Journal of Computing in Civil Engineering (JCCE)	776	55	55	6
Advanced Engineering Informatics (AEI)	504	19	19	1
Computer-Aided Civil and Infrastructure Engineering (CACIE)	703	38	12	6
Construction Innovation: Information, Process, Management (CI)	249	116	53	27
Total	11,635	635	473	145

- Information technology;
- Communication technology;
- ICT;
- Information communication and technology;
- Communications technology; or
- Information communications and technology.

Based on these criteria, each paper was searched in a specific domain consisting of *title* or *keywords* or *abstract* published during 1998–2012 to determine its eligibility and level of relevance. Consequently, the 635 ICT-related articles in each of the searched journals are shown in Table 1.

Step 3: Filter ICT Application Articles

ICT is supposed to encompass a board spectrum of computing technologies that can be used to create, store, exchange, and use information in various forms, such as, e.g., hardware, software, telecommunications, Intranet and Extranet, wireless connection, and social media. This broad definition also leads to a variety of search results from the first round, in which many articles mention ICT briefly but focus on other topics. To refine the search, this research scope is narrowed to articles related only to ICT applications. This step excludes articles that concentrated solely on pure theoretical or technological development of ICT, such as computer software methodology, single computational optimization, and computer-aided mathematical optimization. The number of articles is reduced to 473 after this step.

Step 4: Focus on ICT Applied in Organizations Articles

The 473 articles are further reduced with the filter of only applying to the AEC organizations, such as improving organizational information processing capacity or facilitating team management. This step therefore excludes papers with unclear application purposes or with little potential to apply for organizations, such as a pure technical system development or mathematical algorithms. After this screening process, 145 articles were identified as the review range of this study.

Step 5: Identify Extract Research Articles

This step confirms that all 145 selected papers align with the research scope and the foundation of this research. A more detailed article selection is given in Table 1.

Overview of Research Trends

Time Span

The number of ICT articles published annually in the AEC organization is depicted in Fig. 1 (Table S1 shows the corresponding raw data). The articles published before 2009 are similar in the small quantity of them. Since 2001, published articles jumped considerably from 3 per year to 11, and then kept an annual average of 13 articles per year. The number of articles increased to the peak of 17 in 2010, followed by a two-year decline. The trend in published articles clearly shows that the interests and efforts of organizational ICT research increased rapidly since the beginning of the 21st century and are continuously growing.

Journal Distribution

Journal shares of a total of 12 publications are shown in Fig. 2. ITCON published the most articles (36 articles, 25%). The number

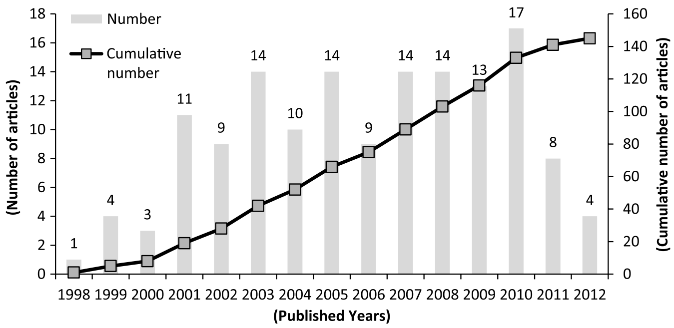

Fig. 1. Number of articles published during 1998–2012

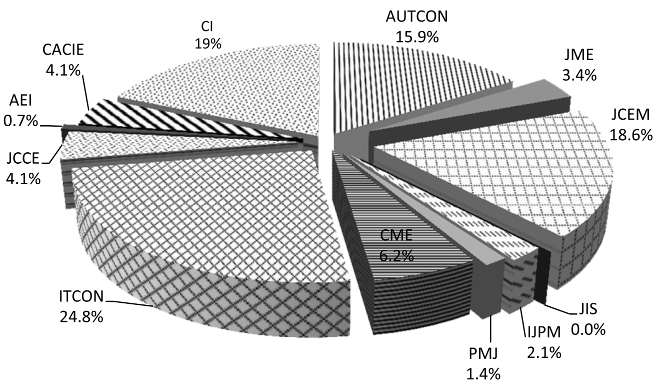

Fig. 2. Journal shares during 1998–2012

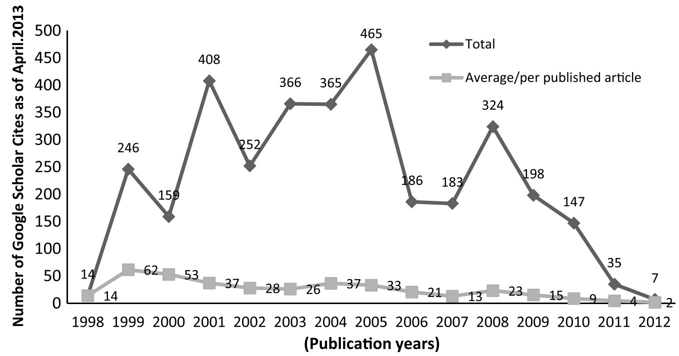

Fig. 3. Number of Google Scholar cites of 12 total publications per published year during 1998–2012, by total and average citations

of articles shared by CI, JCEM, and AUTCON are similar in quantity, nearly 16–19%. These four journals shared up to 78% of the total 12 publications. The remaining eight journals shared 22% of the articles, of which *Journal of Management in Engineering* (JME), *International Journal of Project Management* (IJPM), *Construction Management and Economics* (CME), *Journal of Computing in Civil Engineering* (JCCE), and *Computer-Aided Civil and Infrastructure Engineering* (CACIE) shared the average of approximately 3–4%; *Project Management Journal* (PMJ), *Advanced Engineering Informatics* (AEI), and *Journal of Infrastructure System* (JIS) shared the least number of articles (1.4, 0.7, and 0%, respectively). This distribution demonstrates that ICT research in organizations appeared in a wide cross section of publications and primarily presented in IT-related construction journals.

Citation and Influences of the Research

ICT articles included the most citations. Fig. 3 shows the total number of Google scholar citations for all reviewed articles published during 1998–2012. The citations grew considerably in 1999 (246 times). The average number of citations per article increased to a peak of 62 during the same year. During the period from 1998 to 2005, ICT-published articles continued to be highly cited (an average of 323 per year), with 35 citations per article. However, citations decreased to 186 in 2006 and declined during the last six years, reflecting the fact that ICT articles took 8–12 years to reach a wide academic influence.

The 10 most highly cited articles during 1998–2012 are given in Table 2, of which citation-based rankings reveal interesting patterns. These 10 articles were highly cited (873 times in total and 87 times per article, on average). Among those contractors and subcontractors are the leading research subjects (five articles, cited 457 times). Cross organizations and project management–related organizations take second and third place, respectively, in their popularity of ICT applications in the organization (3 articles with 277 citations, and 2 articles with 139 citations, respectively). This identifies the general research interests and values in current literature, of which contractors, cross-organizational users, and project service providers are the potential audience. Both Fig. 3 and Table 2 provide a longitudinal perspective to the research influence and popularity in the existing body of knowledge.

Group of Users

ICT can be adopted by different users in the AEC industry. This study grouped various users into six types and showed the accumulated number of articles from each group in Fig. 4. Among those contractors and subcontractors are the leading adopters (53 articles, 36.6%). Articles in this group have grown considerably since 2003, an average five articles per year. The increasing number of contractor-oriented articles is a result of the construction process demanding massive and accurate information to make decisions and to improve efficiency and performance. Cross- and multiorganizations rank second in popularity (29 articles, 20%) because the application of ICT can significantly enhance communication and collaboration among various project participants. Engineering and project management firms place third with 21 articles, followed by architecture/design firms with 15 articles (10%). Both groups show a growing adoption rate in recent years, revealing a rapidly increasing interest. Few papers focus on the owner's perspective [six articles in total (4.1%)] during 1998–2012.

Top Research Keywords

The top keywords in the reviewed articles are provided in Table 3, of which keyword-based rankings reveal popular research fields. *IT/ICT, construction*, and *communication* are the highest-frequency keywords. The rest of the keywords are dispersed among a variety of research fields, adopted technologies, or organizational functions. Specifically, construction management (12, 8%) and project management (11, 8%) emphasize the research fields; radio frequency identification (RFID) (7, 5%) and building information modeling (BIM) (6, 4%) show prevailing technologies; and decision support, collaboration, and innovation diffusion indicate ICT-induced benefits to organizations.

Research Methods

Different research methods applied in the reviewed articles can be classified into three groups in Table 4. Most articles fall into the category of empirical analysis (87 articles, 60%). Among those,

Table 2. Top 10 Cited Articles in 1998–2012

Citations	Article	Author and year	Keywords
113	Time-cost-quality trade-off analysis for highway construction	El-Rayes and Kandil 2005	Algorithms; construction industry; contracts; cost control; highway construction; information technology (IT)
113	Forces driving adoption of new information technologies	Mitropoulos and Tatum 2000	N/A
105	An application of the Internet-based project management system	Deng et al. 2001	Construction communication; information technology; internet; project monitoring
91	A/E/C teamwork: A collaborative design and learning space	Fruchter 1999	N/A
83	Enhancing construction quality inspection and management using RFID technology	Wang 2008	Quality management; information management; RFID; mobile; portal; PDA
81	Industry-centric benchmarking of information technology benefits, costs and risks for small-to-medium sized enterprises in construction	Love et al. 2004	Benchmarking; benefits; construction; costs; evaluation; IT; Risks; SMEs
81	Use of the Internet to enhance construction communication: total information transfer system	Tam 1999	Internet; construction communication; information technology; live cam; data exchange
72	Automated classification of construction project documents	Caldas et al. 2002	Classification; construction industry; information retrieval; document handling; civil engineering computing
67	Technology adoption decisions in construction organizations	Mitropoulos and Tatum 1999	N/A
67	Automating hierarchical document classification for construction management information systems	Caldas and Soibelman 2003	Construction management; classification systems; information management; information systems; text/data mining

Note: Data from Google Scholar, April 2013.

38 articles were conducted by case studies, 28 articles by questionnaire surveys, and 14 articles by interviews. The data from empirical analyses are distributed across countries, with 22 articles in Europe; 16 in the United States; 12 in China, Hong Kong and Taiwan; and 9 in Australia. The second-most popular research method is modeling (39 articles), which consists of 15 articles of prototype model, 9 articles of conceptual model, 4 of theoretical model, and 11 of other models. The remaining of 19 articles (13%) use hybrid models or other methods, such as a promising theory or algorithm, to investigate organizational ICT applications.

Levels of ICT Application

The effect of ICT applications can be grouped into three levels: individual level, organizational level, and across organizations. *Individual level* indicates a person and personal behavior; *organizational level* indicates a collection of individuals with a common goal, typically a company or a special task force; and *across organizations* indicates a group of organizations and the connections among them. As shown in Fig. 5, the across-organizations articles attracted the greatest amount of research interest with 43 articles and a 42% share of the 12 total journals. Organizational level is tied to personal level with the similar weight of 30%, but shows a stronger growth trend since 2008 with an average of five articles per year.

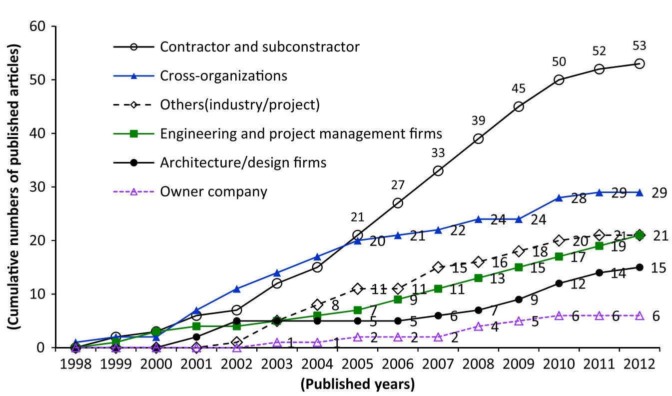

Fig. 4. Cumulative number of ICT articles in the layer of organization of 12 total journals by publication years during 1998–2012

Table 3. Most Popular Keywords in the Published Articles during 1998–2012

Keywords	Number of published articles	Frequency (%)
ICT; IT communication; communication technology	62	43
Construction; construction industry; construction projects	48	33
Information management	14	10
Internet	12	8
Construction management	12	8
Project management	11	8
Modeling	11	8
RFID	7	5
Information systems	7	5
Implementation	7	5
SMEs	6	4
BIM	6	4
Decision support systems	5	4
e-business	5	4
Innovation diffusion	5	4
Collaboration	5	4

Note: Because the papers have multiple keywords, the sum of research keywords is greater than that of the published articles.

Table 4. Distribution of Used Research Methods

Method	Subclass	Number of published articles	Percentage (%)
Empirical analysis		87	60
	Case study	38	26
	Questionnaire/survey	28	19
	Interview	14	10
	Hybrid (interview and questionnaire)	7	5
Modeling		39	27
	Prototype model/experimental	15	10
	Conceptual model	9	6
	Theoretical model	4	3
	Others	11	8
Hybrid model and other methods		19	13
Total		145	100

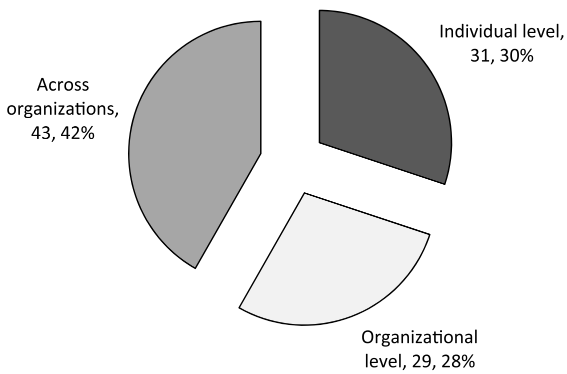

Fig. 5. Distribution of research articles among different organizational levels

Research Framework

The fundamental aim of this review is to examine ICT as an agent of the relationship between organizational characteristics and organizational outcomes through different technologies and practical implementation (Dewett and Jones 2001). To appreciate the essential role of ICT in the AEC organizations, this study proposes a research framework in Fig. 6 that was inspired by the general role of information technology in the organization (Dewett and Jones 2001). This analytical framework allows the exploration of ICT as a central role of organizational transformation, and offers a larger array of organizational strategic discussions.

Among the four boxes in Fig. 6, the left box depicts the ICT levels of effect that include individual, organizational, and cross-organization levels. Three levels of effect are intertwined with one another in literature and are presented as an entire topic in this study. The other three aspects include ICT implementation (71 articles), technologies of ICT (96 articles), and organizational outcomes (145 articles), and make up the core discussion of the following content.

State of Practices of ICT Implementation

The articles on ICT practical implementation and critical successful factors (CSF) shared the highest overall percentage in the past 15 years. A total of 72 ICT articles were related to implementation (CSF). After reviewing these articles, hundreds of different factors were identified as critical success factors for ICT implementation in AEC industry projects (see a detailed list in the Supplemental Data). Fig. 7 summarizes the top 10 most influencing factors for successful ICT adoption and diffusion in AEC organizations, and categorizes them into the following five groups: personal characteristics, organizational characteristics, technology characteristics, project characteristics, and external environment.

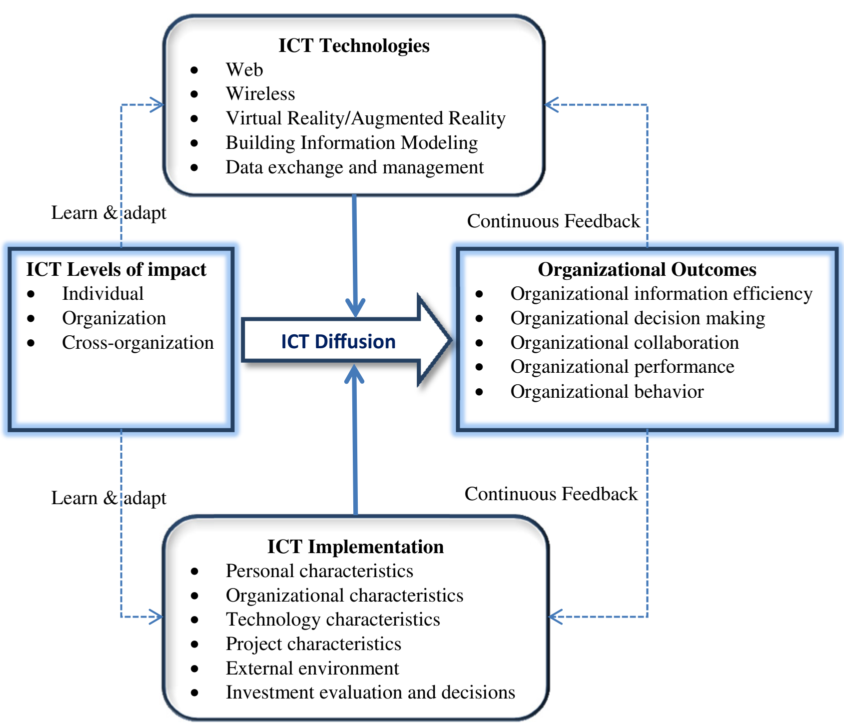

Fig. 6. Framework of ICT application in AEC organizations

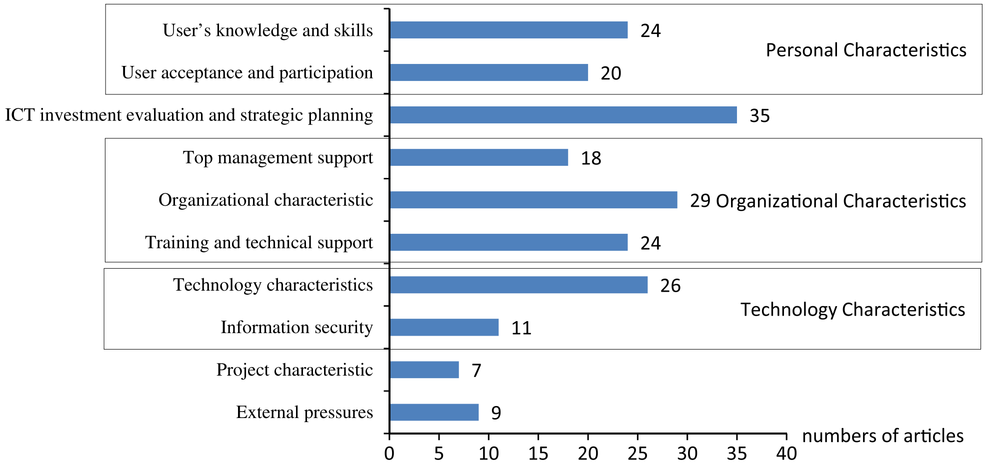

Fig. 7. Top 10 most influential factors for ICT adoption and diffusion in the AEC industry

Personal Characteristics

Three personal characteristics were identified as important factors to successful implementation of a new ICT, which are user's knowledge and skill, acceptance, and participation.

The user's ICT knowledge and skills refer to the degree that actors know how to use ICT (Adriaanse et al. 2010b). Unfortunately, a lack of knowledge and skills to use ICT was repeatedly listed as one of the major barriers or critical factors for new ICT adoption in construction projects. Almost one-third of the articles provided related evidence to support this argument. For example, Benjaoran (2009) concluded that small and medium enterprises (SMEs) that are unable to afford a high-salary job to attract proficient personnel with sophisticated ICT skills led to their employees' lack of knowledge and skills concerning ICT. A broad sense of education has been proposed to raise the level of ICT knowledge and skills for construction practitioners, especial for the first-time users, to overcome the technical difficulties.

User's acceptance depends primarily on the degree of the user's resistance and fear to change. Seven articles discussed how user resistance and fear to change has been a key barrier for the adoption and diffusion of a new ICT. The Swedish investigation showed that the use of ICTs is perceived to bring benefits to the construction industry, yet users are reluctant to increase the level of using ICTs (Jacobsson and Linderoth 2012). Reasons for resistance to change were concluded to be fear of the unknown, lack of information/knowledge/skills, threats to status, fear of failure, lack of perceived benefits, and uncertainty regarding the change outcomes (Erdogan et al. 2008). Davis and Songer (2009) collected 156 samples among AEC professionals and found that individuals from different demographics have different levels of computer knowledge and experience, and a different likelihood resist ICT change. As a result, the user's requirements should be correctly captured (Ugwu and Kumaraswamy 2007) and sufficient training and communication are key to overcoming the resistance (Erdogan et al. 2008). Lack of user's participation was identified as another barrier for the adoption and diffusion of a new ICT in construction. Evidence also shows that users' participation can change at different stages as a result of the unbalanced development of various ICTs (Adriaanse and Voordijk 2005).

Organizational Characteristics

Over two-thirds of the articles (52 articles) focusing on successful adoption and diffusion of ICTs in the AEC industry discussed factors of organizational characteristics, such as organizational culture (11 articles), structure (17 articles), decision-making ability, organizational commitment (Lam et al. 2010), strategy (19 articles), training (24 articles), and management support (18 articles).

Organizational culture can affect the use of ICTs primarily in two ways. First, organizational culture can affect the decision-making process on whether to adopt new technologies (Mitropoulos and Tatum 1999). Second, organizational cultural traits will influence the level of ICT engagement in construction projects (Gajendran and Brewer 2012). In practice, a variety of companies do not value the culture of innovation in the AEC industry (Mitropoulos and Tatum 2000). The organizational culture traits are considered to be a major barrier to successful adoption and diffusion of innovative ICT. To address this issue, some researchers pointed out that AEC firms need to change their organizational culture to strive toward becoming an adaptive learning organization that will support the use of ICTs (Love and Irani 2001).

Organizational structure was identified as a key factor affecting investment in ICT innovation since 1989 (Tatum 1989). Later research discussed the effects of organizational structure in more detail, and most of those studies referred to the effects of organizational size. The size of the firm is considered critical in its willingness to adopt new ICTs. Interestingly, scholars are split into two controversial views on the relationship between organizational size and the use of ICTs. Some scholars argued that large-size firms preferably support a new ICT implementation because they own greater organizational resources and economies of scale (Nikas et al. 2007) and smaller firms are unaware of the potential benefits of ICTs (Acar et al. 2005). Other researchers stated that SMEs are more likely to adopt ICTs successfully because of their greater flexibility (Hua 2007; Nikas et al. 2007).

Alignment between corporate business strategy and technology strategy was concluded to be another critical factor for successful ICT implementation (Voordijk et al. 2003). Furthermore, the lack of ICT strategic planning was suggested to be a significant organizational-level barrier in the construction industry (Stewart et al. 2004). As a result, detailed strategic planning on new ICT implementation should be prepared before the adoption.

Organizational training, especially the insufficient IT training and experience, was also highlighted as a significant barrier to IT implementation at both the project level and industry level (Wong and Lam 2011). Training was confirmed to be an effective way to ease the ICT use and the extent of technological functionality (Peansupap and Walker 2005), and to help the users' understanding and perceptions of adopting ICT applications. Training is particularly important in the SMEs' formal project-management processes (Ahuja et al. 2009a). Sometimes retraining is also required to upgrade construction practitioners' skills (Mak 2001).

Management support is also essential in a successful adoption of new ICTs. Numbers of empirical investigations revealed that top management support could be ranked as one of the most significant success factors (Ugwu and Kumaraswamy 2007; Tatari et al. 2007). Top management support reflects, in many ways, the significance that top management executives place on new ICT, which might affect the facilitation of technology transfer throughout the organization (Nikas et al. 2007). Lack of top management support usually leads to user resistance to use new technologies (Peansupap and Walker 2006). However, the importance of these characteristics varies among construction organizations. For example, contractors might consider top management support to be less important than ICT ease of use (Ugwu and Kumaraswamy 2007).

Technology Characteristics

Nearly half of the articles (33 articles) discussed technology characteristics as key elements that affect the adoption and diffusion of ICT in construction. These characteristics include, e.g., ICT applications' ease of use, compatibility (Weippert et al. 2002), reliability, extendibility, and information security. Recent development of knowledge characteristics (Lee and Sexton 2007) and interoperability of ICTs have become a spreading topic.

Both construction practitioners and academic researchers have perceived that the poor performance on ease of use and compatibility of ICT applications were two major barriers to successful use of ICTs (Hua 2007; Ugwu and Kumaraswamy 2007). Ease of use is a major issue related to training requirements and the associated operational cost (Ugwu and Kumaraswamy 2007). Providing multidimensional technical support to assist an ICT application was proposed as an effective method to address this problem. This technical support can be provided by technical support groups, a help desk group, groups who develop in-house applications, or by specialist software support organizations (Peansupap and Walker 2005).

Early studies proposed that information security is the primary concern to construction practitioners when deciding whether to adopt an IT project (Walker and Rowlinson 1999). However, other researchers argued that users may not pay much attention to security-related issues if an ICT system is deployed to solve non-mission-critical support process (Ugwu and Kumaraswamy 2007). Recent studies on solutions to information security threats are of high significance and have made some progress. For example, three key issues regarding to information security were easily recognized: the availability of technical security features embedded in the ICT tools, the availability and level of awareness of intellectual property rights and their preservation, and the perception of the users (Brewer and Gajendran 2009).

Project Characteristics

Project characteristics are considered to be significant factors that affect the implementation of ICTs. Researchers have presented the effects of project characteristics in a variety of topics such as project structure (Bäckblom et al. 2003; Brewer and Gajendran 2012; Love and Irani 2001; Nitithamyong and Skibniewski 2007; Whyte 2003a), project type (Nitithamyong and Skibniewski 2007), project cost (Hassan and McCaffer 2002; Nitithamyong and Skibniewski 2007), project duration (Hassan and McCaffer 2002; Nitithamyong and Skibniewski 2007), project specification (Ryoo et al. 2010), and project location (Nitithamyong and Skibniewski 2007). Interestingly, the same project characteristics could have various influences on different ICT applications. For example, project size was considered to affect the use of ICTs in an electronic document management system (Bäckblom et al. 2003) and virtual reality (Whyte 2003b) quite considerably, but was found to have little effect on the performance of web-based project management systems (Nitithamyong and Skibniewski 2007). Project complexity, as an emerging topic, is attracting more attention in the use of ICT and needs further study.

External Environment

Existing articles revealed that the adoption of new technologies within AEC organizations is, to some extent, influenced by forces from the external environment, such as government regulations (Brewer and Gajendran 2011; Jacobsson and Linderoth 2010), competitive forces (Jacobsson and Linderoth 2010; Kale and Arditi 2005; Nikas et al. 2007; Rowlinson 2007; Wong 2007), market demand (Nikas et al. 2007; Oyediran and Odusami 2005), vendor strategies (Orlikowski 1992), professional norms (Orlikowski 1992), and states of knowledge about technology and socio-economic conditions (Orlikowski 1992). These influences generally cause indirect chain reactions. For example, external requirements such as government adversarial projects and geographical pressures can affect organizational innovative behavior, which is related to the decision making on innovative IT investment (Rowlinson 2007).

Investment Evaluation and Decisions

ICT adoption depends largely on the initial evaluation results of benefits, costs, and risks of potential ICT implementation. However, the assessment of benefits, costs, and risks in the construction industry is more acute than other industry sectors, possibly because of the industry's structure, fragmented supply chain, and undercapitalization (Adriaanse et al. 2010b; Love and Irani 2001). Related investigations revealed that construction organizations, especially the top management, usually do not perform quantitative analyses of benefits versus costs, despite the high costs involved. In most cases, cost justification was intuitive (Mitropoulos and Tatum 1999). Meanwhile, unsuccessful ICT investment evaluation commonly failed to get the necessary support from project clients and professional consultants regarding to the IT benefits and skills (Rowlinson 2007). Therefore, future ICT investment evaluation is expected to encompass a broader range of beneficial interests from both internal and external stakeholders.

Although numerous articles have investigated the ICT implementation in various AEC organizations and contributed valuable knowledge to guide ICT diffusion, several key directions and suggestions can be concluded for future research. First, most of the existing literature studies ICT implementation through case studies, which are generally based on a limited sample of construction companies or projects in a regional or national context. Therefore, results from both quantitative and qualitative analyses cannot be generalized to guide the business practice as an industrial standard. Future ICT implementation research needs a more generalized and widely acknowledged standard to provide essential guidelines to benchmark construction practices, regardless of the project's geographic constraint. Second, research should shift its focus to the pre-ICT implementation stage, such as in the stakeholder-based ICT investment evaluation of the boarder benefits versus costs, and system qualification review for both ICT organizations and ICT vendors to measure the organizational readiness. This proactive, pre-implementation research can serve as a visible way to reduce the risk of uncertain ICT investment. Third, the most current ICT products are designed with little consideration of the human skills inside a construction organization, especially, e.g., for the workers' professionalism, educational background, intensive workloads, and capability of mastering a new technology. Therefore, effectively embedding and appreciating the human factors in the ICT development process can help the ICT products to be diffused quickly in the organizational environment and construction practices.

Enabling Technologies of ICT

Existing literature covers a variety of ICT technologies that were employed to achieve overall organizational performance and efficiency in the AEC industry. Among the 145 total articles, 96 articles specified one or more enabling technologies in ICT practices (75 articles addressing five mainstream types of technologies are listed in Table 5) and 21 articles covered widely diversified technologies listed (Table 6). The remaining of articles discussed ICT as a general issue.

Web

The use of web technology in the AEC industry can be traced from the very beginning of ICT application. After years of development, most ICT applications depend heavily on the web technology development in both the design and management process, such as a web-based project management system (Deng et al. 2001; Dossick and Sakagami 2008; Nitithamyong and Skibniewski 2007; Stewart and Mohamed 2004; Tam 1999), web-based information management system (Lam and Chang 2002; Weippert et al. 2002), web-based decision support system (Abdou et al. 2003), and online collaborative contract change management system (Sun and Oza 2010). Over 40% of existing articles used the web as an agent to link and access various kinds of information that the user can browse at will. The benefits of using web technology are generally focused on effective collaboration, communication and coordination (20 articles), and the decision-making process (8 articles).

Virtual/Augmented Reality

Virtual reality (VR) technology provides an interactive, spatial, real-time medium and enables the real-time viewing of, and interaction with, spatial information (Whyte 2003b). Augmented reality (AR) is a variation of VR that creates an environment in which digital information is inserted in a predominantly real-world view (Wang et al. 2013). VR technology completely immerses a user inside a synthetic environment in which the user cannot see the real world, whereas AR allows the user to see the real world with virtual objects superimposed on or composited into the real world (Azuma 1997). Many studies focused on the application of VR and AR technologies in the design and construction process, especially focusing on promoting collaboration among participants, such as the design review process (Fu and East 1999; Shiratuddin and Thabet 2011) and construction progress monitoring (Golparvar-Fard et al. 2009, 2011). VR and AR technologies were also applied to improve organizational performance and decision-making capacity, especially for architecture design companies.

Wireless Technology

Wireless technology allows the transfer of information between two or more points that are not connected by an electrical conductor. Common wireless technologies in the construction industry include radio frequency identification technology, personal digital assistants (PDAs), and global positioning systems (GPS). All of these applications offer considerable benefits in terms of information collection, exchange and storing, thus improving collaborative work (Demiralp et al. 2012; Kuladinithi et al. 2004; Shin et al. 2011; Tserng et al. 2005; Zhang et al. 2009), the decision-making process (Demiralp et al. 2012; Shin et al. 2011; Zhang et al. 2009), and project performance (Demiralp et al. 2012; Tsai et al. 2007; Wang 2008). Half of the wireless studies focused especially on the applications of RFID technology designed to enhance on-site construction operations (Akinci et al. 2006; Demiralp et al. 2012; Elmisalami et al. 2006; Kim et al. 2011; Kiziltas et al. 2008; Shin et al. 2011; Sørensen et al. 2009; Wang 2008). In addition, wireless technology can be integrated with other ICT applications. For example, the integration of wireless technology and agent-based systems can support collaborative work by providing real-time field data capturing (Zhang et al. 2009).

Electronic Data Interchange/Electronic Data Management System

Electronic data interchange (EDI) or electronic data management system (EDMS) is a seamless data interchange tool that enables communication among different computer systems or computer networks. As a result, various EDI systems in the construction industry were designed to remove the barriers for collaboration in a

Table 5. Top Five Enabling Technologies of ICT Used in AEC Organizations

ICT technologies	Years covered	Number of published articles	Percentage (%)	Research focus
Web	1999–2010	32	43	Collaboration/communication/coordination (20) Decision making (8) Performance (3) Efficiency (3)
VR/AR	2001–2011	15	20	Collaboration/communication/coordination (8) Decision making (2) Performance (2)
Wireless	2003–2012	16	21	Collaboration/communication/coordination (5) Decision making (4) Performance (3)
EDI/EDMS	1999–2011	10	13	Collaboration/communication/coordination (3) Efficiency (1)
BIM	2005–2012	7	9	Collaboration/communication/coordination (3) Decision making (1)
Total	—	75[a]	100	

[a]The aggregate of individual cells is not equal to the total number because one article may use multiple methods.

geographically fragmented industry. EDI and EDMS solutions can improve the competitiveness of a firm by providing a strategic advantage over competitors through automation, streamlined communication and waste elimination (Agdas and Ellis 2010), and improved organizational capabilities in the centralized, digitalized, standardized, and documentary management systems (Zipf 2000). However, lessons learned from EDI studies revealed that the standardization of EDI systems is a major barrier of successful adoption and diffusion for AEC organizations (Agdas and Ellis 2010).

Building Information Modeling

Building information modeling refers to the development and use of digital representations of physical and functional characteristics of a facility to simulate the construction and operation process. Characteristics of the BIMs were identified as object-oriented, open/extensible, comprehensive, three-dimensional, spatially related, and rich in semantics (Isikdag and Underwood 2010). As one of the most popular technologies in recent years, BIM has drawn an increasing amount attention from both researchers and practitioners. Numerous studies demonstrated BIM's important role in improving information exchange and management and thus enhancing collaborative working capabilities among different project participants (Cerovsek 2011; Gu and London 2010; Jung and Joo 2011). However, some researchers argued that recent BIM-enabled construction projects are often tightly coupled technologically, but divided organizationally (Dossick and Neff 2010).

In addition to these five dimensions, the database is also used in almost every ICT application. The number of electronic documents stored in the construction management information system is considerably increasing as a result of the widespread use of ICT. In project management division alone, 12 database systems are needed for developing and monitoring project schedules, budgets, costs and change approvals, and for tracking drawings (Zipf 2000). Organizing and improving the database access to the necessary information becomes essential to the construction information management (Caldas and Soibelman 2003). Existing solutions include integrating various database systems for a particular need (Zipf 2000), developing automated methods for construction document database classification (Caldas and Soibelman 2003), employing intelligent data and data mining technologies (Wong 2006), using a database-web link to store, organize and archive information, and setting up a relational database management system server to run a variety of project database systems (Mak 2001). In practice, Fan et al. (2008) validated the use an electronic database that stores the process, the tool, and objectives, and the outcome of value management studies that support the interactive value of management workshops.

In general, ICT has a significant influence on the electronic production, exchange, and storage of information generated in the organizations. Most studies discussed intensively the issues of collaboration, communication, or coordination in the construction process (47 articles). These technologies also show considerable development of the virtual organization/enterprise, which is discussed in subsequent sections.

However, the fragmented nature of the AEC industry raises an emerging issue of interoperability as information exchange and sharing among different ICT technologies. Early efforts have been proposed to address this issue such as a distributed, integrated construction environment based on the industry foundation class (IFC) (Alshawi and Faraj 2002). Recently, building information modeling has also been active in the field of information integration and interoperability, and promises to tackle this issue (Isikdag and Underwood 2010).

Future enabling technologies of the ICT trend provide more intelligent services in all information processes, e.g., information recognition, processing, and representation. To satisfy the fast-changing and complex construction requirements, the ICT services are expected to deliver in a user-friendly interface on a portable or mobile device that is integrated in a collaborative system or platform (e.g., BIM). For example, intelligent VR and BIM systems can be integrated in relation to convenience portable devices to flexibly serve broader end users in a variety of challenging environments. Industrial-based standards and body of knowledge, such as the classification of ICT intelligence and user interface in the construction industry, should also be developed further to support all construction ICT products in common standards and protocols.

Taxonomy and Influences of ICT in AEC Organizations

Research Taxonomy

The classification of ICT articles in the AEC organizations can be organized in a five-dimensional taxonomy. The taxonomy and publication numbers are given in Table 7. Communication, collaboration, and coordination are highly interrelated research topics and have the highest number of articles (43). The number of organizational decision-making, performance, and organizational behaviors are similar in quantity (approximately 21–24 articles). Efficiency appears in 16 articles and shares the average of 11% by published years. This classification of literature provides an integrated and comprehensive framework to summarize state-of-the-art ICT

Table 6. Technologies for ICT Application in AEC Organizations

ICT technologies	Author and year
Database	Zipf 2000; Mak 2001; Fan et al. 2008
XML	Tserng and Lin 2002; Ma et al. 2004; Agdas and Ellis 2010
Data mining	Caldas and Soibelman 2003; Wong 2006
Speech	Tsai et al. 2007
ERP	Nikas et al. 2007; Erdogan et al. 2008; Zipf 2000; Voordijk et al. 2003
3D	Moum 2010; Ahmad 1999; Mitropoulos and Tatum 1999; El-Rayes and Kandil 2005; Shiratuddin and Thabet 2011; Teizer 2008; Zhang et al. 2009; Woksepp and Olofsson 2008
4D	Hartmann 2011; Golparvar-Fard et al. 2009, 2011
nD	Tse et al. 2005; Lee and Sexton 2007
GPS	Perkinson et al. 2010
Barcode	Ahmad 1999; Elmisalami et al. 2006; Tserng et al. 2005
Digital mapping	Ahmad 1999
Artificial intelligence	Ahmad 1999; Menzel et al. 2004
Neural network techniques	Wong 2006
GIS	Zipf 2000; Anumba et al. 2005
Laser scanning	Akinci et al. 2006; Kiziltas et al. 2008
Agent-based	Zhang et al. 2009
Java	Chan et al. 1999
Enterprise information systems	Tatari et al. 2007
CAD	Kale and Arditi 2005; Kale and Arditi 2010; Mitropoulos and Tatum 2000; Tse et al. 2005; Whyte and Bouchlaghem 2002
Vision tracking	Park and Brilakis 2012; Park et al. 2012

Table 7. Taxonomy of ICT in AEC Organizations

Research classification	Total	Percentage (%)	Covered years
Organizational outcomes			
Organizational collaboration	43	29	1998–2011
Communication	—	—	—
Coordination	—	—	—
Collaboration	—	—	—
Organizational decision-making	23	16	1999–2012
Information enabled	—	—	—
Simulation enabled	—	—	—
Organizational behavior	24	16	1999–2010
Structure	—	—	—
Operational style	—	—	—
Culture	—	—	—
Organizational performance	21	14	1999–2012
Managing project	—	—	—
Managing process	—	—	—
Organizational information efficiency	16	11	1998–2010
Timeliness and accurate transmission	—	—	—
Massive information collection	—	—	—
Digitized and visualized expression	—	—	—
Total	145[a]	100	1998–2012

[a]Because the papers refer to multiple fields, the sum of the shared field distribution is more than that of the published articles.

research studies on the AEC organizations. This classification highlights multiple research fields that offer wide values of ICT applications in the AEC organization.

Organizational Information Efficiency

ICT, as a state-of-the-art technical application, has fundamentally improved the efficiency of information transmission and information processing in the AEC industry. The improved efficiency primarily manifests itself in timeliness and accurate information transmission with ease and diversity of information expression. AEC organizations improve information-processing capacities in the aspects of information capture, information collection, and information exchange, thus yielding better organization outcomes.

Timely and Accurate Information Capture and Transmission

Construction projects often demand a quicker and more accurate approach to information transmission, which is discussed at length in existing literature. Scholars use data-capture technologies or devices (e.g., radio frequency identification, laser scanners, sensors, wireless local area network, bar code) to increase the speed and accuracy of capturing information, and thus to improve the efficiency and productivity of a construction project. The three most frequently used technologies are radio frequency identification, wireless local area network (WLAN), and sensing technologies. Akinci et al. (2006), Kim et al. (2011), Sørensen et al. (2009), and Wang (2008) applied RFID technologies to capture quality data and construction resource information timely and accurately, and thus to enhance material management in terms of performance and productivity. Specifically, Wang (2008) carried out a case study in Taiwan, showing that use of a RFID-based quality inspection and management system increased the efficiency of monitoring progress by 23–28%, with the degree of satisfaction regarding real-time sharing of concrete specimen quality inspection results for customers increasing by 13%. Ward et al. (2003) used a mobile WLAN with the IEEE 802.11b protocol to realize real-time data capture in the site environment. In addition, Teizer (2008) applied a three-dimensional (3D) range-imaging camera as part of active sensing technologies to collect range data. The collected range data were used to generate real-time feedback about the location of objects in the field of view of the sensor, and thus to allow fast and accurate range measurements.

Various technologies and devices are commonly integrated in an information system to provide accurate customized solutions for the complex and diversified construction process. The synergy of technologies enables multiple functions to work collaboratively, and thus deliver a more effective and seamless working process. For example, Zhang et al. (2009) developed a collaborative multiagent system using field data–capturing technologies accompanied with agents, wireless communication technologies to improve real-time monitoring, and planning of construction sites. Tserng et al. (2005) streamlined the information-transition process of data identification and acquisition from a job site to a field office by using automated reality-capture technologies (laser scanners, bar code scanning, and radio frequency identification). Tsai et al. (2007) developed a synchronous system integrated with wireless and speech technologies to improve working efficiency through 13% improved productivity, 13% increased time efficiency, and 63-65% better comparative work efficiency.

Web-based information systems are another widespread approach to realizing timely (or sometimes real-time) information exchange among participants through Internet, intranet, and extranet (Deng et al. 2001; Ma et al. 2004; Mak 2001; Tam 1999). Thorpe (2003) investigated web-based information systems to realize real-time information exchange among participants through Internet, intranet, and extranet. For example, Thorpe (2003) used online remote construction management (ORCM) on road-construction projects to enhance online, real-time information exchange between parties to a construction project, and thus to improve the project delivery process. The estimated time saving was approximately 500 hours during the project contract of 12 months, equating approximately to 1% of the project cost.

The future trend of information transmission is the development of advanced identification technologies and automated equipment to make the construction works more intelligent and smart (Shin et al. 2011). Emerging technologies including range-sensing technology, 3D range-imaging cameras, and fast data-processing algorithms are all promising tools that could be highly influential in construction for accurate, high frame rate, and wide field-of-view range sensing (Teizer 2008).

Massive Information Collection among Organizations

Research on this theme focuses on developing an integrated system to collect information from different project organizations or teams to facilitate information management, such as information exchange, storage, tracking, verification, and distribution. For example, scholars developed integrated web systems for the key stakeholders in construction projects to collaboratively improve the management of information exchange and to facilitate each party to effectively grasp most related information, and thus to realize information management (Chung et al. 2008; Deng et al. 2001; Fruchter 1999; Ma et al. 2004; Mak 2001; Peña-Mora et al. 2010). Hegazy et al. (2001) and Lee et al. (2008) presented information models in which there is a central library of generalized building components that can be used to describe a complete building project hierarchy, and thus to store design information, record design rationale, and manage design changes. Kanoglu and Arditi (2001) developed an information system called an automation system for architectural practices (ASAP) that was applied in large architectural offices to obtain, handle, and distribute information among participants in the building-design process.

Massive information collection can be achieved using a variety of approaches. For example, Shin et al. (2011) used a service-oriented architecture (SOA) to improve the efficiency of information collection and sharing in RFID/WSN-based construction-supply-chain management environments. Wong (2006) used a computerized construction-integrated management system equipped with intelligent database and data mining technology to enhance the integrity and effectiveness of information flow among the various construction parties. Agdas and Ellis (2010) applied extensible Markup Language (XML) to develop automated data interchange platforms for a large organization to improve data interchange methods. Their results showed that XML could improve traditional information flow by enabling seamless data exchange among different levels of organizations and the third parties involved in business transactions. Supported by extensive computer programming and web support, the future information collection requires a simple but powerful solution system to integrate independent data processing and analysis modules (Perkinson et al. 2010).

Digitized and Visualized Information

Digital information has been showing a strong trend in the construction industry as the best way to help engineers foresee and solve problems. With the availability of advanced technologies, types of digital information grow rapidly, such as electronic documents and images, 3D or four-dimensional (4D) information, and spatially oriented information archived by global positioning systems or geographic information systems (GIS). Digital information brings critical information to the construction document management sector. For example, Bäckblom et al. (2003) and Hjelt and Björk (2006) investigated electronic document management systems to store, record, and exchange documents produced during a construction project in an electronic and digital manner. Caldas et al. (2002) and Caldas and Soibelman (2003) developed automatic document classification systems to provide easy deployment and scalability to the classification process of digital files, and thus to improve information organization and access in inter-organizational systems.

Visualization enables the diversified expression of information in improving design and production processes of a construction project (Nitithamyong and Skibniewski 2007). Information visualization is primarily realized by 3D or 4D technologies. For example, Shiratuddin and Thabet (2011) used a 3D game engine as the driving tool to provide a common language for project stakeholders in the development and implementation of design review processes to realize 3D visualization of designs. Golparvar-Fard et al. (2009, 2011) investigated 4D (3D plus time) and AR models to automatically collect, process, and exchange construction progress monitoring data, and thus to generate integrated visualization. Sacks et al. (2004) developed a precast concrete product model to support integrated 3D-based modeling of the information describing precast projects.

Recent research shows the trend of introducing innovative functions through advanced programming, elaborative and interdisciplinary applications to the construction practices [such as real-time 3D object manipulation and collaboration with virtual design review system (Shiratuddin and Thabet 2011)], integration of ICT and GPS (Perkinson et al. 2010), visual tracking of onsite construction workers (Park and Brilakis 2012), 3D range-imaging camera equipment (Teizer 2008), and interactive visualized tools to support the group decisions (Fan et al. 2008).

Organizational Decision Making

Organizations need to acquire adequate information to make optimal decisions, and thus to meet organizational objectives. ICT can facilitate this process by providing decision makers with both wide-ranging and relevant information. The literature review reveals three ways to achieve better decision making: diversified information–based decision making, human knowledge–based decision making, and simulation-based decision making.

Diversified Information–Based Decision Making

With access to a vast amount of information from multiple sources and perspectives, one can sharpen the analysis and render optimal decisions to a higher degree. Scholars presented a multi-objective decision model that supports organizations in making an advanced three-dimensional (time-cost-quality) trade-off analysis (El-Rayes and Kandil 2005). Ahmad et al. (2004) developed a decision support system to integrate various databases and information sources and analyzed them to provide explicit information in selecting construction sites. Chung et al. (2009) and Tatari et al. (2008) presented the use of enterprise resource planning (ERP) systems in the construction organization to make more better-quality decisions. Scholars also developed a model together with BIM to enable project stakeholders to work cohesively with each other within their specialties across time zones (Kazi and Charoenngam 2003; Rivard et al. 2004). Thus, they can negotiate and collaborate their ideas to bring about an improved design by enabling true what-if analysis of design decisions.

A web-based decision-making system is the most common tool that engineers can use to acquire more information among project parties across geographical positions (El-Diraby 2006; Fan et al. 2008; Gajendran and Brewer 2012; Peña-Mora et al. 2010; Tserng and Lin 2002). For example, Lam et al. (2010) and Fan et al. (2008) presented a web-based decision-support system (GDSS) to exploit the full benefits of the alternative communication modes and the effectiveness of value-management workshops for geographically remote team members.

Human Knowledge–Based Decision Making

ICT-enabled decision-making systems can extract experts' knowledge and build advanced capacity in the construction organization. Specifically, Baltzan and Phillips (2008) showed that use of ICT could aid in the capturing of transactional information of an organization to assist in strategic decision making. El-Diraby (2006) presented a knowledge-based assessment of a product's life-cycle costs in an effective, concurrent product development environment based on a web-based semantic system that allows for fast and efficient exchange of information by different stakeholders early on in the project development. Dunston and Wang (2005) proposed that the mixed augmented reality can enhance an individual's knowledge of the present environment or work plan, and thus improve information accessibility for decision-making activities such as design review, work planning, work execution and monitoring, and inspection. To pursue the maximal possession of information for decision making, the future topic may develop innovative, integrated, and interactive technologies to automatically acquire knowledge from a boarder sense, like professionalism big data.

Computing or Simulation-Based Decision Making

One advantage of ICT is the performance of simulation-based modeling that can demonstrate working processes and provide valuable information to improve the effectiveness of decision making. For example, Hegazy et al. (2001) and Akinci et al. (2006) used a simulation-based framework to model information flow processes from a job site to a field office, to help decision makers to measure and highlight existing deficiencies. Caldas and Soibelman (2003) and Demiralp et al. (2012) used a simulation-based tool to model the exterior concrete panel supply chain. Based on the *trade-off* approach, Cheung et al. (2004) and Williams et al. (2007) proposed a computerized construction dispute negotiation program, namely, construction negotiation online (CoNegO), to perform simulated negotiation. Tserng and Lin (2002) developed the accelerated subcontracting and procuring ASAP decision support system that can perform the scenario simulation for general contractors to easily choose an appropriate trade-off between risk and revenue for different subcontracting combinations.

Simulation can be achieved by a variety of virtual technologies, primarily in virtual reality, mixed reality, and augmented reality. Virtual technology–enabled simulation can fully consider external resources during construction project operations and processes (Dunston and Wang 2005). Mixed-reality strategies blend real and virtual information by using intuitive human–computer interface devices, and thus enhance information accessibility for decision making in activities such as design review, work planning, work execution and monitoring, and inspection. For example, Fu and East (1999) and Shiratuddin and Thabet (2011) developed virtual design review systems that allow reviewers to work simultaneously on a three-dimensional representation of an incomplete building model, and thus to provide a flexible, open, and robust environment for decision making. Scholars also investigated the application of augmented reality to enhance the decision-making process, creating an environment in which digital information is inserted in a predominantly real-world view (Wang et al. 2013).

Future simulation modeling aims to establish a new class of interdisciplinary tool that expands the current understanding of human–computer interactions and computer-mediated human-to-human interactions (Dunston and Wang 2005). In addition, the research also calls for further improvement of virtual technologies in connecting various construction phases, such as the integration of as-built and as-planned visualizations, and in developing automated progress-monitoring systems by linking text-oriented information to daily site images (Golparvar-Fard et al. 2011).

Organizational Collaboration

Effective communication, coordination, and collaboration among organizational members are widely acknowledged to support highly efficient organizational operation. Collaboration may be seen as the combination of communication, coordination, and cooperation (Fuks et al. 2005) and these topics have often intertwined in literature. ICTs are considered to facilitate information collecting, exchange, and expression and thus support organization and interorganizational collaboration. Throughout the past 15 years, various applications of ICTs have been implemented on the different stages of construction and different organizational levels to facilitate collaborative work, among which are primarily computer-supported collaborative work systems, collaborative virtual environments, web-based information management systems, and augmented reality technology. The next section presents 43 articles of ICT-supported collaboration at three different phases: design phase, construction phase, and life-cycle or interface collaboration (Table 8).

Design Phase

Collaborative design is an activity that requires designers to share information and organize design tasks and resources (Chiu 2002). Therefore, collaborative work platforms such as computer-supported collaborative work (CSCW) systems, are collaborative environments that support dispersed working groups to improve the quality and productivity (Eseryel et al. 2002). Early CSCW systems focused on communication, meeting support or coordination, such as the ASAP computer-based information system in response to the information handling and distribution problems of large architectural design offices (Kanoglu and Arditi 2001), or a collaborative design system for sharing documents, reviewing changes, and conferencing among remote design participants as a design coordination tool (Zaneldin et al. 2001). With the development of innovative technology such as augmented reality, an experimental augmented-reality, computer-aided drawing prototype was developed as a platform to study human factors with the use of 3D virtual models and collaborative work scenarios, such as design review, to support remote field collaborations and information accessing (Dunston and Wang 2005). To address the deficiencies in the computer-mediated communication systems, Pena-Mora and Hussein (1999) formulated a set of principles and solutions involving levels of participants' engagement and interaction among designers (Pena-Mora and Hussein 1999).

As a result of a convergence of research interests between virtual reality and CSCW, collaborative virtual environments (CVEs) were proposed as a distributed virtual reality system that offers a potentially infinite, graphically realized digital landscape within which multiple users can interact with each other and with simple or complex data representations (Churchill et al. 2001). The virtual design review system, a typical example of successful application of CVE technology at the design stage, can improve the coordination and communication among different project partners and stakeholders (Aspin 2001), allow groups of reviewers to work simultaneously (Fu and East 1999), or encourage collaboration among designers and design reviewers (Shiratuddin and Thabet 2011). To check the value of using CVE to facilitate collaboration, Dermott McMeel

Table 8. Technologies Used to Enhance Organizational Communication, Coordination, and Collaboration in Different Phases

Phase	Technology	Author and year
Design phase	CSCW system	Pena-Mora and Hussein 1999; Kanoglu and Arditi 2001; Zaneldin et al. 2001
	CVE, 3D technology	Aspin 2001; Fu and East 1999; McMeel and Cockeram 2011; Sher et al. 2009; Shiratuddin and Thabet 2011
	Augmented reality	Dunston and Wang 2005
Construction phase	Web technology	Chan et al. 1999; Tam 1999; Deng et al. 2001; Caldas et al. 2002; Ma et al. 2004; Cheung et al. 2004
	Wireless technology	Tsai et al. 2007; McMeel and Cockeram 2011
	Mobile ad hoc communication	Kuladinithi et al. 2004
	Agent-based systems	Kubicki et al. 2006
	Multiview cooperative platforms	Zhang et al. 2009
	Augmented reality	Golparvar-Fard et al. 2009, 2011
Life cycle and interface	Web technology	Lam and Chang 2002; Alshawi and Faraj 2002; Thorpe 2003; Mohamed and Stewart 2003; El-Diraby 2006
	Integrated collaborative system	Lu and Issa 2005
	BIM	Isikdag and Underwood 2010; Dossick and Neff 2010

and Cockeram (2011) revisited Brian Lawson's design problem through the mapping of analysis, appraisal, and synthesis as a framework to scrutinize design and construction in the virtual environment. However, there are operational differences inherent in design professionals when working in CVE rather than traditional methods. Sher et al. (2009) developed a generic framework to present the changes in designer's skills by comparing virtual teams with traditional separate modes.

Construction Phase

Effective construction-coordination methods should be based on comprehensive appreciation of existing coordination modes adapted to the nature of the industry, such as decentralized decisions. Zhang et al. (2009) defined three main coordination modes from the perspective of informal relations in building construction, namely, as *multi-actor, inter-actor*, and *extra-actor* coordination, and proposed a multiview cooperative platform to assist in building-construction coordination. After years of development, construction collaboration has experienced profound influences by various ICT enabling technologies including web, wireless, portable devices, and agent-based systems. Among these, the web technology was considered to have the greatest potential in facilitating collaborative work in the construction phase. Various web-based systems were designed to enrich the information flow among construction participants (Deng et al. 2001; Ma et al. 2004; Tam 1999), to address depute information negotiations during the construction process (Cheung et al. 2004), and to improve scheduling information performance (Chan et al. 1999) or document management (Caldas et al. 2002).

To address the fragmented and discontinuous information in the construction process, wireless technology has become a significant way to enhance collaboration. For example, Tsai et al (2007) developed an integrated system of wireless and speech technologies to enhance the cooperation among construction workers. Wearable computing along with advanced mobile communication can also address communication issues in the working environment without external networking infrastructure. Kuladinithi et al. (2004) presented a networking protocol called ad hoc on-demand distance vector routing (AODV), which allows the workers to create mobile ad hoc network send to obtain access to the Internet to achieve better communication. Another approach to support seamless communication across construction sites is to develop an agent-based system that is integrated with real-time monitoring and planning functions (Kubicki et al. 2006). The emerging augmented reality can benefit the construction workers by enhancing coordination and communication during the construction process (Golparvar-Fard et al. 2009; Zhang et al. 2009).

Project Life Cycle and Interface Information Exchange

Existing literature has discovered a variety of systems based on web technology to support collaborative work among all parties throughout a project's life cycle. These systems were proposed in conceptual models, prototypes, or empirical research. Typical examples include the following: a web-based or IFC-based distributed computer integrated environment supporting a project team to work collaboratively over the Internet (Alshawi and Faraj 2002); a web-based project information management (WebPIM) system working as an information platform for all design and construction participants of a construction project (Lam and Chang 2002); an online collaborative platform called online remote construction management of road construction projects that enhances online real-time communication among the parties involved in a construction project and thus improves the project delivery process (Thorpe 2003); and a web-based semantic system allowing various project partners to collaborate over the web to develop a knowledge-based model for managing a product's life cycle cost (El-Diraby 2006). To examine the key role of web technology in facilitating collaborative abilities, Mohamed and Stewart (2003) conducted an empirical investigation on a large construction project, and the results showed that web technology made a positive contribution to the participants' communication efficiency and collaboration.

In recent years, building information modeling has become an active research area to tackle the issues of information integration and interoperability, and is believed to play an important role in facilitating collaboration throughout the life of a construction project (Isikdag and Underwood 2010). Although most research has acknowledged the collaboration benefits of BIM throughout the project, concerns and future development are also discussed also for further research. Tserng et al. (2005) surveyed the coordination process of mechanical, electrical, plumbing, and fire safety systems and found that BIM-enabled projects were often tightly coupled technologically, but divided organizationally. The results also show how BIM makes visible the connections among project members, but do not foster closer collaboration across different companies (Dossick and Neff 2010). Meanwhile, an integrated system in which existing software applications can be easily incorporated should be developed to meet various participators' requirements throughout the life cycle of a project. Lu and Issa (2005) proposed a prototype of a loosely coupled process integration system supported by a viable collaboration mechanism, and demonstrated the functionality in a real case.

The complex supply-chain relations of the construction industry, coupled with a substantial amount of information shared among involved parties, cause AEC organizations to suffer from low efficiency in information handling and exchanging in different interfaces. A variety of systems were proposed to improve the information flow in the construction supply chain and several of them were demonstrated to be effective in practice, such as a barcode-enabled PDA application called the mobile construction supply chain management (M-ConSCM) system (Tserng et al. 2005) or an XML-based electronic data interchange system (Agdas and Ellis 2010). In addition, radio frequency identification and wireless sensor network technologies could help to improve the collection and sharing of information in the supply-chain process (Shin et al. 2011) to minimize the difficulties in interface collaboration.

Existing literature primarily discusses the collaborative system through communication and exchange of verbal contexts. However, nonverbal interactions have not been effectively supported in the current process, occasionally leading to confusing or even invalid expressions for ICT users. Future research can develop both verbal and nonverbal interactions as a new protocol in the collaborative system.

Organizational Performance

Using ICT can improve organizational performance in various aspects. Stewart and Mohamed (2004) showed how IT has provided construction-consulting industries with great advantages in speed of operation, consistency of data generation, accessibility, and exchange of information. Ahuja et al. (2009b) evaluated the perceived benefits of using interpretive structural modeling (ISM) in aspects of projects, team management, technology, and organization. The results showed that organization and technology-related benefits have great power as *strategic benefits* of the project organizations. In addition, Aound et al. (2005) conducted a conceptual model to demonstrate how the construction industry was provided with a significant value improvement and cost reduction as a result of virtual reality technology–based integrated software solutions. Empirical analysis also showed how the firm's performance increased two times for every dollar of ICT investment (Aspin 2001). Based on the industrial attributes, AEC organizational performance can be classified into three dimensions: performance of managing projects, performance of managing process, and overall competitiveness.

Performance of Managing Projects

Organizations in the AEC industry are more focused on improving the performance of managing the projects in terms of project time, cost, strategic, quality, risk, and communication. For example, Mohamed and Stewart (2003) and Stewart and Mohamed (2004) evaluated users' perceptions of a web-based communication tool based on project performance. Increased performance were grouped into fives perspectives by the following specific evaluation indicators: operational in 74%, benefits in 65%, technology/system in 73%, strategic competitiveness in 69%, and user orientation in 55%. Sun and Oza (2010) investigated the benefits of a contract-change management system to help construction projects by saving costs, reducing risk, and increasing predictability through anecdotal evidence.

Interestingly, scales and degrees of ICT-induced performance are different. Sacks et al. (2004) conducted case studies by getting data from the Construction Industry Institute (CII) data set and southeastern U.S. contractors' data set; the results showed that schedule performance has a strong positive association with increased IT use, whereas cost performance has a weaker relationship. Nitithamyong and Skibniewski (2007) investigated WPMS performance from a survey of 82 construction projects. The results showed that strategic, time, and communication improvements are obvious to most practitioners, whereas the benefits related to cost savings, quality improvement, and risk management still remain unsatisfied. Aspin (2001) conducted a regression analysis showing how firm performance increases with the investment of IT use, but no relationship was found between IT use and customer satisfaction, safety performance, and profitability.

Improved project performance is generally attributed to increased productivity of a specific process or activity, which is typically manifested in reduced operational time and cost saving. Scholars have made great contributions to reducing execution time in the processes of quality inspection, quality management, site management, and data collection, and thus improving work productivity (Adriaanse et al. 2010a; Shin et al. 2008, 2011; Tsai et al. 2007; Wang 2008; Zhai et al. 2009). For example, Tsai et al. (2007) increased work productivity for activity completion by developing a synchronized and integrated system. Wang (2008) and Ma et al. (2004) enhanced construction quality inspection and management performance by proposing an RFID-based quality management system. The efficiency of monitoring progress and the degree of customer satisfaction increased by 23–28% and 13%, respectively, and there was a reduction in the operation costs and time savings in the inspection operation and management progress. Furthermore, Shin et al. (2008) demonstrated that additional work hours for site management was decreased and the duration of site management was reduced by 43% after applying a finishing information system to a finishing work in an actual apartment construction. Demiralp et al. (2012) conducted a case study on a prefabricated exterior concrete wall panel supply chain to show the cost savings of using RFID technology at 3% of total project cost, 19% reduced labor costs, and 16% reduced number of transfers, resulting from a reduced number of missing panels, reduced number of incorrectly delivered/identified panels, and reduced durations of certain activities. Hegazy et al. (2001) improved the design coordination and control over changes by presenting an information model, thus increasing consistency and productivity of the overall design process.

Organizational performance increases as a result of ICT application, which reduces the operational time and cost, and thus improves productivity. Based on the use of advanced data mining techniques, future research needs to provide more quantitative validation and fundamental insights into the value-creation relationship between technology and organizational performance, and to explore the influence of organizations' intangible assets such as corporate culture and employees' engagement (Sun and Oza 2010).

Performance of Management Process

The effects of ICT on design and the construction process inside the AEC organizations can be concluded in the following ways. First, several ICT applications were developed to eliminate some non–value-adding tasks associated with the corresponding project management processes, thus streamlining the associated processes. For example, the use of automated reality capture technologies (laser scanners and radio frequency identification) can simplify the data collection process for the on-site construction (Akinci et al. 2006). Second, the use of ICT may also lead to a business reengineering process in the construction organization. Many articles that focused on information management or ICT applications usually discussed the reengineering process of information collecting, handling, exchange, and storing. Third, the use of ICT can promote business process innovation. Findings from the multiple case studies revealed that the adoption of ICT-enabled operational alliance modes would promote business process innovation for SMEs in the construction sector (Rezgui and Miles 2010).

ICT applications affect all working processes along with a project's life cycle implementation. Virtual reality technology, for example, was proposed to improve the current design review process by providing a central and integrated information base for efficient exchange and flow of information (Shiratuddin and Thabet 2011). Chun et al. (2012) discussed the use of computer simulation techniques in assisting the safety management team's hazard identification process. In addition, the effect of ICT on the planning process (Woksepp and Olofsson 2008), procuring process (Tserng and Lin 2002), and project delivery process (Thorpe 2003) were also all discussed.

Existing literature reveals that by adopting ICT, construction organizations usually change or reengineer the existing process with the improved one. However, little research provides convincing evidence to support this argument or to empirically investigate the relationship between ICT adoption and organizational process. Future research needs to deepen the understanding of how an organizational reengineered process could facilitate the design and new system diffusion process.

Overall Competitiveness

In line with the improvement of organizational performance and productivity, AEC organizations also use ICT as a generic strategy to achieve and sustain overall organizational competitive advantages. The application of ICT in AEC organizations creates competitiveness in three aspects: differentiation strategy, operational effectiveness strategy, and technology-based competitive strategy (Porter 2008). Love et al. (2004) explored IT in support of their operational effectiveness strategy within SMEs in the Australian construction industry. This research presented benchmark metrics of IT adoption at strategic, operational, and tactical levels. The results showed that the most significant benefits for the aforementioned levels were "improved organizational and process flexibility," "improved service quality," and "improved data management." Stewart and Mohamed (2004) evaluated a web-based system in the construction projects and found that organizations gained stronger technology-based competitiveness in the *soft* technology by adding IT to the process of project information management. Moreover, Shin et al. (2008) investigated the finishing information system (FIS) to support mass customization as a differentiation strategy in the Korean housing construction market. This FIS system, as a hybrid computing and networking technology, decreased the work-hour commitment by reducing the duration of site management (43%), simplifying the management process, and improving the efficiency of communication. However, the empirical analysis regarding the increased customer satisfaction, market penetration, and profit growth are limited and need further investigation.

Organizational Behavior

AEC organizations will gradually shape new behaviors by the effect of ICT applications. This study classifies the behavior changes into two aspects: organizational working environment and organizational flexibility.

Organizational Working Environment

Many existing studies refer to the organizational virtual working environment and its different synonyms, such as virtual organization, virtual team, virtual enterprise, and extended enterprise. Virtual organization concentrates on joint collaboration so that information from many different organizations can be coordinated and brought together based on a standardized format and work processes to produce a particular output through a network (Han et al. 2007). For the whole AEC industry, virtual organization is one of the inter-enterprise collaborative ways of using ICT to support information exchange and collaborative work among distinct geographically dispersed entities (Kazi et al. 2001). By using virtual organization, project participants can quickly come together and share a common view of needs and proposed solutions that are devised with a whole life-cycle view accounting for finance, design, construction, and operational effects (Hassan and McCaffer 2002). In addition, based on the concept of virtual organization, ICT-enabled operation was proposed and demonstrated to be a viable way to allow SMEs to compete in a new way, get better rewards for their work, and gain greater financial strength to develop their products and services (Rezgui and Miles 2010). However, there are increasing needs for virtual organization that are organizationally independent and beyond the control of management and formal lines. To address this issue, Kazi et al. (2001) presented the virtual enterprise reference architecture and methodology (VERAM) to support inter-organizational collaboration.

Establishing virtual organization has already become a significant way to achieve organizational collaboration. Existing literature briefly mentions the sharing of benefits, risks, and responsibilities for all project participants (Rezgui and Miles 2010). However, participants' equitable sharing mechanism in a virtual organization needs to be further explored to reduce conflicts and disputes in the aspects of income, financial risk, and responsibility share in the collaboration process.

Organizational Flexibility

The use of ICT enables organizations more flexibility and adaptable operations in the AEC industry. Existing research proposed that SMEs could establish virtual organization based on the latest advances in ICTs to provide flexibility to satisfy increasingly demanding clients, in addition to achieving economies of scale in the production of standardized processes in various stages of construction projects (Rezgui and Miles 2010). Organizations are also required to self-adapt or improve change management to control all factors affecting the successful use of ICT when involving new ICT implementation (Erdogan et al. 2008; Zhang et al. 2009). In other aspects, the clients' and contractors' requirements of the large-scale engineering ICT environment are changing to support the virtual organization culture that has been developing within project delivery of large-scale engineering (Hassan and McCaffer 2002).

Conclusions

The primary aim of this study was to review and categorize developments in data and to forecast future research opportunities in which ICTs can further contribute to better organization and operations of AEC organizations. This study reviewed 145 related journal articles published between 1998 and 2012. The review provides detailed insights to help understand the general trend of ICT adoption, the most influential factors in ICT application, popular ICT technologies, and ICT-induced organizational outcomes. The major findings from the significant review are as follows:

- ICT research for AEC organizations started in the 1970s and picked up quickly since the beginning of 21st century. Most reviewed articles were published in computer or IT-related construction journals, 25% in the Journal of Information Technology in Construction, 19% in Construction Innovation, and 16% in Automation in Construction.
- ICT articles attracted relatively more citations than non-ICT construction articles with an average 35 citations per article, up to 113 citations per article. Yet these articles took 8–12 years to accumulate considerable numbers of citations. Case studies (26%), questionnaire/surveys (19%), interviews (10%), and prototype models (10%) are most popular methods for research product delivery.
- Articles are equally distributed with respect to focus on individual ICT users (30%) and organization-level use (30%), and the cross-organization or multiorganization-level focus represents 40% of the articles. Contractors (53, 37%) and cross organizations (29, 20%) have received most of the attention of ICT applications as compared with other AEC users. Architecture/design and project management firms have grown quickly as focus areas of ICT applications in recent years.
- Among all 72 articles implementing ICT practices and lessons, the top 10 factors that influence the most ICT implementation include ICT evaluation and planning, organizational characteristics (35), technology characteristics (26), user's knowledge and skills (24), training and technical support (24), user's acceptance and participation (20), top management support (18), information security (11), external environment (9), and project characteristics (7).
- Most articles (96) used at least one or more specific technology to enable ICT function. The top five ICT-enabled technologies in the AEC organizations are web (43%), wireless (21%), VR/AR (20%), EDI/EDMS (13%), and BIM (9%).
- A five-dimensional taxonomy is established to summarize state-of-the-art studies: (1) organizational information efficiency, (2) organizational decision making, (3) organizational collaboration, (4) organizational performance, and (5) organizational behaviors.
- Three organizational decision-making approaches are identified: (1) diversified information–based decision making, (2) human knowledge–based decision-making, and (3) simulation-based decision making. Future research calls for more focus on the interdisciplinary research of human–computer interactions and computer-mediated human-to-human interactions, integration of visualizations in various interfaces, and interactive and automated big data analysis.
- Three classified types of organizational information efficiency include: (1) timely and accurate information capture and transmission, (2) massive information collection among

organizations, and (3) digitized and visualized information. Future trends in smart, intelligent, and interdisciplinary applications are also identified for future research.

- Communication, coordination, and collaboration are intertwined with one another in literature and bring significance to various project phases and interface management. Both verbal and nonverbal interactions should be developed in future systems.
- Organizational performance in managing projects, in managing the process, and overall competitiveness are discussed. More research on the quantitative validation or empirical investigation of ICT adoption and organizational performance, especially the intangible assets like corporate culture, should be conducted.
- Behavior in organizations involving changing virtual environments and organizational flexibility are presented. An equitable sharing mechanism in a virtual organization needs to be further explored.

This review can become a foundation for the classification and integration of the state of the art in ICT research on behalf of AEC organizations. The results should help AEC practitioners to better understand how to encourage and manage ICT diffusion in their organizations. This analysis summarizes the literature in a five-dimensional taxonomy to be followed in future research.

The scope of this article is limited to the searched journals and selected keyword of "ICT" between 1998 and 2012. Although 145 articles retrieved from 12 IT-related construction journals show the significance of ICT application in AEC organizations, this scope did not include the remaining journals also publishing ICT-related works as part of their mission and scope. Other ICT-related research topics have not been studied in this research, such as e-commerce, sustainability, safety and health, and legal and contract-related problems. A follow-up study is needed to include these additional areas.

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Supplemental Data

Table S1 is available online in the ASCE Library (http://www.ascelibrary.org).

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