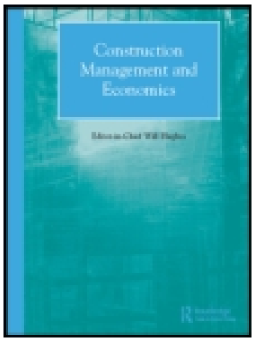

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Applying advanced technology to improve safety management in the construction industry: a literature review

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Technology application is deemed an effective way to further construction safety management. Various technologies have been adopted for construction safety, including information communication technology (ICT), sensor-based technology, 3S (GIS/GPS/RS) technology, radio frequency identification (RFID) and virtual reality. A review of previous studies in the area of technology applications for construction safety would be indispensable for the main stakeholders in this field to share innovative research findings and gain access to future research trends. A three-step method was used to obtain relevant publications (119 papers met the ultimate selection criteria) and compile a database of the findings. The results present a general review of technology application for construction safety from the aspects of number of papers published annually, publication type, publication name, country/region of distribution, research level, project phase and project type. Corresponding analysis was performed with the collected data and the radar chart was used for analysing the trend of technology application for construction safety and the trend of research topics. Five research gaps were identified in the review process. The trends and gaps can serve as motivation for researchers and practitioners to work on the next generation of studies and the development of future effective measures, which can ensure a safe construction environment.

Keywords: Advanced technology, construction safety, literature review, radar chart.

Introduction

Safety is a major issue across global construction industries (Zhou *et al.*, 2012a). Almost every publication concerning construction safety may begin with ‘construction is one of the most dangerous industries with a poor safety record’, or other similar statements. There are two main approaches to studying construction safety. One approach, from the perspective of management, usually focuses on accident cause analysis, safety climate, safety culture, workers’ safety perception and competency, behaviour-based safety, hazard management, etc. The other approach focuses on how to apply different types of technologies in construction safety management, such as automation, building information modelling (BIM), data mining, geographic information system (GIS), radio frequency identification (RFID), robotics, sensing technology, wireless networks and virtual reality among others.

It is well known that the construction industry is considered to be hesitant in adopting advanced technology (Andresen *et al.*, 2000; Gonzalez de Santos *et al.*, 2008). Mitropoulos and Tatum (2000) brought forward two main reasons for the reluctance to utilize innovative technologies: uncertainty in using new technologies and lack of information regarding technologies and corresponding benefits. With the development of various technologies, more and more researchers have realized that technology could be an effective solution to the issue of construction safety. Kim and Cho (2010) argued that automation was an alternative way to improve the construction environ-

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ment for ensuring safety. Wu *et al.* (2010b) thought that using Zigbee RFID sensor networks for tracking near-misses could avoid accidents and effectively improve safety performance. Yang *et al.* (2012) also considered that the technical solution proposed in their study had a significant importance in promoting safety performance on construction sites. As we know, to err is human (Mokdad *et al.*, 2000). This indicates that it is impossible to absolutely eliminate all errors. But an error is necessary rather than sufficient for an accident. Using innovative technologies for timely detection and correction of errors can be a feasible way to finally avoid various accidents. In an era with endless emerging technologies, many have been considered for accident prevention in the construction industry. A review of previous studies would be indispensable for the main stakeholders in this field to share innovative research findings and access future research trends. The literature review can contribute to in-depth investigation and provide an opportunity for researchers and practitioners to fill the gaps between research and practice in this area.

The remainder of this study is structured as follows. The second section proposes a three-step method of literature search, selection and coding. This method was used for gaining relevant papers and compiling a database of the findings. In light of the results from the database, the third section presents a general review of technology application for construction safety from six aspects, namely the number of selected papers annually, publication type and name, country/region of distribution, research level, project phase and project type. In the fourth section, the radar chart is applied for discussing the trends of technology application for construction safety and the trends of research topics. Finally, five research gaps were identified. They can offer potential opportunities for researchers and practitioners to conduct more relevant studies and effective measures, in order to ensure a safe construction site. The final section provides conclusions and suggestions for the next steps of the study.

Methods

Literature search

Relevant papers on the topic of advanced technology application for construction safety were obtained through searching in multiple databases till July 2012. Four computerized databases (EBSCO Host, Engineering Village, Science Direct and Web of Science) which cover the main peer-refereed journals and conference proceedings in the field were selected. A systematic and extensive search was conducted under the ‘title/abstract/keyword’ field in the databases. There is some difference between the search terms of the four databases, due to the different codes among them. The total search terms and results (number of relevant publications) are shown in Table 1.

In the preliminary review of relevant papers, some other keywords pertinent to advanced technology were identified, including ‘computer aided’, ‘database’, ‘data mining’, ‘expert system’, ‘intelligent navigation strategy’, ‘laser scan’, ‘robotics’, ‘remote sensing (RS)’, ‘software’, ‘sonar’, etc. Then the search was expanded and supplemented. Because the EBSCO Host database covered the papers in *Construction Innovation: Information Process Management* only from 2001 to 2006, the Emerald database was selected to supplement relevant papers in this

Table 1 Search terms and results in four databases

Database	Search terms	Results
EBSCO Host	AB ((‘augmented reality’ OR ‘automation’ OR ‘BIM’ OR ‘e-learning’ OR ‘GIS’ OR ‘GPS’ OR ‘management information system’ OR ‘RFID’ OR ‘sensor’ OR ‘ultra wideband’ OR ‘virtual reality’ OR ‘wireless network’ OR ‘3D’ OR ‘4D’) AND (‘construction’) AND (‘safety’ OR ‘accident’ OR ‘incident’ OR ‘hazard’))	361
Engineering Village	((‘augmented reality’ OR ‘automation’ OR ‘BIM’ OR ‘e-learning’ OR ‘GIS’ OR ‘GPS’ OR ‘management information system’ OR ‘RFID’ OR ‘sensor’ OR ‘ultra wideband’ OR ‘virtual reality’ OR ‘wireless network’ OR ‘3D’ OR ‘4D’) AND (‘construction’) AND (‘safety’ OR ‘accident’ OR ‘incident’ OR ‘hazard’)) WN KY	428
Science Direct	TITLE-ABSTR-KEY((‘augmented reality’ OR ‘automation’ OR ‘BIM’ OR ‘e-learning’ OR ‘GIS’ OR ‘GPS’ OR ‘management information system’ OR ‘RFID’ OR ‘sensor’ OR ‘ultra wideband’ OR ‘virtual reality’ OR ‘wireless network’ OR ‘3D’ OR ‘4D’) AND (‘construction’) AND (‘safety’ OR ‘accident’ OR ‘incident’ OR ‘hazard’))	11
Web of Science	TS = (‘augmented reality’ OR ‘automation’ OR ‘BIM’ OR ‘e-learning’ OR ‘GIS’ OR ‘GPS’ OR ‘management information system’ OR ‘RFID’ OR ‘sensor’ OR ‘ultra wideband’ OR ‘virtual reality’ OR ‘wireless network’ OR ‘3D’ OR ‘4D’) AND TS = (‘construction’) AND TS = (‘safety’ OR ‘accident’ OR ‘incident’ OR ‘hazard’)	465

journal. As a result, three relevant papers were added. Considering the recent *Proceedings of Construction Research Congress 2012*, four relevant papers were obtained from the ASCE database. Two rounds of search results were exported into Endnote X4. Duplicates were inevitable, due to employing overlapping databases. Finally, a total of 540 papers were gained, after excluding the duplicates.

Literature selection

In spite of the strict specifications, some publications which matched the research topic could still be missed. This literature review aimed to study the research trend of advanced technology application in construction safety, instead of obtaining the complete numbers of papers. On the other hand, parts of the publications which didn't match the research topic but matched the research terms, were possibly included. It was necessary to refine and filter the total literature further.

A two-step selection was conducted at this point. Considering the types of publications first, book reviews, editorials, editor's notes, generics, letters to editors, news items and patents were excluded. The number of relevant literature items was reduced to 329. Then a preliminary review was undertaken by reading the abstract and keywords of 329 publications. Four criteria were applied in making a further selection to eliminate ill-fitting papers, as follows. Papers were excluded where:

(1) The keywords in the search terms were used in other settings or for other meanings (e.g. one paper's title (Shindoa *et al.*, 2006) contained the word 'construction'. The meaning of 'construction' here was not the construction industry, but constructing a safety management system for drug use).
(2) The keywords in the search terms were only mentioned, but not studied in depth (e.g. accident databases were mentioned in the paper by Wu *et al.* (2010a), but databases were only the source of accident precursor analysis).
(3) Construction safety was studied from the perspective of structural mechanics (e.g. one paper (Ding *et al.*, 2011) used computer simulation for safety control by analysing structural mechanics).
(4) Some other aspect of construction rather than construction safety was the objective (e.g. one paper (Miller and Bernold, 1991) focused on construction productivity rather than construction safety).

Through the two-step selection, the total number of relevant publications was reduced to 119. The full list of 119 papers is shown as an Appendix.

Literature coding

Title, keywords and abstract were the main sources for coding a paper. If complete information couldn't be found from them, the body of a paper would be used for further coding. Two paramount parts of a paper were sections entitled 'Research methodology' and 'Conclusion'. In the process of coding papers, the following information was stored in the database (see the Appendix):

(1) the title of each paper;
(2) publication year of each paper;
(3) publication type (namely journal paper (J), conference paper (C) and report (R));
(4) publication name;
(5) country or region (this information refers to where the studies were conducted, rather than where the authors were from);
(6) research level (namely industry level (I), company level (C), project level (PJ), sub-project level (SP) and process level (PC));
(7) project phase (namely planning (P), design (D), construction (C), and maintenance (M));
(8) project type (including building (BU), bridge (BR), pipe installation (P), tunnel (T), underground construction (U), etc.);
(9) advanced technology (including augmented reality (AR), automation (AU), BIM, computer aided (CA), database (DB), data mining (DM), expert system (ES), e-learning (EL), GIS, GPS, integration (IG), intelligent navigation strategy (INS), knowledge management (KM), laser scan (LS), management information system (MIS), other innovative technology (OIT), RFID, robotics (RO), RS, sensor (SE), software (SW), sonar (SO), ultra wideband (UW), virtual reality (VR), wireless network (WN), 3D, 4D, etc.);
(10) research topic (including accident collection (AC), cause analysis (CA), cause model (CM), design for safety (DFS), hazard identification (HI), integrated safety management (ISM), literature review (LR), safety assessment (SA), safety information (SI), safety knowledge (SK), safety measure (SME), safety monitoring (SMO), safety performance (SPE), safety planning (SPL), safety regulation (SR), safety training (ST), technology application (TA), etc.).

Results

Number of selected papers annually

The earliest paper in the database was from 1986. In that study, the technology of an expert system was applied to construction safety assessment. It concentrated on the issue of knowledge representation, reasoning and explanation which arose in the development of 'Howsafe' rather than on the domain knowledge of construction safety management (Levitt, 1986). As presented in Table 2, the number of relevant papers published annually was no more than five before 2008. Especially before 1991, only one paper or none referred to technology application in construction safety. This revealed that advanced technology hadn't played an important part in construction safety management in the past. Recently, a wide range of innovative technology has been developed and applied in construction projects. Researchers and practitioners believe that technology application can be an effective way to provide an accident-free construction environment. An ever-increasing number of academic papers have concentrated on this topic since 2008. Although there were only six relevant papers in 2009, the trend is upward for advanced technology application in construction safety. The number climbed to 20 in 2011. There have been 19 papers selected in the database from the first seven months of 2012. It can be seen that there will be more and more studies on how to apply advanced technologies for construction safety with the continued development of information communication technology (ICT), sensors, 3S (GIS/GPS/RS), virtual reality, RFID, etc.

Table 2 The number of papers distributed annually (from 1986 to July 2012)

Year	Number
1986	1
1987	0
1988	0
1989	1
1990	1
1991	0
1992	3
1993	0
1994	4
1995	3
1996	3
1997	1
1998	1
1999	2
2000	4
2001	0
2002	5
2003	2
2004	1
2005	4
2006	5
2007	4
2008	12
2009	6
2010	17
2011	20
2012	19

Publication type and publication name

It was indicated that some publication types were excluded in the process of literature selection (see above). There were only three kinds of publication types left in the database. Most of them were journal papers (67%) and conference papers (32%). Additionally, there was one report, which presented the main results of the BIM safety research project (*BIM-Based Safety Management and Communication for Building Construction*) carried out in Finland from April 2009 to June 2011. The main objective was to develop procedures and utilize BIM technology for safety planning, management, and communications, as part of 4D construction planning (Kiviniemi *et al.*, 2011). More than 20 types of journals contributed to the database in the Appendix. It was implied that the research topic of advanced technology application to further construction safety management had attracted widespread attention. Table 3 presents the publication names and the number of corresponding papers in detail. Some of these journals belong to the list of top construction journals ranked by Chau (1997), including *Construction Management and Economics, Journal of Construction Engineering and Management, Engineering Construction and Architectural Management, International Journal of Project Management* and *Automation in Construction*. Some famous journals about safety management are also included, such as *Accident Analysis and Prevention, Journal of Safety Research, Reliability Engineering and System Safety* and *Safety Science*. Other journals focus on technology application in construction, such as *Journal of Information Technology in Construction* and *Construction Innovation: Information, Process, Management*. There were 33 papers from *Automation in Construction*, which comprised 27% of all papers. This demonstrated the significance of *Automation in Construction* in the domain of applying advanced technology in construction safety promotion.

Country/region distribution

In some previous literature reviews in the construction industry (Osama *et al.*, 2004; Ke *et al.*, 2009), country distribution was related to authors or institutions. This has a different meaning in this review, which focused on where each study was conducted. Some of the papers, which couldn't be classified within one country, would be classified under 'others'. Over 20 countries/regions from four continents (except Africa and South America) were covered, as shown in Table 4. Both developed countries/regions and developing countries/regions were contained. This indicates that there has been a global focus on the topic of technology application in construction safety. Approximately a quarter of the studies were conducted in the United States. Following were studies in China, Japan, Hong Kong, Korea, United Kingdom and Taiwan. Not more than five studies were conducted in other countries. These previous seven countries/regions accounted for a large proportion of publications (up to 69%). With the exception of China, the other six were developed countries or regions. This shows that currently, there is a greater amount of construction projects in developing countries, which indicates that more attention should be given to the application of technology in the construction industry of developing countries/regions.

Table 3 Publication names and the number of corresponding papers

Publication name	Number
Accident Analysis and Prevention (AAP)	4
Advanced Materials Research (AMR)	1
Applied Ergonomics (AE)	1
Automation in Construction (AIC)	33
Chinese Journal of Rock Mechanics and Engineering (CJRME)	1
Computers and Education (C&E)	1
Construction Innovation: Information, Process, Management, (CIIPM)	3
Construction Management and Economics (CM&E)	1
Economic Affairs (EA)	1
Engineering Mechanics (EM)	1
Engineering, Construction and Architectural Management (ECAM)	1
International Journal of Occupational Safety and Ergonomics (IJOSE)	1
International Journal of Project Management (IJPM)	1
Journal of Architectural Engineering (JAE)	1
Journal of Construction Engineering and Management (JCEM)	12
Journal of Information Technology in Construction (ITcon)	3
Journal of Performance of Constructed Facilities (JPCF)	2
Journal of Safety Research (JSR)	2
Journal of Transportation Systems Engineering and Information Technology (JTSEIT)	1
Journal of Wuhan University of Technology (JWUT)	1
Procedia Engineering (PE)	1
Reliability Engineering and System Safety (RE&SS)	2
Safety Science (SS)	4
Tsinghua Science and Technology (TSS)	1

Table 4 The number of relevant papers by country/region

Country/region	Number
India	1
Iran	1
Israel	1
Singapore	1
Slovakia	1
Sweden	1
Canada	2
Finland	2
Italy	2
Netherland	2
Thailand	2
Spain	3
Australia	5
Taiwan	6
United Kingdom	6
Korea	8
Hong Kong	9
Japan	9
Others	13
China	15
United States	28

Research level

The research on innovative technology in construction safety management was conducted on several levels: industry level, company level, project level, sub-project level and process level. Cheng *et al.* (2012) used data mining techniques to explore the causes and distribution of occupational accidents in Taiwan's construction industry. Another study focused on Hispanic workers in the construction industry, applying information and communication technologies (ICTs) to locate and design computer-based safety training solutions for Spanish-speaking construction workers (Evia, 2011). In total, there were 16 papers which studied advanced technology in construction safety management from the industry level. Some

Table 5 Research levels of the studies considered

Research level	Number	Percentage
Industry level	16	13%
Company level	6	5%
Project level	78	66%
Sub-project level	8	7%
Process level	11	9%

studies were conducted from the company level. For example, a safety management information system (SMIS) was developed to take corrective actions to maximize safety performance in an industrial construction company (Saba and Mohamed, 2009). Most of the studies were pertinent at project level, accounting for 66% as presented in Table 5. A sub-project is often a large task that can be worked on independently within a project. Eight papers were undertaken at the sub-project level, covering e.g. excavation work (Huang *et al.*, 1996; Seo *et al.*, 2011; Kim *et al.*, 2012), installation (Gonzalez de Santos *et al.*, 2008; Kim *et al.*, 2008) and crane work (Lin *et al.*, 2012; Hwang, 2012). Other studies concentrated on the construction process. Irizarry and Abraham (2005) used virtual reality for safety training in the process of steel erection. Hu *et al.* (2008) proposed a method for safety analysis based on a continuous and dynamic simulation of the construction process. Chi and Caldas (2012) analysed the impact of errors on spatial safety assessment of earth moving and surface mining activities.

Project phase

There is a better chance of providing a hazard-free environment for construction workers if measures are taken from the onset of a project. The ideal time to influence construction safety is during the planning and design phases. The ability to influence safety performance diminishes as the schedule moves from planning toward maintenance (Szymberski, 1997). According to the literature coding results, 106 papers focused on the construction phase. It was indicated that compared with the construction phase, there were fewer technologies that were applied at other phases for safety management, such as planning, design and maintenance. Findings from another literature review supported this viewpoint. It was found that various digital tools were used for addressing safety issues in the construction phase, but there were few tools to support design for construction safety (Zhou *et al.*, 2012a). Only four studies concentrated on the design phase. One study developed the 'Design for Construction Safety Toolbox' which incorporated design suggestions into a computer program to assist designers in recognizing project-specific hazards and implementing the suggestions into a project's design (Gambatese *et al.*, 1997). Cooke *et al.* (2008) proposed an innovative information and decision support tool (ToolSHeD) to help designers to integrate the management of occupational health and safety (OHS) risk into the design process. Another study applied computer simulation techniques to create virtual environments where users could explore and identify construction safety hazards in the early design stage (Chun *et al.*, 2012). Compared to new construction projects, there were more and more buildings or other facilities needing repairing or maintaining in the construction market of developed countries. This kind of sector, named 'repair, maintenance, minor alteration and addition' (RMAA), occupied about 45% of the construction industry in the UK from 2002 to 2008 (Office for National Statistics, 2008) and accounted for 53.2% of the total construction market of Hong Kong in 2007 (Census and Statistics Department, HKSAR, 2008). But it was often neglected, because RMAA project sizes were small and usually carried out by small-sized contractors (Hon *et al.*, 2010).

In addition, some studies concentrated on the integration of several phases in the total life cycle of a project. A 4D CAD model was applied to an integrated system for construction safety management throughout the design, planning and control phases (Benjaoran and Bhokha, 2010). Rowlinson (2000) used virtual reality to allow the end-user to view a 3D model of a project, so that a design-for-safety-process (DFSP) and construction processes could be added before real construction was undertaken. Hadikusumo and Rowlinson (2002) integrated a virtual reality construction model and design-for-safety process database to identify safety hazards during the design phase and the construction phase. Similar studies integrated the design phase with the construction phase for safety management (Rwamamara *et al.*, 2010; Dawood *et al.*, 2012; Zhang *et al.*, 2012).

Project type

In this section, papers covering only three research levels (project, sub-project and process) were chosen to be categorized into different project types, because studies at company level and industry level focused on construction companies and the construction industry, respectively. There were five kinds of project types in the database. Building projects were the subject of most of the selected papers, accounting for 71%. Others were concerned with tunnels (4%), underground construction (3%), pipe installation

(2%) and bridges (2%). It was interesting to find that the five papers relating to tunnel projects were all from China. This is largely a result of the development of subway construction at a high pace and volume in China at the present time. The total length of subway transit network will be up to about 2259.84 kilometres in 2015, with investment rising to 136 billion dollars (Ding *et al.*, 2012). Geographic information system (GIS) was applied to develop the management information system for subway construction safety (Wang and Wang, 2009; Wang *et al.*, 2010). On the basis of point cloud data, virtual reality technology was used to build the three-dimensional scenery model for safety monitoring in tunnel construction (Qiu and Wan, 2010). Zhou *et al.* (2012b) developed a versatile subway construction incident database (SCID) for assisting in safety risk analysis. Almost 150 subway construction accidents have been noted in China and other countries so far.

Discussion

Trend of technology application for construction safety

As mentioned in the 'Literature search' section above, different types of advanced technologies were adopted in the search terms. Table 6 shows the frequency of technology application for construction safety management. There are nearly 30 types of technologies in Table 6. The technology application in one study was often an integration of several types of technologies. For example, an integration of 'database', 'radio frequency identification (RFID)', 'sensor' and 'wireless network' was applied in an identification system for proactive accident prevention (Yang *et al.*, 2012). Thereby the total number of technology applications was more than that of the selected papers. Most technologies were high-tech, such as automation and robotics, information and communication technology (ICT), sensing technology, 3S (GIS/GPS/RS), RFID, augmented reality, wireless and visualization technology. Some innovative crafts which didn't belong to high-tech could also benefit construction safety management. It was found that virtual reality was utilized most (up to 13 times) (see Table 6). The next most used applied technologies were sensor (12), database (12), 4D visualization technology (11), 3D visualization technology (10) and robotics (10). The frequency of use of other technologies was under 10 times. The category of 'integration', a special type, was referred to in two publications. One publication focused on the relationship between safety performance and information technology (El-Mashaleh *et al.*, 2006). The regression analysis denoted that there was no obvious association between safety performance and information technology use, although 60% of the respondents affirmed that information technology would contribute to furthering safety management. Another publication was a literature review with regard to construction safety and digital design (Zhou *et al.*, 2012a).

Technology application is constantly changing with the development of new technologies. Figure 1 illustrates the trend of technology application for construction safety, as time goes on. In order to depict the trend more clearly and conveniently, the time span from 1986 to 2012 was divided into six periods. Each period contains five years except the last one. The last period only comprises the years 2011 and 2012.

As shown in Figure 1, there was no significant trend in the first three periods. Technology application was distributed as discrete dots, because there were not many diverse types of technologies used for construction safety before 2000. Several studies had prioritized automation and robotics as effective technologies with great potential to promote construction

Table 6 Different types of technologies applied in construction safety management

Advanced technology	Number
AR	1
EL	1
ING	1
RS	1
SO	1
IG	2
LS	3
SW	3
ES	4
GPS	4
MIS	4
UW	4
DM	6
WN	6
AU	7
GIS	7
OIT	7
RFID	7
BIM	8
CA	8
KM	8
3D	10
RO	10
4D	11
DB	12
SE	12
VR	13

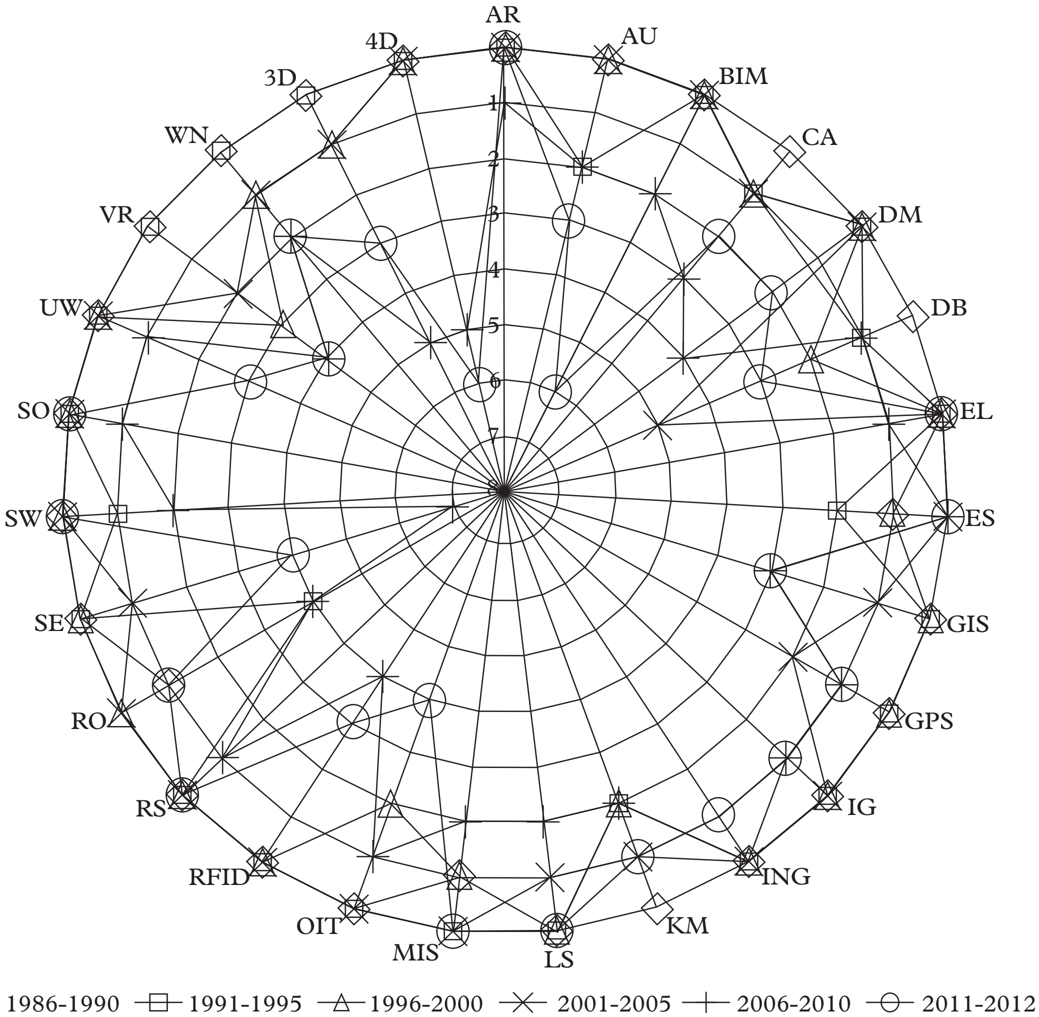

Figure 1 Trends of technology application for construction safety

safety. Some Japanese construction companies developed fully automated and self-rising platforms for high-rise building construction. This automated building construction system was less dependent on labour and could improve construction safety effectively (Skibniewski and Wooldridge, 1992). Aiming at avoiding over-exertion injuries, automation and robotics were applied to modify the task or work environment to accommodate workers' capabilities and limitations to provide an injury-free environment (Everett, 1994). One study considered robots themselves as a source of danger and the new technique of Consequence Led Analysis of Safety and Hazards (CLASH) was proposed to analyse hazards from mobile construction robots (Seward *et al.*, 1994). In addition, expert systems, knowledge management, management information system (MIS) and virtual reality were also focused on in the early studies.

After 2000, the distribution in each period gradually became complicated. Especially after 2006, technology application in construction safety was getting more and more diversified, with the development of information and communication technology (ICT), sensor-based technology, 3S technology, visualization technology, etc. The lines of '2006–10' and '2011–12' covered over 75% of the whole circle in the radar chart. Augmented reality was used to provide engineers and supervisors with a collaborative platform where some engineers were at the site and some supervisors were in the office and where they could see the options of safety measures as well as the real construction site, for discussing safety measures (Yabuki *et al.*, 2010). Augmented reality was a technology application based on virtual reality. The functions of various technologies were different from and complementary to each other. Thereby technologies were usually integrated for application. A situational awareness system was the integration of differential global positioning system (DGPS), wireless and web-based technologies to track vehicles and detect collisions for equipment operators (Oloufa *et al.*, 2003). Similar integration of global positioning systems (GPS), smart sensors and wireless networks was developed to track operatives and equipment, notify management and employees of pending danger and ultimately contribute to reducing accident rates (Riaz *et al.*, 2006). The integration of building information modelling and 4D technology was used for construction safety assessment (Hu *et al.*, 2008), safety planning (Bansal, 2011) and safety information management (Merivirta *et al.*, 2011). Some studies focused on RFID wireless sensor networks to acquire real-time information from construction sites for safety alerts (Teizer *et al.*, 2010a). Recently ultra wideband technology was also applied to transmit real-time information for proactive safety management (Hwang, 2012). Considering the external environment and inner structure of a project, Bansal (2011) integrated GIS and BIM for construction safety planning in a real-life project in India. In order to make better use of past accidents and share safety knowledge effectively, web-databases, knowledge base and data mining were developed from traditional technologies of database and knowledge management.

Trend of research topics of construction safety

Each publication was categorized according to the main research topic, even if some papers contained more than one research topic. Seventeen research topics were obtained based on this rule (see Table 7). Safety monitoring captured the most attention from researchers with 28 papers focusing on the topic. Following those were safety assessment (20), technology application (15) and hazard identification (13). The concentration ratio of the first four (CR4) research topics was over 60%. Most of the other topics were covered in no more than 10 studies, except for the first four categories, as illustrated in Table 7. The category of 'technology application' referred to the studies where an innovative technology replaced an existing technology and was applied to further construction safety management. The Construction Automation and Robotics Laboratory at North Carolina State University developed a prototype of the active metal detection and tracking system for safe excavation to replace the traditional approach (Huang *et al.*, 1996). Buswell *et al.* (2007) outlined some of the major issues facing construction technology and used mega-scale rapid manufacturing for construction. Kim and Cho (2010) proposed an alternative detail for the column-girder joint for automated construction.

Research topics were closely associated with technology application. They also changed with time. As presented in Figure 2, research topics concentrated on cause analysis, hazard identification, safety assessment and safety information before 1995. These topics belonged to passive or reactive safety management, which could not fundamentally avoid construction accidents. It was gradually realized that designers had a significant influence on construction safety. Design suggestions were incorporated into a computer program, titled 'Design for Construction Safety Toolbox'. It linked the design and construction phases to promote construction worker safety (Gambatese *et al.*, 1997). Rowlinson (2000) applied virtual reality and 3D modelling into a design-for-safety-process (DFSP). With the development of information technology, databases, management information systems and virtual reality were used to evaluate the safety risk on construction sites. A geographic information system (GIS)-based decision support system was developed for safety monitoring of geotechnical construction. Safety monitoring could be regarded as proactive construction safety management (Cheng *et al.*, 2002). Later, more studies concentrated on safety monitoring. There were nine papers relevant to safety monitoring in the period of 2011–12. In the process of construction safety monitoring, global positioning systems (GPS), laser scanning, radio frequency identification (RFID) and sensor-based technology were applied to acquire the real-time information on construction sites; wireless networks and ultra wideband were applied to transmit the information in a timely fashion; based on the platform of geographic information system (GIS), building information modelling (BIM), 3D visualization technology, 4D visualization technology and virtual real-

Table 7 Different types of research topics of construction safety

Research topic	Number
AC	1
ISM	1
SME	1
SR	1
CM	2
LR	2
SPE	2
DFS	3
SI	4
CA	5
SPL	5
SK	6
ST	9
HI	13
TA	15
SA	20
SMO	28

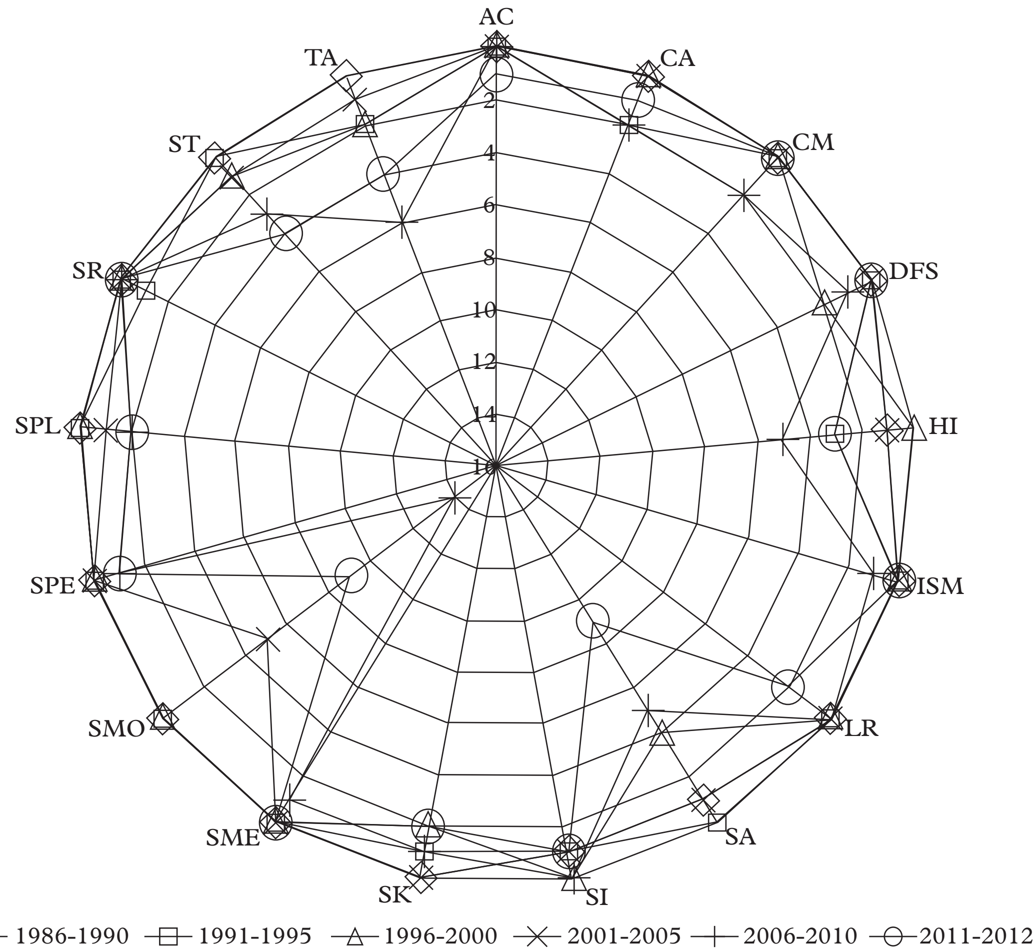

Figure 2 Trend of research topics of construction safety

ity, diverse kinds of mathematical methods were applied to deal with the large amounts of information to control risk or predict accidents, such as Bayesian networks (Rivas *et al.*, 2011), fuzzy set theory (Cheng *et al.*, 2002), network topology (Giretti *et al.*, 2008), and support vector machines (Rivas *et al.*, 2011).

Summary

The trend of advanced technology application in construction safety is more diversified at present. Twenty types of technologies were studied and utilized in the period of 2011–12 (see Figure 1). The diversification of technology application is attributed to continuous development of innovative technologies and various requirements of research topics. In the past, studies mainly focused on reactive safety management methods, such as hazard identification, safety assessment and cause analysis. But ceaseless construction accidents implied that the goal of zero-injury couldn't be realized by way of reactive safety management. Researchers and practitioners paid more attention to proactive safety management, including design for safety, safety monitoring and safety information. Real-time information is the key instrument for proactive safety management. Considering the variety of types of safety information, various types of technologies were employed, including RFID, sensor, sonar, GPS, RS, wireless and ultra wideband. Another trend is the integration of information collection technology and visualization technology. RFID, sensor, sonar, GPS and RS were applied to collect real-time construction safety information. Wireless and ultra wideband were used to transmit the information at the right time, to the right place and the right person. Visualization technologies, such as virtual reality, augmented reality, laser scanning, 3D, 4D, BIM and GIS, were employed to visualize the results of safety assessment and safety monitoring, in order to avoid safety risk and prevent accidents.

Actually, construction safety management is a process of safety information collection, transmission, storage, analysis, evaluation and response. Various advanced technologies were utilized to assist in the process. Although researchers and practitioners have already done a significant amount of study, some critical gaps were identified as follows:

(1) Technology application for construction safety needs to be extended from the construction phase to the pre-construction phase as well as to the maintenance phase. There were 105 publications that focused on the construction phase, accounting for 89%. The time/safety influence curve revealed that there is greater opportunity to influence safety from the beginning of the project (Szymberski, 1997). In addition, around half of the projects in the construction industry of some developed countries/regions, such as the United Kingdom and Hong Kong, are RMAA projects. Therefore advanced technology for construction safety should be considered for application in the total life cycle (TLC) of a project.
(2) Most studies regarded advanced technology application as an effective way to further construction safety. But a survey conducted in 74 construction firms revealed that there was no relationship between information technology utilization and safety performance (EI-Mashaleh *et al.*, 2006). This disagreement should be studied further and the relationship between technology utilization and safety performance should be quantified. On the other hand, innovative technology application will result in an unavoidable increase in cost or investment. The cost-effectiveness analysis will be significant for construction companies. More attention should be paid to this aspect.
(3) Technology application usually gives rise to unintended risk. Seward *et al.* (1994) indicated that robots themselves could become a source of danger, because robots required considerable size and power to be effective. The authors didn't find other similar studies. The risk from technology itself shouldn't be overlooked.
(4) Different types of technology had been applied for construction safety, including information communication technology, sensor-based technology, 3S technology, RFID and virtual reality. But most of these technology applications were limited to academic research and limited implementation had been carried out for construction safety management. Researchers and practitioners should focus more on technology transition from research into practice.
(5) Legal issues were generally overlooked when applying advanced technology to promote construction safety. Other problems might arise if relevant legal issues were disregarded. Advanced technology application should conform to the laws, regulations and rules that would normally apply in the construction industry.

Conclusions

It is realized that technology application can be an effective way to further safety management in the construction industry. Various types of technologies have been involved in construction safety already, such as information communication technology, sensor-based technology, 3S technology, RFID, visualization technology and virtual reality.

A three-step method was used to obtain relevant publications and compiling a database of the findings. Through search and selection, 119 relevant papers were obtained from EBSCO Host, Engineering Village, Science Direct and Web of Science, covering the main journals and conference proceedings in the field, such as *Construction Management and Economics, Journal of Construction Engineering and Management, Engineering Construction and Architectural Management, International Journal of Project Management, Automation in Construction, Accident Analysis and Prevention* and *Safety Science*. Through literature coding, publication information about title, year, type, country or region, research level, project phase, technology, and research topic, was compiled in the database.

The results presented a general overview of technology application for construction safety. From 1986 to the present, there was an increase of studies focusing on this topic. Journal papers accounted for most of the compiled papers, especially the journal *Automation in Construction*, accounting for 27%. Geographic distribution covered approximately 20 countries/regions from four continents (except Africa and South America). These studies were conducted from several levels: industry, company, project, sub-project and process. The project level occupied more than half of the total. Although it was known that there was more opportunity to influence construction safety from the onset of a project, less attention was paid to the phases of pre-construction and maintenance, compared to the construction phase. Five kinds of project types were included in the studies, namely buildings, bridges, pipe installation, tunnels and underground construction. It was interesting that five papers about tunnel projects were all from China. The high pace and volume of subway development and construction may be the potential reason.

The discussion made some contributions to grasping the research trends and making better use of technology application for construction safety. And the radar chart was utilized to study the trends of technology application and research topics. Automation and robotics were the main technologies initially. With the development of 3S technology, information communication technology, sensing technology, virtual reality, visualization technology, etc., almost 30 kinds of technologies had been studied till now. Because the functions of technologies were different from and complementary to each other, technology application tended to be a combination in construction safety. The method of construction safety management has changed from reactive into proactive; correspondingly the research topics have changed from hazard identification, cause analysis and safety assessment into design for safety, safety monitoring and safety information. In fact, construction safety management is a process of safety information management, including collection, transmission, storage, analysis, evaluation and response. Various advanced technologies were utilized to assist in the process. Some technologies are responsible for gaining real-time safety information, such as global positioning system (GPS), laser scanning, radio frequency identification (RFID) and sensors; some are used to transmit safety information at the appropriate time, such as wireless network and ultra wideband; databases are used to store large amounts of information; some were employed as the platform for risk evaluation or accident prediction, such as geographic information system (GIS), building information modelling (BIM), 3D, 4D and virtual reality.

Five research gaps were identified, namely the lack of studies focusing on the phases of pre-construction and maintenance; many studies ignored the cost-effectiveness of technology application; many studies overlooked the unintended impacts resulting from technology application itself; incomplete technology transition from construction safety research into practice; and overlooking legal issues when applying advanced technology. Future researchers and practitioners can conduct more relevant studies and propose effective measures to take into account these identified gaps, which could provide an injury-free environment in the construction industry.

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Appendix

We report here the full list of 119 papers which were selected and coded.

Table A1 Table of full list of 119 papers and corresponding coded data

Year	Publication type	Publication name	Volume (issue)	Initial page	Country or region	Research level	Project phase	Project type	Advanced technology	Research topic
1986	C			55	Others	C	C		ES	SA
1989	J	JCEM	115(1)	126	Others	PJ	C	BU	RO	HI
1990	J	JCEM	116(3)	383	US	PJ	C	BU	MIS	SI
1992	J	JPCF	6(4)	246	Others	I	C		ES	CA
1992	J	JPCF	6(4)	261	Others	I	C		ES	CA
1992	J	AIC	1(3)	251	Japan	PJ	C	BU	RO	TA
1994	J	AIC	3(1)	79	US	PJ	C	BU	RO	TA
1994	C			19	US	PC	C	BU	AU, RO	HI
1994	C			35	Others	PC	C	BU	CA	HI
1994	C			13	Japan	PC	C	BU	AU, RO	HI
1995	C			1545	Japan	C	P, D, C		DB	SR
1995	C			997	US	C	C		KM, SW	SK
1995	C			211	Others	PJ	C	BU	KM	SI
1996	J	JCEM	122(1)	91	US	SP	C	BU	OIT	TA
1996	C			167	Others	PJ	C	BU	DB, KM	SK
1996	C			581	US	PJ	C	BU	3D, VR	ST
1997	J	JAE	3	32	US	PJ	D	BU	OIT	DFS
1998	J	AIC	7(4)	327	US	PJ	C	BU	WN	TA
1999	C			559	US	PJ	C	BU	DB, KM	SA
1999	C			551	Others	I	C		CA	SK
2000	C			955	Japan	PJ	C	BR	ES	SA
2000	J	AIC	9(5)	2000	Japan	PJ	C	BU	VR	SA
2000	C			961	China	PJ	C	BU	MIS	SA
2000	C			1058	HK	PJ	D, C	BU	VR	DFS
2002	J	AIC	11(6)	629	US	PJ	C	BU	3D, SE	TA
2002	J	IJOSE		321	US	PJ	C	BU	CA	ST
2002	C			298	Singapore	PJ	C	BU	KM	SA
2002	J	AIC	11(4)	375	Taiwan	PJ	C	U	DB, GIS	SMO
2002	J	AIC	11(5)	501	HK	PJ	D, C	BU	DB, VR	HI
2003	J	AIC	12(6)	737	Others	PJ	C	BU	GPS, WN	SI
2003	C			141	Japan	PJ	C	BR	DB	SMO
2004	J	JSR	35(2)	159	HK	PJ	C	BU	DB	SMO
2005	J	CIIPM	5(2)	99	Thailand	PJ	C	BU	4D	SPL
2005	C			460	Spain	PJ	C	BU	DB, GPS	SMO
2005	C			148	US	PC	C	BU	VR	ST
2005	J	AIC	14(5)	666	Korea	PJ	M	BU	LS	SMO
2006	J	JCEM	132(5)	499	US	C	C		IG	SPE
2006	C			101	US	PJ	C	BU	3D, SE	SMO
2006	J	CM&E	24(11)	1199	HK	I	C		DB, DM	SME
2006	J	JCEM	132(2)	197	UK	PJ	C	BU	KM	HI
2006	J	AIC	15(6)	719	UK	PJ	C	BU	GPS, SE, WN	SMO
2007	J	AIC	16(4)	518	US	PJ	C	P	RO	TA
2007	C			510	China	C	C		MIS	SA
2007	J	AIC	16(2)	224	UK	PJ	C	BU	AU	TA
2007	C			290	Others	PJ	C	BU	VR	ST

(*Continued*)

Table A1 (*Continued*)

Year	Publication type	Publication name	Volume (issue)	Initial page	Country or region	Research level	Project phase	Project type	Advanced technology	Research topic
2008	J	ITcon	13	103	US	PJ	C	BU	SE	SMO
2008	J	AIC	17(3)	322	Korea	SP	C	BU	RO	TA
2008	C			292	Japan	PJ	C	BU	RFID	SMO
2008	J	RE&SS	93(10)	1523	Netherlands	I	C		SW	CM
2008	C			300	Italy	PJ	C	BU	UW	SMO
2008	J	TSS	13(S1)	266	China	PC	C	BU	4D, BIM	SA
2008	J	SS	46(7)	1091	Taiwan	I	C		DM	CA
2008	J	CJRME	27(7)	1297	China	PJ	C	T	SO	HI
2008	J	AIC	17(4)	459	Spain	SP	C	BU	RO	TA
2008	C			319	Iran	PJ	C	BU	GIS	SA
2008	J	SS	46(2)	186	Netherlands	I	C		SW	CM
2008	J	ECAM	15(4)	336	Australia	PJ	D	BU	OIT	DFS
2009	J	JCEM	135(11)	181	Australia	I	C		CA, KM	HI
2009	J	AIC	18(3)	258	Korea	PJ	C	BU	SE	SMO
2009	J	JWUT	31(23)	72	China	PJ	C	T	GIS	SMO
2009	C			1324	Canada	C	C		DM, MIS	SK
2009	J	JCEM	135(8)	726	Israel	PJ	C	BU	CA	HI
2009	C			2549	US	I	C		VR	ST
2010	J	EM	27(12)	192	China	PJ	C	BU	4D, BIM	TA
2010	J	SS	48(3)	395	Thailand	PJ	P, D, C	BU	4D	ISM
2010	J	AIC	19(3)	368	Japan	PJ	C	BU	RFID	SMO
2010	J	AIC	19(4)	491	US	PJ	C	BU	3D, LS	SMO
2010	J	AIC	19(5)	630	US	PJ	C	BU	RFID, RS	SMO
2010	C			132	US	PJ	C	BU	3D, LS, SE	SMO
2010	J	JCEM	136(2)	170	Australia	PJ	C	BU	CA	HI
2010	J	AIC	19(7)	954	Slovakia	PC	C	BU	RO	TA
2010	C			282	Japan	PC	C	BU	AR	SPL
2010	J	C&E	55(2)	858	Taiwan	PJ	C	BU	EL	ST
2010	J	JTSEIT	10(4)	33	China	PJ	C	T	GIS	SA
2010	J	JSR	41(3)	229	US	PJ	C	BU	SE	SMO
2010	C			2338	Korea	PC	C	BU	AU	SA
2010	C			809	China	PJ	C	T	3D, VR	SMO
2010	J	AIC	19(2)	134	Others	PJ	C	BU	RFID, SE, WN	SMO
2010	J	SS	48(4)	436	Taiwan	I	C		DM	CA
2010	J	CIIPM	10(3)	248	Sweden	PJ	D, C	BU	3D, 4D, VR	SPL
2011	J	ITcon	16	335	UK	PJ	C	BU	GIS	SK
2011	J	AE	42(3)	445	Korea	PJ	C	BU	RO	SA
2011	J	ITcon	16	69	US	I	C		3D	ST
2011	J	AIC	20(6)	686	Italy	PJ	C	BU	SE, UW, VR	SMO
2011	J	IJPM	29(1)	66	India	PJ	P, C	BU	4D, BIM, GIS	HI
2011	J	AIC	20(2)	155	China	PJ	C	BU	4D, BIM	TA
2011	J	AIC	20(2)	167	China	PJ	C	BU	4D, BIM	TA
2011	R				Finland	PJ	C	BU	4D, BIM	SA
2011	J	AIC	22(3)	102	Others	I	D		IG	LR
2011	C			6418	China	PJ	C	BU	SE, WN	SMO
2011	J	JCEM	138(10)	1169	China	PJ	C	T	DB	AC
2011	J	RE&SS	96(7)	739	Spain	I	C		DM	SA

(*Continued*)

Table A1 (*Continued*)

Year	Publication type	Publication name	Volume (issue)	Initial page	Country or region	Research level	Project phase	Project type	Advanced technology	Research topic
2011	C			402	Finland	PJ	C	BU	BIM	SI
2011	J	JCEM	137(6)	452	US	I	C		CA	ST
2011	C			2028	Canada	PJ	C	BU	DB, RFID, SE	SMO
2011	J	AIC	20(2)	101	Others	I	C		RFID	LR
2011	J	AIC	20(5)	519	US	PJ	C	BU	UW	SPE
2011	J	AIC	20(7)	954	Korea	SP	C	BU	AU	SPL
2011	J	AIC	22(3)	545	US	SP	C	BU	UW	SMO
2011	J	EA	31(1)	73	HK	PJ	C	BU	KM	SK
2011	J	AIC	22(3)	498	HK	PJ	C	BU	4D, VR	SA
2012	C			574	US	PJ	D, C	BU	BIM	HI
2012	J	AIC	21(1)	81	Korea	SP	C	BU	OIT	TA
2012	J	AAP	48	214	Taiwan	I	C		DM	CA
2012	J	AAP	48	193	UK	PJ	C	BU	DB, RFID, SE, WN	SMO
2012	J	AIC	22(3)	212	Australia	PC	C	BU	AU	SA
2012	J	JCEM	138(3)	341	Australia	PC	C	U	AU	SA
2012	C			255	UK	PJ	D, C	BU	4D	SPL
2012	J	AIC	21(1)	132	Korea	SP	C	BU	INS	TA
2012	C			2091	US	PJ	C	BU	3D	ST
2012	J	AAP	48	235	HK	PJ	C	BU	CA	SMO
2012	J	AIC	22(3)	175	Taiwan	PJ	C	BU	OIT	SMO
2012	C			787	US	PJ	C	BU	GPS	SA
2012	J	JCEM	138(10)	1139	China	SP	C	BU	OIT	SA
2012	J	AMR	463	1533	China	PC	C	BU	OIT	SA
2012	J	PE	29	940	China	PJ	C	BU	GIS	SMO
2012	J	CIIPM	12(1)	29	HK	PJ	D	BU	VR	HI
2012	J	AAP	48	204	HK	PJ	C	BU	VR	ST
2012	C			1032	US	PJ	C	BU	3D	SMO