The Role of Information Technologies to Address Data Handling in Construction Project Management

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Abstract: Construction is an extremely information-dependent industry in which a project's success largely depends on good access to and management of data. Effective project management requires the characterization of its challenging issues and the use of appropriate tools for data handling. For this purpose, the construction industry is increasingly adopting the use of information and communication technologies (ICT) in recent years. Given the acknowledged potential of ICT to bring about improvements in other industries, many initiatives have been undertaken to develop appropriate tools to support various tasks during the construction project lifecycle. This paper focuses on the proposals that use ICT to provide access to the data and take advantage of this access to manage crucial issues within project management such as costs, planning, risks, safety, progress monitoring, and quality control. The authors will demonstrate that suitable data handling facilitates and improves the decision-making process and helps to carry out successful project management. **DOI: 10.1061/(ASCE)CP.1943-5487.0000538.** © *2015 American Society of Civil Engineers.*

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Introduction

The construction industry presents unique characteristics that differentiate it from other industries including a project takes place over a long period of time, it involves on-site production, a large number of people are implicated, and company staff is highly variable. Additionally, during the project lifecycle, an enormous amount of documents with relevant data are produced and exchanged. These data have many diverse formats and are stored in different databases (DBs) and applications (even on paper). This complexity makes the project management difficult.

The lifecycle of a project can be divided into three main phases: design, execution, and maintenance. Although each phase is generally independently managed and has its own data, many data are shared across the different phases. Effective data management is an integral part of successful project management, with the primary objective being completing the project on time and within budget limitations while meeting established quality requirements and other specifications. In this regard, appropriate data storage is crucial so that integrated data become organized and exploitable to ease the decision-making process throughout the project lifecycle (Abudayyeh et al. 2001; Jiang et al. 2012). Unfortunately, most of the important data are exchanged in unstructured text documents, making the data storage task difficult (Caldas et al. 2002; Al Qady and Kandil 2013). Moreover, from a data management perspective, this fact produces several problems such as increasing the complexity level for data retrieval, poor interoperability between different management systems, and harder information reuse (Forcada et al. 2007; Al Qady and Kandil 2013).

Furthermore, data are shared not only through documents. Many data are not stored but only verbally exchanged among the involved professionals. Thus, important experiences gained during the construction process only remain in the mind of project participants; when engineers and experts complete projects or leave the company, they normally take knowledge with them, a valuable asset that could benefit subsequent projects in the company. This knowledge can be reused and shared to enhance construction processes and decrease the time and cost of solving problems (Kanapeckiene et al. 2010).

To deal with the project data management, information and communication technologies (ICT) play a fundamental role. In the 1980s, Gilmore (1989) anticipated the need to include ICT in the diverse phases of the construction lifecycle. A review of the results from recent years shows that his advice was not misguided. Nowadays, their use is becoming increasingly necessary to bolster the competitiveness of construction companies, and there are many efforts that focus on the design, development, and practice of techniques for the management of construction information (Benjaoran 2009).

Although the construction industry is adopting the latest ICT available to improve collaboration, coordination, and data exchange among the participants involved in construction projects, their potential in this domain is being exploited more slowly than in other industries (Lam et al. 2010; Ahuja et al. 2010; Sardroud 2015). The main reasons for this are:

- The highly fragmented structure of the industry (Adriaanse et al. 2010; Rezgui et al. 2011; Lu et al. 2014);
- The relative uniqueness and complexity of projects (Caldas and Soibelman 2003; Rezgui et al. 2011; Lu et al. 2014);
- The temporary nature of construction projects (Adriaanse et al. 2010);
- The inadequate coordination and inefficient means of communication of project information and data (Forcada et al. 2007; Chassiakos and Sakellaropoulos 2008);

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- The lack of knowledge and skills to use ICT (Lu et al. 2014; Viljamaa and Peltomaa 2014; Sardroud 2015);
- The lack of standardization in documents and data (Soibelman et al. 2008);
- The organizational culture (Gajendran and Brewer 2012); and
- Return on investment is not clear in short term (Sardroud 2015).

This paper focuses on the approaches that use ICT to provide access to the data and take advantage of this access to manage the main tasks within the project management as cost, planning, risks, safety, progress monitoring, and quality control. Data handling plays a key role in construction project management to ensure the success in project objectives. As the authors will show, there are many remarkable proposals in which proper data handling facilitates and improves the decision-making process and help to successfully carry out the project. Additionally, the authors analyze current situation and point out future directions with the aim of fostering and directing further research on the application of ICT in construction project management.

After "Introduction," the remainder of this paper is structured as follows. First, this paper focuses on the main ICT tools. Secondly, ICT based proposals are analyzed in relation to the project management tasks that ICT aims to improve. Following this review, some reflections on the topic and recommendations are proposed. Lastly, some of the most important needs identified for future research in this area are discussed.

ICT Pillars for Construction Project Management

As noted in the "Introduction," the construction industry is characterized by fragmentation, lack of integration, and complexity in all processes and activities. These characteristics could threaten the delivery of project objectives, which might have a negative affect on the construction project success. In this challenging context, a crucial issue is to improve the collaboration and communication between the parties within the construction industry, which will enhance productivity while maximizing efficiency and effectiveness. Nowadays, access to accurate and up-to-date information becomes very important, and there is an increase in the development of construction collaboration and communication tools.

In recent years, developments in ICT have allowed for suitable data management. This paper will now analyze what are the main technologies that allow for this proper data management.

Web, Semantic Web, and the Cloud

One of the elements that supports the noted collaboration and communication need in construction-related companies is software systems that enable effective, timely sharing of project-related information between geographically-dispersed members of a construction project team. In the implementation of such systems, the Internet is the technology that best facilitates a collaborative working environment in a construction project. The use of web technology in the construction industry can be traced from the very beginning of ICT application and, after years of development, most current applications heavily depend on the web technology in both the design and management process (Lu et al. 2014). This technology provides a suitable platform on which organized attempts to manage and share construction information could be fruitful (Chassiakos and Sakellaropoulos 2008). The use of web technologies can benefit contractors in issues such as removing a great deal of paper documents, improving access to data, allowing common documents between agents in different locations, eliminating discrepancy and misunderstanding in the versions of documents, and recording data in a multimedia format.

Unfortunately, on many occasions, software application interoperability and data exchange between different actors and companies is available only at the file level, based mainly on proprietary formats with poor semantics (Rezgui and Zarli 2006). Many commercial web-based (WB) management systems are document based, acting as common information repositories for drawings and textual documents. The problems with a document-based system lie in many aspects, among which information overload occupies a prominent place; the relevant information, buried in the midst of irrelevant information, is difficult to locate. This fact produces a waste of time and energy in searching for information to make decisions (Chan and Leung 2004). Another well-known problem, previously discussed, is data incompatibility. Because drawings, calculations, and schedules are produced by various particular software applications, users have to run different applications to view a small part of useful information in each file and switch between applications to get all fragmented information integrated in their minds.

This leads the authors to probably the most pressing drawbacks in WB collaborative tools: the absence of standard formats (Han et al. 2007) and the lack of semantic representation of knowledge and processes (El-Gohary and El-Diraby 2009a; Zhang and El-Diraby 2011).

In this sense, the semantic web (Berners-Lee et al. 2001) offers technology that contributes towards solving the noted interoperability problem at all three of the layers: physical, syntactic, and semantic interoperability. Different from the traditional web, the semantic web aims to exchange *meanings* in addition to hypertext. This allows people and machines to exchange knowledge not data through a set of interoperable ontologies (El-Diraby et al. 2005; van Oosterom and Zlatanova 2008).

Within the framework of the semantic web, ontologies allow applications to describe the vocabulary and the domain knowledge that they will use for communication. Using a shared ontology (O), among interoperating applications, facilitates the exchange of data and information on the semantic level, thereby enabling semantic interoperability (El-Gohary and El-Diraby 2009b). Semantic interoperability makes model data sharable and understandable across multiple design disciplines and heterogeneous computer systems such as those based in building information modeling (BIM) and geographic information systems (GIS) technologies (which will be analyzed subsequently) (Karan and Irizarry 2015; Karan et al. 2015). It provides integration at the highest level. However, it is well agreed in the community that no single ontology can fully cover the architecture, engineering, and construction (AEC) domain (El-Gohary and El-Diraby 2010; Lee et al. 2014; Karan and Irizarry 2015). For this purpose, and in recognition of the importance of ontologies in collaborative working, there is an increase in ontology engineering studies proposed in the construction literature, as will be seen in this paper.

Emerging from research into the semantic web, linked data are a new concept that help to overcome interoperability difficulties to enhance information exchange in the AEC domain (Curry et al. 2013; Karan and Irizarry 2015). Linked data leverage the existing open protocols and world wide web consortium standards of the web architecture for sharing structured data on the web. Links are established at the information level (data) and not in the infrastructure level (system), paying attention to the conceptual similarities (shared understanding) between information. This concept can be easily applied to existing information infrastructure, as a complementary technology for data sharing to be added to conventional ICT infrastructure such as relational databases and data warehouses. Data are exposed within existing systems but only are linked when they need to be shared (Curry et al. 2013).

Another recent technology, which has been established by the ICT industry in the Internet field, is cloud computing. The most common definition of cloud computing has been given by the National Institute of Standard and Technology (2011) as "a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction." This technology intends to provide the ability to communicate and exchange data and information easily, efficiently, effectively, and accurately regardless of time and place, thereby providing major benefits for the construction data management (Fathi et al. 2012; Rawai et al. 2013; Jiao et al. 2013). In recent years, a great deal of applications for the construction domain have been developed, many of them related to BIM (a topic that is analyzed in the next section). *Autodesk BIM 360* (2015), *BIMServer* (van den Helm et al. 2010), and *BIM9* (2015) are relevant examples of cloud BIM applications. In Chong et al. (2014), interested readers can find a review of a total of 42 cloud computing applications from the construction area perspective.

Just as happens in traditional building management systems, interoperability is a critical need to reflect on the design of cloud-based data services. If new cloud data services are designed in the same way as traditional building management systems, they will suffer from the data interoperability problems (Curry et al. 2013). This crucial problem of interoperability has been addressed in initiatives such as Industry Foundation Classes (IFC), which is a standard that specifies object representations for AEC projects developed by BuildingSMART (2015), and ISO 10303 series Standard for the Exchange of Product Data (STEP), which also addresses the interoperability requirements of the AEC industry [International Organization for Standardization (ISO) 2004]. However, besides the standardization approach, other technologies are necessary to deal with information integration and interoperability problem. That is, to successfully achieve efficient and effective collaboration, systems integration becomes an important prerequisite (Shen et al. 2010). This integration problem is a major concern with regard to information systems.

Information Systems

Information systems allow organizations to collect, process, store, and distribute information to support daily operations and decision making. Currently, information systems are the core of computer systems in most companies and capitalizing information systems-related technology has a deep affect on their performance and competitiveness in the market. Companies in the field of construction are not immune to this process and are increasingly concerned about having information systems with applications that take full advantage of the information they collect in their daily operation.

The quality of the information system of a company largely rests on the use of suitable models to represent information, on the presence of integrated repositories to facilitate data storage and retrieval, and on the use of appropriate data analysis techniques to support decision making. Fortunately, there is

- Growing concern about the use of appropriate data models that allow the representation of information transversely and shared throughout the construction process. The flourishing BIM is the clearest example.
- Data warehousing technology (DW), which, together with the technology of conventional databases, makes possible the design and building of repositories for integrated information management, is increasingly present in the world of construction.
- Knowledge discovery (KD) techniques, which allow to explore the data collected and try to find novel valuable information for the company, are more and more used by construction practitioners to get a better understanding of building production and business models in their look for the best performance.

This can be observed in a growing number of significant proposals in the literature on these three pillars of information systems.

Data Modeling through BIM

BIM provides a framework for collaboration, a multidisciplinary environment that brings together all the parties of the AEC industries, allowing that any related information of a three-dimensional (3D) entity model (e.g., geometry, spatial relationships, geographic information, quantities and properties of building components) could be retrieved by users during the whole lifecycle of a project (Vanlande et al. 2008; Benjaoran 2009).

Currently, BIM is most often used in the design and preconstruction stages, with a notably lesser use in the construction stage. Related to the design phase of a project, BIM allows design integration, virtual (V) prototyping, identification and analysis of design conflicts, simulation (S), cost estimation, scheduling, and distributed access, retrieval, and maintenance of the building data. In the operation and management stages, its use is limited to use as a static repository of information concerning building entities (Eadie et al. 2013; Curry et al. 2013). Through the use of BIM, conventional 3D or four-dimensional (4D) models turn into an *n*D model that incorporates multiple aspects of design information required at each stage of the lifecycle of a project (Aouad et al. 2005; Fu et al. 2006; Ding et al. 2014).

Once a BIM model is complete, building data can be incorporated in other information system tools to streamline as many tasks in the construction process. For example, data from GIS (Niknam and Karshenas 2015) and tracking technologies (TT) (Kim et al. 2013a; Bosché et al. 2014; Golparvar-Fard et al. 2015) can be combined, which can offer substantial benefits to construction project management.

Unfortunately, although BIM is expected to bring information technology into the construction industry and change the way of information-sharing, it is still in a relatively infant stage (Cao et al. 2015). The main reasons are that computing-intensive models require a lot of computing resources, the lack of expertise within the project team and external organizations, and the high subcontracting of work during the construction stage (Eadie et al. 2013).

Geographic Information Systems

GIS is among the most widely embraced software technologies of the past decade (Dib et al. 2013). GIS consists of organized collections of computer hardware, software, and geographic data designed to efficiently capture, store, update, manipulate, analyze, and display all forms of geographically referenced information. It handles both spatial and attributes information, which are synchronized, so that both can be queried, analyzed, and displayed (She et al. 1999).

GIS can be used to complement and extend the representation capabilities of CAD and BIM. Although a GIS implementation may never be as detailed nor as semantically rich as a BIM, much information can be derived from a BIM or CAD file to create a system of geographic references (Dib et al. 2013). The integration of BIM and GIS could offer substantial benefits, if they could exchange data effectively. Whereas BIM systems focus on developing objects with the maximum level of detail in geometry and mainly centered on indoor environments, GIS are applied to analyze the objects that already exist in the physical outdoor environment in a most abstract way (Karan et al. 2015). Data integration between BIM and GIS schemas is challenging because the schemas in these two domains are designed and created for completely different purposes (Cheng et al. 2015a). As this paper will show, to fully integrate GIS and BIM, there is a need to provide interoperability at the semantic level.

Recently, simulation and visualization are both widely applied tools in construction project management. These tools offer unique opportunities to the users to understand the system behavior and predict future events without having to test scenarios on a real system or interfere with the current operations of an existing system (Behzadan et al. 2015).

Data Warehousing

As discussed in this paper, large amounts of data are generated at different stages of the construction process. Thus, it is important to have an integrated repository of consolidated data that is user-friendly when accessed at the time of decision making. Within the field of ICT, construction of such repositories is done with technologies of data warehousing (Kimball 1996). A DW contains current and historical data about the operation of the business coming from one or more different sources, which are later used to build ad hoc reports during the process of decision making. A variety of end-user interfaces are available from the leading database vendors to access and analyze decision-support integrated information stored in the data warehouse. These tools are commonly known as online analytical processing (OLAP) applications.

The analytical function of OLAP, combined with the data storage capability of a DW, provides an opportunity to improve data control in the construction domain. It allows for complex analytical and ad hoc queries with a rapid execution time based on historical data facilitating decision making.

Knowledge Discovery

Complementary to the analytical capabilities of aggregation and summarization provided by OLAP tools, it is also interesting to consider the KD problem using data mining techniques, which focus on data analysis from another perspective. These techniques are directed to the discovery of interesting patterns in large data sets and involve methods from different fields like artificial intelligence, machine learning, statistics, and database systems (Soibelman and Kim 2002). Data mining techniques can be designed to discover groups of data (e.g., cluster analysis), unusual data (e.g., anomaly detection), and dependencies among data (e.g., association rule mining).

Intelligent Information Systems

Together with data mining, The construction community has benefitted from intelligent information systems. In fact, techniques like case-based reasoning (CBR) or fuzzy logic (FL) approaches represent opportunities in this sense.

The CBR (Aamodt and Plaza 1994) process consists of retrieving previous cases similar to a new problem, solving the new problem by adapting previously determined solutions of the similar previous cases, and storing the new successful solution for future use.

FL, which was first suggested by Zadeh (1965), has been gaining popularity in the research area of construction management during the 1980s (Bakht and El-Diraby 2015). The application of FL techniques provides an effective tool to handle the uncertainties and subjectivities arising during the construction lifecycle.

FL may be combined with other techniques such as neural networks (NNs); whereas NNs are strong in pattern recognition and automatic learning, fuzzy set and FL are strong in modeling uncertainties (Chan et al. 2009).

Tracking and Location Technologies

Tracking and location technologies have much to say regarding the data acquisition task in construction projects (Jang and Skibniewski 2009). The use of these technologies permits automatic data collection (Caldas 2004) and makes it possible to improve information integration, team collaboration, and communication (Sardroud 2015).

In recent years, many researchers have carried out substantial work on investigating, tracking, and location technologies and their applications. Their adoption on construction sites can be justified for several reasons, ranging from a basic need for increased awareness to the development of specific applications (Giretti et al. 2009; Naticchia et al. 2013).

The global positioning system (GPS) is a prominent example of these technologies. GPS is a well-known, widely used technology for position and navigation through the use of a constellation of satellites and ground control stations that allow the determination of a 3D outdoor position by a GPS receiver using triangulation on the basis of these satellites. The main disadvantage is that it cannot be used as the sole TT on construction sites, in which resources may travel between indoor and outdoor environments (Maalek and Sadeghpour 2013). Atmospheric conditions and a satellite's location above the receiver influence the resulting position and its accuracy (Caldas et al. 2006).

The authors can additionally mention the radio frequency identification (RFID) technology. RFID refers to a branch of automatic identification technologies in which radio frequencies are used to capture and transmit data from a tag, or transponder. RFID enables efficient automatic data collection because readers can be set on any structure in the reading range and each reader can scan multiple tags at a given time (Park et al. 2012). Unfortunately, the only application of RFID has been found to be unsuitable for ubiquitous real-time tracking on large construction sites because of its limited communication range. To face a complete real-time tracking, the combination of technologies like RFID and GPS should be explored (Vasenev et al. 2014).

Another type of radio technology that can be applied to short range communications is ultra wideband (UWB). It is a wireless communication technique with its bandwidth equal to or greater than 500 MHz. It can generate accurate two-dimensional (2D) localization of the tags, with three or more receivers; and 3D localization, with four or more receivers. Compared to GPS and RFID, UWB systems can localize and identify multiple targets at the same time, which makes them superior for construction application (Yang 2013).

Vision technologies and laser technologies are attracting increasing interest for tracking in large-scale, congested sites because they are free of tags. Laser scanner, also known as laser detection and ranging (LADAR), is very popular for construction applications because it can capture very accurate 3D data for an entire construction scene, using only a few scans. Most applications using laser scanner are applied to generate as-built models.

Over the past few years, cheap and high-resolution digital cameras, extensive data storage capacities, and the availability of Internet connections on construction sites have enabled capturing and transmitting information about construction performance on a truly massive scale (Golparvar-Fard et al. 2015). Photographic data has become the favored documentation medium, as it contains rich information (geometry and appearance), and data are collected quickly and inexpensively (Dimitrov and Golparvar-Fard 2014).

When a third dimension is needed, 3D laser scanning is an appropriate alternative (Bosché 2010; Kim et al. 2013a).

The use of these kind of technologies offer timely and accurate monitoring of on-site construction operations. This monitoring can bring an immediate awareness on project-specific issues (Golparvar-Fard et al. 2011, 2015) and the collected data provide practitioners with the information they need to easily and quickly make project control decisions (Bosché et al. 2014; Yang et al. 2015).

Data Handling in Construction Project Management

Following the review of the tools (presented in the previous section) that ICT offers for proper data handling in construction projects, the authors set out to review significant works that can be found in the literature that take advantage of these ICT in relation to the main tasks of project management. To this end, this section of the paper provides a review of proposals that exist in the literature focused on the management of information and knowledge from a general point of view in the field of project management; then, a review of particularized proposals (in relation to each of the main tasks within project management) is presented.

General Information and Knowledge Management

As noted in the "Introduction," one of the main reasons why the construction sector has taken advantage more slowly of ICT is the inadequate coordination and inefficient means of communication of project information. In many cases, the exchange of the information generated during the project lifecycle is conveyed using documents or verbally, although the suitable storage of this information is a crucial issue to be able to reuse it in the same or in future projects.

In the best case, construction information is available in data tables and worksheets; unfortunately, most construction information is presented within complex unstructured documents (Caldas et al. 2005; Soibelman et al. 2008; Al Qady and Kandil 2013; Antony Chettupuzha and Haas 2015). There are many sources of data: text documents (e.g., contracts, bill of quantities, specifications, requests for information, and meeting minutes); semi-structured multimedia data (e.g., 2D or 3D drawings audio, and video); and structured data for specific applications that need more complicated data structures for storage and analysis than single data tables (e.g., network-based schedules).

To be easily accessible and reused, the data need to be structured. Having structured data, it is possible for building information to be created once, re-used, and enriched in the whole building lifecycle. There are proposals that attempt to solve this issue. For example, automatically creating an organizational document structure over an existing classification structure using KD technology (Caldas et al. 2005; Caldas and Soibelman 2003; Forcada et al. 2007; Wen-der and Jia-yang 2013; Qady and Kandil 2014). In this sense, Chan and Leung (2004) retrieved useful data from the original documents, reorganized the information according to specific tasks or users, and displayed the information in an integrated web page; and Martínez-Rojas et al. (2013) structured the data contained in bill of quantities documents in a hierarchical structure by means of classification techniques based on soft computing.

Having structured data, it is possible to have an integrated repository of consolidated data in a DW that can be easily accessed at the time of decision making. In this regard, the authors of this paper can find remarkable works in the literature.

- Chau et al. (2003) develop a construction management decision support system that uses a multidimensional data model that pays a special focus on inventory decision making.
- Ahmad et al. (2004) develop a system to determine the most appropriate site for residential houses. The authors consider both the spatial and the business factors incorporating the GIS software and analytic hierarchy process tool into the DW.
- Fan et al. (2006) propose an equipment DW linked to a WB decision support system, which integrates data from disparate sources and assists users in obtaining valuable insights into equipment management from the interactive analysis of discovered knowledge.
- Rujirayanyong and Shi (2006) develop a project-oriented DW for a contractors' company-level data facility, providing a robust tool for collecting, storing, and using historical construction project data.

Apart from DW technology, the implementation of knowledge management systems that make possible the exchange and reuse of knowledge has been faced by many authors.

- Tserng and Lin (2004) point out that during the execution phase of projects, an effective means of improving construction management is to share experiences among engineers. The proposed WB system lets users access available activity-related knowledge just by clicking on the desired activity. It also provides links to other similar available activities of past projects.
- Lin et al. (2006) propose a map-based knowledge management system to enable knowledge transfer between projects. Knowledge can be captured and managed to benefit future projects by effectively using information and web technologies during the construction phase of a project.
- Kivrak et al. (2008) develop a WB system, knowledge platform for contractors, which allows capturing tacit knowledge (e.g., know how, expert recommendations) and explicit knowledge (e.g., documents, reports) that can be used in forthcoming projects.
- Lin (2008) presents a people-based maps (PBMs) approach that captures and represents engineer experience and project knowledge, using web technology during the construction phase. This system provides dynamic experience exchange and management services for reuse of domain knowledge and experience.
- Tan et al. (2012) propose a methodology for live capture and reuse of knowledge through WB technology. The system is intended to bridge the communication gap between the company's geographically dispersed offices by connecting the people together and, hence, facilitating the timely sharing of both tacit and explicit knowledge.
- Lin and Lee (2012) propose a new and practical methodology to capture and represent construction project knowledge by using project-based communities of practice (CoPs) and web technology that provide forums for participants to help one another in solving problems.
- Dib et al. (2013) present a GIS-based integrated visual database model that allows for effective use of computer technologies for communication, project documentation, and knowledge sharing throughout the lifecycle of a facility.
- Lin (2014) and Deshpande et al. (2014) introduce a new and practical methodology to capture and represent construction project knowledge in the design and execution phase by using a BIM approach.
- Antony Chettupuzha and Haas (2015) propose a methodology that uses data mining techniques to identify documents that have the potential to disrupt a process and that could result in delays and costs.

- Finally, many proposals present an information and knowledge management portal for representing information and knowledge flow, which is based on the use of semantic web, social web, and publish and subscribe systems (El-Diraby et al. 2005; Lima et al. 2005; El-Gohary and El-Diraby 2009a, 2010; Zhang and El-Diraby 2011; Park et al. 2013c; Viljamaa and Peltomaa 2014).

As it is reflected in the literature, there are many proposals that address knowledge management with the main objective of reusing this knowledge in the same or forthcoming projects by web technology. The benefits of these systems could only be achieved if the company creates a knowledge-sharing culture and encourages all participants involved in the project to share their knowledge.

Following the review of some significant proposals for the management of information and knowledge from a general point of view in the field of project management (presented in this section), this paper will now examine particularized proposals that focus on a specific task within project management, starting with tasks related to costs.

Costs

Over the last few decades, there has been much research into the factors that affect cost performance. Construction companies face a major challenge in controlling project costs over the time span between the design and the completion of the construction project. In the early stages, cost estimation is the key to prevent any cost overruns and it is critical for the overall success of a project (Doloi 2013). During the execution phase, cost control is one of the most significant tasks for project managers because the vast majority of cost overruns occur during this phase and so is reflected in the literature. A large number of studies and research projects have identified individual factors that lead to an increase of the project cost (Trost and Oberlender 2003; Iyer and Jha 2005; Shane et al. 2009; Williams and Gong 2014). Features such as poor site management and supervision, waiting for information, design complexity, changes in scope, aggressive competition at tender stage, low speed of decision making, and client-initiated variations have reportedly been some of the most significant causes of cost overruns in the construction phase of projects.

Cost estimation is the technical process of predicting expenditure in the early phase of a project for each work description provided to be executed in the project. Success depends on the accurate integration of project information, resources, and control over project implementation. Usually, cost estimates are performed within a brief period using limited information and in an uncertain environment in the early project phase [S. Staub-French et al., "An ontology for relating features of building product models with construction activities to support cost estimating," working paper, Center for Integrated Facility Engineering (CIFE); Ji et al. 2011a; Lawrence et al. 2014]. In this process, the access to historical data is essential because cost estimators are based on them in addition to price databases and market prices (Chou 2011). Inaccurate cost estimates may have critical consequences for project success; cost estimates are one of the key tasks in the construction process because they are the foundation for other several tasks (Baloi and Price 2003). Because of the importance of this issue, ICT can provide many benefits, particularly technologies such as DW, OLAP, CBR, and BIM.

To predict construction costs more accurately, an analytical approach is required to extract meaningful information from the large amount of historical cost data stored in a database. For this purpose, OLAP analysis tools offer rapid analysis by storing and refining a massive volume of cost data in a DW.

- Moon et al. (2007) develop a cost data management system to improve the effectiveness of using historical cost data from previous projects. The system, which uses DW technology, helps people understand the uncertainties in construction cost estimation and provides a method for reliable construction cost budget planning.
- Nie et al. (2007) develop two OLAP cubes for two project management tasks (cost control and manpower allocation) across five dimensions including time, participant, task, product, and cost type.
- Cho et al. (2013) propose an OLAP application to integrate cost, schedule, and performance data. The authors concentrate on project execution data related to project control functions including quantity takeoffs, cost estimation, cost control, schedule control, periodic monthly payment, and performance measurement.
- Martínez-Rojas et al. (2015) propose an application of fuzzy OLAP cubes for cost analysis. It allows analyzing cost data associated with the set of projects of a company in an integrated way, and it provides flexible access to data.

Some significant works propose the use of CBR, even together with genetic algorithms (GA).

- Chou (2009) presents a WB approach using case-based reasoning technology for preliminary cost estimation.
- Ji et al. (2011a, b) develop a CBR model for estimating construction costs. This model uses the Euclidean distance concept for similarity measuring and GA for attribute weight assignment.
- Kim and Kim (2010) propose a cost estimation model that overcomes the uncertainty in choosing the correct case by using a GA. This study investigates the appropriateness of a GA as an alternative to generate the weight of each attribute, which is needed in evaluating similarity and in retrieving similar cases to produce the minimum prediction error.
- Du and Bormann (2014) propose a new algorithm to improve the similarity measure, which is critical for proper case retrieval when applying CBR in quantity takeoff.

Several approaches apply BIM technology to assist in the generation of accurate quantity takeoffs and cost estimates throughout the lifecycle of a project. BIM offers the capability to generate takeoffs, counts, and measurements directly from a model, so the time necessary for estimation process decreases.

- Cheung et al. (2012) provide a method for the dynamic and adaptive elaboration of cost estimations yet in the design stage.
- Lawrence et al. (2014) propose an approach for creating and maintaining a cost estimate by using mappings to relate cost information to a BIM.
- Lee et al. (2014) propose an ontological inference process for building cost estimation by automating the process of searching for the most appropriate work items using BIM data.
- Niknam and Karshenas (2015) present a semantic-based estimating application that combines information from a BIM knowledge base, an estimating assembly knowledge base, and material suppliers' semantic web services to prepare a cost estimate.

Apart from these technologies, it is also possible to find significant proposals such as:

- S. Staub-French et al. ["An ontology for relating features of building product models with construction activities to support cost estimating," working paper, Center for Integrated Facility Engineering (CIFE)] propose an ontology that enables estimators to maintain construction cost calculations more completely and consistently than traditional tools.

- Bansal and Pal (2007) propose a methodology that uses the capabilities of GIS to store spatial data, which can later be manipulated for building cost estimation.
- Benjaoran (2009) develops a WB cost control system with the aim to monitor the progress of project costs and to make a real-time comparison with the bill of quantities.
- Chou (2011) presents a cost simulation approach that offers a decision tool for assessing construction cost and uncertainties on the basis of the experienced judgment of project managers.
- Kim et al. (2012) reduce the uncertainty associated in the early phase combining two different estimating methods, historical data-based and assembly-based estimating methods. The proposed method acknowledges the estimator's role in the estimating process, providing transparent estimations to facilitate user acceptance, and making an efficient use of historical data.
- Chi et al. (2012) investigate data mining strategies and develop an analysis framework based on data-mining for multiattribute project data analysis and project performance prediction.
- Williams and Gong (2014) propose text mining, numerical data, and ensemble classifiers for estimating construction costs. Construction project text descriptions can be usefully combined with numerical data to improve prediction of cost overruns.

The cost estimation process is crucial within the cost management, and so is reflected in the literature. In this regard, proposals that allow access to historical data to establish a more accurate cost estimation have attached more attention in the literature. Throughout the project lifecycle, a proper cost control will determine the success of any project, both in the estimation phase and in the execution phase. Moreover, to examine the success of project control, time has been typically used as key issue. Thus, reliable estimates of project cost and duration are necessary inputs for decision making in the different stages of construction projects.

Project Planning

Construction project planning is considered an important task in the early phases and can determine the successful implementation and delivery of a project. Project planning consists of deciding when activities should be started and finished and how many resources should be assigned to each activity. Currently, decision making for project planning in the construction industry continues to be mostly manual. The project team analyzes the site, studies the contract documents including the 2D design drawings, and develops a plan to organize the major activities of the construction process (Waly and Thabet 2003). This method places a large burden on the project team because of the large amount of information that must be handled. Moreover, the traditional human-centered decision-making process has critical limitations in terms of performing what-if scenario analysis because of the inability of properly incorporating real-time data, which can provide valuable pieces of information (Behzadan et al. 2015).

Such shortcomings of traditional tools together with the advances in digital technologies have stimulated various efforts to develop new construction process planning techniques to enhance the visualization and simulation of the construction sequence and finished product (Waly and Thabet 2003; Huang et al. 2007; Li et al. 2009). These proposals enable users to establish more effective construction plans by predicting the results of projects.

BIM enables construction planners to make more detailed, concise, and rigorous schedules by providing a visual of the details of the project. Fortunately, there is an increasing amount of proposals regarding planning tasks on the basis of BIM technology (Song et al. 2012; Moon et al. 2015; Tserng et al. 2014; Liu et al. 2015). Several other studies also suggest the usefulness of GIS in the construction industry to handle this task (Poku and Arditi 2006; Bansal and Pal 2008, 2009; Karan et al. 2013). Some recent works integrate BIM and GIS technologies, e.g., to manage the planning process during the design and preconstruction stages by means of semantic web technology to convey meaning (Karan and Irizarry 2015; Karan et al. 2015). Moreover, the combination of these two technologies allows for management of general planning information, e.g., to identify feasible locations for tower cranes (Irizarry and Karan 2012) and facilities management (Kang and Hong 2015).

Similarly, several research efforts have attempted to develop tools that facilitate planning tasks on the basis of historical data. The generation of schedules, based on experiences from similar construction projects that were successfully executed. is extremely beneficial to project managers because it facilitates the determination of more realistic durations. In this regard, Zayed and Wakil (2012) present a data mining engine to prepare, use, analyze, and extract the hidden patterns from the project data. The proposal includes a fuzzy logic approach to predict work task duration for a construction process. Mikulanova et al. (2010) present a knowledge-based integrated approach for the automated generation of construction schedules by using experiences from similar successfully executed projects by means of a BIM-CBR system.

Labor productivity is a fundamental piece of information for estimating and scheduling a construction project. The current practice of estimating and scheduling relies on several sources to get productivity values including an estimator's personal judgments, published productivity data, and historical project data. In this sense, Song and AbouRizk (2008) propose a systematic approach of measuring productivity, collecting historical data, and modeling productivity using these historical data.

Because of the characteristics of the construction field, activities are often subject to considerable uncertainty, which results from many different possible sources (e.g., activities may take more or less time than originally estimated, resources may become unavailable, material may arrive behind schedule, adverse weather conditions, strikes, workers may be absent). Traditional methods for production planning may be inappropriate to deal with uncertainty and variability during the execution phase. To minimize the effect of risk factors over time, lean construction principles are being applied. Lean construction is a new philosophy oriented toward construction production management. It sets productive flows in motion to develop control systems with the aim of reducing losses throughout the process (Issa 2013). Koskela (1992) sets the basis for the implementation of lean construction. In practice, the last planner system (Ballard 2000), and adaptations of it, are increasingly applied to reduce variation, improve coordination and work flow, and, thus, to reduce various forms of waste in construction projects.

The identification of overlapping activities is also a problem that has received the attention of researchers. Moon et al. (2015) propose an optimization method that minimizes these activities applying fuzzy theory and analyzing risk levels for schedule overlap issues. Besides, for the reduction of the overlapping of highly risky activities, GA theory was adopted.

As can be observed, in construction project planning, the proposals have mainly focused on two approaches. First, proposals that allow a more accurate plan through the access to historical data, and secondly, proposals that allow visualization of the construction process with the aim of enabling users to set more effective construction plans.

Risk Management

In construction projects, risk may be defined as the likelihood of a detrimental event occurring to the project (Baloi and Price 2003). The risks in the construction industry may be of a different nature (Zaini et al. 2012), such as:

- Natural, in which the occurrence is not certain or controlled (e.g., bad weather conditions, heavy rains, and flood).
- Financial, which is one of the major risks faced by companies. Examples of financial risk include labor cost fluctuations, material price fluctuations, cost of equipment, and budget overruns attributable to underestimates of costs.
- Social, which includes personnel risks, inadequate communication, and poor relationships among companies involved in the process.
- Technical, which includes poor workmanship, poor project design, and bad site condition.

The construction industry is exposed to more risk factors than other industries because of the work environment. The term, risk management, can be broadly defined as the work that classifies, analyzes, and responds to unpredictable risks that exist in the project implementation processes (Kang et al. 2013). Thus, the management risk process includes three phases: risk identification, risk quantification, and risk control. In the identification phase, the main objective is to become aware of the diverse uncertainties that may occur during the construction lifecycle to make the decision-making process easier. Kang et al. (2013) present a system that links schedule and risk information as simulations so that the order of the processes implemented can be understood while visually comprehending the risk levels of the processes.

Readily available repositories of risk data from past projects are fundamental to the identification phase. Learning from risks may lead to the construction of more realistic risk models and more informed guesses about the future (Atkinson et al. 2006). Serpella et al. (2014) points out that risk management in construction projects is still very ineffective and that the main cause of this situation is the lack of knowledge exchange. Fortunately, there is an increasing amount of significant proposals regarding risk management based on historical data.

- Knight and Fayek (2002) describe a model to predict potential cost overruns on engineering design projects. The data used to build the model are based on previous projects and information obtained from project managers. The model uses fuzzy logic to relate the existence of the project characteristics and the occurrence of the risk events to determine the overall cost affect on the design phase of the project.
- Baloi and Price (2003) develop a fuzzy decision framework for a systematic modeling, analysis, and management of global risk factors affecting construction cost performance to take appropriate measures to reduce their affect on cost performance.
- Dikmen et al. (2008) propose a learning-based approach for risk management, in which risk-related information is defined, stored, and updated in the form of a lessons learned database. Based on risk information regarding the previous projects, decision makers may make more reliable decisions about forthcoming projects.
- Han et al. (2008) develop a WB risk management model, which is closely associated with each phase of key decisions, using documentation analysis and previous case reviews.
- Tserng et al. (2009) propose an ontology-based risk management framework to enhance the risk management performance by improving the risk management workflow and knowledge reuse.
- Nieto-Morote and Ruz-Vila (2011) present a new methodology for construction project risk analysis to deal with risks associated with the construction projects in the complicated situations in which the information to assess risks is unquantifiable, incomplete, or nonobtainable. The approach allows users to make their judgements by means of linguistic terms associated with a trapezoidal fuzzy number.
- Yildiz et al. (2014b) propose a tool for risk assessment of international construction projects that considers causalities among risk-related variables, effects of risk paths, and lessons learned from previous projects.
- Zhong and Li (2014) propose an ontological and semantic model for construction risk knowledge formalization and risk considering inferring.

Although risk management has traditionally been applied in the area of safety, cost, and time management, its application area has also been expanded to include fields such as bid-decision making, feasibility studies, marketability studies, performance evaluations, and contingency management by reflecting the various factors spanning all phases of the project lifecycle (Han et al. 2008).

The increasing complexity and dynamics of construction projects have plagued the construction industry with substantial risks (Yildiz et al. 2014a). The bad treatment of these risks often results in poor performance with increasing costs and time delays. Thus, there is a direct relationship between effective risk management and project success because risks are assessed by their potential effect on the objectives of the project (Issa 2013).

Safety

Safety is another of the great concerns in the construction industry. Accidents cause many human tragedies, demotivate construction workers, and disrupt construction processes, generating delays in the progress of the works. Moreover, accidents affect the cost, productivity, and reputation of the construction industry. The context in which construction work is carried out and its characteristics are really important, in many cases impeding effective risk management and accident prevention.

Identification of hazards in the workplace is one of the foundations of successful safety management. Carter and Smith (2006) indicate that current hazard identification in construction projects is far from ideal. These authors identified several significant barriers to improve hazard identification: knowledge and information barriers (e.g., failure to share information across projects, lack of resources in smaller projects, and reliance on tacit knowledge) and process and procedure barriers (e.g., lack of a standardized approach and undefined structures for tasks and hazards). The identification of hazards begins in the design phase (prevention through design), incorporating safety considerations into the project or involving designers in considering construction worker safety, and continues until the completion of the project (Manase et al. 2011; Zhang et al. 2013; Qi et al. 2014; Zhang et al. 2015b).

One of the main barriers is the lack of communication across the project. Unfortunately, the data referring to accidents in a construction site are rarely shared with all other interested stakeholders. Most construction companies do not even share related information about safety among their own projects and staff. In this regard, there are many proposals in the literature that focus on this topic.

- Rivas et al. (2011) evaluate diverse data-mining techniques (such as Bayesian networks, decision rules, classification trees, logistic regression, and support vector machines) with a view to, ultimately, reducing workplace accident rates by enabling preventive measures to be concentrated in an effective way in areas of greatest risk.

- Martínez-Rojas et al. (2011) propose a DW model to provide integrated data management to facilitate the data analysis process for safety decisions. The analysis of large amounts of historical data stored in a database might be very useful to identify and prevent future workplace accidents.
- Similarly, Kim et al. (2013b) propose an automated information retrieval system that can automatically search for and provide similar accident cases to prevent future accidents. The retrieval system extracts BIM objects and composes a query set (based on work, work conditions, and laborers) by combining BIM objects with a project management information system.
- Fan and Li (2013) describe an approach to reduce construction accidents on the basis of application of text-mining techniques to automatically retrieve similar cases from an electronic case repository of construction accidents using a vector space model. By comparing the similarities and differences between the current case and the retrieved past cases, a set of actions can be developed to prevent the occurrence of accidents.
- Wu et al. (2013) analyze struck-by-falling-object accidents on construction sites and propose an integrated information management model. The model is established in three steps. First, on the basis of past accident cases, the frequency of a particular type of falling objects is analyzed and identified. Next, information required for proactively preventing struck-by-falling-object accidents is identified using a sensor network. Then, an integrated information management model is developed.
- Le et al. (2014) propose a social network system for coordinating and sharing construction safety and health information and knowledge in the construction industry, which uses semantic web and ontology.

The analysis of accidents through historical data provides valuable but general information for safety planning. This information is not sufficient to predict when and where accidents will occur because of the uniqueness of each project. The occurrences of accidents can be reduced but cannot be completely prevented because of construction characteristics such as the risky and uncertain nature of construction work. However, the analysis of historical data can be supplemented with other current approaches such as virtual designs, simulations of construction processes, and real monitoring. These approaches may provide an easier understanding of construction sequence and may predict places and activities, which have a higher potential for accidents. In this regard, ICT such as BIM (Zhang et al. 2013, 2015a, b; Qi et al. 2014), TT (Giretti et al. 2009; Wu et al. 2010; Chae and Yoshida 2010; Carbonari et al. 2011; Lee et al. 2011; Yang et al. 2012; Cheng and Teizer 2013; Han et al. 2013, 2014; Naticchia et al. 2013), simulation and visualization (Guo et al. 2013; Chun et al. 2012), and GIS (Bansal 2011; Manase et al. 2011) have become established tools in the construction industry.

A large portion of these studies have focused on the application of sensing technologies, which collect large amounts of on-site data. They provide safety and health monitoring, which allows for the automatic detection of workers' unsafe actions and for feedback on their behavior, both of which enable the proactive prevention of accidents by reducing the number of unsafe actions that occur (Han et al. 2014). However, they fail to fully specify how to evaluate the data for detecting unsafe conditions and acts (Seo et al. 2015).

The localization and TT are commonly studied in the literature to control and monitor construction progress, as will be presented in the next section.

Progress Monitoring

During the execution of a project, procedures for measuring construction progress become indispensable tools for project control (Han and Golparvar-Fard 2015). For a successful construction project, as-built progress should be constantly monitored and compared with the as-planned construction progress and real-time corrective actions should be taken in case of observed discrepancies (Golparvar-Fard et al. 2009; Yang 2013; Braun et al. 2014). The as-built project information represents how construction was actually performed. Traditional methods are time-consuming and error-prone because on-site engineers acquire and re-enter data into various isolated systems to help project managers in decision making. Consequently, a time and space gap exists between the construction site and the office, which reduces efficiency and creates a lack of data and data confusion (Wang et al. 2007).

With the increasing complexity of construction projects and increased budget and time constraints, field data collection is becoming increasingly important. These data are essential to monitor the progress, to support decision making, and to allow managers to react to changes as the projects are being executed. This problem has been addressed in several proposals focusing on diverse monitoring problems.

- Cheung et al. (2004) develop a WB system to streamline the project performance monitoring process, from data input to the presentation of results. It includes eight categories of project performance measures: people, cost, time, quality, safety and health, environment, client satisfaction, and communication.
- Wang et al. (2007) present a system for improving the acquisition of construction information on-site and providing an information sharing platform among all participants of the construction chain using web technology and an RFID-enabled personal digital assistant (PDA).
- Elbeltagi and Dawood (2011) develop a BIM-GIS visualization system to evaluate construction performance and to facilitate monitoring of repetitive construction progress.
- Caldas et al. (2006), Park et al. (2012), Razavi and Haas (2012), and Pradhananga and Teizer (2013) present frameworks for an integrated solution for automated identification and localization of construction resources. In the third work, the authors use evidential belief reasoning and soft computing techniques to deal with the imprecision, vagueness, and ambiguity within the acquired data.

In recent years, the combination of BIM and TT are becoming essential for process monitoring. This combination allows for appropriate comparison of as-built with as-planned progress.

- Irizarry et al. (2013) integrate the BIM approach with GIS to track the status of a supply chain and to provide warning signals that would result in successful delivery of materials.
- Bosché et al. (2014) explore a framework in which the built status can also be tracked and identified using scan versus BIM. They take advantage of the availability of BIM a priori information for generating the as-built models.
- The tracking of as-built progress with the as-planned construction progress has been addressed with various tracking technologies, such as, laser scanning (Bosché 2010; Turkan et al. 2012; Kim et al. 2013a), RFID (Jang and Skibniewski 2009; Bosché et al. 2009), digital images (Golparvar-Fard et al. 2011; Park et al. 2012; Golparvar-Fard et al. 2015; Han and Golparvar-Fard 2015; Dimitrov and Golparvar-Fard 2014), and UWB (Maalek and Sadeghpour 2013; Shahi et al. 2014).

Most of the research effort on automated construction progress tracking has focused so far on structural work (Bosché et al. 2014). However, other works are not as constrained as structural works, resulting in differences between the design and installation, as for example, mechanical, electrical, and plumbing works (Bosché et al. 2014; Shahi et al. 2014).

Quality Management

Last but not least, this paper considers the quality management task, which is closely related to progress monitoring. Within the quality management task, quality control is what ensures that products and service meet with established requirements. This task consists of the comparison of the obtained results with desired results to make decisions that will correct any differences.

Quality control represents an increasingly important concern for project managers because defects or failures may result in additional costs. It involves a great deal of data because it implies inspection and testing, nonconformance reporting, and corrective action taken during the construction phase (Chin et al. 2004). Existing methods for quality management are performed by on-site inspection in a fairly traditional way. Site managers usually use manual recording by paper-based documents, making it difficult to perform quality management efficiently (Park et al. 2013a). As a consequence, inspections are often omitted, resulting in faulty construction and quality degradation that may necessitate rework. This may adversely affect project costs and schedule (Kwon et al. 2014).

The implementation of quality management systems, which assist in the process of acquisition, accessing, sharing, and reusing quality data at project and company levels, has been faced through various technologies:

- Chin et al. (2004) present a WB management system that facilitates collaboration and communication among participants, efficient documentation and recording of quality information, tracing of the whole quality control process, and the accumulation of as-built information.
- Lam and Ng (2006) present a WB quality management system for effective information sharing.
- Wang (2008) proposes an RFID-based quality inspection and management system that integrates web and RFID technologies to enhance the efficiency and effectiveness of automated data acquisition and information sharing among participants facilitating the monitoring and control.
- Kim et al. (2008) propose a computerized quality inspection and defect management system, which can collect defect data at a site in real-time (using a PDA and wireless Internet) and effectively manage statuses and results of the corrective work performed.
- Cheng et al. (2015b) propose an approach to improve the quality of construction works using GA. It provides defect-related knowledge from past cases to make defect prevention strategies for construction projects.

Some proposals, in addition to assisting in the data acquisition and inspection process, make it possible to automatically analyze the data. For example:

- Akinci et al. (2006) outline a process of acquiring and updating detailed design information, identifying inspection goals, inspection planning, as-built data acquisition and analysis, and defect detection and management.
- Zhu and Brilakis (2009) present an approach for automatically assessing the affect of two concrete surface defects analyzing images.
- Park et al. (2013a) present a conceptual system framework for construction defect management by linking ontology and augmented reality with BIM. It allows users to search and retrieve project or work-specific defect information and to support field defect management.
- Chen and Luo (2014) propose an integrated solution to improve current quality management processes with assistance of a BIM working environment. The information collected on-site is entered into a BIM-based quality model and processed so as to compare the actual quality testing data with reference data.
- Kwon et al. (2014) present a defect management system for reinforced concrete work, using BIM, an image-matching system, and augmented reality to prevent building work defects proactively, save inspection time, and reduce rework related costs at construction sites.

Current State and Research Challenges

It is clear that, the construction industry is an industry with intensive production of information; throughout the lifecycle of a construction project, large amounts of data are generated, transferred, and exchanged. Good management of these data is vital to ensure the success in project objectives; timely access to appropriate information is essential not only to facilitate the daily operation but also to help in the decision-making process.

Analysis of the Current State

The use of ICT, although slower than in other areas given the idiosyncrasies of the world of construction, has brought great benefits to the problem of data handling in managing construction projects. The authors have seen in their review of the literature both general proposals aimed at facilitating collaboration and information exchange among the scattered members of a project, and more specific proposals aimed at assisting professionals in relation to the concrete tasks of project management such as cost estimation and control, planning, risk management, safety, progress monitoring, or quality control.

In these proposals, it can be observed that web technologies have provided infrastructure for the development of distributed work systems, including the use of concepts of the semantic web to facilitate the exchange and retrieval of information in an environment of interoperability.

Information systems, and business intelligence technology built on them, also have had a clear effect on the area. In the context of data modeling, a significant number of proposals based on the use of BIM technology call for a coherent data management in projects through the use of a single model incorporating the relevant data of the various project tasks. In this regard, tracking and location technologies offer timely and accurate monitoring of on-site construction operations that can be integrated in BIM and other technologies. Data are called to be shared and centrally managed.

Regarding data storage, query and analysis, DW and data mining are also being applied in construction organizations to provide integrated stores of historical data that can be accessed through ad hoc OLAP analysis tools or explored by intelligent algorithms in search of relevant patterns useful to adjust the operation of the business. Finally, the review of the literature also found proposals based on intelligent information systems beyond data mining, such as CBR- or FL-related approaches.

Fig. 1 graphically summarizes the distribution of reviewed proposals regarding the main technologies that have been applied to each of the tasks in the construction project management.

- As is shown in the graph, for the cost management task, nearly all technologies have been applied. The technologies that highlight substantially with a greater number of proposals are DW, BIM, and CBR. This diversity of technologies is similar in the planning management task, although the technologies that stand out are BIM and GIS.

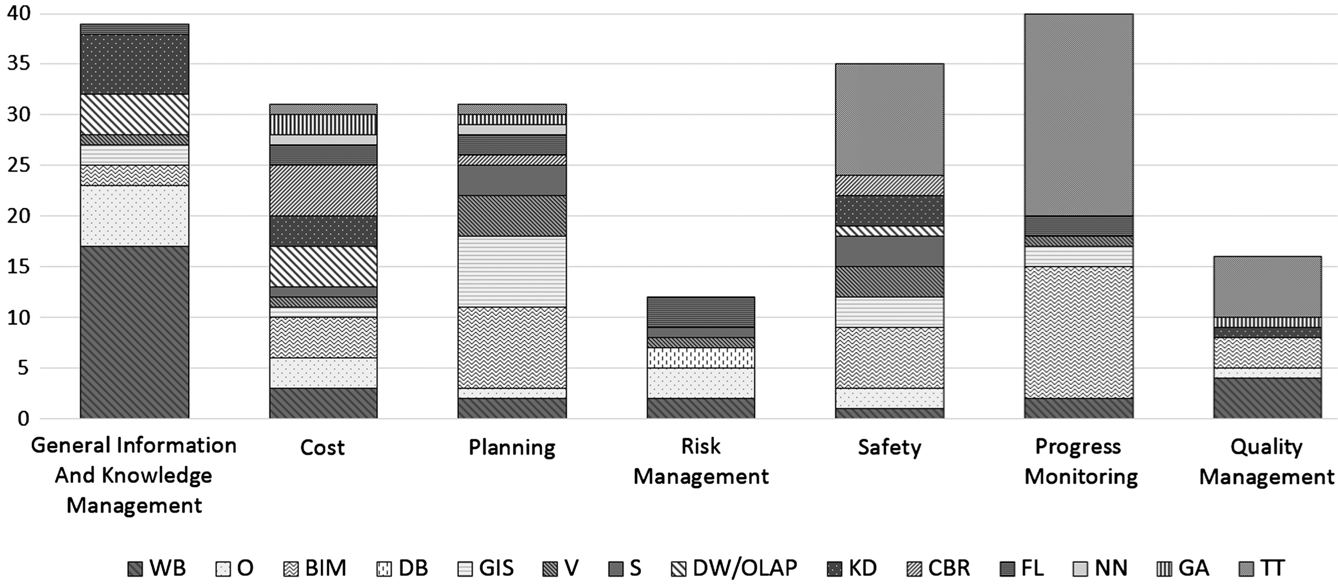

Fig. 1. Distribution of technologies per task

- Regarding the risk management and quality management tasks, the number of applied technologies is lower. In the first management task, fuzzy logic and ontology are the most applied technologies, whereas tracking and web technologies are highlighted in the second.
- For information and knowledge management, it can be observed that web is the technology that has provided infrastructure to facilitate the exchange and retrieval of information.
- Finally, in safety and progress monitoring, both BIM (with the help of other technologies like GIS) and tracking technologies play a key role in the management of these important tasks.

A summary of the analyzed proposals (see Appendix) indicates for each reference: the task of project management that is mostly focused on, the main technology that is used, and the general objective pursued by the authors. As is shown, the list of proposals is broad and the achievements are significant.

Although these achievements are many, the traditional nature and the complexity of the construction domain has prompted that ICT are not as close as desired of construction management. Thus, the construction industry is facing major challenges related to crucial data handling tasks like acquisition, storage and process, visualization, and query.

Research Challenges

Information systems and database technologies provide an efficient way to handle data in project management, but to take advantage of these information systems, data have to be integrated and unified. Information systems are reliable when they can guarantee, among others, consistency and absence of data redundancy and this can only be done when the information is strongly structured (Chassiakos and Sakellaropoulos 2008). Unfortunately, as previously noted, information in the construction domain is strongly unstructured because of the diversity of tools and participants involved in the process. This problem is present both in current and historical data.

The data integration problem is a challenge in the project at hand, in which data regarding the design coexists with data regarding the project execution. Concerning the data integration, the most promising technology is BIM because it facilitates effective project collaboration and integration of data in project activities from the design phase to the completion of the project. In recent years, BIM has attempted to support a wide range of design and construction applications including quantity takeoff, 4D simulation, planning, facility management, and clash detection. However, the huge potential of BIM has not been fully explored mainly because of the use of different BIM models among different project participants that leads to duplication of information and interoperability problems. BIM solutions will necessary come from the collaboration between the different participants at early stage to establish a reference framework with the required detail level. Additionally, the integration of other technologies are neccesary to increase the representation capability (Karan et al. 2015). This fact produces more sophisticated tools but, at the same time, limitations of existing data exchange and sharing methods become more apparent (Karan and Irizarry 2015). In any case, it is clear that all the effort of well-done data generation being carried out around the BIM technology can be useless if it is not accompanied by a necessary process of standardization. Otherwise, the benefits of integration will be local and the desired interoperability will be very limited. Unfortunately, the reality is that there is a lack of interoperability, with several standards competing for data management (Behzadan et al. 2015).

As stating that owners, designers, and contractors (in the absence of reference standards) tend to develop their own internal rules, according to the specifications of their proprietary standards. As a result, project documentation remains unstructured, irregular, and ambiguous. This heterogeneity is present in one of the most important documents, the bill of quantities, which prevents exchange and search of information in an automated and integrated way. It makes very difficult to make a comparison between similar projects that have been written by different professionals (Presto 2015).

Besides the standardization approach, other technologies are necessary to deal with information integration and interoperability problems to successfully achieve efficient and effective collaboration. Systems integration becomes an important prerequisite (Shen et al. 2010). Attempts to integrate information models using IFC have aimed to achieve these relevant objectives. However, there are practical issues in solving the integration problem. For example, during information exchange between heterogeneous systems or commercial modeling software using IFCs, some loss or change of information has been reported (Kang and Hong 2015). The open

IFC standard promotes interoperability within the building and construction domain, and for BIM in particular (BuildingSMART 2015). However, IFC by itself is not sufficient to enable interoperability with systems outside of the AEC domain, or with systems that are dynamically producing data during the operational phase (i.e., sensor and meters) (Curry et al. 2013; Karan et al. 2015).

The semantic web, which represents a fundamentally new way of formatting data that can be processed directly and indirectly by machines, offers a powerful technology that can contribute towards solving the noted interoperability problem. However, because semantic web technologies are still developing and maturing, it is often time-consuming to find efficient ways of using these technologies (Karan and Irizarry 2015). Though ontologies play an important role in information integration and in enabling semantic interoperability, there is not a single ontology available that supports all the construction management tasks (El-Gohary and El-Diraby 2010; Lee et al. 2014). Despite the contributions of these approaches, the integration of heterogeneous information sources continues to be a major challenge (Karan et al. 2015). Also in relation with the semantic web, research efforts (i.e, those related to linked data) can transform the way data are shared in the web. Moreover, this technology is essential to design cloud data services as an alternative to the way traditional building management systems are designed.

Concerning the integration of execution data, in recent years, research has focused on facilitating the on-site acquisition process to support decision making through the use of tracking technologies that allow real-time data collection. The performance of these technologies is improving every day. However, on-site data acquisition still faces important difficulties regarding the detection of operation-level progress, such as lack of detail in plan model, high-level work breakdown structure in construction schedules, static and dynamic occlusions, difficult scene understanding, lack of accuracy, and simultaneous recognition (Han and Golparvar-Fard 2015; Seo et al. 2015). The disadvantage is that most site data are still manually entered far from an automatic data acquisition. As a result, the data are produced by diverse sources, resulting in poor data compatibility.

Fresh data regarding the project at hand are important not only to feed operational databases but also to feed integrated repositories of historical data. The building of these repositories will be easier in the future when standardization and automatic data acquisition are a reality, but today historical data already generated with the conventional methodologies have to be managed somehow. And it is not a trivial matter. As previously discussed, the data in many cases are unstructured in several formats; conversely, while sharing format, each professional involved in a project has his or her own language and way of organizing data. The reason is that the community of professionals involved in the project development process is very diverse and that diversity is very clearly reflected in the language used to describe the projects, despite being a highly technical language. To mention only an example, bill of quantities are quite different in their wording and structure depending on the professional who develops them, even within the same company. In this sense, the use of text mining techniques and intelligent classification methods can help to automate the process of extracting information from existing documents to be incorporated into a centralized warehouse. Although there are some proposals on this matter (Martínez-Rojas et al. 2013), studies in this area are still few and there is much work to do (Caldas and Soibelman 2003). To develop research in this sense is vital. In spite of the previously noted efforts of standardization, the current kinds of documents are not going to disappear in the foreseeable future because of the traditional nature of the construction industry.

Beyond issues related to data acquisition, data processing also presents significant challenges. The amount of available data has gradually increased with the growing complexity of construction projects and the large number of participants involved in them. Moreover, as progress is made towards overcoming the challenges for achieving automatic data acquisition, this problem will become greater. Dealing with this big data problem requires technological advancement for managing, analyzing, visualizing, and extracting useful information from large data sets. However, the processing and reduction of data to produce meaningful conclusions and the fusing of data from a variety of sources remain obstacles, e.g., to the achievement of a practical and comprehensive automated progress-tracking solution for construction sites (Shen et al. 2010; Shahi et al. 2014).

Finally, in the visualization and query data area, there are also many challenges to be explored to facilitate user access to the data they need. Fortunately, the rapid improvements in ICT have provided engineers with powerful tools for visualizing and querying data.

- Visualization techniques are growing and have become an essential part in many tasks, such as those related to safety, planning and progress, and quality monitoring. In spite of the feasibility of visualization techniques, it still faces the previously discussed challenge related to efficiently processing the massive on-site data collected from construction sites and also in the computational complexity of detailed deviation between as-planned and as-built analysis (Golparvar-Fard et al. 2013). Moreover, to provide full information on the current stage of execution, it will be necessary to extract (from the collected data) material information and spatial relationship and interconnectivity among elements, beyond geometrical information (Dimitrov and Golparvar-Fard 2014). Generally, tools cannot easily visualize the site layout beyond the construction-related elements and the visualization of dynamics operations or temporary objects is still limited (Chen and Luo 2014).
- Data query is the other access point for users. Although conventional database systems incorporate query capabilities, which are well assumed and tested, they are not flexible enough when nontechnical users need to pose ad hoc queries to the information system. This is a challenge in both operational and analytical data processing. In recent years, research on data warehousing and OLAP has been conducted to make it easier to access the data and these technologies have been profusely used in the construction domain. However, the database community has also explored other query solutions more friendly to human users (e.g., those based on the use of natural language and context-awareness in the interaction with the system) (Galindo 2008; Turner et al. 2010; Cadenas et al. 2014).

In an ideal scenario, the authors would be working with an nD single data model of reference that incorporates all required data in the different phases of the project lifecycle. In this integrated context, ubiquitous and interoperable data generation processes (based on the use of mobile computing and automatic real-time sensors) would provide adequate data to the information system of enterprises (Yang et al. 2015). Even in this ideal scenario, difficult to spot in the short term in many organizations, the problem of data management, far from being resolved, will become a problem of big data, given the difficulties that conventional data management and visualization techniques have when faced with large and complex data sets. Therefore, the major research being done in the world of ICT in relation to the big data management and analysis must be carefully observed by those responsible for data management in companies. In any case, the first step is to consider data management as a major requirement in every project.

Appendix. Findings in ICT Regarding the Main Tasks in Construction

References	Task	Technology	Goal
S. Staub-French et al., "An ontology for relating features of building product models with construction activities to support cost estimating," working paper, Center for Integrated Facility Engineering (CIFE)	C	O	To represent knowledge and enable knowledge sharing
Moon et al. (2007)	C	OLAP/DW	To provide useful information for strategic decisions
Bansal and Pal (2007)	C	V/GIS	To enhance the accuracy of cost estimation
Nie et al. (2007)	C	OLAP/DW	To provide useful information for strategic decisions
Benjaoran (2009)	C	WB	To improve the efficiency of the business process
Chou (2009)	C	WB/CBR	To enhance retrieval of similar previous projects at project initiation phases for helping the decision making
Kim and Kim (2010)	C	CBR/GA	To enhance the accuracy of cost estimation
Ji et al. (2011a)	C	CBR	To enhance the accuracy of cost estimation and user-friendliness
Chou (2011)	C	S	To increase the cost simulation accuracy
Ji et al. (2011b)	C	GA/CBR	To enhance the accuracy of cost estimation
Kim et al. (2012)	C	KD	To improve accuracy in cost estimation and provide transparency in the estimating process
Cheung et al. (2012)	C	BIM	To incorporate cost estimation into the early stage of design
Chi et al. (2012)	C	KD	To predict the performance of construction projects
Cho et al. (2013)	C	OLAP	To access multifunctional, multidimensional, and multiple levels of detail of project execution data
Williams and Gong (2014)	C	KD	To improve prediction of cost overruns
Lawrence et al. (2014)	C	BIM	To decrease the time needed for an estimator to update their estimate given an updated design and to generate a more accurate estimate
Du and Bormann (2014)	C	NN/CBR	To save time for estimators
Lee et al. (2014)	C	BIM/O	To automatically infer the most appropriate work item on the basis of work conditions
Martínez-Rojas et al. (2015)	C	OLAP/DW/FL	To provide useful information for strategic decisions
Niknam and Karshenas (2015)	C	BIM/WB/O	To facilitate finding, accessing, and combining the information necessary for cost estimation
Knight and Robinson Fayek (2002)	C/RM	FL	To enable the assessment of the project characteristics and risk events to be made subjectively. A more realistic model in the design context
Caldas and Soibelman (2003)	GI/KM	KD	To improve information organization and access in construction management information systems
Chau et al. (2003)	GI/KM	DW	To provide useful information for strategic decisions
Tserng and Lin (2004)	GI/KM	WB	To capture and reuse project knowledge
Chan and Leung (2004)	GI/KM	WB	To enhance Information management
Ahmad et al. (2004)	GI/KM	DW/OLAP/GIS	To provide useful information for strategic decisions
Lima et al. (2005)	GI/KM	WB/O	To provide adequate search and indexing capabilities
El-Diraby et al. (2005)	GI/KM	O/WB	To represent knowledge and enable knowledge sharing
Caldas et al. (2005)	GI/KM	KD	To integrate project documents in model-based information systems
Lin et al. (2006)	GI/KM	WB	To enhance knowledge management
Fan et al. (2006)	GI/KM	DW/WB	To provide useful information for strategic decisions
Rujirayanyong and Shi (2006)	GI/KM	DW	To provide useful information for strategic decisions
Forcada et al. (2007)	GI/KM	WB	To successfully manage project documents
Soibelman et al. (2008)	GI/KM	KD	To discover novel knowledge from large construction databases
Kivrak et al. (2008)	GI/KM	WB	To enhance knowledge management
Lin (2008)	GI/KM	WB	To capture and reuse project knowledge
Chassiakos and Sakellaropoulos (2008)	GI/KM	WB	To facilitate construction information management and communication
El-Gohary and El-Diraby (2009a)	GI/KM	WB/O	To represent knowledge and enable knowledge sharing
El-Gohary and El-Diraby (2010)	GI/KM	O	To represent knowledge and enable knowledge sharing
Zhang and El-Diraby (2011)	GI/KM	WB	To enhance knowledge management
Tan et al. (2012)	GI/KM	WB	To capture and reuse project knowledge
Lin and Lee (2012)	GI/KM	WB	To enhance knowledge management
Al Qady and Kandil (2013)	GI/KM	WB	To successfully manage project documents
Martínez-Rojas et al. (2013)	GI/KM	FL	To integrate project's data from diverse sources a posteriori
Park et al. (2013c)	GI/KM	WB/O	To enhance knowledge management
Dib et al. (2013)	GI/KM	GIS	To enhance communication, documentation, and knowledge sharing throughout the project lifecycle
Wen-der and Jia-yang (2013)	GI/KM	KD	To retrieval documents from vast databases
Qady and Kandil (2014)	GI/KM	KD	To find semantic relations between documents in data sets
Lin (2014)	GI/KM	WB/BIM	To capture and represent construction project knowledge

Appendix (*Continued.*)

References	Task	Technology	Goal
Deshpande et al. (2014)	GI/KM	BIM/V	To capture and reuse project knowledge
Viljamaa and Peltomaa (2014)	GI/KM	O	To improve process management through more effective information integration, processing, and exploitation
Antony Chettupuzha and Haas (2015)	GI	KD	To manage the flow of information in an organized manner
Waly and Thabet (2003)	P	V	To test various execution strategies in a near reality sense before the actual start of construction
Poku and Arditi (2006)	P	V/GIS	To effectively communicate the schedule and progress information
Huang et al. (2007)	P	V/S	To assist project planners to better understand the construction process and predict possible mistakes in early stages
Song and AbouRizk (2008)	P	NN/S	To measure and predict labor productivity
Bansal and Pal (2008)	P	GIS	To facilitate a better understanding of the construction sequence and to visualize a buildable schedule on a computer screen
Bansal and Pal (2009)	P	GIS	To facilitate a better understanding of the construction sequence
Castro-Lacouture et al. (2009)	P	FL	To generate construction project schedules using fuzzy mathematical models and to incorporate restrictions on items such as materials, time, and cost
Li et al. (2009)	P	V/S	To assist project planners to better understand the construction process and predict possible mistakes in early stages
Mikulakova et al. (2010)	P	BIM/CBR	Automated generation of construction schedules by using experiences from successfully executed similar projects. Evaluation of construction alternatives
Zayed and Wakil (2012)	P	FL	To predict task durations for construction activities
Irizarry and Karan (2012)	P	GIS/BIM	To identify feasible locations for tower cranes
Song et al. (2012)	P	BIM	To enable users to establish effective construction plans and to make the right decisions by predicting the results of projects
Moon et al. (2015)	P	GA/BIM	To find an optimal schedule with the minimum overlapping activities for the enhancement of a project's operational performance
Tserng et al. (2014)	P	WB/BIM	Easy and effective visual updating of as-built schedule information
Karan et al. (2013)	P	GIS/TT	To improve decision making about design and planning of preconstruction operations
Liu et al. (2015)	P	BIM	To generate schedules for construction projects by performing simulation-based scheduling from the BIM model
Karan and Irizarry (2015)	P	BIM/GIS/WB/O	To enable semantic interoperability between building and geospatial heterogeneous data
Kang and Hong (2015)	P	GIS/BIM	To integrate data from heterogeneous sources
Cheung et al. (2004)	PM	WB	To help project managers in monitoring and assessing project performance
Caldas et al. (2006)	PM	TT	To improve the tracking and locating of materials on construction job sites
Wang et al. (2007)	PM	WB/TT	To improve the efficiency and effectiveness of on-site data acquisition and information sharing among participants
Jang and Skibniewski (2009)	PM	TT	To improve traditional methods of construction progress tracking
Bosché et al. (2009)	PM	TT/BIM	To automatically tracking, analysis, and visualization of progress to improve decision making
Golparvar-Fard et al. (2009)	PM	TT/BIM	To represent progress deviations through superimposition of 4D as-planned model over time-lapsed photographs
Bosché (2010)	PM/QM	BIM/TT	To automatically tracking, analysis, and visualization of progress to improve decision making for project control
Elbeltagi and Dawood (2011)	PM	BIM/V/GIS	To facilitate tracking and monitoring of construction progress. Effective communication of the actual progress information
Park et al. (2012)	PM	TT	To track and locate materials on construction job sites
Golparvar-Fard et al. (2011)	PM	BIM/TT	To enhance identification, processing, and communication of progress discrepancies
Razavi and Haas (2012)	PM	FL/TT	To deal with the imprecision, vagueness, and ambiguity within the acquired data
Turkan et al. (2012)	PM	BIM/TT	To improve traditional methods of construction progress tracking
Jiang et al. (2012)	PM	TT/FL	To select a suitable technology for tracking construction materials
Pradhananga and Teizer (2013)	PM	TT	To track and analyze construction site operation of equipment resources
Irizarry et al. (2013)	PM	GIS/BIM	To facilitate tracking and monitoring the supply chain process
Kim et al. (2013a)	PM	BIM/TT	To measure construction progress

Appendix (*Continued.*)

References	Task	Technology	Goal
Naticchia et al. (2013)	PM/SF	TT	Real-time information for proactive prevention
Bosché et al. (2014)	PM	BIM/TT	To improve assessment of as-built status of construction projects
Dimitrov and Golparvar-Fard (2014)	PM	BIM/TT	To improve progress monitoring by automating recognition of materials
Golparvar-Fard et al. (2015)	PM	BIM/TT	To automatically tracking, analysis, and visualization of progress to improve decision making for project control
Shahi et al. (2014)	PM	BIM/TT	To automate progress tracking of construction activities
Han and Golparvar-Fard (2015)	PM	TT/BIM	To represent progress deviations through superimposition of 4D as-planned model over time-lapsed photographs
Liu and Golparvar-Fard (2015)	PM	TT	To facilitate the analysis of large collections of videos
Chin et al. (2004)	QM	TT/WB	To enhance the efficiency and effectiveness of automated data acquisition and information sharing among participants
Lam and Ng (2006)	QM	WB	To improve communication and coordination and enhance quality
Akinci et al. (2006)	QM	TT	To improve traditional project quality control processes
Wang (2008)	QM	TT/WB	To enhance the efficiency and effectiveness of automated data acquisition and information sharing among participants
Kim et al. (2008)	QM	WB/TT	To improve the efficiency and effectiveness of on-site data acquisition
Zhu and Brilakis (2009)	QM	TT	To automatically assess the effect of two common concrete surface defects
Park et al. (2013a)	QM	BIM/O	To reduce and prevent the defect occurrence during the construction process
Kwon et al. (2014)	QM	BIM/TT	To reduce and improve the workload of site managers
Chen and Luo (2014)	QM	BIM	To ensure information consistency and facilitate quality management process
Cheng et al. (2015b)	QM	GA/KD	To provide defect related knowledge from past cases to make defect prevention strategies
Baloi and Price (2003)	RM	FL	To handle uncertainty in risk factors affecting construction cost performance
Han et al. (2008)	RM	WB	To enhance information access to make better decisions
Dikmen et al. (2008)	RM	DB	To store risk-related information
Tserng et al. (2009)	RM	O	To assist in risk identification, analysis and response. To increase effectiveness of RM workflow
Nieto-Morote and Ruz-Vila (2011)	RM	FL	To deal with subjective judgement
Kang et al. (2013)	RM	V/S	Graphically analyze the degrees of risks
Zhong and Li (2014)	RM	WB/O	To enable risk knowledge to be presented in a computer-interpretable and semantically inferable way. To enable knowledge executable and reused in a more flexible, dynamic and semantic way
Yildiz et al. (2014a)	RM	O/DB	To store risk-related information
Giretti et al. (2009)	SF	TT	To monitor in real-time the position of both workers and equipment at outdoor construction sites
Chae and Yoshida (2010)	SF	TT	To prevent collision accidents of workers with heavy equipment
Wu et al. (2010)	SF	TT	Real-time information for tracking near-miss accidents
Manase et al. (2011)	SF	GIS	To enhance the analysis of construction environment information and understanding of various factors in the construction industry for the mitigation of accidents
Martínez-Rojas et al. (2011)	SF	OLAP/DW	To facilitate the analysis of safety indicators to extract potential and useful patterns from large amounts of data to improve decision-making process
Bansal (2011)	SF	GIS	To facilitate understanding construction sequence and predicts places and activities that have higher potential for accidents
Lee et al. (2011)	SF	TT	To provide accurate and robust localization performance in construction sites
Carbonari et al. (2011)	SF	TT	To alert potential overhead hazards
Rivas et al. (2011)	SF	KD	To extract information on workplace accidents from a database
Chun et al. (2012)	SF	V/S	To assist project planners to better understand the construction process and predict possible mistakes in early stages
Yang et al. (2012)	SF	TT	To improve construction site safety
Zhang et al. (2013)	SF	BIM/S	To detect safety hazards and suggest preventive measures to users
Fan and Li (2013)	SF	KD/CBR	Effective retrieval of historical cases
Wu et al. (2013)	SF	TT	Real-time information for proactive prevention
Guo et al. (2013)	SF	V/S	To simulate and identify safety problems of construction processes
Han et al. (2013)	SF	TT	To automatically detect unsafe actions of workers

Appendix (*Continued.*)

References	Task	Technology	Goal
Cheng and Teizer (2013)	SF	TT/V	To automatically monitor and visualize safety and activity information in field operations
Kim et al. (2013b)	SF	BIM/CBR	To retrieval similar accidents
Qi et al. (2014)	SF	BIM	To plan for preliminary safety measures to address construction site hazards from the beginning of the project
Le et al. (2014)	SF	WB/O	To improve communication and representation for construction safety information
Han et al. (2014)	SF	TT	To automatically detect unsafe actions of workers
Zhang et al. (2015b)	SF	BIM	To identifies potential fall hazards dynamically on the basis of the construction schedule
Cheng et al. (2015a)		GIS/BIM/KD	To semi-automatically map BIM and 3D GIS schemas
Zhang et al. (2015a)	SF	BIM/O	To formalize construction safety knowledge and connect it with BIM for automated hazard analysis and safety task scheduling
Seo et al. (2015)	SF	TT	To monitor safety and health at real construction sites and identify potential solutions

Note: General information and knowledge management (GI/KM); cost (C); planning (P); risk management (RM); safety (SF); progress monitoring (PM); quality management (QM); ontology (O); web-based (WB); building information modeling (BIM); geographic information systems (GIS); virtual (V); simulation (S); data warehouse (DW); ontology (O); online analytical processing (OLAP); knowledge discovery (KD); case-based reasoning (CBR); genetic algorithm (GA); neural network (NN); fuzzy logic (FL); tracking technologies (TT).

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