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Design Principles of Integrated Information Platform for Emergency Responses: The Case of 2008 Beijing Olympic Games

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This paper investigates the challenges faced in designing an integrated information platform for emergency response management and uses the Beijing Olympic Games as a case study. The research methods are grounded in action research, participatory design, and situation-awareness oriented design. The completion of a more than two-year industrial secondment and six-month field studies ensured that a full understanding of user requirements had been obtained. A service-centered architecture was proposed to satisfy these user requirements. The proposed architecture consists mainly of information gathering, database management, and decision support services. The decision support services include situational overview, instant risk assessment, emergency response preplan, and disaster development prediction. Abstracting from the experience obtained while building this system, we outline a set of design principles in the general domain of information systems (IS) development for emergency management. These design principles form a contribution to the information systems literature because they provide guidance to developers who are aiming to support emergency response and the development of such systems that have not yet been adequately met by any existing types of IS. We are proud that the information platform developed was deployed in the real world and used in the 2008 Beijing Olympic Games.

Key words: emergency response; fire safety; Olympic games; situation-awareness oriented design; participatory design; action research; integrated information platform
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1. Introduction

Around the world fire has been categorized as a major disaster, and is responsible for more deaths than any other disasters. The possibility of a fire occurring is an ever-present safety issue at any Olympic event. At the opening of the 25th Barcelona Olympic Games, the hotel where the former President of the International Olympic Committee (IOC) was staying caught fire. During the 26th Olympic Games, a fire occurred in the Olympic park in Atlanta that left 2 people dead and more than 100 injured. Prior to the 2008 Beijing Olympic Games, there was a demand from firefighters and fire safety related organizations for the development of an information system for emergency response, which could improve their performance and decision-making capabilities should any fire emergency operation be required during the games. It is always a challenge for information systems (IS) researchers and developers to apply IT

technologies and provide appropriate decision support services to support fire emergency response. As IT develops and technical knowledge grows, IT is increasingly applied to a wide range of areas such as emergency response management that are in need of support from IT systems. This paper is primarily concerned with emergency response operations to potential fire incidents in and around the Beijing Olympic venues and focuses on the use of an emergency response information platform before and during an incident. The other two stages in the disaster life cycle, i.e., mitigation and recovery activities, are not included in this study.

The rest of the paper is organized as follows. Section 2 introduces the features of the Beijing Olympic venues and explains why an integrated information platform was needed. Section 3 describes the existing work in IS research, emergency management systems, and on-site emergency response systems. The research approaches employed in this study,

including action research, participatory design, and situational-awareness oriented design, are presented in §4. Field studies and user requirement analyses are given in §5. Section 6 presents five design principles that offer guidance to developers in the general domain of IS development for emergency response and illustrates the implementation of these design principles by reference to the emergency information platform designed and used at the Beijing Olympic venues. An evaluation of the platform together with a description of its use in the Beijing Olympics is presented in §7.The practical values of the research and the lessons learned are summarized in §8. Finally, the paper concludes in §9 by summarizing the work and discussing potential future work.

2. Why Was an Information Platform Needed for Beijing Olympics?

The environmental conditions in and around the Olympic venues form the most basic and important pieces of information required by fire fighters in the event of a fire emergency. Lack of a comprehensive understanding of the fire's environment might influence responders' ability and confidence, and may cause them to take wrong actions or make wrong decisions in their response operations. There is a great deal of existing literature (Jiang et al. 2004a; Carver and Turoff 2007; Yang et al. 2009a, b; Turoff et al. 2004; Mehrotra et al. 2004; Upadhyay et al. 2009) concerning the use of information systems by fire fighters to perform fire-fighting training, drilling, and on-site operations. Such systems are also known as information platforms, and normally present information to the fire fighters based on a virtual environment developed using real information about the buildings. Based on the information provided, the emergency officers and fire fighters respond collaboratively to control the fire in accordance with their respective duties.

There were three reasons why a flexible information platform for fire emergency response was needed for the Beijing Olympic venues. Firstly, Chinese firefighters previously made little, if any, use of computers when at the scene of a fire. They tended to make decisions based only on limited on-site dynamic information, supported by paper-based or oral information, which might not be up to date or accurate. The Beijing Olympics team needed to make significant steps in improving this approach, by putting an on-site fire emergency response system in place before the games. Secondly, fire brigades always carried out exercises to simulate their response to fires at important public buildings, but because many of the new Beijing Olympic venues were only completed shortly before the start of the Games, such exercises were not

always possible. Thirdly, firefighters and emergency personnel had to face complex and unprecedented challenges due to the following four features of the Beijing Olympic venues.

Feature 1: Some venues, such as the gymnasium, had complex structures determined by the competition requirements and the functional needs of the different events, as well as the need to maximize the spectators' view of the events. As a consequence, not only could people easily get lost in the building, but it also made fire protection and firefighting more difficult. The fire fighters needed to have appropriate and precise information about the buildings and environmental conditions, the structure related to fire prevention and protection, together with details of all available equipment and resources.

Feature 2: New construction materials were widely used. For example a new kind of wood-plastic material was used that has the same shape and feel as wood, but is combined with plastic to make it more flexible and longer lasting. This material was used in a number of internal and external structural frames and furniture at the venues. The Aquatics Center, known as the Water Cube, was built using ETFE, i.e., ethylene tetrafluoroethylene, a translucent plastic somewhat similar to Teflon. The use of such new materials brought uncertainties to the firefighting process. The firefighters needed to be informed about the fire characteristics of such materials and how to control the spread of fire in buildings constructed of these materials.

Feature 3: New design methods and systems for fire prevention were adopted in some venues. Some Beijing Olympic venues, such as the National Stadium, known as the Bird's Nest, adopted performance-based fire safety design, and used it in combination with a prescriptive approach. The performance-based design methodology provided an alternative means of implementing the building and fire codes. This approach has become more common as buildings are designed to incorporate unique aesthetic features while achieving restrictive, cost, and functional goals and maintaining safety levels for both the occupants of the building and the emergency responders. At the same time, it had a significant impact on the decision making and actions of any fire emergency responders. The firefighters needed to have information about the performance-based design to maximize their ability to control any fire incident.

Feature 4: New technologies and new fixed fire protection devices replaced conventional ones at some venues. In the Wukesong Basketball Gymnasium, remotely controlled water cannons replaced the more conventional fixed fire-extinguishing water system.

Such changes inevitably had an impact on fire emergency management. The firefighters needed to have information about the positive and negative aspects brought about by new fire protection systems.

To establish the information platform taking account of the above features, there were a wide number of challenges that needed to be addressed (Jiang et al. 2004b, Carver and Turoff 2007, Mehrotra et al. 2004, Upadhyay et al. 2009, and Yang et al. 2009b). These are often categorized into technological, sociological, and organizational perspectives (Manoj and Baker 2007). This project aimed to develop and deploy a user-specific information platform for the Beijing Olympics and was faced with the following challenges of

• How to select the participants when a wide range of organizations were involved at national, regional, and local levels;

• How to complement the possible lack of hard sensors in and around the sports venues resulting from the situation where a large number of geographically distributed sports venues were under construction and not available until shortly before the Games started;

• How to remove the fear of emergency personnel that their lack of experiences in using new technologies in real operations might exclude them from the decision-making loop;

• How to decompose the large-scale perspective of the designed platform into smaller components to make it easier to develop and evaluate;

• How to best present the vast amount of information available for decision making.

3. Related Work

The emergency response information platform that was considered for the Beijing Olympic venues was, in principle, a typical information system, facilitating emergency response operation by offering decision support services to emergency personnel, particularly fire commanders. In this section we briefly review information system design theory, design science, and decision support systems, and then focus on emergency management systems and also on-site emergency response systems in order to identify the most recent relevant developments in these areas.

3.1. IS Design Theory, Design Science, and Decision Support Systems

IS design theory is a term that could refer to general systems theory and the relationship between developers, clients, and users (Churchman 1979). Walls et al. (1992) uses the term "IS design theory" to refer to an integrated specification consisting of a set of user requirements, a set of system features, and a set of design principles. The benefit of IS design

theory, according to Walls et al. (1992), is to make the design process more tractable to developers by focusing their attention and restricting their options, thereby improving development outcomes (Markus et al. 2002). The value of following an IS design theory approach is to reduce developers' uncertainty by restricting the range of allowable system features and development activities to a more manageable set, thereby increasing the reliability of the development and the likelihood of success. Markus et al. (2002) presented an IS design theory for systems that support emergent knowledge processes by specifying six specific design principles that offer guidance to developers. Xu et al. (2008) proposed an integrated IS for agricultural ecosystem management. Based on the existing works from Markus et al. (2002), Turoff et al. (2004), and Hevner et al. (2004), we developed a set of IS design principles.

Design science in IS seeks to extend the boundaries of human and organizational capabilities by creating new IT artifacts (Hevner et al. 2004). It differentiates system design in the nature of the problems and solutions. System design is the application of existing knowledge and "best practice" in a problem domain to design processes. Furthermore, the design science research addresses important "unsolved" problems in unique or innovative ways, or "solved" problems in more effective or efficient ways, therefore contributing to the archival knowledge base of foundations and methodologies (Hevner and Chatterjee 2010). Knowledge and understanding of IS design and its solution are achieved in the building, evaluation, and application of the designed IT artifacts in the design science paradigm. This is a process that involves frequent iteration between development and evaluation. There are multiple definitions of the term IT artifact, many of which include people and organization components (Weber 2003, Orlikowski and Iacono 2001). The definition given by Hevner et al. (2004) is broader in the sense that the constructs, models and methods applied in the development and use of information systems are included, and narrower in the sense that people or elements of organizations are excluded. In our work we followed the design science paradigm from two perspectives—firstly, design as research, and secondly, evaluating the research findings achieved along with the actual design processes. Because of the features of the Beijing Olympics described in §2, not all of the knowledge required for designing the integrated information platform existed initially. Doing innovative design results in contributions to the knowledge and understanding of IS design in the form of a set of design principles. We first built the designed IT artifacts, which were a series of software models, design methods, and prototypes in our design case, and then evaluated

and updated the IT artifacts with the involvement of end users before actually applying them in the real design. The software prototyping evolved over time through the iterative prototyping and evaluation process. Furthermore, similar to the focus group methods in design research (Smolander et al. 2008, Tremblay et al. 2010), we involved an end user group both for continual evaluation and also for requirement gathering and definition of system specifications.

The phrase decision support systems (DSS) is an umbrella term used to describe computer applications that enhance the user's ability to make decisions. More specifically, the term usually refers to IS, which facilitates decision-making activities. It could be an automatic decision-making system such as an autonomic aviation system, but in most cases it refers to a support system that helps decision makers use communications technologies, data, documents, knowledge, and/or models to identify and solve problems, complete decision process tasks, and present recommendations. DSS can reduce uncertainty, and thereby improve efficiency and accuracy in the decision-making process. A traditional definition of DSS was given by Sprague and Carlson (1982) as "a class of information system that draws on transaction processing systems and interacts with the other parts of the overall information system to support the decision-making activities of managers and other knowledge workers in organizations." A modern version of DSS concerns both dynamic decision-making environments and multiple criteria (Campanella and Ribeiro 2011). A literature survey (Arnott and Pervan 2005) suggested that the major applications for DSS involved manipulating quantitative models, accessing and analyzing large databases, and supporting group and multiple-criteria decision making. DSS applications can be separated into five categories (Power 2004), each aiding decision making by different methods. Communication-driven DSS enhance decision making by enabling communication and sharing of information between groups of people. Data-driven DSS focus on the provision of internal and sometimes external and real-time data to aid decision making. An example of data-driven DSS would be a geographic information system (GIS), which is used to visually represent geographically dependent data using maps. Document-driven DSS provide document retrieval, analysis, and converts documents into valuable business data. Examples of document-driven tools can be found in Internet search engines. Knowledge-driven DSS are the system designed to recommend actions to users, identify hidden patterns in database and present recommendations based on those patterns. Model-driven DSS involve access to and manipulation of optimization and/or simulation models. Model-driven DSS use limited data and

parameters provided by decision makers to aid them in their decision-making processes. In general, large databases are not needed for model-driven DSS.

The scope of the information platform for the Beijing Olympics is both broader and narrower than the definitions given above. It is broader in the sense that the integrated information platform was a hybrid DSS of all these five categories in building on different service components and adding real-time dynamic information gathering, storage, and management in the platform. For example, the architecture design was based on the communication-driven approach to facilitate information sharing among the emergency personnel, but the disaster development prediction service was based on the model-driven approach as numerical predictive models were the core part in the service. However, it is narrower in the sense that we did not give any recommendation to the decision makers. We used the phrase decision support services in the platform rather than decision support systems to emphasize that the intention of our work was to provide emergency personnel and fire commanders with the most relevant information at the right time, in the right format, and for the right people to enhance their decision making, thereby to improve the effectiveness of their emergency response operations.

It was evident from our field studies that fire commanders would not accept the provision of too much automation in a system because it would take them out of the decision-making loop. This fear of automation was one of the main reasons that fire commanders sought to keep the use of any technology out of their decision-making process, even though they recognized the importance of keeping in touch with the environment and operations. Thus, the proposed information platform sought only to enhance fire commanders' situation awareness (SA) rather than to automatically make any decision on their behalf, and should allow their active participation during a decision-making process.

3.2. General Emergency Management Systems
Emergency management systems are usually used by local, national, and international organizations to assist their responses to an emergency situation. These systems can support the activities during an emergency response, including communications, data gathering and analysis, resource management, and decision making. However, emergency management systems are infrequently used in practice because emergency situations are not a common occurrence. However, when they are used, they thus must be capable of functioning effectively and without failure. The General Service Administration (GSA) (Annelli 2006) of the United States adheres to the following

philosophy: An emergency management system that is not used regularly would not be used in an actual emergency. Many countries such as the United States, Canada, and the United Kingdom, as well as many other European countries, have established their national emergency management systems (Annelli 2006). No matter what the scale of an emergency management system is, a standard model normally consists of the following basic components: databases, data analysis capability, normative models, and interfaces (Bellardo et al. 1984). Jennex (2004) expanded the emergency response system model from these basic components to also include trained users, collaborative methods to communicate between users and between users and data sources, protocols to facilitate communication, and the processes and procedures used to guide the response and to improve decision making during the emergency. The goals of the emergency response systems defined in this extended model are to facilitate clear communications, improve the efficiency and effectiveness of decision making, and manage the data to prevent information overload. Turoff et al. (2004) developed a set of eight general design principles and three supporting considerations for a dynamic emergency response management information system. These principles cover not only emergency response, but also off-site activities such as system training and simulation. The information platform established for the Beijing Olympics would operate at a city level with a focus on on-site fire emergency response rather than general emergency management. The end users were mainly on-site fire commanders and other emergency personnel. Therefore, the design of the database, data analysis, and interface should meet their specific requirements. Emergency mitigation and recovery were excluded from the functions of the proposed information platform.

3.3. On-Site Emergency Response Systems

In recent years, a significant amount of effort has been devoted to the development of information systems both for emergency response operations and first responders' training. Typical examples include emergency management systems for containing chemical and nuclear pollutants (Gheorghe and Vamanu 2001), for building fire safety (Upadhyay et al. 2009, Han et al. 2010), and for firefighters' training (Schurr et al. 2006, Massaguer et al. 2006). It has been widely recognized in emergency communities (Carver and Turoff 2007; Manoj and Baker 2007; Prasanna et al. 2007; Turoff 2002; Yang 2007; Yang et al. 2009a, b; Upadhyay et al. 2009) that on-site dynamic information is critical to emergency response and will assist in improving the initial key decision making. Traditional emergency management systems, which

only provide information that is precompiled and prepared beforehand rather than being generated in real time, will not be appropriate for unforeseen highly dynamic incidents such as earthquakes, hurricanes, and terrorist attack. Furthermore, Prasanna et al. (2007) recognized that existing information systems independently addressed the information needs of different emergency responders, rather than sharing information between them. Yang (2007) provided an on-site information-sharing mechanism for emergency response management, but those participating organizations in the emergency operations must build trust among themselves beforehand.

Information presentation and human-computer interaction in emergency management information systems have been discussed by Carver and Turoff (2007) and Yang et al. (2009a), because the pressure of the situation, the need for quick response, and the rate of information flow can conspire to overwhelm the decision makers. Information overload should be avoided in the interface not only because it may obfuscate essential information that would guide the action of the emergency responders, and thus slow down their response, but it also may lead to them making incorrect and damaging decision. A low-fidelity prototype of large displays for incident command (Jiang et al. 2004b) demonstrated the most useful features in the information presentation, including location tracking, area maps, fire status, and resource allocation. We have adopted these features in the on-site user interface design of the information platform for the Beijing Olympics.

Communication and information sharing among various emergency response organizations are important aspects in emergency management. Communication challenges in emergency management in general have been classified into three categories by Manoj and Baker (2007): technological, sociological, and organizational. These three major areas are the key to developing and maintaining healthy and effective disaster communication systems. Yang et al. (2009b) gave an on-site information systems design for emergency first responders, named Safety NET, in which four core members in emergency response were identified as incident commanders, sector commanders, entry control officers, and front-line firefighters. These four groups were selected as the participants in the interview sessions of this study. RFID (Radio Frequency Identification), wireless sensor networks, and Wi-Fi technologies were used in data gathering and information sharing. Information was presented at perception, comprehension, and projection levels. Upadhyay et al. (2009) presented architecture for an integrated fire emergency response system for a building environment. A number of different technologies such as wireless sensor networks, database

management systems, grid-enabled high-performance computing implementation of fire models, and artificial intelligence tools were integrated in their proposed system, known as Fire Grid. As by Yang et al. (2009b) and Upadhyay et al. (2009), we employed wireless sensing and communication technologies in the information platform for the Beijing Olympics.

In addition to the specifications just described, our field studies identified a need for people to act as sensors for data gathering, and also a need for immediate risk assessment and a response preplan to support the operation of the first responders. The support provided by a simulation of the fire's development was also recognized in our field studies as one of the important decision support services offered to emergency personnel, particularly fire commanders. These new needs gathered from the end users in our field studies distinguished the information platform for the Beijing Olympics from any existing on-site emergency response systems.

4. Research Approaches

This research was grounded in the combination of action research (AR) strategy (Wood-Harper 1985), participatory design (PD) (Greenbaum and Kyng 1991), and situation-awareness (SA) oriented design (Endsley et al. 2003). Because AR refers to a class of research approaches rather than a single, monolithic research method, our work particularly emphasized the participatory form of action research and followed the design science build-and-evaluate approach (Dang et al. 2011) and the life cycle of software systems development requirements-prototyping-development-deployment-evaluation. The cycle is repeated until the expected results are produced. PD relies on domain experts and the direct involvement of practitioners from relevant disciplines. Consequently, the development of the design focus is part of the ongoing work of the project group and not something specified beforehand. PD has been used in designing emergency medical service for future practice (Kristensen et al. 2006). The basis of SA is an awareness of what is happening around you and understanding what that information means to you now and in the near future. This awareness is important to first responders and the fire commanders in emergency response because they need to be adequately aware of the real situation if they are to have confidence in making what could be life-and-death decisions. SA has been used in graphic user interface design of emergency response systems in the work of Yang et al. (2009a). We believe that the employment of AR, PD, and SA in the design of an integrated information platform for managing emergency responses can identify not only what functions the

end users require, but also what investments should be made in new types of information platform. This proposal also helps in identifying how the required information is structured, as well as the best way to present this information to satisfy user needs.

4.1. Action Research Strategy

The AR strategy starts with the identification of user requirements and then proceeds with system prototyping, development, and deployment. Once the system has been developed and deployed, the use and impacts of the system can be observed and evaluated. If the outcome of the system is not as expected, a new set of requirements are generated and the AR strategy cycle is repeated. The Beijing Olympic emergency response information platform project followed this action research strategy, and started with two full-time researchers being seconded to the Emergency Response Office in the State Council of China for two years, whereas another researcher sat in on the Beijing Olympic Organization Committee (BOOC) for one year. These three secondees collected and brought firsthand user requirements and feedback on the design of the integrated information platform to the research team. The user requirements gathering was further conducted by the research team via interviews with corresponding emergency officers and fire fighters, observations, and group discussions. These findings were validated by feeding them back to the end users. Details are given in the following field studies. There are two software prototyping approaches considered in this study (Sommerville 2006), throwaway and evolutionary. A throwaway prototype is usually a practical implementation of the system to be produced, used to help identify requirements problems, and then discarded. In the evolutionary prototyping approach, a basic initial implementation is developed and subsequently refined through a number of stages to obtain the final system. We used the throwaway approach at the beginning of the study to validate user requirements and to understand the development and deployment of the system, because there was no other existing system to use as a benchmark. The evolutionary approach was employed for the actual system design once the user requirements were more or less fixed.

4.2. Participatory Design

Because PD practitioners are so diverse in their perspectives, backgrounds, and areas of concern, there can be no single definition of PD. This study took PD as an approach to the design, development, and assessment of our platform that placed a premium on the active involvement in the design and decision-making processes of potential or current end users of the system and that recognized that collaboration with participants, particularly end users, was a

prime source of innovation. An important aspect of employing PD is to achieve, maintain, and continuously develop a common understanding across all disciplines. PD has developed both moral and pragmatic propositions (Landgren 2010):

- The moral proposition—"the people whose activity and experiences will ultimately be affected most directly by a design outcome ought to have a substantive say in what that outcome is" (Caroll and Rosson 2007).

- The pragmatic proposition—"the people, who will need to adopt, and perhaps to adapt to an artifact or other outcome of design, should be included in the design process" (Caroll and Rosson 2007).

But who are the people referred to in the above moral and pragmatic propositions? The means of identifying these people in our work was based on the actor-network theory (Latour 2005), which aims to cover a network of actors. All the Beijing Olympics related organizations were included on board at the very first stage. This group of actors includes firefighters from the Beijing Fire Bureau, police officers from the Beijing Police Bureau, ambulance services, safety and security officers in the sports venues, BOOC officers, and emergency response officers in the State Council of China. The involvement of these participating organizations started with interviewing their representatives and continued with a number of other types of field studies such as team observation, work placement, workshop, and group discussions. The detail of the participants' involvement in the design processes is given in §5.

4.3. Situation-Awareness Oriented Design

After information has been collected from various sources and has been stored in the integrated information platform, the next step in the process is to present the collected information to the end users. Presenting information in the right format, to the right people, and at the right time, is always a challenge in any emergency management system design whether it is used for emergency response training or in an actual on-site emergency response operation. The problem is to determine exactly what information is needed as well as where and when it is needed; that is, to determine from the vast amounts of data available, exactly what information the responders need, how that information should be organized to avoid duplication and overload, what is the best way to present this information to the responders to maximize their performance. It must also be decided what platform should be used to process and display this integrated information.

Situation-awareness oriented design may provide a solution to these questions by designing a dynamic platform "to maximize the person's ability to perceive

needed information, comprehend what that information means, and use it to predict the future state of the system" (Endsley 1995). It is represented by a three-level model. The three levels are perception of the elements in the environment, comprehension of the current situation, and projection of the future status. It can be summarized as the knowledge of the status and dynamics of the situational elements and the ability to make predictions based on that knowledge. The ability to perceive critical information about extreme environments, and then to comprehend and project a future state of the situation, is important in making appropriate decisions. A number of studies into SA have explored how technology can be used to improve SA in dynamic and information-intense environments such as emergency management. Two typical examples are the user interface design for an on-site fire emergency management information systems (Yang et al. 2009a, b) and the design of human-systems interaction for the command and control of emergency ambulances in a large metropolitan center (Blandford and Wong 2004). The former grouped and presented emergency information in three levels according to the SA three-level model—perception, comprehension, and projection. The latter suggested techniques for good SA during routine operations, i.e., keeping track of a dynamic situation, and for good SA during major incidents, that is a "picture in the mind." This awareness is important to fire commanders and other emergency personnel, who need to be sufficiently aware of the real situation, in order to have the confidence to make any decision on how to respond to the situation. We employed an SA-oriented design in the integrated information platform for the Beijing Olympics, which provided first responders with two decision support services. One was to identify the situational overview and exist at two increasing levels of knowledge, i.e., knowledge of the status (perception) and dynamic knowledge (comprehension), whereas the other was the knowledge necessary for prediction, identified as disaster modeling, simulation, and forecasting.

5. Field Studies and Findings

This section explains the field studies carried out in the study, including interviews with emergency personnel, observation, and workshop. The findings of these field studies are a set of information and service requirements. Interviews and workshops with emergency personnel were also used in the system evaluation described in §7. The intention here is not to present the field studies and findings in detail, but rather to describe the general aspects and insight of the work.

5.1. Field Studies

The field studies included interviews carried out over six months with a large number of emergency personnel, observations of training sessions and secondments over two years to both the BOOC and the Emergency Response Office in the State Council of China, together with a series of workshops held throughout the whole duration of the study.

Interviews. Over 100 emergency-related personnel including 40 front-line firefighters, 20 fire incident commanders from three fire stations, 6 fire safety managers in three Olympic venues, and a number of police force and medical staff, were interviewed about their assignments for the Beijing Olympics. Only the interviews with front-line firefighters and fire commanders are described here. Based on the actor-network theory (Latour 2005), the selection of actors followed the following principles to cover the diversity between different jobs and positions:

• Select participants from all positions, ranging from the highest to the lowest positions;

• Select participants from all lengths of experience, ranging from those having few years of experience to those having many years of experience;

• Select participants from all types of experience, ranging from those having recent experience to those not having any recent experience in sport fire incidents.

The four categories of core members in emergency response, which were identified in Yang et al. (2009b), were involved in interview sessions. The firefighters and fire commanders were interviewed over a six-month period. Before the commencement of an interview, a brief introduction was given to each participant to outline the expectations of this particular interview. Furthermore, each participant was briefed on the importance of this particular interview with respect to the end results of the study. Participants were motivated by explaining how they could benefit from the outcomes of this study. After the initial introduction, participants were introduced to four scenarios that were developed based on the history of previous fire incidents at sports venues used for the Olympics. Participants were then asked to describe what they thought their objectives and actions might be during the response operation for the assumed scenario, and also were encouraged to describe their requirements, duties, and behavior that they expected to have for similar emergency response situations. Such questioning, combined with the relevant emergency scenarios, led participants to describe their information and service requirements during their response work. Variations in the scenarios were introduced during the interviews to obtain finer details and to extract more cognitive information relevant to each task. The interviews were conducted with one individual at a time from the fire brigades and took, on average, one hour. Each interview was recorded using a digital recorder and transcribed subsequently. These semistructured interviews consisted of three types of probing elements:

(a) Four fire scenarios were developed as the primary planned interview basis: a fire in the National Stadium, a fire in the Aquatics Center, a fire in the Olympic village, and a fire in the Asia Hotel next to the National Stadium. The four scenarios were explained step by step, and a verbal walk-through was carried out with the interviewees so that the interviewees would have a clear mental picture of the situations being elaborated on in the scenarios.

(b) Open-ended specific grand tour questions. A specific grand tour question was formulated as "during the abovementioned scenario situations what sort of tasks would you have to carry out in order to make a successful operation?"

(c) Simple floating prompts and variations to the primary scenarios to facilitate continuous and meaningful discussion. Such prompts were "Can you explain this particular situation further?" The variations to the primary scenarios were "What would the situation be if a similar type of fire occurred in the National Stadium during an evening rather than a daytime event? Would there be any additional tasks you may have to perform during the operation?"

The interviews became unstructured after this initial structured session, and firefighters including front-line firefighters and fire commanders were encouraged to discuss particular instances where new technologies failed or excelled, their overall feeling towards the technological components, and how they collaborated with other on-site professional groups such as police, ambulance, and medical staff. The other format used in the interviews was round-table group discussions, where a number of firefighters would have an open discussion on what investments should be made and which requirements they felt must be met by any information platform that would be subsequently developed.

Observations. Observations were conducted during joint training sessions involving firefighters and commanders, police, ambulance, and medical staff, and through secondments to both the Emergency Response Office in the State Council of China and the BOOC. Most existing field studies were limited to shadowing emergency personnel in incident response. We went a little further by sending three researchers to participate in the real emergency management work in both the Emergency Response Office of the State Council of China and the BOOC. The secondees received firsthand experience of current practice rather than research-focused emergency management, and identified the way of thinking required

by emergency personnel in incident response. Their positions were to assist emergency response planning managers, emergency response managers, BOOC IT managers, and sports venue safety managers. The secondments commenced before the project was formally started.

The research team observed the work of the police, ambulance, and fire brigade centers. They shadowed the routine work and emergency calls to the police stations. They also shadowed ambulance personnel's work at road accidents and firefighters' work at home fire incidents. The shadowing sessions lasted for six months in total. The research team also watched videos of emergency responses made by fire brigades, including serious fire incidents that had occurred in shopping centers, chemical plants, and theatres in Beijing.

To emulate scenarios that might happen during the Beijing Olympics, three training sessions of various scales were jointly conducted by the police, ambulance, and fire brigade centers in Beijing, and organized by the BOOC. The three scenarios were an incident occurring at a single sports venue in a university campus, one at a dedicated sports venue used for the Beijing Olympics, and two incidents occurring simultaneously in two different sports venues. The training sessions were videoed and used as a reference for the design and development of the integrated information platform.

Workshops and Round-Table Discussions. Workshops were used as a way of assessing the initial interview-driven and observation-driven requirements and functional designs of the potential integrated information platform. We conducted three such workshops over the first year of the study. The first workshop was carried out six months into the project. By that time, the interviews with the firefighters and other emergency personnel had been completed and the researchers seconded to the Emergency Response Office in the State Council of China and the BOOC had returned to the research team, whereas the shadowing of the work in the police, ambulance, and fire brigade centers was still ongoing. The participants at the workshop included all the research team members, the police officer from the Beijing Police Bureau, and the fire brigade officer from the Beijing Fire Bureau, together with the representatives from the Emergency Response Office in the State Council of China and the BOOC. The materials presented to the workshop were a list of user requirements and a list of the core functions, which were elicited from the interviews and observations. This workshop refined and confirmed these two lists. A paper-based functional design of the proposed integrated information platform, including the relevant network architecture and software, was presented to

the second workshop three months after the first one. The final workshop was conducted in our theatre-like emergency response laboratory. The layouts of all the user interfaces implemented in a throwaway prototype were presented to the participants at the workshop, and they were encouraged to imagine the functionality available once a full implementation had been completed and imagine their roles in these core functionality. The outcome of each workshop was captured by the use of questionnaires and the minutes of the round-table discussions.

5.2. Information and Service Requirements for Emergency Response

The ultimate objective of any emergency response information system is to provide support to incident commanders in decision making, to guide and protect emergency front line responders in their response operations, and to protect members of the public who may be located in or near to the disaster scene. The faster the emergency responders are able to gather, analyze, share, and act on key information, the more effective their response will be, the better the needs will be met, and the greater the benefit to all affected people (Van de Walle and Turoff 2007). This statement, for example, has been interpreted by the fire brigades based on the findings of the above field studies as

> The major goal of the emergency response information platform was to increase the situation awareness of the core members such as incident commanders, sector commanders, entry control officers, and front-line firefighters in an emergency response operation, together with any major subgoals necessary for meeting this major goal.

Jackson (2006) summarized information requirements for protecting emergency responders in his speech to the Government Reform Committee of the United States House of Representatives. Although managing overall emergency management has a broad set of information requirements, Jackson pointed out that the key pieces of information to guide decision making were information about the hazard environment, information concerning the responder workforce, information on evolving safety issues, and information about safety equipment. Yang et al. (2009b) stated that the following four general categories of information are essential in any on-site information system, not only for protecting emergency front-line responders, but also for ensuring the success of the emergency response operations. These four general categories are:

(a) Environmental conditions such as the building infrastructure, number of occupants, and the exact location of any hazard;

(b) Information on the response participants such as who is involved in the response, what skills they

could offer, and what resources they bring to the scene;

(c) The status of any casualties, the accident location, cause, and severity; and

(d) The available resources including equipment and food.

These four general categories of information were highlighted through our field studies, and it was verified that they are essential to the fire incidents response in and around the large-scale building structures such as Olympic venues. Timeliness, accuracy, and completeness are the critical dynamic attributes of these four categories of information. For example, the exact location of and the environmental conditions around any front-line firefighters who may have entered the building are extremely critical pieces of information for the on-site fire commanders in order to protect their staff from any danger. The details of the information requirements in each category have been used in the implementation of the integrated information platform discussed in §6. Presenting these four categories of information in a situation-awareness oriented way allows the emergency responders to quickly recognize the current situation at any incident sites, and therefore to improve their capability for decision making and emergency response.

In addition, two service requirements for decision making during an on-site emergency response have been identified through the field studies. They are (a) instant risk assessment and (b) emergency preplan.

The immediate action of firefighters on arrival at any incident site is to produce an instant risk assessment and to report this assessment result to their control center within the first five minutes after arrival. The result of this risk assessment will determine the tactical mode to be employed—for example, defensive or offensive—and would also be used for further resource allocation. Timing and accuracy are the two key characteristics in this instant risk assessment. It is not realistic to expect the first arriving responders to spend a significant amount of time collecting on-site information, filling in forms, and determining the risk grade. Any support system that might reduce the time spent on the instant risk assessment while increasing its accuracy would greatly facilitate the work of the emergency response officers.

The second service requirement was that an emergency response preplan be produced in advance for the important buildings or events, from which the on-site emergency response commanders can quickly produce an updated response plan for the current incident. The field studies also showed that a preplan is often used as guidance during the emergency response daily training. Although an emergency environment covers a wide range of situations, the differences do not require radically different plans (Wybo 1998). It was suggested from fire rescue practices that the system could be proceed by instantiating and executing stored skeletal plans, namely preplan, rather than generating response plans from scratch, especially when working in real time. The emergency response preplan for fire safety used in this study focused on those activities that are directly related to fighting an evolving fire or responding to a potential incident. It was derived from the all-hazards plan that provides the structure and mechanisms for policy and operational coordination for emergency response and management. It can be partially or fully implemented in the context of a threat, anticipation of an event, or the response to an event, therefore allowing for maximum flexibility in meeting the unique operational and information requirements of the situation (Blandford and Wong 2004, Fan and Su 2005).

We fully addressed the above needs in the design of the information platform for the Beijing Olympics. The four general categories of information were presented as the situational overview service, with the other two services for supporting instant risk assessment and providing the initial response plan. We also included the fourth service for disaster development prediction, which was implemented following the model-driven approach. By doing this, the end user requirements can be fully satisfied. The detail is given in the following section.

6. Design Principles and the Use in the Beijing Olympic Case

In this section, we present a set of design principles for integrated information platforms for emergency response in the context of the Beijing Olympics case that prompted our development. We first describe the background of the emergency response system for the games, and then present the design principles by referring to the use of them in the Beijing Olympic Games case.

6.1. Emergency Response Background for the Beijing Olympics

• Fire response force

The emergency response force for the Beijing Olympics consisted of 72 permanent fire stations and 25 temporary fire stations built around the Olympic venues. These 97 fire stations were commanded by two fire command centers; one was located in the headquarters of the Beijing Fire Bureau and the other in the Olympic park. There was a safety and security monitoring system in each Olympic venue. The fire stations communicated with the command centers through wired and wireless communication networks. A nearest available fire command mobile unit was

dispatched to any incident site with one or more fire engines from the permanent or temporary fire stations that were directly responsible for the venue where any emergency call was received. The fire command mobile units had been equipped with environmental sensors, video cameras, and mobile communication technologies, and maintained a wireless link to the corresponding fire stations and the command centers. They were able to request additional response resources from the command centers if necessary.

• Beijing Olympics operation management

In parallel with the above fire response force, the BOOC had its operation management structure. The headquarters was named as the Main Operation Center (MOC), which was directly responsible for a number of Functional Operation Centers (FOCs) such as technical support center, media and communication center, and news release center. There were 32 Venue Operation Centers (VOCs) in Beijing and 6 VOCs in other cities. Figure 1 illustrates the triangle relationship between MOC, FOC, and VOC. Information in video, audio, and text message formats was shared between them. Any incident information was immediately reported to the others. In the MOC, FOC, and VOC there was a dedicated security and safety monitoring system equipped with CCTV monitor, audio and video communication, and wired/wireless communication facilities. These security and safety monitoring systems accessed the integrated information platform via its user portal layer.

6.2. Design Principles

This section describes our design principles as a set of design and development guidance in the context of the Beijing Olympics case study. Our intent here is not only to capture the general design guidance for emergency response, but also to illustrate the way of using them in a large-scale information system development, to assist researchers and IS designers to best understand the general design guidance. The research and development work followed the research methods outlined in §4. The action research strategy was followed by commencing the

Figure 1   Beijing Olympics Operation Structure

development work with the requirement gathering through the two-year industrial secondment and over six months of field studies. The prototype of the system was developed and repeatedly evaluated and improved as a result of the end-users' response. The participatory design principle was followed by the involvement of potential users in the system development, from conceptual design to prototype design and then to system design, implementation, evaluation, and deployment. Situation-awareness oriented design principle contributed to both key service identification and user interface design and evaluation in the study. Two of the key decision support services derived based on the situation-awareness principle are situational overview and disaster development prediction. The entire user interface was evaluated against the SA principle.

Table 1 summarizes the five guidelines. Each is discussed in detail below by reference to their implementation in the information platform for the Beijing Olympics. The evaluation of the established information platform and the actual use are described in §7.

6.2.1. Principle 1: End-User Involvement. The questions we asked ourselves at the beginning of the study were: "Which occupational groups would use the integrated information platform?" "What were the required platform functionalities, which cannot be obtained without the platform?" "How were the identified occupational groups likely to use the platform?"

We started with a long list of the Beijing Olympics related organizations and shortened the list by checking it against the criteria:

• Is the organization directly responsible for the safety of any sport-relevant venues?

• Is the organization expected to directly participate in the emergency response operation during the Olympic Games?

• Does the organization have any direct authority over the organizations that meet the first two criteria?

Interviews with the representatives from the candidate organizations revealed that the potential user set included security and safety officers in Olympic venues, fire brigade commanders, police officers, ambulance staff, and medical staff. The interviews further revealed that the front-line firefighters were unlikely to use the integrated information platform during the response operation, because front-line firefighters are rarely required to make any decision in any emergency operations but simply to do what they have been commanded to do by their commanders. The integrated information platform was most pertinent to incident commanders and sector commanders working in the incident scene, and emergency officers working in the incident control center. This finding did not apply to the police force and medical staff
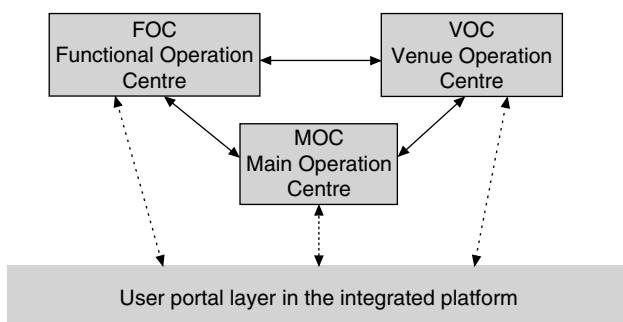
Table 1   IS Design Principles for Large-Scale Sport Events

Design principles (DP)	Description
DP1: End-user involvement	End user must be involved not only in the requirement gathering stage but also along the entire design process.
DP2: Humans as the most widely deployed sensors	Humans as soft sensors can result in much more accurate situation awareness. However, the disadvantages such as malicious and hoax fire calls must not be ignored in the design when incorporating them and communicating with the end users within the information platform.
DP3: Service-centered system architecture	All components in the architecture must serve the service provision.
DP4: Component-based design, and simultaneous prototyping and evaluation	Component-based software design creates the space for refining or modifying the individual components or adding new service in the system maintenance stage. Iterations introduced in simultaneous prototyping and evaluation can reduce the bias from the desirable design during the design process.
DP5: Visualization for situation awareness	The nature of the emergence response and its need for quick response demand an easy-to-use and straightforward user-interface design. Visualization is a promising way to achieve this.

because they are much more flexible in their roles and actions conducted at the incident scene.

The study followed the principle of participatory design. A police officer from the Beijing Police Bureau, a fire brigade officer from the Beijing Fire Bureau, and a safety officer from the BOOC were assigned to form a domain team and join the research team as representatives of their organizations. It has been recognized that the domain team became very knowledgeable after a couple of months about the potential platform as a result of their daily involvement in the research. They lost their role as end users and became developers (Markus et al. 2002). In order to accurately assess the potential of the platform, we changed the domain team members every six months to ensure that the role of the domain team continued to accurately represent the end users.

Fire and other emergency personnel have an almost paradoxical relationship with new technologies, particularly fire commanders. Their lack of enthusiasm to use the new technologies is a consequence of their experience of the unreliability of the information platform and their prolonged use of such new technologies. It was evident through the field studies that their fear of automation was one of the reasons why fire commanders sought to keep their decision making away from the use of new technologies. Fire commanders recognized the importance of keeping in touch with the environment and operations. This finding told us that the potential information platform should seek only to provide support to their decision making rather than making decisions for them. The immediate benefits from using both the platform and the associated new technologies in the field trials and training sessions eliminated to a certain level the concern they had, and significantly reduced the fear of the new technologies.

Unlike many other types of information systems, the main end users of the on-site emergency response system are organized in a paramilitary structure with strict ranks and roles (Yang et al. 2009b). For example, the incident commanders have a higher rank

and more important responsibilities than the sector commanders. On-site dynamic information is made available to both incident commanders and sector commanders, but must be presented in different details. Incident commanders are at the top of the paramilitary structures and hold all the information about the incident, including the status and capabilities of other participating organizations. The sector commanders will need little or no information at the organization level. This paramilitary structure means that end-user information requirements should be presented in terms of the emergency first responder's roles and responsibilities, rather than presenting them in a way that is technology oriented. It is important to recognize information sharing among different end users and the complexity and content of the information required at different levels. The frequency and the depth of the end-user involvement in the development of information systems for emergency response should reflect this paramilitary structure. The unique aspects of the end-user involvement in our work are threefold: (a) a full coverage of the categories of end users in the participation of the research; (b) a significant period of secondment for research team members working in end users' sites; and (c) regularly changing the domain team members to ensure that their role in the project continued to accurately represent the end users.

6.2.2.   Principle 2: Humans as the Most Widely Deployed Sensors. Critical information may be generated by hard sensors and soft sensors. Hard sensors are hardware devices such as wired/wireless sensor networks, which have proved to be efficient and autonomous data sources for the building environments being monitored (Yang et al. 2009b, Upadhyay et al. 2009). Hard sensors also include CCTV and video cameras embedded in civil infrastructure and dispersed around the incident sites. As efficient and autonomous data sources for the building environments being monitored, wireless/wired hard sensors have been widely embedded in all the newly built Olympic venues such as the Bird's Nest

and the Water Cube. These embedded wireless/wired sensors were connected with the management security and safety monitoring systems in the venues and collected large quantities of data for monitoring the venue's safety. CCTV was also deployed along with the wireless/wired sensor and resulted in much more accurate situation awareness during the Beijing Olympic sports venues than normal.

Soft sensors could be in various forms, such as field observations communicated via voice and/or textual conversations between emergency personnel. Humans as soft sensors can result in much more accurate situation awareness and have wide coverage and a greater adaptability than any hard sensors (Jiang and McGill 2010). Humans as sensors has become practically and economically feasible since mobile phones have become ubiquitous in people's daily lives and have been equipped with digital camera, Internet access, and GPS in addition to the traditional microphone. There are millions of such phones in use around the world, particularly in Chinese cities where the take-up rate of mobile phones is almost 100%. Not surprisingly, engineers are trying to add all sorts of sensors to them. Digital camera and GPS are two of the most common built-in capabilities. The Berkeley Sensor and Actuator Center (Pescovitz 2005) launched an effort to develop a carbon monoxide sensor for cell phones. Eventually, a combination cell phone/CO detector could enable environmental scientists to monitor and track pollution across densely populated urban centers.

The issue of humans as sensors has been systematically exploited in this study. There are two ways to employ humans as sensors in the integrated information platform—namely, as participatory sensing (Burke et al. 2006) or opportunistic sensing (Lane et al. 2008). Participatory sensing means that human intervention is required during data collection and transmission, i.e., manual sensing and transmission. For example, when a fire occurs in a sports hall, the human takes a photograph on their mobile phone and sends it to an emergency response center via the cellular networks. In contrast, opportunistic sensing means that data collection and transmission were carried out by mobile phones without any human intervention when a remote request is made or an event occurs, i.e., automatically sensing. In this case, for example, the locations of the people trapped inside a building on fire will be automatically sent to the firefighters nearby. Humans as sensors could be considered as humans as carriers for the purpose of moving the sensor around the observation space; humans as facilitators in which the human is responsible for operating the sensor; and humans as sensors where the human reports on what he/she senses via the mobile phone (Jiang and McGill 2010). There exists

rich research on humans as sensors recently. Campbell et al. (2008) lumped both participatory sensing and opportunistic sensing into peoplecentric sensing, Hall and Jordan (2009) named humans as soft sensors, and Jiang and McGill (2010) called it human-centered sensing, and further divided participatory sensing into direct and indirect participations. The use of mobile phones to support opportunistic sensing is still in the research phase. Therefore, the term of humans as sensors in this study particularly means participatory sensing and the human reporting what he/she sees.

There are a number of advantages of using humans as sensors in an emergency response system. The first advantage is that humans as sensors complement the coverage of hard sensors. Every Beijing Olympic venue was equipped with a huge number of smoke detectors and CCTV, and some of the venues were equipped with wireless sensor networks. The coverage of these hard sensors, however, was insufficient. The mobility of humans as mobile sensors complements traditional sensing systems or is useful in situations when hard sensors cannot provide sufficient coverage. The second advantage is the intelligence of humans as sensors. The capability of any hard sensor is limited by its preinstalled programs. Hard sensors are generally poor at handling any unexpected events that are not explicitly coded (Jiang and McGill 2010). Humans are able to adjust to, and work alone or collaboratively in, changing environmental conditions. The disadvantage of humans as sensors is that human participants are not necessarily and persistently dedicated to a particular sensing task. Jiang and McGill (2010) gave an example to illustrate this drawback, e.g., after an earthquake, a participant may be more interested in saving his friends and family than collecting data on neighborhood damage. This disadvantage may be compensated for by the number of redundant participants who are generally in the vicinity of any public building. Also, it has less impact if the public buildings are sports venues rather than dwelling houses. Another disadvantage is the possibility of malicious and hoax fire calls that place an unnecessary burden on service resources and endanger life by making response resources unavailable for genuine incidents. A close-loop automatic verification has been used in this study to reduce the number of malicious and hoax fire calls. When an emergency call, text message, voice message, or video message was received from mobile phones by a dedicated portal, or a centralized access point in the central database, this message was simultaneously sent back to the security and safety monitoring system at the corresponding venue for immediate verification. A rejection message from the security and safety monitoring system triggers a possible pause in the response operations.
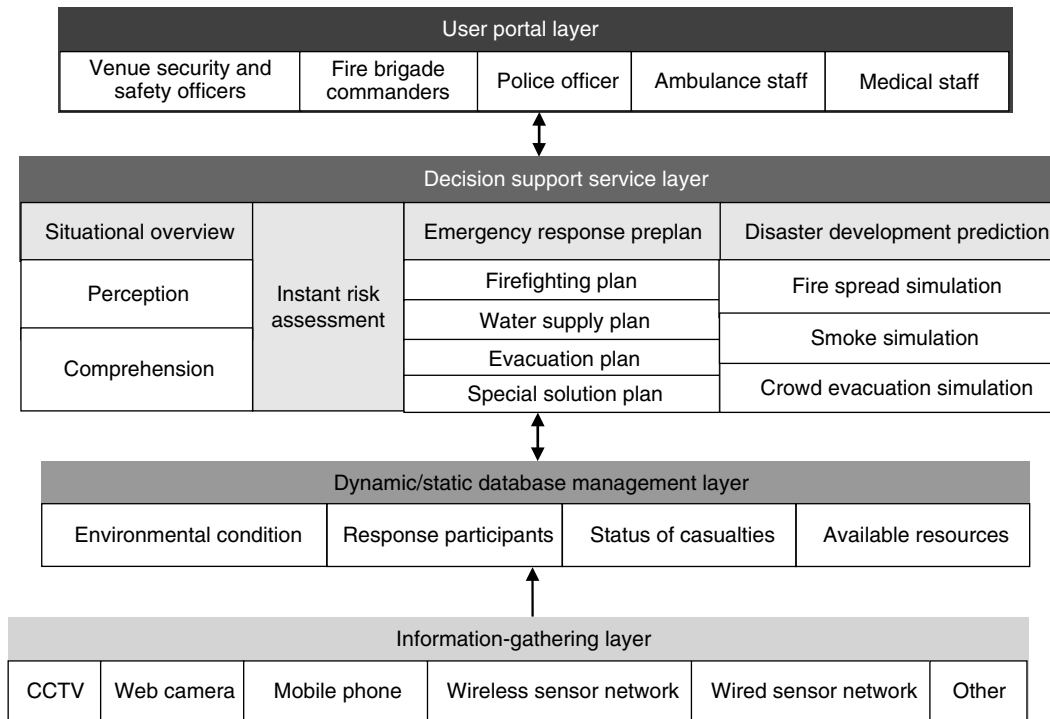
The information platform provides a centralized access point to the mobile communication infrastructure at its information-gathering layer, which is described in the following section and utilized for emergency management. The human sensors, i.e., owners and their mobile devices, transfer the collected data through communication channels such as Instant Messaging (IM), Short Message Service (SMS), Multimedia Messaging Service (MMS), and e-mails to the centralized access point. Different channels have different data receivers that are responsible for receiving data from the human sensors. The data received from different channels will be very diverse in terms of data format and quality. The data fusion engine is required to do the cleansing and transformation before passing the data to the database at the data management layer (Yang et al. 2010). This is because the data generated by the human sensors and the information required by the decision makers can differ in terms of accuracy, conciseness, timeliness, and meaningfulness. Decision makers require accurate information, whereas human sensors might give false readings. Decision makers require concise information, whereas human sensors might include a large amount of duplicated information. Decision makers would like to know the latest state of the environment; however, human sensors might report out-of-date information. Decision makers require task-specific information, whereas human sensors might provide diverse information. These differences are applicable not only to human sensors, but also to the ordinary wired and wireless sensors as well.

6.2.3. Principle 3: Service-Centered System Architecture. There are three views that influence information system architecture design. The planner's view defines the scope and the ultimate objectives of the system and the budget. The owner's view raises the end-user requirements of the system. The designer's view ensures that the objectives and end-user requirements are satisfied by the implemented system. Finding the common ground for these three views should provide the most suitable system architecture for a particular system development. The planner's view in this study was "enhancing to situation awareness of the core members." The owner's view was represented by the four categories of information requirements and two service requirements in §5.2. This section presents the designer's view as a service-centered system architecture in order to meet both the planner's view and the owner's view, i.e., all components in the architecture must serve the service provision. This designer's view was formed based on the conclusion of our field studies: *the expected information platform would not be designed to have any decision-making capabilities because it was not realistic*

for any emergency commanders to trust the automatic decision-making system in a stressful circumstance, rather than providing efficient decision support services.

There are a number of generic architecture models for emergency response available. In terms of the review in §3, a generic architecture model (Bellardo et al. 1984, Jennex 2004) for an emergency response system should include components such as a database, data analysis capability, decision-making support facility, and an interface. The service-centered architecture follows this generic model with the focus on the provision of various services identified from the field studies, and is in a spirit similar to that of Service Oriented Architecture (SoA), where service producers and service consumers are not initially designed to fit together, but are matched at run time by the service-oriented middleware. To match a service producer with a service consumer, it is necessary to have a service repository, which in our case is a database management layer located between an information-gathering component and an end-user portal. As shown in Figure 2, the architecture is a hierarchy and follows the information flow from the information producers—i.e., various sensing networks—to the information consumers—i.e., the end users. In detail, the architecture consists of four layers, beginning with an information-gathering layer for capturing and processing dynamic data, followed by a database management layer for storing and organizing the data, a service support layer for providing services to the end users, and an access portal layer at the top level of the hierarchy to allow the end users to request and receive services for emergency response and management. Of particular interest to emergency responders is the decision support service layer, which provides the situational overview service, instant risk assessment service, emergency response preplan service, and disaster development prediction service for the decision makers. This enables the decision-making process to become quicker, easier, more straightforward and more accurate, although the extent and manner in which this layer operates depend on the effectiveness of the other layers. The end users do not need direct access to the dynamic and static database from the user portal in this hierarchy architecture. Any query made by the end users is answered via different services at the decision support service layer. We argue that this service-centered architecture eases the system operation, and is particularly suitable for the use in a stressful circumstance with the need of quick response. In this section we describe some of the implementation details of each of these layers and highlight the features of these four services in Figure 2. Figure 3 shows the interactions of the four layers in the hierarchy illustrated in Figure 2, in which data and information are indicated.

**Figure 2   A Service-Centered Architecture for Emergency Response**

User portal layer				
Venue security and safety officers	Fire brigade commanders	Police officer	Ambulance staff	Medical staff

(↕)

Decision support service layer			

Situational overview	Instant risk assessment	Emergency response preplan	Disaster development prediction
Perception		Firefighting plan	Fire spread simulation
		Water supply plan	Smoke simulation
Comprehension		Evacuation plan	
		Special solution plan	Crowd evacuation simulation

(↕)

Dynamic/static database management layer			
Environmental condition	Response participants	Status of casualties	Available resources

(↑)

Information-gathering layer					
CCTV	Web camera	Mobile phone	Wireless sensor network	Wired sensor network	Other

The individual components were integrated in the architecture to form the information platform. To maintain the flexibility for any possible changes that a design may have to undergo in the future, interdependencies between one component and another has been reduced. The pattern of service producer-service consumer adopting from the SoA (Yang et al. 2003) was followed in our implementation. For example, various sensors shown at the bottom of Figure 3 were serving as data producers and the receivers as data consumers. Hard coding was avoided between the data producers and data consumers because only their IDs and features were required in service registration which was part of the receivers in this case. Similarly, the query manager was a service consumer and four service components at the decision support service layer were service producers. The link between them were established and maintained through service registration where only their IDs and features were needed. The service registration for the query manager and those four service components was implemented as part of the query manager here.

Various technologies contributed to the implementation of this architecture in the various layers. The information-gathering layer relied on wireless/wired sensors, CCTV, mobile phone, and other relevant technologies, and ensures that information pertinent to decision making is available and clearly presented to the decision makers through the corresponding services. Similar to the description about the human sensors in the previous section, image sensors, human sensors, and ordinary wired/wireless sensors were connected with their corresponding receivers, which receive and temporarily store the raw data from the sensing networks. The raw data must be processed by the data fusion engines before it is categorized and fed into the central database or venue databases. Ensuring the quality of the data such as accuracy, conciseness, timeliness, and meaningfulness was the driver of the data fusion engines. Unlike the human sensors, which were randomly distributed and linked with the central database via a centralized access point, the image sensors and other ordinary wired/wireless sensors were deployed in the individual sports venues and linked with the local venue database and the local venue safety and security monitoring systems through their specifically designed receivers, such as a gateway for wireless sensor networks.

The database contains four categories of information—information on environmental condition, information on response participants, information on the status of causalities, and information on available resources, as specified in the information requirements described in §5.2. The information stored could be dynamic or static. Static information is time-invariant data such as venue name, address, building layout, any adjacent road, and specific sections. Dynamic information is time-variant data that is continuously fed into the database from information sources such as sensor networks, humans, and video camera. We

Figure 3   Interactions of Layers and Components
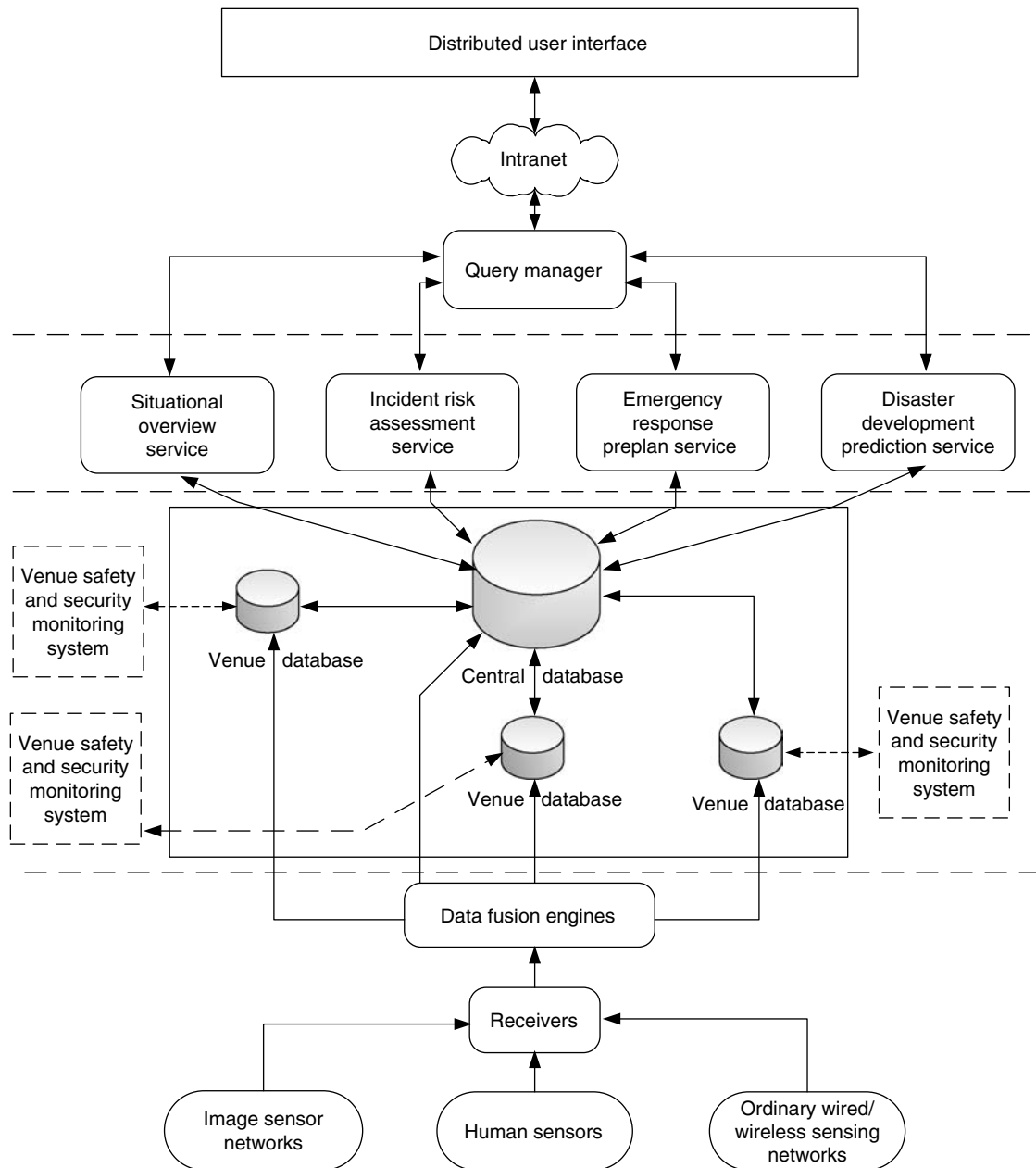
emphasize that the dynamic information must be both time and location stamped, and the information must be stored in an ordered structure for ease of retrieval and the prompt processing of queries, regardless of the increase in the volume of data. As illustrated in Figure 3, we designed a central database that was physically located in the two headquarters, one in the Beijing Fire Bureau and the other in the Olympic park. Each Olympic venue established its venue database linked with the local venue safety- and security-monitoring systems. The information gathered from the sensing networks deployed locally was first fed into the venue database and then exchanged with the central database through the database management layer. The information exchange between the venue databases and the central database were inherited from the existing database management system used in the Beijing Fire Bureau.

Among the four components in the service layer, the situational overview and disaster development prediction were fashioned to meet the four categories of information requirements elicited from the field studies, but the instant risk assessment and emergency response preplan were directly adopted from the service requirements derived from the end users.

In any large-scale disaster, the on-site emergency personnel from the various organizations must work together but normally have no previous history of doing so, and consequently have not developed trust in or understanding of each other's abilities (Van de Walle and Turoff 2008). Providing a common basis for their collaboration and decision making is crucial in such a stressful circumstance. The common basis should be based on clear and accurate situation awareness of the current position, together with a prediction of the probable imminent development of the disaster. Therefore, the most important decision support service is to provide a real-time situational overview and prediction with different levels of details for the emergency personnel, based on their roles. Situational overview was developed at the perception and comprehensive levels in this study, which are the first two levels in the situation-awareness three-level model. The situational overview service was built as the only means of real-time information presentation, and therefore completely removed the necessity of direct access of the end users to the central database. There are two benefits of doing this. Database management is made simple and less risky, and, more important, the service provided enhances the situation awareness for emergency responders. The prediction of the disaster development was based on our simulation models (Sun et al. 2006), which can predict both the development of the fire spread and the propagation of smoke and carbon monoxide (CO). We integrated this disaster development prediction service into the information platform and also allowed the service to run independently because it did not interact with other services and did not require the dynamic information gathered from the sensing networks.

Instant risk assessment is one of the most important actions carried out by fire commanders on arrival at an incident. The result of their assessment determines the tactical mode to be employed. An initial short report needs to be sent to the control center within five minutes of arrival and will directly impact how many more resources should be allocated for the ongoing response operation (West Yorkshire Fire and Rescue Service 2007). The current instant risk assessment in the Beijing Fire Bureau was carried out based simply on the experience of fire commanders arriving first. A formal instant risk assessment service was implemented in the integrated information platform that was carried out in three separate stages of an incident—the initial stage, the development stage, and the closing stage. The initial stage assessment evaluates the situation, tasks, and persons at risk and decides on the required tactical mode; the development stage reassesses the tactical mode as the incident is developing, for example, firefighting tactics may

change from defensive to offensive. The closing stage includes maintaining control and incident debriefing. It was impractical to expect the incident commander arriving first to carry out some kind of checklist, summarize it manually, and then determine the tactical mode. With the assistance of the simple interactive interface design, a hand-held PDA embedded with an electronic form communicated wirelessly with the venue database through the information platform and assisted the first responders to quickly and accurately carry out the risk assessment by determining whether there was no response required or by choosing from one of the three options—serious, medium, or minor. The assessment result was immediately sent to the control center from the PDA via the on-site information platform. This service was highly appreciated by the firefighters in our field studies.

An emergency response preplan, which was identified as one of the most requested decision support services in our field studies, acted as an operation guide for the emergency response. It was also set up for the daily training of the fire brigades. The emergency response preplan that was integrated into the information platform covered a firefighting plan, a water supply plan, an evacuation plan, and special solution plans such as a plan for searching for and rescuing disabled people in a sports stadium. Emergency response preplans have been generated in a number of separate studies for various types of scenarios (Yuan and Su 2007), informed by the fire-safety building code, the fire service manual, firefighting guidance, as well as other relevant standards, and were stored in the central database for on-site guidance.

The user portal layer shown in Figure 2 indicates the categories of end users of the information platform. These groups of end users are not always working at the same location when an incident occurs. They require different information, or the same information but in different details in terms of their roles and responsibilities. A unified distributed user interface was designed to run in a dedicated intranet for both the BOOC and the Beijing Fire Bureau. A single user portal leads to different user-specific interfaces for different groups of the users. The following attributes were implemented: (a) multiple, remote users can collaborate in real time using rich media such as image, text, video, and audio; (b) users can access the services anywhere and anytime; (c) users can view data and results visually with excellent graphs and charts; (d) users can receive real-time data when needed. Even though these features are increasingly common in new and updated decision support systems (Power 2009), the way of implementing them here was emergency-response specific considering the nature of the applications and the need for quick response. For example, we employed

a private intranet rather than public communication media such as the Internet to run the information platform and share the information; therefore, the security risk was not a big issue. Another example is that the query manager in the user portal layer contains a whole set of standard queries and reasoning mechanisms for emergency response. Typing text into the interface is not required for most of the use.

The unique aspects of this design principle are that by following this principle, the integrated decision support services will not only be able to function within the integrated system, but also be able to function as a standalone system independently from each other. Even though all the information supporting these decision support services came from the central database, the information was originally collected by various means, including hardware and humans sensors locally stored in distributed databases geographically located across the Olympic venues and then passed to the central database. The dual central/distributed database structure enhances the reliability and flexibility of the integrated information platform.

6.2.4. Principle 4: Component-Based Design and Simultaneous Prototyping and Evaluation.

Componentization has long been recommended as a practice in large-scale information system development. In this study we went a step further by simultaneously conducting component prototyping and evaluation following the participatory design principle. Each layer shown in Figure 2 was implemented as a subsystem. Each subsystem consisted of a number of components that could work alone as well as support each other, depending on the component specification. For example, the CCTV module is an independent component in the information-gathering subsystem, and the output of the CCTV components feeds into the venue database in the database management subsystem. Voice messages received from human sensors are treated differently and are verified before being fed into the central database by an information-retrieving component. This requires the participation of call center operators and the owner of the mobile phone. A close-loop verification mechanism involving a venue safety manager worked with the mobile phone information-retrieving component to reduce the possibility of a false alarm.

This component-based structure has a number of features and allows refining or modifying the components or adding new components. The emergency response preplan service and the disaster development prediction service are allowed to run either independently or within the information platform. The models used in these two services (Sun et al. 2006, Yuan et al. 2007) might need updating or removing if the disaster scenarios change. As components

were updated, they could be plugged into the existing system to create a new version available for immediately testing (Markus et al. 2002). It is also reasonably easy to respond to changes in user requirements and associated hardware updates. The challenge is in the design of the interfaces between the components and the subsystems. A consistent interface specification should be followed during the design processes of components and subsystems. The unique feature of this design principle is employing simultaneous prototyping and evaluation to identify any problems in the component design and therefore to guarantee the advantages of the design were obtained.

As indicated in §4.1, we used the throwaway approach in the requirement validation stage but used the evolutionary approach in the system development stage for developing the prototype from a very simple implementation to a fully functional version. Unlike previous existing work, our evaluation of components was conducted alongside the prototyping process rather than waiting for the fully functional version to be generated. We used hybrid evaluation walk-through and evaluation workshops to conduct our component-based evaluation. In the evaluation workshops (Fitter et al. 1991), users and developers met together, and the user representatives used the system to carry out set tasks while the designers observed their actions. The designers later explored any issues identified by this process through a facilitated discussion. An evaluation walk-through (Nielsen 1993) is a similar process, where a member of the design team steps through a system design and obtains feedback from the other participants. As is the case with almost all other qualitative methods, the reliability of both these methods has been questioned, despite their capability for providing rich feedback. In addition, the output of both these methods is usually in the form of opinions rather than objective data. To reduce the impact of these deficiencies, we combined these two approaches, i.e., we first conducted a prototype walk-through session, and then followed this by a workshop session. Before the walk-through session started, we identified a number of appropriate end-user participants, decided what task scenarios should be covered, and explained to the participants the aims of the sessions. After the workshop session was finished, a question-and-answer session was conducted, and the comments that were made in the sessions were analyzed.

This hybrid evaluation approach was applied to individual components, subsystems, and finally to the whole integrated information platform. The problems in the interfaces between the components and between the subsystems were recognized and solved in the multiple iterations of the prototyping and evaluation phases.

The specific features of the Beijing Olympic venues were fully addressed in the individual component design. For example, the new construction materials and complex structure of the venues, described as Features 1 and 2 in §2, were taken into account during the design of the components for the disaster development prediction in the service layer. The use of nonrigorous numerical fire and smoke propagation models (Sun et al. 2006) enabled quick calculation of fire development. These calculations were less accurate but more efficient than those developed by other methods, and hence more suitable for real-time use. The models were built and stored in the static database of the database management layer. As an example, Figure 4 illustrates the fire-spreading process in the Ditan sports stadium, at 120 seconds, 360 seconds, and 600 seconds taken. This was from a continuous animation of the fire-spreading process. Figure 5 was taken from the smoke-spreading process animation for the same fire. However, the spreading process was much quicker. At 360 seconds, the stadium was full of smoke. The new building materials and building structure used in the venue significantly affected the fire behavior and were used in the fire brigade training.

In addition to the new construction materials and complex building architecture, new design methods and new fixed equipment for fire prevention described in §2 as Features 3 and 4 were also taken into account in the development of the emergency response preplan. For example, the fire-fighting plan used the remote autolocated water cannons as an available resource that had never been used before in practice in China. Another example is the component design for the evacuation preplan. Most of the existing evacuation plans assume that the evacuees take predefined optimal routes to their destination and evacuate in an optimized way (Lin et al. 2008). The evacuation preplan integrated in the decision support service layer took into consideration the fact that the number of evacuees was extremely large, the density of the population was high, and there

would be a number of fire marshals always in the crowd. This evacuation preplan can run within the integrated information platform or, alternatively, as a standalone system.

6.2.5. Principle 5: Visualization for Situation Awareness. Situation awareness is the first priority in emergency response management. The emergency commanders need to be aware of the nature and scope of the disaster as quickly and precisely as possible in order to allocate the limited available resources for the disaster response operation. As an emergency event unfolds at a venue, data are generated at a rapid pace from the various data sources such as mobile phones, emergency calls, CCTV, and embedded sensors. All this data contributes to the understanding of what has happened and is happening at the emergency location. Visualization has been recognized as the most comprehensive and efficient way of presenting information and can be invaluable in helping to make the right decision at the right time in such stressful circumstances (Li et al. 2001).

An online desktop Geographic Information System (GIS) (Mehrotra et al. 2004), which has been widely used by emergency management agencies to create maps that help coordinate response and recovery efforts, was employed in the integrated information platform for the Beijing Olympics. The visualization in this integrated information platform followed the situation-awareness oriented design principle (i.e., the perception-comprehension-projection model). The ways of presenting data varied from a summary data table through items list, 3-D graph, and geographic map, to hazard propagation prediction. Navigating information within the platform was driven either by multilayer menu systems, by mouse clicking, or by zooming in or out.

Figure 6 shows four visual displays including the structure of a sports stadium (top-left) and basic static information; a traffic control GIS map (bottom-left) contains dynamic information; a response operation plan (top-right) and a fire development prediction (bottom-right) provide two decision support services.

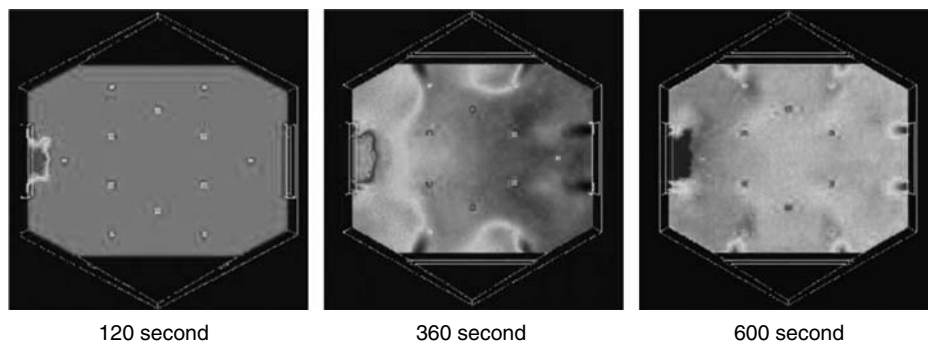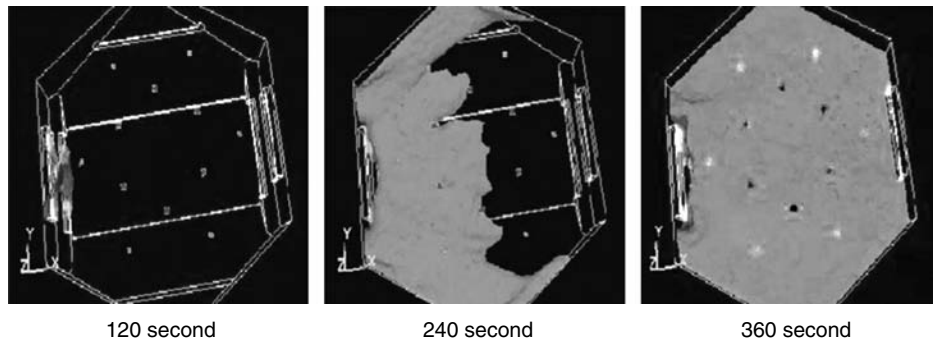**Figure 4   Fire-Spreading Process in Ditan Sports Stadium**

120 second   360 second   600 second

Figure 5   Smoke-Spreading Process in Ditan Sports Stadium

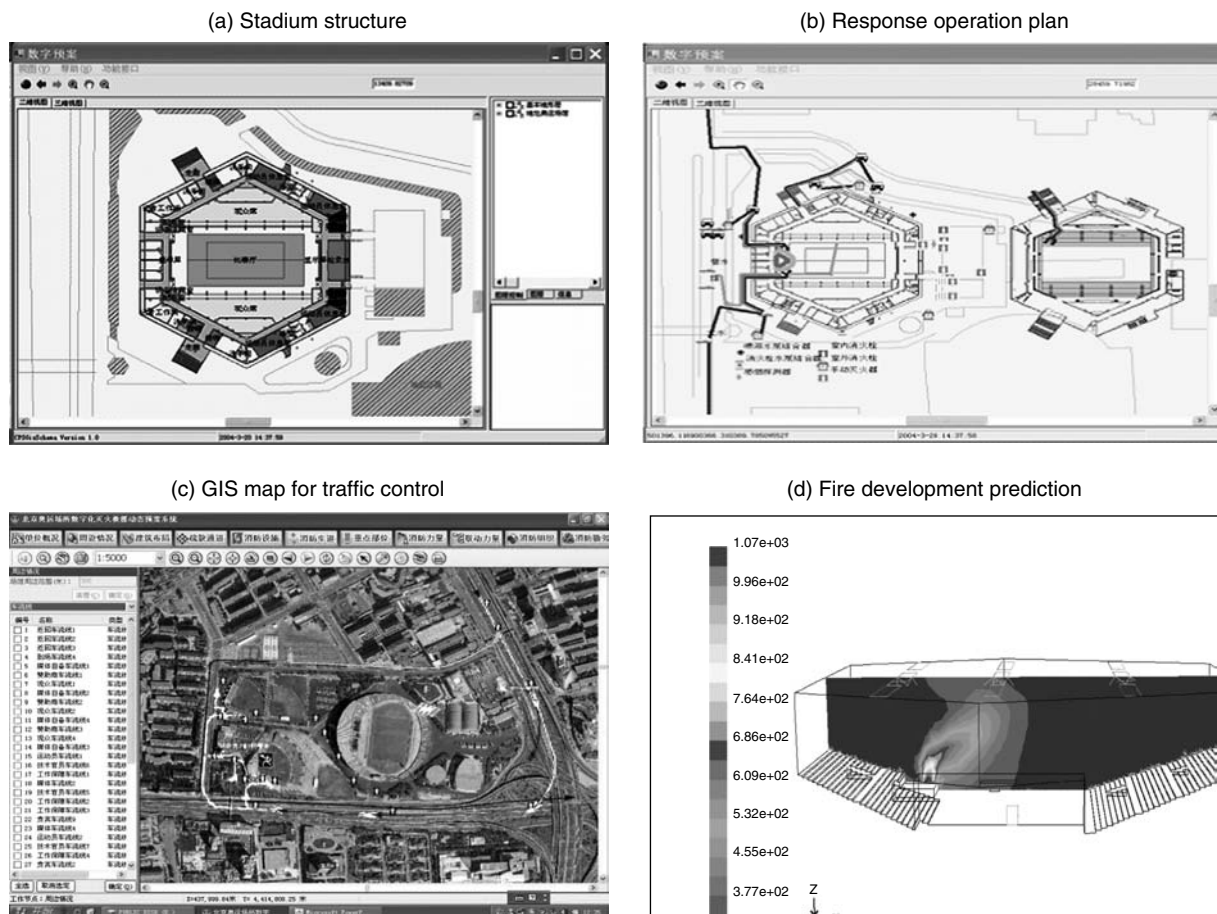| 120 second | 240 second | 360 second |

The building structure shown at the top left of Figure 6 was presented as a two-dimension plan in the platform to provide better situation awareness to the fire emergency responders. Firefighting, rescue path, and hydrants around the stadium were shown in the top right of Figure 6 to support the decision making. A three-dimensional animation of the fire propagations in the sports stadium was built into a fire development forecast window displayed at the bottom right of Figure 6. The bottom left of Figure 6 presented the latest traffic control information provided by the local traffic authorities around the sports stadium. The different color lines represent the different traffic functional guidance lanes, such as the fire access lane, athletes' access routes, and logistic support routes. In addition, this display also showed the overall picture near the stadium, such as the external hydrant location, the water resource, the adjacent buildings, and the road conditions.

The nature of the visualization enables the information presentation to be perceived by the end users without any training beforehand. In this study we

Figure 6   Visualization for Situation Awareness

(a) Stadium structure

(b) Response operation plan

(c) GIS map for traffic control

(d) Fire development prediction

used 2-D, 3-D diagrams to present the sports venue structures and street maps. We used animation to present the development of the fire. Animation was also used to show the progress of the response operations such as the evacuation of a massive crowd from a sports venue, or rescuing a disabled person from a high-building hotel. By using the touch screen technologies, the visual presentation allows the end users to rotate 3-D pictures, change the angle of view, and quickly search a path from a particular location inside the venue to the nearest exit. With the rapid increase of computer computation capabilities and the significant reduction of their costs, more and more low-cost and easy-to-use visualization tools are being made available for the use in emergency management. Our work clearly demonstrates the power and potential of visualization in the emergency response domain.

7. System Evaluation and Use in the Beijing Olympics

Our evaluations focused on user satisfaction because user satisfaction has been identified by previous information systems research as a critical measure of system success (DeLone and McLean 1992, 2003). Following the design science build-and-evaluate approach and our design principle, we evaluated all the components integrated in the information platform along the development process to ensure user satisfaction with the individual components. The purpose of the system evaluation was to examine the utility and efficacy of the information platform as a whole. No formal evaluation was attempted in the sense of comparison with other benchmark systems. This is not surprising, nor is it a criticism of this work. There simply are no existing benchmark systems that address the same problem. We performed multiple evaluation studies at a system level by conducting our demonstration sessions as part of the BOOC emergency training sessions in collaboration with the Beijing Fire Bureau. Four emergency scenarios were planned for the demonstration sessions beforehand by the senior BOOC safety managers and kept secret from the end-user participants before the demonstration session actually took place. These four scenarios were a fire in the National Stadium, a fire in the Aquatics Center, a fire in the Olympic village, and a fire in the Asia Hotel next to the National Stadium. Even though these four scenarios were previously used in our field studies to gather the user requirement, they were still new to the participants of the demonstration sessions because we deliberately selected participants who did not take part in our previous field studies. The demonstration sessions were conducted in the training base of the Beijing Fire Bureau. We set up an actual fire in the building with

a similar structure to one of the sports venues. The fire commanders and other relevant emergency personnel were asked to use the information platform to understand the situation and analyze the risk and conduct resource deployment, and make their decisions on their response operations. Feedback on the performance of the information platform was gathered through a workshop session immediately after the demonstration sessions. Three main topics were discussed:

(a) The performance of the information platform related to the capability of supporting the decision making of the emergency personnel and thereby improving the effectiveness of their response operations; related to the performance drawbacks and means of overcoming them;

(b) Possible design failures on the user interface design, the services provided, as well as how to avoid failures;

(c) Feedback on the controllability, overall appropriateness and usefulness.

We summarize part of the findings from the system evaluation here:

(a) The information platform may add extra stress to the emergency personnel rather than reduce or remove work-related stressors, not because the amount of training has not been properly provided, but because of the functions provided. For example, most participants mentioned that the display of health indicators, such as heart rate of a first responder who is already in stress, created additional further stress. A design feature "relief management" was subsequently added to the situational overview service for fire commanders as it can have a direct impact on reducing welfare related stressors. In general, the participants in the system evaluation agreed that the information platform could minimize the workload, time pressure, and welfare-related stressors as well as help to avoid the physical stressors common in the incident grounds.

(b) The complexities of the information platform may slow down the decision-making process. The feedback from the system evaluation indicated that providing the option of end-user customization for organizing information around the goals may reduce the complexity of the system. Such an option may lead to quick decision making and avoid partial situation awareness or information overload caused by the unwanted system complexities. In response, we provided flexibility in the user interface design to allow the end users to organize the information around their operational goals.

(c) The participants in the system evaluation were satisfied with the coverage and contents of the information provided by the information platform but expressed their concern about some inconsistencies in

the display of similar information in different interfaces belonging to a particular job role. These inconsistencies ranged from the use of colors, symbols and abbreviations in the user interface design to the coverage of the available information resources. Some suitable modifications were introduced to make the system more consistent across both the user interfaces for different job roles and the services provided.

The proudest achievement of this study is that the developed integrated information platform was deployed in the real world and used in the Beijing Olympics. We do not claim that the integrated information platform helped the first responders and emergency personnel to save people's life or reduce the loss of properties because there were no fire incidents or other natural or manmade disasters during the 2008 Beijing Olympics. However, we do claim that the platform contributed to the success of the events because it provided comprehensive situation awareness for the safety managers at the sports venues and the fire commanders in the Beijing Fire Bureau 24 hours a day and seven days a week during the events. More importantly, the integrated information platform was used in the extensive emergency response training by the Beijing Fire Bureau and the BOOC before the events, in some case even before the actual sports venues were built. These Olympics specific trainings for emergency response significantly built up the confidence of the emergency personnel and enhanced their capabilities in decision making for emergency response operations. Our contribution to the success of the Beijing Olympics was recognized by receiving several national awards from various Chinese government bodies. The integrated information platform has been continuously serving the safety of the sport facilities and other public buildings in Beijing ever since the Olympic Games.

8. Practical Value to IS Research and Lessons Learned

Using the case study as the core of the research, this study derived five design principles. We argue that these five design principles form a contribution to the IS literature because they provide guidance that could be used in the general domain of emergency management planning and help to mitigate the challenges this study faced.

Design principle 1, which we called "end-user involvement," presents solutions to the three challenges caused, respectively, by a wide range of organizations involved, a domain team becoming unrepresentative of the end-user group, and the end users' fear of new technologies. All of these challenges and solutions are generic. The core values of this design principle focus on a way of refining the involvement of end users, ensuring that the domain team continue to represent the end users, and eliminating the end users' fear of using new technologies.

Design principle 2, which we named "humans are the most widely deployed sensors," states that people complement the lack of hard sensors deployment inside and outside the geographically distributed sports venues. This design principle is generic and can be applied in every possible IS development. The unique features of humans as sensors, such as mobility, flexibility, intelligence, and wide coverage, should be employed intensively in any future IS development with the rapid increase of the environmental-sensing capability provided by wearable mobile devices.

Design principle 3, which we called "service-centered system architecture," aims to provide decision support rather than decision-making services for emergency personnel, which should remove their fear of being excluded from the decision-making loop. Assessing the architecture of an IS can be conducted in terms of various indices, such as system performance, robustness, and openness, etc. Service-centered system architecture focuses on service provision. Every component in the architecture must contribute to this ultimate design objective. Even though only four categories of services were identified from the field studies for the Beijing Olympic case, they cover the most requested services for emergency response operation and can be used in the general case of emergency management.

Design principle 4, which we called "component-based design, simultaneous prototyping and evaluation," provides a solution for large-scale IS development and evaluation. It allows for the concurrent development of multiple components if a consistent interface specification is strictly followed during the development. This design principle also emphasizes the simultaneous component prototyping and evaluation from a simple to a fully functional version. Adherence to this principle would most likely reveal any potential problems in the individual component design and their integration, and could resolve any conflict in the interface between components and between subsystems.

Situation-awareness oriented design was one of the main research methods used in this study, particularly for user interface design. Design principle 5, which we called "visualization for situation awareness," points out that enhancing situation awareness is the main aim of information presentation, and using visualization could be the way to best achieve this aim when presenting location-related information. Many available commercial visualization tools such as MapQuest have made visualization extremely easy and straightforward. The appropriate use of the capability of an available visualization tools in IS

development can significantly increase the opportunity of the system being accepted by the end users.

Four of the lessons learned from this study are summarized as follows.

Firstly, front-line firefighters were not the direct users of this information platform, but their firefighting efficiency depended on the decisions made by their commanders, which were based on the information and services provided by this platform. Yang et al. (2009b) classified the core firefighters as incident commanders, sector commanders, entry control officers, and front-line firefighters. Adapting this classification, the information platform was mainly used by the commanders composing the first three categories. Front-line firefighters normally do what they have been commanded to do. They wear designated personnel protective equipment (PPE) required for the particular job. With the increased level of PPE, front-line firefighters have the least amount of physical freedom compared to the other job roles. With thick gloves on, it is very difficult for a front-line firefighter to control a device that needs a precise touch. Also, firefighters always use their hands to carry and operate firefighting equipment such as water hoses, as well as to inspect the surroundings, find their way, and avoid hazards and obstructions. Therefore, the use of the hands for the control of computer-based devices is not feasible for front-line firefighters. This narrows the scope of potential users while also contributing to the user interface design.

Appropriate use of alarms in the real-time information presentation was the second lesson we learned. It not only improves the decision-making capability of the fire commanders, but also minimizes the stress on their basic senses like ears and eyes. Our field studies showed that the appropriate use of alarms allows the fire commanders to maintain a better balance in their attention to the many activities and incidents happening at the incident scene. In contrast, the overuse of alarms could distract the attention of the fire commanders and force them to change their focus. This rapid change of attention at the time of an alarm could cause more harm than good because the fire commanders could be forced to ignore their current focus, which might be of more importance than the situation the alarm was drawing attention to. The need for an alarm to be included in the platform was validated in the simultaneous prototyping and evaluation in the study. All the nonessential ones were removed from the design at this stage.

Communication between the control centers, the on-site incident commanders, the security and safety officers at the sports venues, and other emergency response organizations relies solely on the public information communication infrastructure, which is vulnerable to any malicious attacks or natural disasters. An instantly activated information infrastructure or satellite communications channel might be essential in these cases, but expensive. For example, TETRA (Terrestrial Trunked Radio), standardized by the European Telecommunications Standards Institute, is a specialized private network infrastructure and is being used by police forces, fire and rescue services, and ambulance services in the UK (Yang et al. 2009b). Unfortunately, there was no such specialized information infrastructure available for this integrated information platform during the Beijing Olympics. The third lesson learned from this study was that the communication supporting the information platform must be based on a private network infrastructure and cannot be exposed to any malicious attacks.

The final lesson obtained was on project management. A limited budget was a big threat to the deployment of the integrated information platform. Even though the BOOC was allocated an enormous budget by the Chinese central government, the fire safety departments had a limited budget for new technologies and equipment that were not mandated by a standard body. The trade-offs were not between what they wanted and what they needed but between what they needed and what they needed most. These trade-offs were purely cost driven. There was no engineering advantage for some fire stations to have the information platform installed and others not to. Decisions were made, based on which Olympic venues had the most potential fire risk, most serious consequences if a fire occurred, which were used most often during the games, and which fire stations were closest to these venues.

9. Conclusions and Future Work

An integrated information platform in the context of fire disasters has been constructed and implemented for emergency response at the Beijing Olympics. The platform consisted of an information-gathering layer, a database management layer, a decision support service layer, and a user portal layer. The methodology for designing and implementing the platform was based on the combination of action research, participatory design, and situation-awareness oriented design. A lengthy period of field studies helped us to identify the potential end users of the platform and understand their requirements. The field studies included interviews with the end users, observation of emergency training sessions and operations, and the organization of workshops and round-table discussion. The information requirements were categorized as four types—information on environmental conditions, information on response participants, information on the status of casualties, and information on the available resources.

The user service requirements included situational overview, instant risk assessment, an emergency response preplan, and a disaster development prediction. Generalizing from the experience of building the information platform, we have derived five design principles for use in the general domain of IS development for emergency response. These five design principles are end-user involvement, humans as sensors, service-centered system architecture, component-based design and simultaneous prototyping and evaluation, and visualization for situation awareness. They offered solutions to mitigate some of the challenges this study faced. We claim that these five design principles form a contribution to the IS literature because they could be used in the general design of emergency management systems and could help emergency IS developers in mitigating similar challenges faced in other such emergency situations.

From a practical point of view, the most significant feature was that the platform implemented has actually been deployed and used in the 2008 Beijing Olympic and the Paralympics Games that were held in the same year. The integrated information platform developed for emergency response is not specific to sports venues but could also be applied to numerous locations such as crowded venues, high-rise building, large public areas, and industrial factory and so on. Furthermore, the proposed integrated information architecture is expected to be broadly applicable to other types of emergency management due to the common end-user requirements and standard operating procedures. It will improve comprehensive emergency management and response and help to realize scientific disaster prevention and alleviation.

The next phase of this effort will be directed towards enhancing the performance of the components of the platform, addressing the security issue, adding the capabilities of the location tracking of front-line firefighters indoors and outdoors, and usability analysis across the range of possible users. We intend to pay particular attention to the development of indoor location tracking. It has been identified in our field studies that wearable mobile devices, which can aid navigation during the rescue operation within a sports venue, let firefighters "see" in the dark or through smoke, and allow them to scan a room for people in seconds are urgently needed. Unfortunately, because of the cost and the limited physical freedom of front-line firefighters, this requirement has not been met in practice. Our field studies revealed that these capabilities are important to front-line firefighters, because these tools will help them avoid getting lost. We expect that the location information of front-line firefighters can be automatically gathered and presented in the achieved information platform in the near future.

This study employed human sensors, i.e., owners and their mobile devices, only for data-gathering purpose. There were no direct communications between the affected people and the on-site fire commanders through the established information platform. With the rapid development of mobile communication technologies, these mobile devices are offering other value-adding services such as routing, message publishing, chat client, and friend finder. These value-adding communication services extend the concept of human sensors into human services, which should be significant if integrated into the information platform.

Acknowledgments

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