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A framework for using mobile computing for information management on construction sites

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ABSTRACT

The application of mobile computing in construction is becoming a major research theme in the domain of Information Technology in Construction. However, most research in this area focuses on a detailed aspect or single facet of a mobile computing technology. This paper introduces a framework for the implementation of mobile computing on construction sites, which comprises an application model and a technical model. The application model identifies the features of mobile computing, construction personnel, construction information, and construction sites, and explores the interactions that are likely to affect the implementation of mobile computing. The technological model generalizes mobile computing technologies and gives system designers a clear structure for designing mobile computing systems from a technical perspective. Finally, a case study of a real construction situation is used to validate this framework.

1. Introduction

In recent years, construction information management has greatly benefited from advances in Information and Communications Technology (ICT) through increasing the speed of information flow, enhancing the efficiency and effectiveness of information communication, and reducing the cost of information transfer. Current ICT support has been extended to construction site offices. However, construction projects typically take place in the field where construction personnel have difficulty in gaining access to conventional information systems for their information requirements. The advances in affordable mobile devices, the increase in wireless network transfer speeds and the enhancement in mobile application performance, mean that mobile computing has a great potential to improve on-site construction information management.

First, this paper reviews current research in the area of mobile computing in construction. Following a description of the research methodology, this paper introduces a framework for using mobile computing for construction site information management. This framework includes an application model and a technical model. The application model identifies the key factors that determine the use of mobile computing in particular circumstances and explores both the interactions and restrictions between these factors through the development of sub-models. The technological model generalizes mobile computing technologies and gives system designers a clear structure for designing mobile computing systems from a technical perspective. The framework is validated through a case study of a real construction situation.

2. Mobile computing in construction

2.1. Problems in construction site information management

The construction industry is an information-intensive industry since hundreds and thousands of pieces of information need to be transferred and exchanged during the project life-cycle. There are many research efforts that focus on the design, development and practices of construction information management systems, such as Electronic Document Management (EDM) systems ([17,22,30]; Groupware Systems [15]; Knowledge Management systems [11,23,36], Web-based Project Management systems [37,40] and Collaborative systems[4,16,49].

Information Technology has been widely applied at different information management levels in the construction industry. However, the implementation of construction projects takes place on construction sites where personnel have difficulty in gaining access to conventional computer systems. Managers, engineers and other key personnel move frequently from site to site and from site offices to the sites. It is often inconvenient to carry bulky drawings and documents onto construction sites. The quality, quantity, and timing of information can either hinder or facilitate the success of a project during the construction stage. However, the main information transferred and exchanged on construction sites is in the form of paper-based files and the paper-based tasks that construction personnel carry out in their normal work are numerous [7]. Because current paper-based on-site construction processes are unable to

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deliver just-in-time information, the paper-based pipeline of information gets clogged and creates an information deficit. Ineffective information communication on construction sites can lead to the neglect of important issues that require a quick response, which may result in on-site decisions being deferred [42]. The inefficiency of on-site queries and interactions between project participants may cause downtime, redoing work, waste and cost overruns. Only when the bottleneck of information communication on construction sites is resolved can integrated design and construction be achieved on a larger scale [18].

The emergence of Mobile Computing (MC) has the potential to extend the boundary of information systems from site offices to actual work sites and ensure real-time data flow to and from construction work sites. Because the construction industry has its own specific characteristics, including the involvement of various project partners, the separation between site offices and work sites, and the mobility of construction personnel; mobile computing has the potential to increase the effective use of IT in an integrated and holistic way. However, mobile computing technologies that can be implemented to solve particular problems in construction need to be evaluated and potential areas that can be improved by using these technologies need to be identified.

As a potential technology, mobile computing is becoming a major research theme in the domain of Information Technology in Construction. However, most research in this area focuses on a detailed aspect or single facet of mobile computing. Examples include the "technology push" method that evaluates what a single mobile computing technology can offer and finds a problem it can solve, the test of using mobile computers on sites, and the examination of wireless networks for transferring construction information. For a particular technology to be widely adopted in the industry, the general concept of the technology and the interrelationship between that technology and the industry should be identified and explicated. However, the key factors that can affect the use of mobile computing in construction and the links between mobile computing and on-site information management have not been clearly identified and not comprehensively understood. Therefore, a detailed framework that includes those factors and their interrelationships is necessary to provide guidance on the effective development and implementation of mobile computing for on-site information communications.

2.2. The implementation of mobile computing technologies in construction

Research in mobile computing has mostly been of a "technology push" nature, with a focus on what mobile computing technologies can offer, and investigating solutions to particular industry problems. Examples include the evaluation of IP Telephony technology for construction information communication [5], the implementation of wearable computers on construction sites [9,20,21,27,28,35], the use of wireless sensors [12,13,24,25,29,32,41], and the auto-ID technology that integrates PDAs and bar code scanning together [19,26,43,45–47]. The key findings of some of the above examples are briefly described below.

Efficient communication systems are important for the improvement of information transmission speed between the site office, headquarters and the supply chain. However, traditional circuit-switched based telecommunication systems are expensive and their coverage may not reach remote areas of construction sites. This situation leads to the evaluation of Internet Protocol Telephony technology that is cheaper, rapidly deployable and more efficient, and an investigation into its potential use in construction. Beyh and Kagioglou [5] proposed a theoretical framework to integrate Internet Protocol (IP) Telephony onto construction site communication infrastructures and to overcome the implementation barriers. In their later research, Beyh and Kagioglou [6] further explored various models of communication under this common framework and outlined some of the implementation issues including the business case for an improved way of working. Benefits that IP Telephony can offer to construction information communication include the integration of all types of contact streams (voice, data, fax and video) onto a single network, providing a platform for productivity-enhancing applications, the reduction of line charges, network costs and IT expenses, and simple operation management.

A wearable computer is a small portable computer that is designed to be integrated into the user's clothing or attached to the body through other means such as a wristband. Wearable computers differ from PDAs that are designed for hand-held use. Wearable computers normally integrate other technologies including wireless networks, speech recognition, touch screens, eye-tracking or lip-reading interface, head-worn display, and chest-worn display. Research that aims to introduce wearable computers into the construction industry include the model for site visits using wearable computers [28], the mobile video system [27], the design of wearable computers for supporting construction progress monitoring [35], wearable computers for field users [21], the test of wearable computers in a real-life construction situation [20], and the interaction between users and wearable computer systems [9].

Wireless sensors are small devices which are capable of performing a sensing task. A Wireless Sensor Network consisting of a central station and one or more remote stations is a network of such devices capable of a cooperative sensing task. Delsing et al. [12] described the proposed architecture based on heterogeneous sensors and actuator devices accessible over the Internet. Through a number of possible implementation scenarios, including health and safety applications, asset tracking, logistics, building monitoring and provision of equipment maintenance information, Domdouzis et al. [13] illustrated the potential benefits of Wireless Sensor Networking technology in the construction industry. Lee and Kang [25] applied the wireless sensor technology into a mass concrete curing management system that consists of three components — wireless data acquisition, strength estimation and an alarm. Because of the different performances of wireless technologies including RFID, laser scanners and embedded sensors, Kiziltas et al. [24] provided a comprehensive assessment for technical performance and process implications in using these technologies on construction sites. In order to speed the development of wireless sensor applications, O'Brien et al. [32] provided a flexible software middleware, which enables more flexible reuse of data to make it available to a range of decision support applications. Skibniewski and Jang [29] developed a framework for tracking construction assets, which combined radio frequency (RF) and ultrasound (US) signals, and demonstrated that the combination of RF and US have an enhanced accuracy performance over the utilization of an RF signal only. Shin and Jang [41] discussed the use of ubiquitous AR environments for construction sites and explored displays, tracking systems, and servers for ubiquitous AR environments.

Current deployment of mobile applications has focused on static information delivery without consideration of user-contexts. Awareness of a user's context including the user profile, role, preferences and construction task, can enhance the efficiency and accuracy of transferring construction information to on-site users. Context-awareness and personalised information delivery will save valuable time and has the potential to improve efficiency and productivity [1]. Behzadan et al. [3] developed a location tracking system that tracks a user's spatial context and delivers contextual data continuously in both outdoor and indoor environments. Omar and Ballal [33] reported an ongoing research based on the concept of context-aware services for construction supply chain logistics. Their work focused on the identification of context dimensions (such as users, environmental and project contexts), the selection of technologies (such as wireless sensors and RFID) to capture context-parameters, and the selection of supporting technologies (such as wireless communication, Semantic Web, Web Services and agents).

A bar code system is the automatic identification solution that streamlines identification and data acquisition. A bar code-enabled mobile computer that integrates a bar code scanner can be a powerful portable data collection tool that enables on-site construction personnel to seamlessly integrate work processes. Applications of bar-coding technology in the construction industry include material and build component management on construction work sites [26,43], the identification of documents and drawings [19,45], equipment tracking and management on construction sites [39], and construction supply chain management using PDA and bar codes [46].

Mobile computing technologies have been implemented in many construction processes. Rebolj et al. [34] developed an automated construction activity monitoring system based on a mobile computing supported communication environment. Dong et al. [14] discussed a horizontal tabletop user interface that integrates mobile computing and wireless communication to facilitate synchronous construction site to office collaboration for construction defect management. Other mobile computing research includes security and safety of wireless networks [44], CAD data visualization on mobile devices [48], and the real-time navigation support system [39].

2.3. Potential, benefits and challenges

Although mobile computing can be used to improve the efficiency of information communication on construction sites and has been assessed in a site environment, the potential for mobile computing has not been fully exploited for the construction industry, and mobile computing technologies are not broadly adopted by construction companies. Therefore, it is essential to clearly identify what areas can be improved from the implementation of mobile computing and how mobile computing can benefit the construction industry. After a comparison of traditional construction tasks and the same tasks with the introduction of mobile computers, Saidi et al. [38] identified construction tasks that are suited for applying mobile computing and those that are not suited. Generally, construction tasks that require access to text information, viewing a small detail of a document, the entry of binary data, the entry of data into a form or instant transfer of information, are suitable for mobile computing. On the other hand, tasks that require complex computing, a “big-picture” view of a document, a constant connection to networks, lots of manual data entry, or under tough environment, are not suitable for the application of mobile computing. Compared with Saidi's research that focuses on the identification of construction tasks, the COMIT research project [10] aimed to provide an indication of which mobile computing technologies would be appropriate for each of the construction processes that could benefit from the use of mobile computing. These processes are generally communication processes, data capture processes and identification processes.

In order to convince construction companies to use mobile computing technologies, the development of mobile computing systems should ensure that Return of Investments (ROI) exceeds the cost of obtaining information wirelessly. Olofsson and Emborg [31] conducted a series of in-depth interviews to investigate the Return of Investments from the three aspects of the construction sector in which mobile computing can be applied, the economic impact of mobile computing, and the ways that mobile computing integrates in specific operations. They concluded that the benefits of using mobile computing include reduced lead times, more efficient use of resources in the field and enhanced quality of work. In order to increase the awareness and convince more construction personnel to realise the benefits of using mobile computing in construction, Bowden et al. [8] conducted a number of case studies which involved construction personnel using mobile devices to resolve specific construction problems and summarized the areas that can be improved through the use of mobile IT both in the present and the future. These areas include a reduction in construction time and capital cost of construction, reduction in operation and maintenance costs, reduction in defects, reduction in accidents, reduction in waste, increase in productivity, and increase in predictability.

Although the potential of mobile computing has been explored through various evaluations, other research has revealed limitations and barriers to mobile computing implementations in construction. Saidi et al. [38] found two barriers to the use of mobile computing. The first barrier is the limitations of mobile computers including the screen size, screen visibility, processing capability, and input method. The second barrier relates to the construction industry's characteristics with respect to the conditions of the physical (e.g. temperature, humidity, dust, etc.) and organisational issues such as the industry's fragmentation and low risk tolerance. Key challenges of mobile computing in construction discussed by Anumba et al.[2] include the complexity and cost of developing mobile application, the need to focus on the users' requirements, the need for integration with existing applications, the adaptation of content to fit multiple device types, and the choice of wireless technologies.

3. Research methodology

The aim of this research was to develop a framework that explores how mobile computing technology can be used in construction site environments with respect to the retrieval and transfer of on-site information. The proposed framework includes two models: an application model and a technological model. The application model identifies all the major factors involved and the way they can affect the design, implementation, and maintenance of mobile computing in on-site information communication. The technological model gives the details of the available technologies for building up a mobile computing system. To validate the framework, an operational scenario was developed to demonstrate how mobile computing can be used to retrieve and transfer information on particular construction sites, and how mobile computing can enhance the effectiveness of the construction process for particular users.

The design of methodology and selection of research methods should consider the aims and objectives of the research and the research questions. Table 1 illustrates the research strategy that consists of four steps employed in this research project and the research method used in each step.

Table 1
Research strategy and selected research methods.

Research step	Research objective	Research question	Research method
Step 1	To investigate the concept of construction information management.	What is meant by construction information management?	Literature review
		How do construction personnel manage information on construction sites?	Case study
		What is the existing mechanism of information retrieval and transfer on construction sites?	Survey
Step 2	To investigate the state of the art of mobile computing technologies and their practices in the construction industry.	What are the current developments and practices of mobile computing in the construction industry?	Literature review
Step 3	To develop a framework for exploring the use of mobile computing in construction site information management.	How can mobile computing be used on construction sites by construction personnel to manage on-site information?	Modelling
Step 4	To demonstrate the validity of the framework through an illustrative example.	How can the developed framework be used in real construction situations?	Case study

The literature reviewed by this research project dates back over several years and included academic papers, books, industrial articles, industrial reports, technical specifications and electronic resources.

Initial findings from the literature were used to develop a conceptual model for mobile computing (as comprising: "mobile computer", "wireless network" and "mobile application"). The conceptual model was followed by a case study, which involved visits to three construction sites with varying project types and interviews with various construction personnel. Findings from this case study identified the variety of roles on construction sites, the main information they need to support their construction activities and current IT support.

A web-based survey was then conducted to investigate the information needs of particular users, the nature of on-site information, and the mechanisms for retrieving and transferring information on construction sites.

The validity of the developed framework needed to be demonstrated through an illustrative example. The final research step used a case study as the research method to validate the developed framework in a real construction situation through the use of scenarios for specific construction operations.

Findings from the literature review, case study and the survey were used as the evidence to set up the final framework. The analysis and generalisation of features of commercially available mobile computing products provided the identification of sub-factors for the primary factors of "mobile computer", "wireless network", and "mobile application". The visit to construction sites and the interviews with construction personnel presented the general environment and circumstance of "construction site" that is one primary independent factor in the framework. The survey coupled with the case study identified the sub-factors, such as "user's role", "user's mobility", "information type", "information format", "file size", and "information flow", for the two primary factors of "user" and "construction information". The conceptual framework shows the link between the user and the mobile computer, which is the issue of Human Computer Interaction (HCI) presented in the final framework. The information requirements of different construction personnel provided the evidence of what types of construction information mobile computing have to deal with and the concern of how mobile computing can meet users' information needs. The nature of on-site information investigated in the survey raised the issue of how mobile computers coupled with mobile applications can input and output construction information, and whether a wireless network has the capability to transfer them at satisfactory speeds. The mechanism of construction site information management indicated the information sources from which users retrieve information and the information destinations to which users transfer information using mobile computing technologies. The directions of information flow require mobile computers and mobile applications to have appropriate connection and data transfer methods. In general, findings from the literature review, the case study and the survey provided the identification of primary factors and sub-factors, and the exploration of interrelationships between these factors.

4. The framework for using mobile computing for information management on construction sites

4.1. The conceptual framework

Fig. 1 shows a conceptual framework for using mobile computing for information management. This framework is derived from the review of previous mobile computing research and analysis of current mobile computing systems. According to the review, previous research focused on detailed aspects or single facets of mobile computing. It is necessary to discuss the "whole picture", including technologies, system structure, and the applied background. This framework provides a general consideration for applying mobile computing technologies for managing information on construction sites. It identifies the general structure of mobile computing systems and major research issues including mobile computing technologies, system users, application circumstances, construction information and the relationships between them. However, because of the complexity of managing information on construction sites and the variety of mobile computing technologies, a conceptual framework is not enough to build up a mobile computing system. This research, form an application and a technological perspective, provides two detailed models: the application model and the technological model.

4.2. The application model for using mobile computing for information management on construction sites

The application model identifies six primary factors first of all. Then, each of these primary factors is further divided into sub-factors that correspond to the detailed features of the relevant primary factor. Finally, the model is broken down into different sub-models, each of which presents the specific relationships between two primary factors.

The top-level model, shown in Fig. 2, consists of six primary factors, three independent factors and three dependent factors. The three dependent factors, "mobile computer", "wireless network" and "mobile application", are the fundamental components of the concept of mobile computing. The three independent factors, "user", "construction information" and "construction site", are elements that determine the use of mobile computing in a particular context. The independent factors explain the specific construction environment in which mobile computing will be implemented to manage information, and determine the design of mobile computing systems. Therefore, the three components of mobile computing are the dependent factors where the consideration of implementation should depend on the various construction circumstances defined by the independent factors.

There are three major connections in the developed framework, which include the relationships between the three dependent factors, relationships between the three independent factors, and relationships between the independent factors and the dependent factors. In order to explore these relationships in great depth, the primary factors have been further divided into sub-factors and the top-level model is therefore decomposed into various sub-models, each of which represents the detailed relationship between two primary factors.

4.3. The application sub-model of "user" and "mobile computing"

The "user" in this framework refers to the construction personnel who use mobile computing technologies to assist them with their information management tasks on construction sites. The interrelationship between the "user" and "mobile computing" refers to the implementation of mobile computing from the user's perspective with the consideration of how the user interacts with mobile computing systems to meet their specific information needs. Fig. 3 shows links between identified sub-factors of "user" and "mobile computing".

- *User and mobile computer*. One of the key issues when using mobile computing in construction is the fact that most users need to interact with mobile computers to perform their information management tasks. Therefore, the interrelationship between the "user" and "mobile computer" focuses on Human Computer Interaction (HCI) for the hardware perspective. HCI designs from the hardware perspective require that data input and output equipment of a mobile computer should ensure that users can process information on construction work sites efficiently and

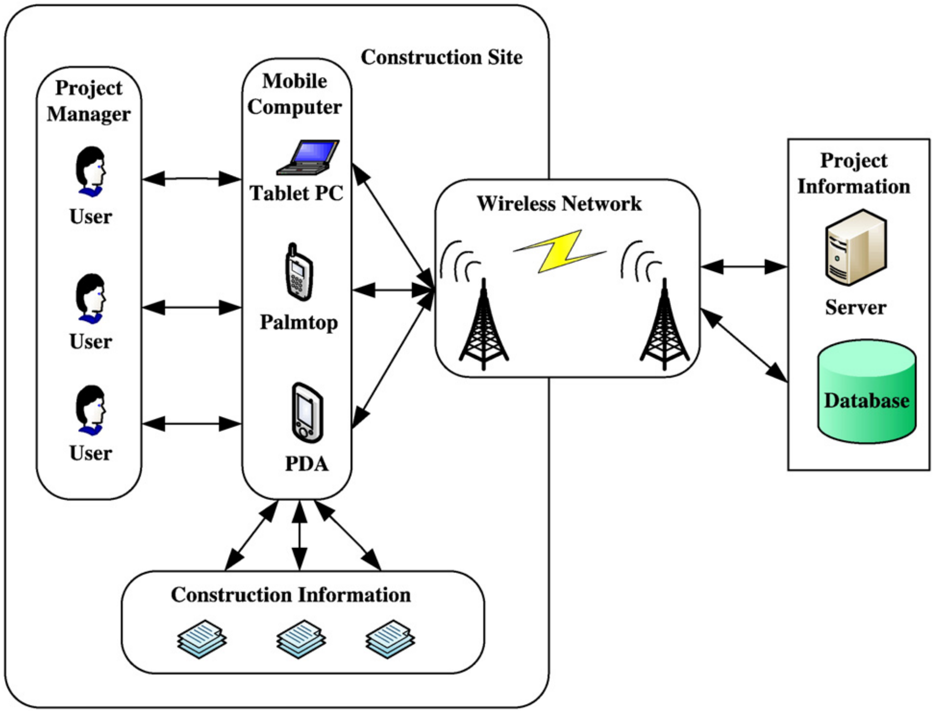

Fig. 1. The framework for using mobile computing for information management on construction sites.

effectively. General data input equipment for mobile computers include the phone keypad, navigation button, QWERTY keyboard, pen-stylus and touch screen, handwriting recognition, touch-sensitive soft keyboards, portable keyboards, voice recognition, voice transfer, and camera for picture capture and video recorder. The "data output" sub-factor represents the way that mobile computers present, display and provide construction information to mobile users. There are two major types of information output equipment: the screen for the information formats of graphic, text, form and image, and the speaker for verbal communication. Because mobile computers are normally used outside site offices, away from a power outlet, another link between the user and mobile computer is the necessity that the battery life of a mobile computer should last for a sufficient period of time when the user is outdoors on construction work sites.

- *User and mobile application*. Construction personnel can perform the functions of mobile application software to enhance the efficiency of information communication on construction sites. Based on their roles in construction projects, different mobile users have different software function requirements. For example, a project manager needs software functions including reviewing drawings, monitoring progress, updating schedules and distributing records, and a site engineer may need different software functions such as the engineering calculations and review drawings. Therefore, the role of a user decides the selection and implementation of mobile application software for the specific information requirements. Mobile users need to have essential computer skills to operate mobile computers and use mobile application software. If users lack the required computer skills and knowledge, training and education are necessary for them before the use of relevant mobile computing technologies. The links between users' "information processing" and "input"/"output" of mobile application concentrate on Human Computer Interaction (HCI) from the software perspective. The design of a human computer interface for mobile applications that aims to increase the efficiency and convenience of data input/output from the software perspective should take account of issues such as the environment of construction sites, the mobility of users, the various types of hardware input/output equipment, and the tasks that the mobile application will have to perform. In order to retrieve and transfer information on work sites, users need to select appropriate data transfer methods provided by mobile applications. Mobile applications normally have two major data transfer methods

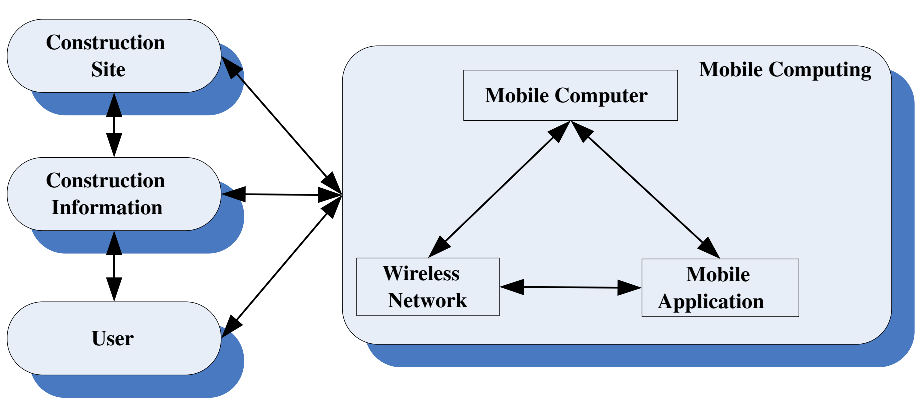

Fig. 2. The application model for using mobile computing for information management on construction sites.

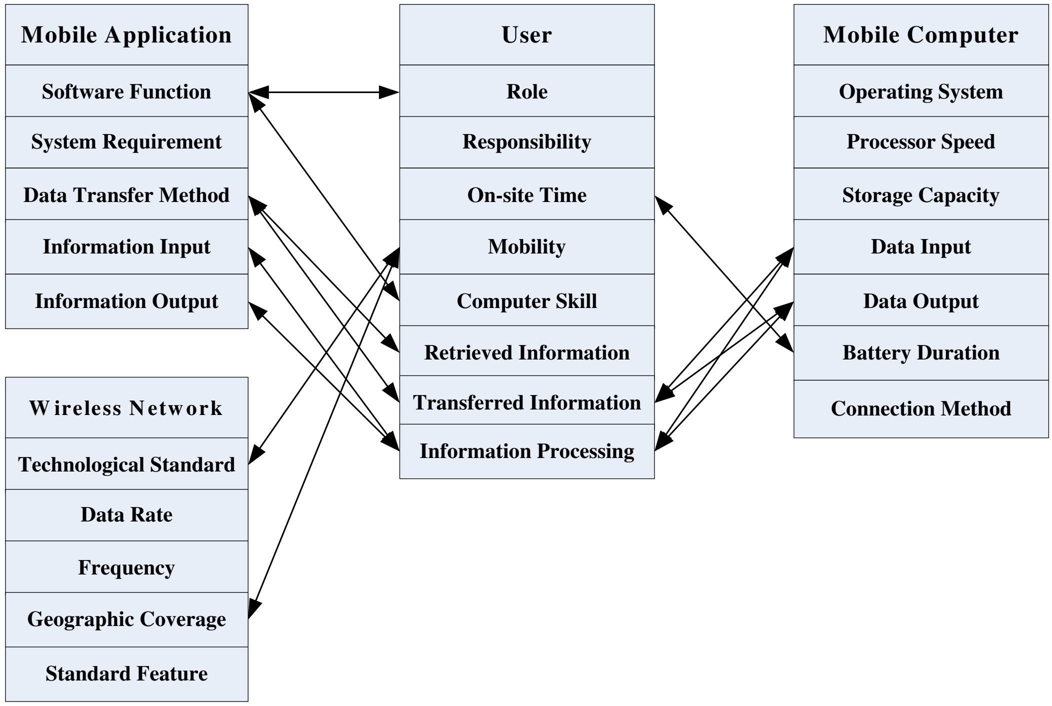

Fig. 3. The application sub-model of "user" and "mobile computing".

including the synchronisation through USB connection, Bluetooth or Infrared, and the connection to Wireless Local Area Network or Wireless Wide Area Networks.

- *User and wireless network*. Interrelationships between the factors "user" and "wireless network" concern the geographic coverage of a wireless network that should cover all the areas where a user moves around on the construction work sites. The selection of technological standards should take account of users' mobility. For example, a Wireless Local Area Network is suitable for users who need to visit only one construction work site with limited areas, but is not appropriate for users who visit more than one construction work site with large geographic areas. Wireless Wide Area Networks such as WAP, GPRS and 3G can be the selection for users who use Pocket PC Phones connected to cellular phone networks that provide the coverage of large geographic areas including one or more construction sites.

4.4. The technical model for using mobile computing for information management on construction sites

Mobile computing makes use of a considerable range of technologies, protocols, standards and devices. For example, the types of wireless networks include Wireless Personal Area Network (WPAN), Wireless Local Area Network (WLAN), Wireless Wide Area Network (WWAN) and satellite connections. Wireless network protocols include Wi-Fi, WiMAX, WAP, GPRS, UTMS, EDGE, 3G and 4G. Therefore, it is necessary to generalize those technologies and give system designers a clear structure for designing mobile computing systems from the technical perspective, shown in Fig. 4. The presentation layer defines end-user interfaces for users' construction information management tasks. Users can access construction information through web browsers, WAP browsers, and client-side applications. Administrators can manage information and setup applications through web browsers at the presentation layer. The application layer defines various functions of applications for users' information management including data input/output, information retrieval, information transfer, information sharing, project monitoring, system security and system administration. It performs the business logic of processing user input, obtaining data, and making decisions. Technologies at the application layer include CGI, Java, JSP, .NET services, PHP and ColdFusion, which are deployed in products like Apache, WebSphere, WebLogic, iPlanet, Pramati, JBOSS and ZEND. The application tier is presentation and database-independent. The database layer is used to store and organize all application data needed by applications for both temporary and permanent data. The data can be stored in any format of database ranging from sophisticated relational database, legacy hierarchical database, to simple text files. It can also be stored in a XML form for interoperability with other systems and data-sources.

4.5. Application of the developed framework

One of the applications for the developed framework is to select a mobile computing strategy for managing on-site construction information. The selection procedure has three major steps:

- *Definition of on-site information management objectives*. The current situation of information management on construction sites can be summarized in two ways: the separation of site offices and construction work sites, and the separation of design and construction. The emergence of mobile computing has the potential to enlarge the boundary of information systems from site offices to actual work sites and ensure real-time data flow to and from construction work sites. Therefore, there are potentially two main objectives of using mobile computing on construction sites: the integration of information management between site offices and construction work sites, and the integration of design and construction.
- *Identification of mobile computing strategy*. Fig. 5 is the pre-defined "square" that identifies the current situation, the desired objectives and different mobile computing strategies and maps out the different ways that on-site information management can be improved from current situations to desired objectives.
- *Selection of appropriate mobile computing technologies*. The third stage of this selection procedure focuses on the selection of appropriate mobile computing technologies for a specific mobile

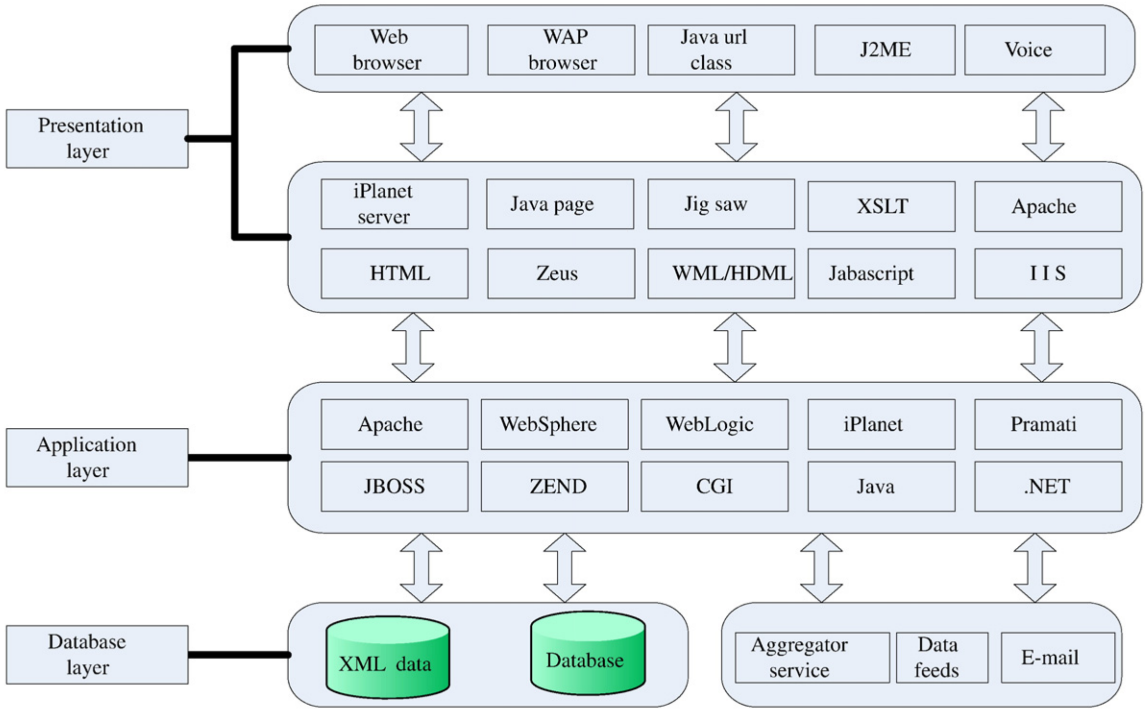

Fig. 4. The technical model for using mobile computing for information management on construction sites.

computing strategy. For each mobile computing strategy identified in the last stage, the appropriate mobile computing technologies including mobile computers, wireless networks and mobile application software, will be selected based on the developed framework of using mobile computing in on-site construction information management. Restrictions and interrelationships that may facilitate or inhibit the implementation of mobile computing in managing on-site construction information will be also identified. This can enable the organisation to develop specific plans to implement the selected mobile computing technology that relates to their mobile computing strategy.

Fig. 6 is the example of how mobile computing technologies can be selected according to the developed model. In order to maintain the coherence with the discussed sub-model in previous sections, this figure only concerns one independent factor "User" (Fig. 3) and represents how construction information can affect the selection of mobile computing technologies. Moreover, the use of the framework should concern all three independent factors and their influence on the technology selected.

In Fig. 6, the selection of mobile computing technologies includes four steps: the identification of independent factors, selection of mobile applications, selection of mobile computers and selection of

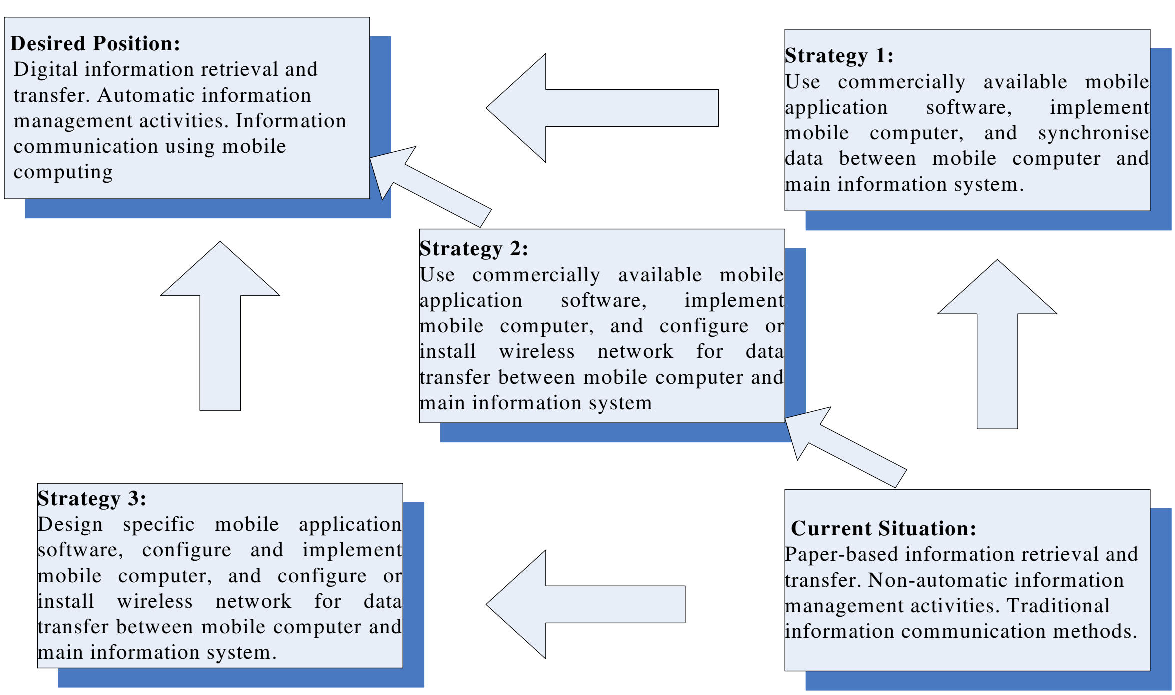

Fig. 5. The mobile computing strategy matrices.

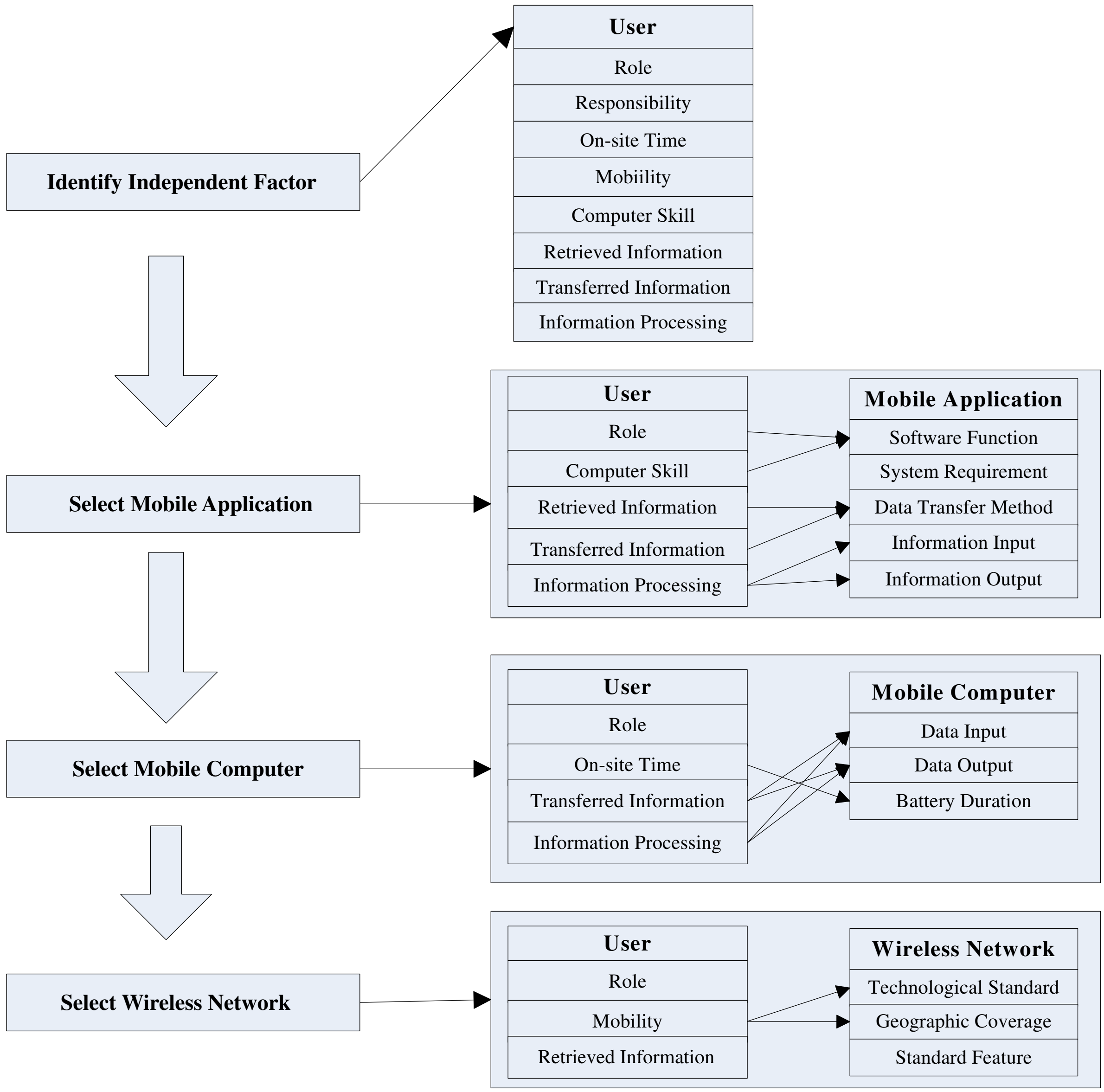

Fig. 6. The process of selecting mobile computing technologies.

wireless networks. The first step is to identify all sub-factors of each primary factor in order to clarify the users who use the system, their information management requirements, the information that needs to be transferred, the construction processes that the mobile computing system is designed to support, and the construction environment where the system will be used. The second step is to select mobile applications based on the interrelationships between independent and dependent factors that have been identified in the developed framework. The selected mobile applications should fulfil mobile users' information management requirements, have enough functions to process required information, and support the information communication of the specific on-site construction process. The third step is to select appropriate mobile computers according to the identified factors and the selected mobile application. The proposed mobile computers should be compatible with the selected mobile application and have the essential capability including processor speed and storage capacity to run it. Its connection methods, such as USB, Bluetooth, IrDA, WWAN and WLAN connections, have to meet the connection standards of the selected mobile application and can transfer information between mobile computers and organisational information systems. According to the site environment, the proposed mobile computers may have specific physical features such as rugged screen, water and dust protection and crash resistance, and should have long-time battery duration to support users' information management activities on work sites. The final step is to select appropriate wireless networks based on the identified factors, selected mobile application and selected mobile computers. The geographic coverage of a wireless network should cover all the areas where a user moves around on the construction work sites. The selection of technological standards should take account of the user's mobility.

5. An illustrative scenario

5.1. The case study undertaken

The final stage of the research reported in this paper was to use the framework with an illustrative construction scenario. The main reason for selecting this construction project for the case study research is because this project is suitable for the use of mobile computing technologies to manage on-site information. In the site offices, the project team is supported by desktop computers, project

Intranet/Extranet, and Internet. In contrast, project team members at construction work sites have difficulty in gaining access to information systems that can only be accessed while they stay in the site offices. Digital information flows are interrupted before reaching the work sites where actual construction activities take place. In order to retrieve information on work sites, project team members have to take vast paper-based construction documents such as drawings, specifications, and design clarifications when they stay on construction work sites. Additionally, construction personnel have to maintain paper-based records when they collect information on work sites. According to the site layout, the site office is located approximately 100 m away from the actual work sites and the construction area of this project is 60,000 m^2 consisting of two high buildings, the current information management situation leads to inconvenience and inefficiency of managing information on work sites, because construction personnel have to transform digital information into paper-based information via printers before their site visits and input the collected information back into computer systems after their site visits.

The evaluation was carried out by three major steps. The first step was to investigate the background information of the selected construction project. These kinds of information included the project name, project type, project budget, construction site location, duration of construction stage, contractor names, challenges it faced, and construction site layout. All of this information was obtained from a search of the project web site, visits to site offices and interviews with appropriate site personnel. The illustrative scenario is based on a real construction environment and mobile computing technologies will be used to assist construction personnel to manage on-site information at a real site.

In the second step, a survey was used to investigate the current situation of on-site information management. Questionnaires were distributed to construction personnel whose workplaces were based on the construction site offices and the construction work site. The questionnaire consisted of closed questions and open-ended questions aimed at investigating the roles of respondents, construction processes they were involved in, received and transferred information on the work site, information resources and destinations, and methods of information retrieval and transfer. At this step, features of potential users of mobile computing technologies and the characteristics of construction information transferred by mobile computing were identified based on the established framework. This case study has identified a number of construction personnel consisting of the business procedures manager, mechanical project engineer, senior procurement manager, and project manager. This paper will choose the mechanical project engineer as the illustrative example to demonstrate what and how mobile computing technologies can assist him to manage information on construction sites.

The final step was to select a mobile computing strategy to manage on-site construction information for the illustrative project in accordance with a real construction environment. This step aimed to demonstrate the validity of the developed framework through the illustrative project. The objectives of on-site information management were set out, and the identification of mobile computing strategy followed; the appropriate mobile computing technologies were suggested to suit the characteristics of the illustrative project.

5.2. Project background

The selected project was a hospital redevelopment project in the North East of England (UK). It includes 60,000 m^2 construction area and comprises 2 main blocks: the clinical block and clinical support block. The clinical block comprises three main elements including a children's wing, a “high tech” block and a ward block, all of which are joined together by an impressive 6 storey atrium. The clinical support block will house medical consultants and support staff as well as a new Education Centre. The major challenge that the project faced was that continuity of hospital services and engineering services should be maintained during the construction of the new buildings. A further challenge for the project construction was that the old building should be demolished as soon as the new buildings become available.

5.3. On-site information management objective

The key objective of using mobile computing on construction sites is the integration of information management between site offices and construction work sites. The integration of on-site information management with project information systems ensures that project team members can have real-time information retrieval and transfer on construction work sites. With the support of mobile computing technologies, they can use mobile computers, such as Pocket PCs or Tablet PCs, with the connection to wireless networks to access project information or personal information stored in remote computers and servers that are normally fixed in site offices. Therefore, construction information can be retrieved, processed, collected and transferred digitally by project team members on work sites and automatic information management activities are possible.

5.4. Identifying mobile computing strategy

In order to achieve the desired objective, it is necessary to select an appropriate mobile computing strategy that can assist users to choose related mobile computing technologies. According to the desired objective of the integration between site offices and work sites and the consideration of mobile computing strategies at different levels, the second strategy in Fig. 5 can fulfil the requirements of improved on-site information management.

The second mobile computing strategy consists of the use of commercially available mobile computers, the selection of related application software and the configuration of wireless networks. This strategy supports real-time information communication that allows mobile users to be able to receive any revised information instantly on construction work sites and any collected data to be immediately transferred to project information systems.

One important reason for selecting the second mobile computing strategy rather than the first strategy is because the first strategy, which synchronises construction information between mobile computers and fixed desktop computers in site offices, cannot provide the full benefits of on-site information management that mobile computing can offer in this construction project. According to the site layout, the site office is located approximately 100 m away from the actual work sites and the construction area of this project is 60,000 m^2 including two tower blocks. If mobile users cannot have the support of wireless networks, they have to travel between site offices and work sites in order to synchronise data between mobile computers and desktop computers, which leads to inefficient information retrieval and transfer.

5.5. Identifying the three independent factors

The three independent factors include “construction site”, “user” and “construction information”. The construction site includes two tower blocks, of which the total construction areas are 60,000 m^2, and the site office is located approximately 100 m away from the actual work sites. The site environment is a typical construction site environment. Construction activities are conducted outdoors, the weather conditions are the typical British weather with sun and rain at intervals, and the working conditions are the standard construction environment with dust, moisture, and noise. The current ongoing construction processes vary depending upon the different construction phases. Internal fit-out is ongoing for the most advanced phase, whereas superstructure is ongoing in the least advanced phase. In between there is a whole range of activities including external envelope, brickwork, M&E (Mechanical and Electrical) installations, and screeding.

The mechanical project manager (the selected "user" for this example) who is in charge of the design and installation management of mechanical works needs to visit nearly all site areas and stays on work sites for more than 20 h per week. On construction work sites, he needs different types of information such as drawings, material information, equipment information, progress information, design clarification, construction methods, and sub-contractor information. Information is received from other construction personnel, computer systems or documents stored in the site office. The mechanical project manager normally takes paper-based drawings or documents to construction work sites in order to support his on-site information needs. Construction information collected on work sites includes drawings, material information, equipment information, progress information, and design clarification. The mechanical project engineer needs more complex information process activities including viewing, editing, marking up, updating, measuring, checking, and clarification. All collected information is recorded on paper and inputted into computer systems when he is back in the site office. Table 2 shows the detailed sub-factors of the primary factor "user" for the illustrative example: mechanical project engineer.

Different construction personnel have varying information needs. According to the information needs of the mechanical project engineer, Table 3 identifies the detailed sub-factors of "construction information" for the potential user.

5.6. Selecting mobile computing technology

The identification of three independent factors and their sub-factors determines the users who use the mobile computing system, the construction information that the mobile computing system needs to deal with, and the construction environment where the system is to be used. Therefore, the following steps aim to select appropriate mobile application software, mobile computers and wireless networks, which comprise the mobile computing system for mobile users to manage information on construction sites.

The first step is to select mobile application software. Based on his role in the construction project, the mechanical project engineer has general and specific requirements of mobile software functions. The software functions should generally support them to process the required construction information on work sites. Because both of them need to retrieve and review drawings, mobile AutoCAD software should be selected to support users to manage AutoCAD-based drawings. In addition to the mobile AutoCAD software, both mobile users need to manage other construction information on work sites, such as their own personal information, construction methods, design clarification, sub-contractor information, labour information and quality information. Therefore, they need other mobile application software to support their information management requirements. This software includes mobile Outlook, mobile Internet Explorer, Mobile Adobe Reader, Mobile Word and mobile picture viewer.

After the identification of required mobile application software, the second step is to select mobile computers that can be used by the mobile user to run the selected mobile software. The selected CAD software can run on Windows XP based Tablet PCs with sufficient system requirements. The software supports a number of data transfer methods including Bluetooth, USB synchronisation, Infrared, and Wireless Local Area Networks, which should be supported by the selected mobile computers. For displaying the CAD drawings, the screen of the selected mobile computer should have sufficient screen size and enough screen resolution. Because the selected mobile computers need to run other mobile applications and deal with various types of information formats, mobile computers should have multi-data-input equipment including the keyboard input for text, touch screen input for graphics, and microphone for voice transfer. The battery life should support the on-site time for the two users. Because the construction site environment is outdoors, dust, moisture and high building blocks exist, the selected mobile computers are recommended to have rugged screen, water and dust protection, and be crush resistant to confront the poor site environment.

For the mechanical project engineer, the rugged Tablet PC is more suitable for him. The selected Tablet PC has the full computer capability of normal desktop computers, but can be used when the user is in motion. It runs the operating system of Microsoft Windows XP Tablet Edition and other professional application software that can be run on desktop computers. The big screen size and high screen resolution ensure that AutoCAD drawings can be displayed more clearly and amended more easily by users on construction work sites. The Tablet PC has a lot of Human Computer Interaction equipment including the touch screen with stylus, QWERTY keyboard, camera, microphone, and speakers, and supports various network connection methods, such as the Bluetooth, Infrared, Ethernet, Modem, Wireless Local Area Network, and Wireless Wide Area Network. Since the mechanical project engineer always works within a tough construction environment, the rugged and weatherised features including the protection for shock, drop and vibration, shock-mounted hard drive, die-cast magnesium case, and resistance to water and dust, ensure that this Tablet computer can be used by construction personnel in the specific construction environment.

For a wireless network that can provide network support for mobile users to use the identified mobile application software and mobile computers, it is suggested Wireless Local Area Network (IEEE 802.11) selected. Firstly, the IEEE 802.11 wireless network protocol is widely used in the commercial market and supported by most wireless commercial products. The selected mobile applications and mobile computers fully support the IEEE 802.11 protocol. Secondly, the digital construction information files that need to be transferred through a wireless network to construction work sites are large and are required to be transferred without delay and lag. The IEEE 802.11 wireless network can provide a bandwidth up to 11 Mbps, which is sufficient to transfer large-size files such as drawings, pictures, and voice. Thirdly, the IEEE 802.11 wireless network can provide a transmission range from 30 up to 100 m and the wireless coverage can be extended by applying more wireless network antennas, each of which can provide coverage to a certain area of the site allowing

Table 2
Detailed sub-factors of the primary factor of "user" for mechanical project engineer.

Role	Responsibility	Onsite time	Mobility	Computer skill	Retrieved information	Transferred information	Information processing
Mechanical project engineer	Design and installation management.	More than 20 h per week on construction work sites.	Mobility covers most of the area of work sites.	Appropriate knowledge on computers, but need extra training on mobile computing technologies.	Drawings, material information, equipment information, progress information, design clarification, construction methods, sub-contractor information.	Drawings, material information, equipment information, progress information, design clarification.	View, edit, draw, mark up, measure, write, update, check, and clarify.

Table 3
Construction information needs of the mechanical project engineer.

Information type	Information format	File size	Information flow	Information processing	Information source	Information target
Drawing	Text, graphic	Large	Retrieve transfer	Viewing, editing, drawing, marking up, measuring	People, computer system, document storage	People, computer system, document storage
Material management information	Text, form, verbal	Medium	Retrieve transfer	Viewing, writing, checking, updating	People, computer system	People, computer system
Equipment management information	Text, form, verbal	Medium	Retrieve, transfer	Viewing, writing, checking, updating	People, computer system	People, computer system
Progress information	Text, graphic, verbal	Medium	Retrieve transfer	Viewing, writing, checking, updating	People, computer system	People, computer system
Design clarification	Text, graphic, verbal	Medium	Retrieve transfer	Viewing, checking, updating, clarifying	People, computer system, document storage	Computer system, document storage
Construction methods	Text, graphic, image, verbal	Large	Retrieve	Viewing, checking	People, computer system, document storage	N/A
Sub-contractor information	Text, graphic, form, verbal	Medium	Retrieve	Viewing, checking, updating	People, computer system, document storage	N/A
Labour information	Text, form	Medium	Retrieve	Viewing, checking, updating	People, computer system, document storage	N/A
Quality control information	Text, form, verbal	Medium	Retrieve	Viewing, checking, updating	People, computer system, document storage	N/A
Safety information	Text, form, verbal	Medium	Retrieve	Viewing, checking, updating	People, computer system, document storage	N/A

roaming users to connect to the project computer systems and can divert the wireless signal around obstructions. Finally, computer systems in site offices are supported by Ethernet that can easily be extended to set up the IEEE 802.11 wireless network through the wireless routers. Therefore, the mobile computing system can be smoothly integrated into the current computer systems without complex configurations.

5.7. Case study findings

This real construction scenario as an illustrative example demonstrates the application of the developed framework to select a mobile computing strategy to suit the characteristics of a specific construction situation. Because of the potential of mobile computing technology, the desired objectives of implementing mobile computing in construction site information management can generally be summarized from two aspects: the integration between site offices and work sites, and the integration of design and construction. The different mobile computing strategies in Fig. 5 can achieve the desired integration at different levels depending on the user's requirements. For the selected strategy, suitable mobile computing technologies can be selected by users based on the developed framework.

In facilitating the implementation of mobile computing in construction, the developed framework can provide the following benefits to the industry:

- It identifies the three key factors of the mobile computing concept and their sub-factors.
- It identifies the three key factors and their sub-factors for the management of construction site information that determine the implementation of mobile computing.
- It represents the interrelationships between the user and mobile computing, the construction information and mobile computing, and the construction site and mobile computing.
- It provides the ways that mobile computing technologies can be used in the construction industry.
- It provides guidance in the effective deployment and selection of mobile computing for on-site information management.
- It helps users to understand and overcome the limitations and restrictions of using mobile computing technologies in the construction industry.

The benefits for the selection procedure derive from its use for the selection of mobile computing strategy and related technologies with respect to the characteristics of a specific project. In particular,

- It helps users to identify the desired objectives of on-site information management.
- It provides the various mobile computing strategies that users can select with respect to their desired objectives.
- It provides guidance for users to select appropriate mobile computing technologies to suit the characteristics of their projects.
- It ensures that the features of mobile computing technologies are compatible with current organisational systems.
- It ensures that the potentials of mobile computing can be explored for the on-site information management for a specific project.
- It facilitates the decision making process for the selection of appropriate mobile computing strategies and related technologies.

The developed framework has its own limitations since it is only concerned with the limited factors that impact on the implementation of mobile computing. Other factors that may affect the application of mobile computing technologies may include the cost, existing organisational information systems, and the specific construction project. All of the remaining factors should be investigated and explored in future research. Meanwhile, the case study assessment for the developed framework also concerned the limited factors and other issues should be involved in future research.

6. Conclusions

Mobile computing includes three major components: mobile computers, wireless networks and mobile applications. Research that focuses on mobile technologies includes the evaluation of IP

Telephony technology for construction information communication, the implementation of wearable computers on construction sites, the use of wireless sensors, and the auto-ID technology that integrates PDAs and bar code scanning together. The test and examination of mobile technologies on real construction sites include the evaluation of mobile computers and examination of wireless networks. Other research has clearly identified what areas can be improved by the implementation of mobile computing and how mobile computing can benefit the construction industry.

This research developed a framework for using mobile computing for information management on construction sites. This framework includes a concept framework, an application model and a technical model. The application model has identified the key factors that determine the use of mobile computing in particular circumstances and explored both the interactions of these factors and their limitation through the development of sub-models. The technological model generalizes mobile computing technologies and gives system designers a clear structure for designing mobile computing systems from a technical perspective.

The final research stage uses a case study to validate this framework in a real construction situation. This real construction scenario demonstrates the application of the developed framework to select a mobile computing strategy that suits the characteristics of a specific construction situation. The evaluation of the selected mobile computing technologies in real construction sites can provide the determination of whether the structure of the framework and the relevant procedure for selecting a mobile computing strategy are appropriate and whether the framework and the selection procedure reflect the realisations of the real construction situations.

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