



## Information Systems Architecture for Fire Emergency Response

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## Information Systems Architecture for Fire Emergency Response

### **Abstract**

#### *Purpose*

There has been a lack of meaningful information systems architecture, which comprehensively conceptualise the essential components and functionality of an information system for fire emergency response addressing needs of different job roles. This study proposes a comprehensive information systems architecture which would best support four of the key fire-fighter job roles.

#### *Design*

The study has built on the outcomes of two previous preliminary studies on information and human-computer interaction needs of core fire fighter job roles. Scenario based action research was conducted with fire fighters in a range of roles, to evaluate human computer interaction needs while using various technology platforms.

#### *Findings*

Several key themes were identified and led us to propose several layers of an integrated architecture, their composition and interactions.

#### *Research limitations*

The selected fire scenarios may not represent every type of fire expected in high risk built environments.

#### *Practical implications*

The current paper represents a shared discussion among end users, system architects and designers, to understand and improve essential components. It, therefore, provides a reference point for the development of an information system architecture for fire emergency response.

#### *Originality*

The proposed information system architecture is novel because it outlines specific architectural elements required to meet the specific situation awareness needs of four of the key firefighters job roles.

## Introduction

Compared to most other disaster related jobs such as emergency operations centre personnel, ambulance services and medical rescues, fire fighters face comparatively stressful and life-threatening environments where they have very little time to make a life and death decision (Sha et al.,2006). Such contextual differences create a unique set of needs and requirements for the frontline fire fighters (Prasanna, 2010). Although there has been several attempts to design or develop information systems supporting fire emergency response it has been a challenge to conceptualise the essential components of an information system (IS) for fire emergency response (ER) addressing needs of different job roles and the functionality of such an IS.

There appears to be very little literature on the higher-level systems architecture of an IS supporting different fire fighter job roles having different information needs which is well understood by both the owners of the system as well as the systems architects. The lack of understandings between system architects, firefighters and fire and rescue service (FRS) could become one of the major constraints during IS development. The lack of processes and dialogue between these groups is, in turn, likely to slow down the progress of implementing fire ER support systems. In effect, a lack of dialogue and shared processes may mean ISs are being developed only to be rejected by end users. Regarding psychology of change in organisations, this represents simply pushing changes onto end users, instead of informing changes according to user needs (see Clegg and Walsh, 2004).

As a response to this situation, the remainder of this paper is organised into five main sections. The first of these sections outlines a brief review of relevant literature, and the subsequent section outlines the overarching research approach and details of adopted methods. Then this paper presents the results which include identified strengths of the proposed ISA. This is followed by a section explaining the components and functionality of layers of the proposed ISA including its applicability and validation. The last section of this paper outlines the contribution of this study to ISA and emergency management literature, followed by the limitations and potentials for further research.

## Literature Review

There have been several attempts to develop Information Systems Architectures (ISAs) for exclusively supporting ER. For example, Madey et al. (2006) developed a wireless phone

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3 based ISA to provide traffic forecasts and emergency alerts for engineering, public safety and  
4 ER personnel. The scope of this architecture remains limited to the technological capabilities  
5 of mobile phones. Other examples include “WORKPAD” (de Leoni et al., 2007), which is a  
6 layered communication architecture to support decision making during ER operations. This  
7 architecture has a Mobile Ad-hoc Network (MANET) based data storage & communication  
8 layer, a middleware layer for the management of various emergency related dynamic  
9 processes, and user layers which support two types of users and their interaction with the  
10 system. Although the MANET architecture aims to support needs of the operators who were  
11 in the field during disasters, there is no evidence that it has addressed the distinct needs of  
12 different types of responders.  
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20 German researchers, Meissner et al. (2006) of Fraunhofer-Gesellschaft (see Fraunhofer-  
21 Gesellschaft, 2007) presented an integrated mobile information and communication systems  
22 architecture for ER operations: Mobile Information and Communication System for Public  
23 Safety Organisations (MIKoBOS). This architecture supports reliable data communications  
24 within an emergency site and between an emergency site and headquarters. Meissner et al.  
25 (2006) were focused on some common needs of emergency management personnel  
26 including: emergency personnel working at the command centres; emergency operation  
27 commanders working inside vehicles located at an incident; and frontline responders who  
28 may be mobile and located anywhere within an incident scene. The MIKoBOS architecture  
29 was developed by comparing technologies for communicating within networks of different  
30 user types (Meissner, et al., 2006). It also reflected actual requirements of end users working  
31 in emergency related domains. However, this architecture addresses generic emergency  
32 situations. It is, therefore, unlikely to comprehensively address ISA requirements specific to a  
33 particular type of emergency, being responded to by a particular type of emergency service.  
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44 There are also ISAs that focus on supporting a particular type of emergency condition  
45 or domain (Kwan & Lee, 2005; Hwang et al., 2007; Lorincz et al., 2004). This includes ISAs  
46 for supporting fire emergencies. Examples include the work of Wilson et al. (2005) and  
47 Wilson et al. (2007) on the Fire project, Jiang et al. (2004a) on the Siren project, Jiang et al.  
48 (2004b) on Large Displays for Incident Commanders (ICs) , Klann (2008) on the LifeNet  
49 project, May et al. (2014) on potential benefits of wireless networks for tunnel fire response,  
50 Roh (2015) on integrating technologies supporting decision making using the transmitted  
51 information, and Scholz et al. (2013) on a system supporting frontline fire fighter  
52 communications. These examples represent significant efforts to develop firefighter related  
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3 ISs. However, and although all this work looked at systems supporting fire ER in built  
4 environments, none of it focused on supporting the specific response operations of the Fire  
5 and Rescue Service (FRS), through the development of an overarching IS architecture.  
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8 Our own search for recent developments on ISAs supporting fire ER is complemented  
9 by a systematic literature review by Dorasamy et al. (2013), which explored knowledge-  
10 driven information systems in support of emergency management in last two decades.  
11 Dorasamy et al. (2013) identified 51 significant pieces of emergency management  
12 information systems research. Much of this research was presented at highly ranked IS  
13 conferences, including the Americas Conference on Information Systems, and published in  
14 prominent journals such as Technological Forecasting and Social Change, Journal of  
15 Information Technology Theory and Application, Management Information Systems  
16 Quarterly, and Disaster Prevention and Management. The majority of the studies reviewed by  
17 Dorasamy et al. (2013) were published in the well-known crisis informatics journal,  
18 International Journal of Information Systems for Crisis Response and Management and  
19 presented at its annual Information Systems for Crisis Response and Management  
20 conference. Close examination of 51 systems considered by Dorasamy et al. (2013) clearly  
21 indicate that except for SafetyNet (n.d.), which is the system associated with the ISA  
22 proposed in the current paper, there had been no other significant, directly relevant research  
23 in this area as at 2013. In particular Dorasamy et al. (2013) reported no other significant  
24 research regarding information systems for supporting various firefighting job roles.  
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37 When considering technology platforms proposed in last two decades, it appears that  
38 the FireGrid Project (Upadhyay et al., 2008) and the hybrid architecture of Nguyen et al.  
39 (2015) are the only substantial architectures exclusively designed for supporting fire ER in  
40 built environments. The high-level architecture proposed for the FireGrid includes sample  
41 components along with data and control connections. This architecture integrates various  
42 technologies in a distributed design. However, and although the FireGrid architecture  
43 recognises a need to use diverse technology to capture contextual information, it does not  
44 identify the technological diversity required for the successful presentation of information to  
45 various types of firefighters. Furthermore, this architecture does not reflect how differences  
46 in firefighter roles, behaviours and working contexts create demands for different Human  
47 Computer Interaction (HCI). Therefore, the proposed FireGrid architecture does not appear  
48 capable of addressing the distinct needs of different firefighter job roles.  
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3 A more recent study conducted by Nguyen et al. (2015) in Germany proposed a hybrid  
4 architecture for firefighters and examined how different smart technologies could be coupled  
5 to support fire fighters. However, this latter study does not substantially address the research  
6 and conceptual gap concerning ISAs for fire ER. Nguyen et al. (2015) appear to have been  
7 driven by traditional software engineering techniques. As a result, their study has not clearly  
8 identified the unique information needs of different fire fighter job roles.  
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13 There are three key limitations in the wider literature related to ER ISAs. Firstly, most  
14 of the proposed architectures are technologically biased and only focus on common needs  
15 held among a broad range of emergency responders. Although there have been some efforts  
16 to support fire ER specifically, these efforts appear to focus on a selection of common needs.  
17 They do not address the needs of different key fire fighter job roles experienced while  
18 responding to a large incident. Most of the architectures proposed are therefore not  
19 comprehensive enough to cover the full scope of expectations of the fire and rescue hierarchy  
20 during fire ER in a built environment. At the time of writing, there appears to be very little  
21 evidence of an existing ISA that supports the diverse needs of different firefighter job roles.  
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29 Secondly, and even more importantly, there is a very little literature on the systems  
30 architecture of an IS for fire ER, which is well understood by both the end users of the system  
31 as well as system architects. Instead, most of the available ISAs are only capable of  
32 communicating system characteristics to IS architects and developers. Although there are a  
33 few highly sophisticated and technically advanced ISAs for supporting fire emergencies, the  
34 development of such architectures appears to have excluded communication with the actual  
35 end-users, especially during very early stages of systems design such as requirements  
36 gathering. It is critically important to review the architecture of an IS, to reduce the cost of  
37 mistakes and to find and fix architectural problems as early as possible. Architecture review  
38 is a proven, cost-effective way of reducing project costs and the chances of project failure.  
39 This helps systems designers to identify issues and recognise areas for improvement  
40 (Microsoft, 2015). As part of this process, especially when designing a complex system for  
41 stressful environments such as fire emergencies, it is essential to communicate the intended  
42 system and its architecture to, and get the feedback from, the owners of the system. In this  
43 case, the owners of the system are fire fighters with a specific range of different job roles.  
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55 Finally, there has been a lack of meaningful ISAs, which comprehensively address the  
56 varying Situation Awareness (SA) needs of different fire fighter job roles. For many decades,  
57 Situation Awareness (SA) has been identified as one of the critical concepts to be considered  
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3 when designing information systems supporting end-users working under stressful  
4 environments. Salmon et al. (2016) argued that systems which are not capable of enhancing  
5 SA lead to decision making failure causing huge economic and human losses. Endsley et al.  
6 (2003) identified eight possible factors that lead to situation awareness (SA) failures and  
7 named them *SA Demons*. Understanding the impact of these SA demons and efforts of  
8 minimising such impacts in the process of design and development of a system is an  
9 important part of the implementation.  
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15 To make things worse, there has been very little evidence to substantiate the success of  
16 any IS implemented for supporting fire ER. A lack of available technology platforms for  
17 exclusively supporting fire fighters is highlighted in one of the recent studies into fire fighter  
18 acceptance of new technology platforms (Yang et al., 2013). In this research Yang et al.  
19 (2013) concluded that firefighters fear using technology as they are worried about the  
20 reliability of the existing systems and have procrastinated in adopting them. This clearly  
21 indicates that there is a significant lack of current literature outlining appropriate technology  
22 architectures for supporting unique and individual information requirements of different fire  
23 fighter job roles when responding to fire emergencies.  
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31 To start overcoming this above described gap in the current literature, this study aimed  
32 to define an Information Systems Architecture (ISA) to support firefighters' response to fires  
33 in large scale built environments. This ISA is based on the comprehensive needs of potential  
34 end users. We aimed to develop definitions which were clearly understood by the system's  
35 potential end users, as well as by the system's designers and architects. Importantly, the  
36 architecture would not be limited to relying on one particular technology or one established  
37 set of technologies.  
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#### 45 *The "Owner's View" of an ISA*

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47 The current approach to defining an ISA was based on the work of Zachman (1987) and  
48 Sowa and Zachman (1992). Zachman (1987) made an analogy between traditional building  
49 architecture and information technology architectures which led them to categorise six  
50 different views or perspectives: planner's view of size, shape, relationships and intent;  
51 owner's view drawn by the architect; designer's view drawn by the architect; contractor's  
52 view drawn by the contractor; subcontractor's view drawn by the sub-contractor; and finally  
53 the enterprise view, which represents the physical makeup of an architecture.  
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These perspectives are associated with three types of description (Zachman, 1987) that characterise each view by categories of data, function and network and descriptive dimensions of what, how and where descriptions (Zachman, 1987). In total, the Zachman (1987) taxonomy forms a six by three ISA matrix. Rows represent the six perspectives and columns represent the three types of description. Sowa and Zachman (1992) went on to add three more types of descriptions: people, time and motivation, which correspond to questions of who, when and why. Figure 1 represents the latter, extended ISA framework.

	<b>DATA</b> <i>What</i>	<b>FUNCTION</b> <i>How</i>	<b>NETWORK</b> <i>Where</i>	<b>PEOPLE</b> <i>Who</i>	<b>TIME</b> <i>When</i>	<b>MOTIVATION</b> <i>Why</i>
Objective/Scope (contextual) <i>Role: Planner</i>	List of things important in the business	List of Business Processes	List of Business Locations	List of Important Organizations	List of Events	List of Business Goal & Strategies
Enterprise Model (conceptual) <i>Role: Owner</i>	Conceptual Data/ Object Model	Business Process Model	Business Logistics System	Work Flow Model	Master Schedule	Business Plan
System Model (logical) <i>Role: Designer</i>	Logical Data Model	System Architecture Model	Distributed Systems Architecture	Human Interface Architecture	Processing Structure	Business Rule Model
Technological Model (physical) <i>Role: Builder</i>	Physical Data/Class Model	Technology Design Model	Technology Architecture	Presentation Architecture	Control Structure	Rule Design
Detailed Representation (out of context) <i>Role: Programmer</i>	Data Definition	Program	Network Architecture	Security Architecture	Timing Definition	Rule Speculation
Functioning Enterprise <i>Role: User</i>	Usable Data	Working Function	Usable Network	Functioning Organization	Implemented Schedule	Working Strategy

Figure 1: Framework of Information Systems Architecture

An extensive understanding of the fire emergency context was gained in this study through user centred and action research based interactions (see Hayes, 2011) with practising firefighters. This approach most immediately corresponded to the planner's view of an ISA framework (Zachman, 1987), while identifying the basic purpose of an IS in the minds of firefighters. However, it became evident that a planner's view was not detailed enough to have a comprehensive understanding of the IS components for supporting firefighters. According to Zachman (1987), the owner's view is made up of architect's drawings depicting final structures. These structures are shown from the perspective of an owner who will have to incorporate them into the daily routines of their business regarding relationships between business entities and processes. This set of drawings could also be referred to as an end-user's



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3 view. They correspond to an enterprise model or a conceptual architecture of an information  
4 system, to align with the overall business model of an organisation. This is how our initial  
5 contextual understanding laid a foundation to propose a comprehensive, “owner’s view”.  
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7 This was achieved by providing a comprehensive conceptual IS architecture which was  
8 clearly understood by firefighters, FRS, and the architects and designers of a fire emergency  
9 IS.  
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### 13 14 15 16 **Methodology**

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18 Pre-existing literature summarised in the introduction section, together with preliminary  
19 interviews with fire and rescue service members, have suggested that many IS architectures  
20 fail after neglecting to identify comprehensive end user requirements and failing to specify  
21 interfaces that will meet those requirements. To overcome such profound limitations, the  
22 current research has built on the outcomes of two preliminary studies conducted over a period  
23 of four years.  
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#### 30 *First Preliminary Study*

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32 The first of the two preliminary studies produced a set of the comprehensive and validated  
33 information needs for core members of the UK Fire and Rescue Service Incident Command  
34 Hierarchy, namely: 1) Incident Commanders (IC), 2) Sector Commander (SC), 3) Breathing  
35 Apparatus Entry Control Officers (BAECOs), and 4) Breathing Apparatus Wearers (BA  
36 Wearers). In this iterative study, acquisition of the information needs of firefighters was  
37 driven by a goal oriented cognitive task analysis tool: Goal Directed Information Analysis  
38 (GDIA) which was exclusively developed for the first preliminary study after considering  
39 many other cognitive task analysis tools (Yang et al., 2014). This study included face-to-face  
40 semi-structured interviews and brainstorming sessions with firefighters, together with  
41 observations of related training, amounting to over 1,000 hours of contact with potential end  
42 users. At the end of the study a comprehensive set of information requirements for the four  
43 core job roles of the UK FRSs was obtained in the form of 310 GDI diagrams which  
44 illustrates the link between Goals-Decisions and Information needs for each fire fighter job  
45 role.  
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### *Second Preliminary study*

Having considered the comprehensive information needs identified in the first preliminary study, the second study produced a validated set of human-computer interfaces. These interfaces were designed to address human-computer interaction requirements for the core job roles outlined above (Prasanna et al., 2013).

The interfaces proposed were designed and developed with the support of Windows-based software prototyping tools, GUI Design Studio Version 2.0, and Adobe Flash. These interfaces form the basis of the first step of an evolutionary development of a fully-fledged IS supporting firefighting response. These interfaces are capable of representing dynamic incidents, changing across time and space. Adobe flash software was chosen to embed high level dynamism in the interfaces. This allowed the interfaces to simulate the movement of firefighters in a building, data entry interfaces with direct manipulation, and dynamically appearing alarms. The design and development of the software prototypes was followed by a series of prototype demonstration sessions with potential end-users, to understand the appropriateness and usefulness of the proposed software prototype for supporting fire ER.

### *Current Action Research*

Study The current paper concerns scenario based action research that was conducted to evaluate the performance of human-computer interfaces developed in the second preliminary study when those interfaces were deployed under different available technology platforms. Action research was considered an appropriate approach to evaluating these interfaces because, according to Hult and Lennung (1980), this approach assists in practical problem solving while simultaneously expanding scientific knowledge. This study was performed collaboratively with members of the FRS being studied, through iterative cycles of research which led towards an incrementally improved understanding of their specific situation.

The current research incorporated feedback from various direct and indirect stakeholders, including members of the FRS directly attached to the fire incident command hierarchy during a fire emergency and other emergency services: Police, the Ambulance and Hospital Service.

The action research included deployment of human-computer interfaces developed and validated during the preliminary research outlined above. These interfaces were deployed alongside a variety of technologies, within a range of operational contexts: at incident sites;

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3 in fire engines which had been deployed near incidents; with mobile fire fighter personnel; in  
4 temporary incident command units near an incident; control room of an incident building; in  
5 a fire and rescue regional incident command centre; in a police command centre; at a local  
6 hospital; and in a local ambulance control centre. Stakeholders were asked to use the  
7 interfaces across a variety of technology platforms. They were asked to use these interfaces to  
8 support fire incident response event in a simulated setting affected by a predefined fire  
9 scenario.  
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### 17 *Evaluation Walkthrough and Evaluation Workshop*

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19 Participants in this scenario were then asked to comment on their experience of using the  
20 interfaces as part of different communication and information technologies. They were also  
21 asked to compare interface performance between variations in the technology provided  
22 alongside those interfaces. Although all variations involved existing software and hardware  
23 technologies, participants were also asked to comment on new technology adaptations being  
24 piloted during the study. Interface evaluations were conducted in both low demand and  
25 simulated stress environments. *Evaluation workshops* and *evaluation walkthrough* were  
26 identified as the most suitable methodologies for evaluation the use of prototype interfaces in  
27 low demand contexts, because of their participatory and less demanding nature. User testing  
28 in a simulated environment provided the setting for evaluation in a more demanding  
29 environment. An evaluation walkthrough is process, where a member of the design team goes  
30 step by step through a system while recording reactions from participants. An evaluation  
31 workshop instead asks user representatives to use the system to accomplish a set of tasks  
32 observed by designers. Both processes provide an detailed description of how a proposed  
33 system design could be used for different tasks under different circumstances (Maguire,  
34 2001). According to Stanton et al. (2005), both processes can provide a powerful assessment  
35 of design concepts.  
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48 During our preliminary workshops and walkthrough sessions, participants were  
49 encouraged to ask any questions they had. They were also asked to comment on the usability  
50 and functionality of the interfaces presented as part of different technology platforms. All  
51 comments from session participants were recorded and collated in a data file. As stated  
52 above, it was acknowledged that the workshop evaluations did not provide genuine usability  
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3 testing. Likewise, walkthrough evaluations do not usually include the kinds of stressors  
4 experienced during actual emergency response operations.  
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### 8 *Field Testing the Prototype*

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11 User testing in a simulated environment was chosen to overcome the limitation of the  
12 prototype evaluation sessions by situating the simulation prototype in a well-established  
13 training environment in the Leicestershire FRS Training School at Loughborough, UK. All  
14 principal categories of emergency responders participated within this training environment.  
15 Information was shared between various interfaces by using the range of proven  
16 telecommunication technologies outlined in Table 1. These technologies were incorporated  
17 under different communication parameters, to reflect the scenario being simulated.  
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24 An incident scenario was designed to feature a well-known shopping centre. The  
25 shopping centre was assumed to be on fire, with a number of shopping centre staff and  
26 customers trapped inside. This scenario was completed within 50 minutes before being  
27 repeated with three different sets of participants. The process was repeated six times in total,  
28 on different dates and under various technology platform arrangements, including different  
29 technology and communication arrangements. Participants' interactions with the interfaces  
30 were recorded by several video recorders, during all scenario sessions. Video recordings were  
31 transcribed into text-based reports once all training had been completed. Transcripts were  
32 then categorised, coded, and organised into a data file for analysis.  
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40 Participants were also asked to complete a questionnaire to record their experiences.  
41 The questionnaire was split into two sections. The first section covered how successfully the  
42 participants could interact with the prototype and asked them to measure the success of their  
43 interactions on a scale of 1 to 10. The second section measured how satisfied or dissatisfied  
44 participants were with both the appearance and functionality of the IS. All answers to the  
45 questionnaire were summarised and later combined with the analysis of data from the  
46 workshop, walkthrough, and training sessions.  
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## Results

Data gathered from this study of human-computer interfaces as part of varying technology platforms highlighted the benefits of taking an “owner’s view” from early in the development of a complex IS. Data analysis produced key themes, describing essential requirements that were expected from an ISA and also transparently understood by both IS owners and designers. Comments from nearly 80 percent of stakeholder and participant feedback clearly suggested that the proposed information output screens would improve decision making capacity and operational effectiveness, but only if the ISA:

1. Consists of a network of technologies to capture data from the incident environment;
2. Consists of a mechanism to process data;
3. Is capable of making unprocessed data more meaningful by organisation or classification; and
4. Can cater for individual needs and display different categories of information in a way which is meaningful for those individuals.

### *Overall Strengths of the Prototype ISA*

A range of sub-themes regarding expected functionality and components of the proposed ISA were also obtained during piloting. Principal themes concerned overall strengths of the ISA characteristics. End user feedback from seventeen out of nineteen evaluation sessions confirmed the overall success of the mock-ups proposed. Feedback also reflected that the mock-up prototypes had been considered a genuine representation of an IS. Participants in all job roles showed that they accepted the mock-ups as a system of human-computer interfaces to support their ER operations. More than 80 percent of participants mentioned that the proposed interfaces matched with their expectations of an ideal system. They considered that the mock-ups presented information in a way which would support real decision making.

Comments from nearly 90 percent of feedback on IC and SC prototypes suggested that the proposed information output screens would improve decision making capacity and operational effectiveness. This feedback showed that ICs preferred to use the summarised information screens more frequently than the SCs. The graphical screens, showing in depth details of internal and external context, still appeared useful to a number of SCs. The simple and rapid combination of graphical information layers, delivering comprehensive decision making support, appeared to be appreciated by most participants. Participants also

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3 highlighted how these interfaces could improve their forecasting capabilities. Other feedback  
4 suggested that the efficiency of proposed interfaces created extra time to extend decision  
5 making cycles.  
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9 More than 75 percent of participants in the BAECO and BA Wearer sessions gave a  
10 positive response to the prototypes. They described how interfaces deployed inside fire  
11 engines can help them to prepare physically and mentally to carry out operations while still  
12 en-route. More than 50 percent of positive feedback also suggested that interfaces for  
13 BAECO and BA Wearers could help the FRS to modify existing fire and rescue procedures,  
14 which participants appeared to find complex and/or lacking effectiveness.  
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19 Feedback from more than 80 percent of participants representing IC, SC and BAECO  
20 roles highlighted the importance of alarms for aiding successful decision making. It seemed  
21 that appropriate alarms would allow the ICs and SCs to better balance attention amongst the  
22 many activities and events occurring during an incident. Feedback also suggested that alarms  
23 could allow BA Wearers to become more mentally and physically flexible during operations.  
24 The alarms appeared to be able to minimise stress on the BA Wearers' basic senses like ears  
25 and eyes. Apart from providing basic alarms on the use of resources, feedback highlighted the  
26 importance of providing alarms for BA navigation, to increase the physical flexibility of BA  
27 Wearers.  
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34 Participants from sixteen evaluation sessions, including a group of third party  
35 specialists, stated that it was vital to have input interfaces which were both simple and user-  
36 friendly. It seemed that these end user data input screens would encourage end users to input  
37 their own information. According to the participants, inappropriate data input screens could  
38 lead to output screens being seen as inaccurate due to insufficient human data input and an  
39 over-reliance on non-human sensors. This appeared related to a loss of trust in the system,  
40 amongst many fire fighters who were not ready to rely on completely non-human sensors.  
41 Feedback from participants in nine sessions suggested that the prototype data input screens  
42 could help address these issues, by facilitating reliable human data input. The following  
43 section discusses these findings and other details about surrounding literature, to propose a  
44 new set of information system layers.  
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### Research Synthesis: Information System Layers

With reference to the themes and other results outlined above, we propose an “owner’s view” of the ISA. This view is capable of delivering on the requirements outlined above, by identifying requirements and supporting information needs during a fire emergency response. To address the architectural needs outlined above, we propose an ISA consisting of four layers:

1. The Data Capture and Networks Layer of the architecture, to capture data from various information sources and provide communication between information sources and other components of the architecture.
2. The Data Manipulation Layer, to provide services that add value to data initially captured from various sources.
3. The Function Modules Layer, to organise information for common functionalities which different end users expect.
4. The Human Computer Interaction Layer, to manage the functionality of various human-computer interfaces, supporting different firefighter jobs through a range of devices.

#### *Data Capture and Networks Layer*

This layer is effectively a communication infrastructure for the IS. When considering the various needs of firefighters, both electro-mechanical and human sources are required to capture data, including data input from firefighters with very different roles. It is crucial to capture information needs from many different types of information sources located in and around incident premises. It is also as vital to maintain communication among: contextual information capturing devices; firefighters located inside and outside incident premises; display devices inside the fire engines and various locations within incident premises; the FRS control room; fire stations; other response services such as ambulance, police and the local government; and third parties providing weather, media and traffic information.

The current ISA pilot shows how there was no single communication technology to meet the requirements of all end users. Instead, network redundancy seems to be an important issue raised by participants. It would, therefore, be most appropriate to use a network architecture that simultaneously supports multiple communication technologies.

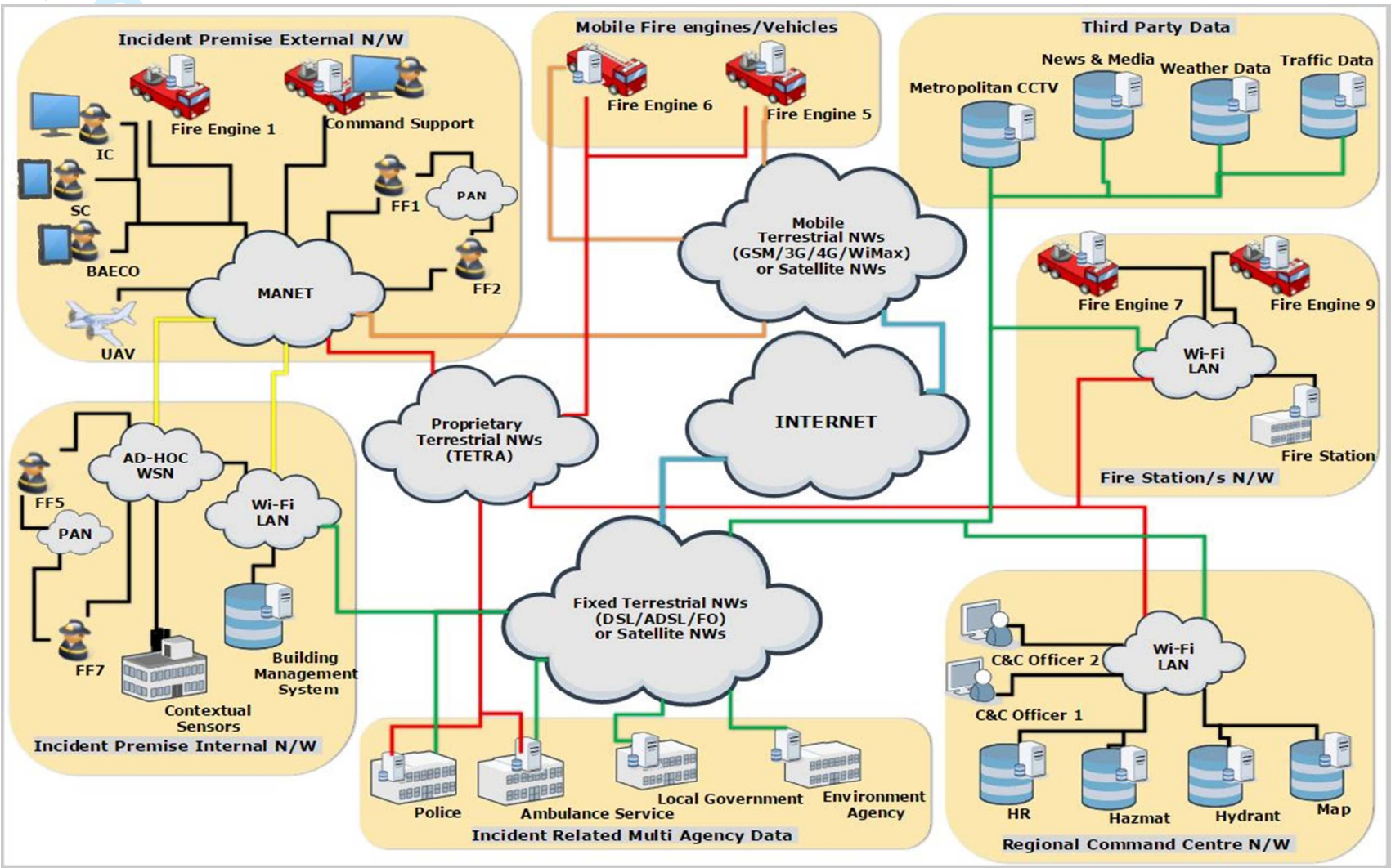


Figure 2: Data Capture and Networks Layer



Integrating various technologies into a single platform which allows them to be used both flexibly and interchangeably mean that various communication alternatives can complement each other. When one network is unavailable, the system can switch to use another available option. Preferably, the ISA will automatically switch from unavailable to available technologies according to predefined policies (see Meissner et al., 2006). This will help guarantee the availability of communications without having to pay for the provision of contingent services when they are not actually used. Based on the considerations outlined, the current paper proposes a high-level architectural layout for the data capture and networks layer as elaborated in figure 2. In addition, Table 1 summarises components and suitable technologies for implementing each component across multiple locations.

[Table 1. Components and Technologies for Data Capture and Networks Layer]

#### *Data Manipulation Layer*

Data captured from the Data Capture and Networks layers are passed up to this layer, which provides support services to carry out common data manipulations such as storing, filtering and processing. This means that more value-added data can be passed on from one layer to another, to carry out higher level functions unique to fire ER. For these purposes, the current research proposes three main considerations: data management; data fusion and the method/model base.

The current paper has highlighted how fire ER information systems should primarily enhance fire fighters' awareness of their operational situation. Data fusion within an IS needs to be executed in a way which promotes such awareness. Salerno et al. (2004) discussed the need for data fusion for achieving situational awareness in multisensory data capturing contexts. They outlined more than thirty fusion models that had already been proposed, and which may have had some relevance for the proposed ISA.

None of these data fusion models appears to have been as influential as the Joint Directors of Laboratories (JDL) model, outlined by Hall and Llinas (1997). Salerno et al. (2004) suggested that the JDL model provided the most appropriate way to use data fusion for complementing the situation awareness model from Endsley (1995), in complex domains. The JDL model outlines data fusion in three increasing levels of inference (Hall and Llinas, 1997): Object Assessment, to combine location and parametric data to identify and represent individual objects; Situation Refinement, to develop a description of current relationships

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3 among current objects and events in the operational environment; and Impact Assessment, to  
4 project situation progress into the future. Blasch et al. (2006) identified that outputs from  
5 these levels of inference corresponded to Level 1 (SA perception), 2 (SA comprehension) and  
6 3 (SA projection) components of the Endsley (1995) situation awareness model.  
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10 The current research indicates a need for ad hoc sensor networks with a variety of  
11 contextual and location tracking sensors. These sensor networks will need to process large  
12 amounts of heterogeneous sensory data and information from spatially dispersed sources.  
13 Sensory data and other information are usually processed centrally (Maris and Pavlin, 2006).  
14 However, central processing can suffer from inadequate communication and processing  
15 capacities. Central processing is also vulnerable to single point failures, because of the  
16 absence of redundancy. Also, centralised approaches to fusion might not be well suited for  
17 dynamic systems operating in highly fluid and challenging environments. This is because  
18 central processing depends on centralised reasoning about the states of the fusion system  
19 itself. This has the potential to result in a massive flow of information and the need for  
20 additional processing (Pavlin et al., 2004), resulting in bottlenecks in the flow of information.  
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24 We, therefore, recommend distributed, rather than centralised, data fusion. An  
25 appropriately distributed fusion system would be able to adapt to operational situations  
26 without human intervention. IS modules should form fusion systems with other relevant  
27 modules which can calculate resource allocation for sensing and processing capacity (Pavlin  
28 et al., 2007). To cope with such complex functionality in a systematic way, this study  
29 proposes a multi-agent system (see Wooldridge, 2009) where each agent takes care of partial  
30 fusion, as defined by Maris and Pavlin (2006).  
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34 Considering data processing capabilities of modern data sensor nodes, we propose a  
35 *tiered* approach to data fusion, as outlined by Mullen (2006), Chong and Kumar (2003) and  
36 Pavlin et al. (2004). A tiered fusion network should consist of two types of agents: 1) the  
37 *sensor agents*, consisting of both physical and human sensors; and 2) the *fusion agents*,  
38 receiving input from sensor agents for further data fusion. By adopting partial data fusion, the  
39 proposed Data Fusion service layer should be able to combine support from various sensor  
40 agents and fusion agents, to fuse data captured from various data sources and store them in  
41 the fusion database. It is anticipated that sensor and fusion agents connected in this tiered  
42 approach to data fusion will be able to fuse data into all three levels of inference outlined in  
43 the JDL fusion model.  
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3 As outlined above, this use of the JDL model forms a systematic approach to  
4 supporting the situation awareness of end-users. However, the proposed ISA cannot meet  
5 Level 2 and Level 3 situation awareness needs unless data fusion is supported by an  
6 appropriate Methods/Models Base, to store supporting methods, models and procedures. This  
7 base needs to provide support for: phrasing and cleaning data to increase salience; alerting  
8 end users to new knowledge; and controlling overall functionality of the system, for example,  
9 speech recognition to control the Head Mounted Display (HMD). Other relevant services  
10 could include Kalman Filters, Alpha Beta Filters, Covariance Error Estimation and expert  
11 build models such as Computational Fluid Dynamics (CFD) models for fire, cloud or  
12 hazardous gas propagation - depending on identified needs.  
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20 Database management can be particularly challenging in an IS which needs to deal with  
21 large and varied data including images, signal data, vectors, textural data, and both incoming  
22 and rapid retrieval data rates (Hall and Llinas, 1997). As outlined above, data managed by an  
23 IS for fire ER have many of these characteristics. A Data Management service is required to  
24 facilitate access to, and management of, data fusion databases and all other supporting  
25 databases. This includes data retrieval, storage, archiving, compression, queries, and data  
26 protection. The type of data stored in these databases can be dynamic, static or historical.  
27 These databases are usually highly distributed and can be located at a number of sites, from  
28 the actual incident to off-site facilities, including facilities provided by third parties.  
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### 38 *Function Modules Layer*

39 Modules in this layer carry out the processing required for a functional HCI Layer by  
40 combining a number of basic services. The Function Modules Layer represents a transparent  
41 ISA layer for end users who interact with the system via the HCI. It should, therefore, be able  
42 to process data in a way which improves the usefulness of information being delivered.  
43 Responsive ISA design means that data processed within the Function Modules layer is  
44 presented at the HCI Layer, according to the unique requirements of end users with various  
45 job roles.  
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52 Both preliminary research and the current IS pilot have indicated a need for modules  
53 that manage: physical and human resources; sectors and cordons; hierarchy and job roles; and  
54 location tracking and navigation. Further modules are required to process geographical data,  
55 monitor variations in the operational context, input other data, and generate alarms, logs and  
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3 reports. End users will often need combinations of these modules to meet ER demands. For  
4 example, monitoring the spread of a chemical plume may require the processed output of  
5 both context monitoring and geographic modules. It is, therefore, vital that the entire  
6 Function Modules Layer is designed so that each module can communicate with any other  
7 main or sub-module required for operational tasks.  
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#### 11 12 13 14 *Human-Computer Interaction (HCI) Layer*

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16 Preliminary research indicated that the requirements for four particular job roles would  
17 directly or indirectly address the needs of other incident command hierarchy members. The  
18 HCI layer of the proposed ISA has therefore been designed to accommodate four main job  
19 roles: an IC, a SC, a BAECO and BA Wearer. Modules for each job role need to be  
20 implemented with technology which ensures human access to required interfaces. For  
21 example, an HCI module for the IC job role should consist of a dashboard, a black box and  
22 many other interfaces which are capable of displaying information for supporting perception,  
23 comprehension and projection.  
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30 In addition to the four main job roles, the proposed ISA will need to provide  
31 operational access to the IS for all other members of the IC hierarchy. As outlined by  
32 Prasanna et al. (2007), this means that the HCI layer needs to include human-computer  
33 interfaces that support a range of other roles. For example, given similarities in work  
34 behaviour, mobility and the working environment, the HCI module proposed for IC's would  
35 also suit Operational Commanders. The HCI module for SC's also appears to suit other  
36 functional and operational SC, Crew Commander and Safety Officer roles. Further  
37 customisation may be required when designing the human-computer interfaces for these other  
38 job roles. Likewise, as observed during the current research, it will be important to provide  
39 online access to additional members who are directly or indirectly linked to the incident  
40 command hierarchy during a response operation. This includes Command Support (CS) team  
41 members and other officers working from a control room.  
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50 Members of the CS team provide the bulk of information management support to an  
51 incident command team. These members play a human sensor role that can input important  
52 information to the system. Officers at the control room are also important for fire detection  
53 and initial resource deployment. Feedback received during the current research also indicated  
54 that if the officers at a control room can continuously monitor an operation, this would further  
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enhance the response operation on site. It is, therefore, important that the HCI Layer also has modules which can support each of these job roles. In sum, an HCI layer for comprehensive fire ER should include the following modules: IC/Operations Commander; SCs (Functional and Operational); Crew Commanders and Safety Officers; BAECOs; BA Wearers and other frontline Firefighters; CS Officers; and officers at the control room. All remaining firefighter job roles are assumed to align with these categories for the purposes of HCI module design.

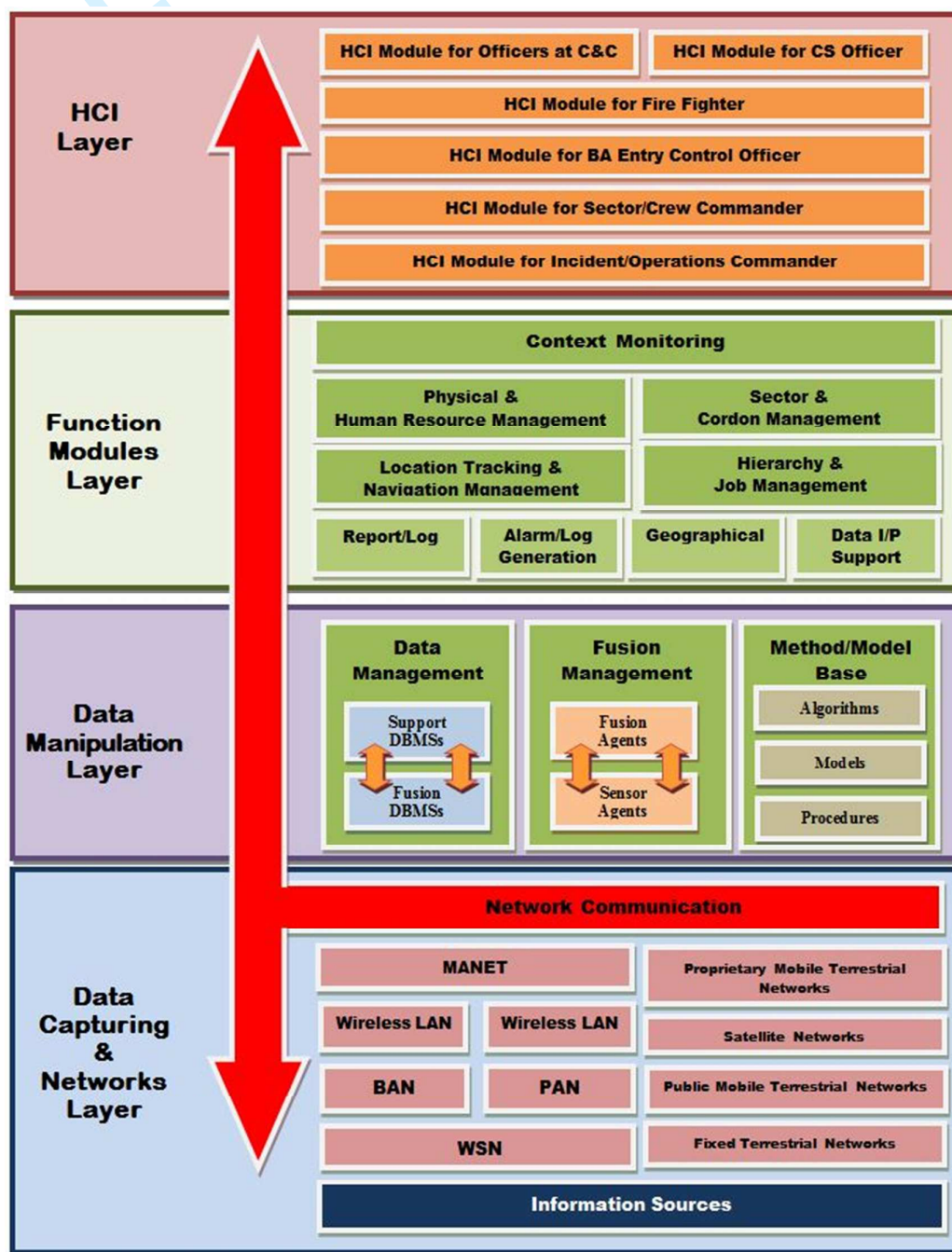


Figure 3. Conceptual ISA for Fire ER Operations

Figure 3 illustrates the comprehensive ISA proposed for supporting emergency response to high risk built environment fires. As shown, this diagram elaborates the implemented components and services of the architectural layers focussing on supporting responses to a scenario involving a high-risk fire emergency response in a built environment. The architectural view, shown in figure 3, needs to be well understood by both the owners of the system as well as the systems architects because this is the basis for identifying and defining the components of future ER ISs. As explained above, this corresponds to an “owner’s view” of an IS.

#### *Applicability and Validation of the Proposed Architecture*

The proposed conceptual architecture was subsequently used to develop a physical prototype of a system supporting fire fighters in the context of high-rise building fires (SafetyNet, n.d.). The physical prototype was tested at the Leicestershire fire training school. Two representatives each from the Police, Ambulance and Hospital Service and 20 firefighters representing different FRs in the UK Midlands took turns to form a team of two fire fighters, one BAECO, one sector commander and one IC. These teams participated in a three-hour field trial of the usability of the physical prototype. Participatory debriefing sessions were carried out at the end of the simulation, to obtain feedback from the fire fighters concerning the usability of the proposed type of a system. This session was video recorded, and researchers maintained field notes separately throughout the simulations. Subsequently recorded video footage and field notes were analysed using similar tools to those used during the requirements capturing phase.

Although a discussion of testing of the physical prototype is beyond the scope of this particular paper, the themes extracted from the testing of the physical prototype were very positive. In summary, all 20 participating fire fighters believed that the proposed type of systems are essential to improve their practice and will help to minimise fire fighter and public casualties. Although most of them proposed many new requirements and modification to the prototype, there was a clear indication of trust in using the type of system proposed. The fire fighters were very positive about the method and the definition of the information architecture and recognised this as a suitable system for supporting when responding to a wide range of infrastructure fire events. Although this particular validation was specifically conducted to test the usability and applicability of the prototype of the proposed system, the

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3 above feedback highlights the potentials to implement the conceptual architecture of the  
4 system outlined in the current paper and used as the primary design specification for building  
5 the physical prototype.  
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## 10 **Conclusion**

11 This paper has outlined the high-level conceptual architecture of a system for deploying  
12 human-computer interfaces in support of various fire ER roles. The ISA outlined defines  
13 essential components to be embedded within an overall IS.  
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### 20 *Implications for Theory and Practice*

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22 There has previously been a very little literature which clearly explains the high-level  
23 systems architecture required to support fire ER. There has also been very little attention to  
24 producing an ISA, which is well understood by both system owners and system architects.  
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26 Likewise, the majority of previous literature has proposed an ISA for either generic ER  
27 operations (for example: de Leoni et al., 2007; Meissner et al., 2006) or for generic ER  
28 purposes which are very different to fire ER (for example: Hwang et al., 2007; Lorincz et al.,  
29 2007; Wilson et al., 2005). Both of these shortfalls are addressed in the current research, by  
30 outlining a specific ISA for fire ER, in a manner which can be understood by system owners  
31 and system architects alike.  
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38 Pre-existing ISAs detailed in research literature appear to be less comprehensive and  
39 only focus on the needs of a few selected end users, or a few selected technologies. In  
40 contrast, the proposed ISA has been driven by a range of validated information, including the  
41 identified HCI needs of potential end users identified from two preliminary research. This  
42 combination has helped to define a comprehensive, and therefore more appropriate, ISA  
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44 Importantly, the composition and functionality of each layer of the architecture proposed was  
45 only defined after considering the following aspects of the research context: 1) Overall end-  
46 user information needs, 2) end user information presentation and sharing needs, 3) existing  
47 opportunities and challenges for proven software and hardware technologies to address these  
48 end-user requirements, and 4) new software and hardware technology requirements reflecting  
49 the limitations technologies available at the time. Furthermore, the proposed high-level ISA  
50 for supporting fire fighters consists of four primary layers 1) Data Capture & Networks, 2)  
51 Data Manipulation, 3) Function Modules and 4) Human Computer Interaction. This ISA was  
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3 subsequently used to build a working physical prototype and later validated with the  
4 participation of end-users for its usability. The findings of the validation study clearly  
5 justified that proposed ISA is suitable to build an IS capable of deploying human-computer  
6 interfaces to comprehensively address the specific needs of four of the key fire fighter job  
7 roles. The proposed ISA is, therefore, both more accurate and comprehensive for fire ER.  
8 Rather than taking a generic approach to the needs of an entire fire ER hierarchy, the  
9 proposed ISA outlines specific components which are essential for enhancing the SA of  
10 firefighters in different job roles during Fire ER.  
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17 The proposed, “owner’s view”, of the ISA architecture supporting specific fire fighter  
18 needs will make a significantly positive impact on the software engineering practices in crisis  
19 informatics. Participatory studies carried out with the support of potential end users has  
20 helped ensure that the proposed architectural view is well understood by both the owners of  
21 the system as well as the systems architects and therefore will have a significant influence in  
22 identifying and defining the components of their future ER ISs. This study therefore clearly  
23 outlines how the proposed ISA serves as a comprehensive platform for shared discussion  
24 among end users, system architects and designers, to understand and improve the essential  
25 components of an IS for fire ER. The proposed ISA may act as a conceptual benchmark for  
26 both clients and designers to a) compare and rank a system already available, or b) develop a  
27 context-specific system with high level of usability and trust among end-users. As a  
28 blueprint, this proposed ISA may guide system’s architects to design technically  
29 comprehensive, architectural representations and support them work alongside with system  
30 developers to develop a more optimised IS for the FRS and other fire ER agencies.  
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41 By proposing an evidence-based ISA supporting fire ER, the outcomes of this paper  
42 fills a significant gap in the crisis informatics literature. It provides valuable input to both  
43 theory and methodological practice for the design and development of ISs for fire ER with  
44 the possibility of extending to other similar crises. This contribution is further justified by the  
45 findings of the systematic literature review of investigating emergency management  
46 information systems in last two decades (Dorasamy et al., 2013). In the literature reviewed,  
47 among nearly 50 systems supporting emergency management, SafetyNet was the only  
48 system that supports firefighters. The SafetyNet system was based on the ISA proposed in  
49 this paper.  
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### *Limitations and Implications for Further Research*

It is acknowledged that the selected scenarios may not represent all types of fire emergencies that occur in high risk built environments. Future research could consider incorporating a greater range of fire scenarios to help build a more robust understanding of the complex situations that can occur. The proposed ISA is an outcome of a participatory action research exclusively focused on fire risks in high-rise buildings and limited to the participation of emergency responders in the East Midlands region in the UK. However, most of the highest fire risk buildings in the UK are located in and around the London Metropolitan area. Further research, with the participation of FRS brigades and other fire ER agencies that are familiar with built environments having much higher levels of fires risk, could increase the applicability of the proposed type of ISA.

Validation studies, with a much broader participation driven by approaches similar to Delphi studies (Linstone & Turoff, 2011) would also make a valuable contribution in the current research domain. Such approaches would provide an opportunity to explore how the proposed type of ISA suits different fire situations (tunnel fires, bush fires, airport fires, etc.) and in other local or international geographical locations. Such extensions of the current research would help better understand the levels of usability of proposed type of ISA in a much broader context. Extended validations could provide recommendations on how to improve the appropriateness of the layers of proposed architecture and embedded technologies to maximise potential benefits. Just as importantly, validation studies could provide recommendations for how an ISA can be implemented, accepted and trusted among a wider community of fire responders.

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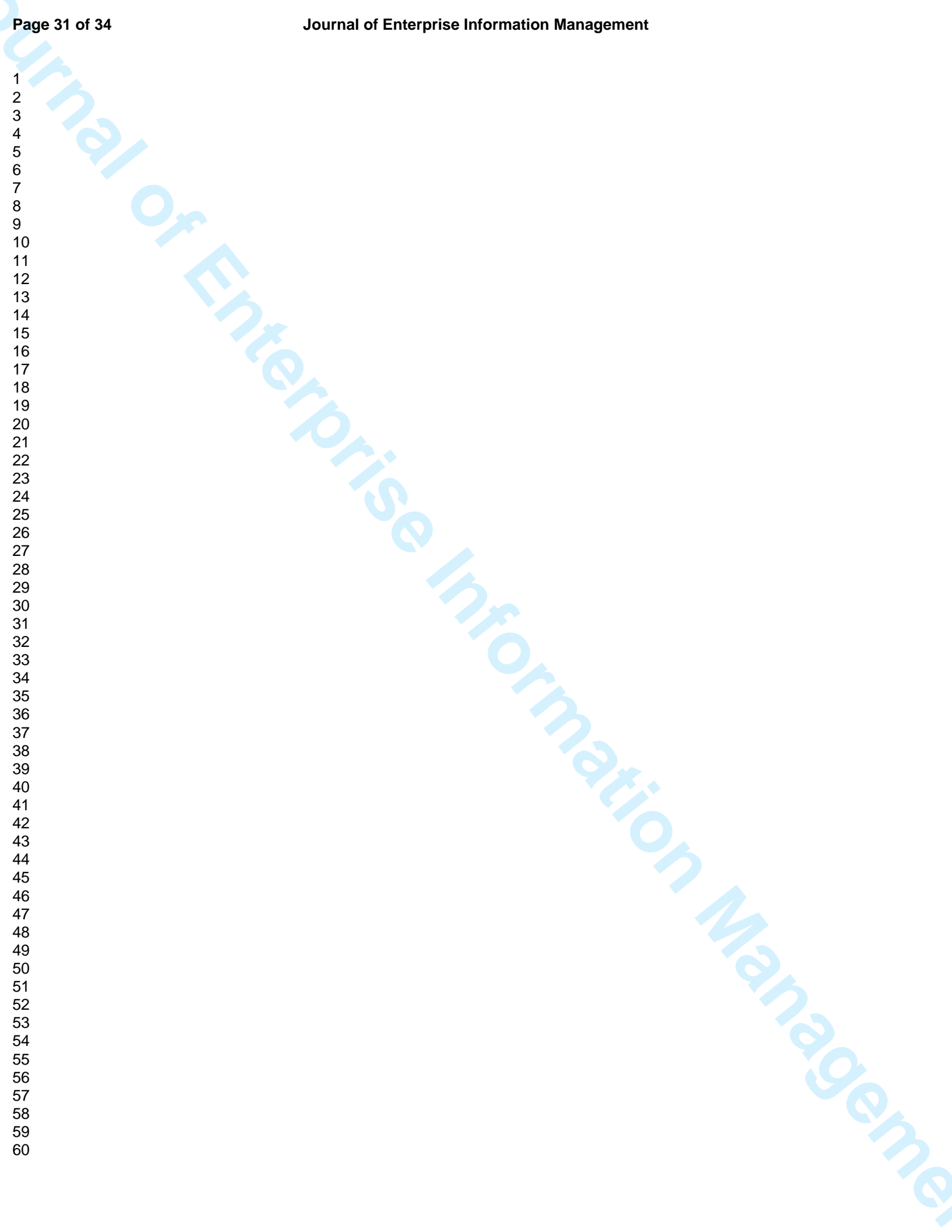
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Location	Systems	Network	Communication Technology/Protocol
Incident Premise-Internal	Responders Systems deployed on to the Body of the Responders	Body Area Network (BAN) for responders	<ul style="list-style-type: none"> <li>Bluetooth</li> <li>Ultra Wide Band (UWB)</li> <li>Zigbee within the BAN devices</li> <li>Zigbee to get connected to all other external networks</li> </ul>
		Personnel Area Network (PAN) responders	<ul style="list-style-type: none"> <li>Zigbee</li> </ul>
	Intelligent Building Systems (Capable of providing access to Sprinkler, CCTV, Lighting, Security Access and Contextual Data)	LAN	<ul style="list-style-type: none"> <li>Wi-Fi</li> </ul>
	Contextual Data Systems	Self-configurable WSN	<ul style="list-style-type: none"> <li>Zigbee</li> </ul>
Incident Premise – Nearby External	Onsite Incident Command Management System/ Mobile Emergency Management Data Systems/Unmanned Aerial Vehicle Emergency Management Systems	Mobile Ad-hoc Network (MANET) (Combination of Ad-hoc WAN/LAN and WSN )	<ul style="list-style-type: none"> <li>Ad-hoc Combination of GSM/3G/4G(GMS Protocols)</li> <li>WiMax (Non GSM)</li> <li>Satellite</li> <li>Wi-Fi</li> <li>Bluetooth</li> </ul>
Moving Responder Vehicles	Mobile Emergency Management Data Systems	Mobile Terrestrial Network	<ul style="list-style-type: none"> <li>GSM/3G/4G</li> <li>WiMax</li> <li>Satellite</li> </ul>
		Airwave Emergency Network	<ul style="list-style-type: none"> <li>Proprietary Terrestrial Trunked Radio (TETRA)</li> </ul>
Regional Command Centre	Fire Emergency Command Centre System	LAN	<ul style="list-style-type: none"> <li>Wi-Fi</li> </ul>
Fire Station/Third Party Expert/Police/Local Government/Environment Agency/Water Supplier/Hospital /Ambulance Service Control	Emergency Management Systems/ News, Weather, Traffic and Metropolitan CCTV Systems	LAN	<ul style="list-style-type: none"> <li>Wi-Fi</li> </ul>
		Fixed Terrestrial Networks	<ul style="list-style-type: none"> <li>DSL/ADSL/Fibre Optic</li> <li>Satellite</li> </ul>

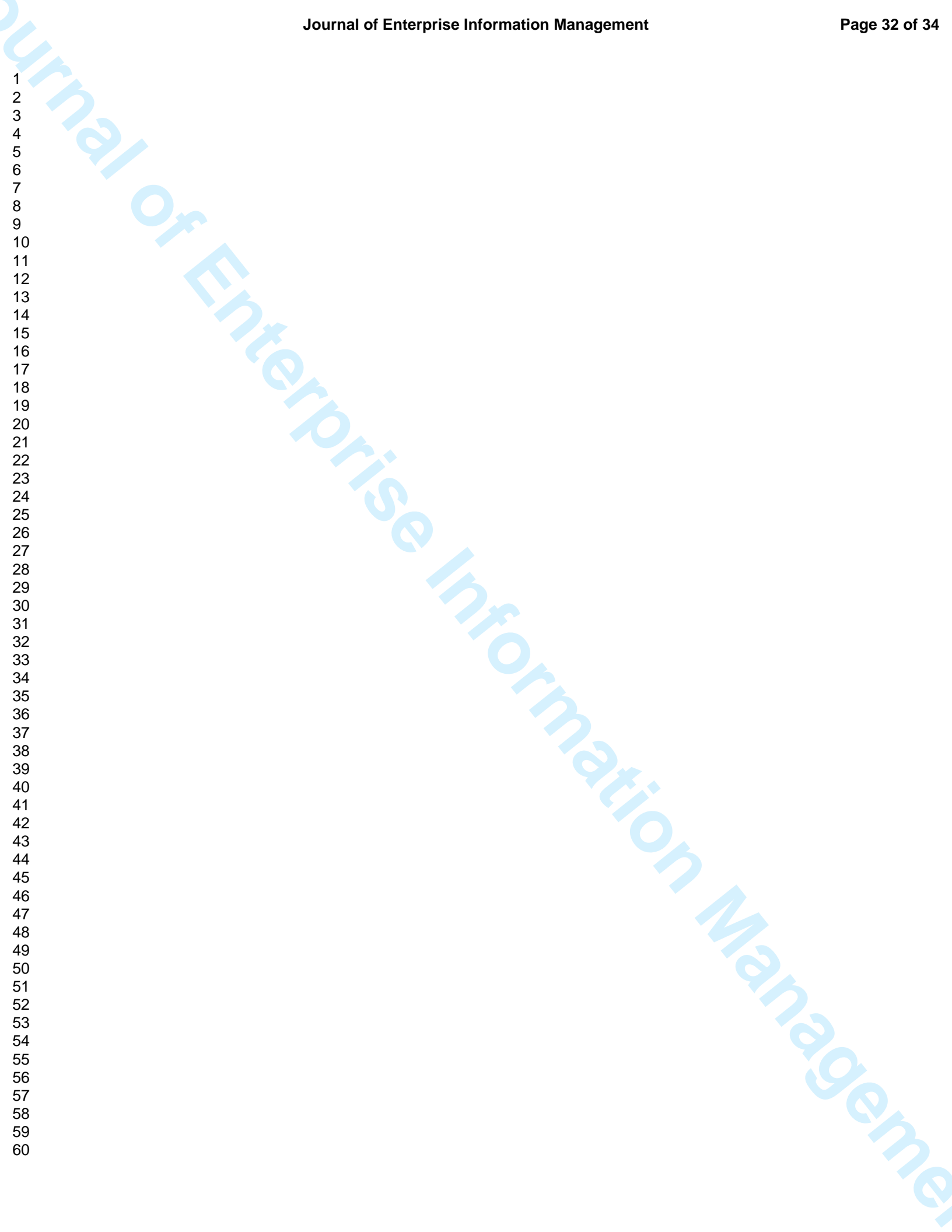
**Table 1. Components and Technologies for Data Capture and Networks**

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## Reply to the comments from the Associate Editor

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- 1) Introduction section is extensively lengthy. Have you by mistake added the literature review with the introduction section?

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Previously we have discussed our literature under the introduction heading. In this revised version we have included a brief introduction and then moved all the literature under a new heading Literature Review.

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- 2) You state in abstract that this study has built on the outcomes of two previous preliminary studies on information and human-computer interaction needs of core fire fighter job roles. But this is not clearly stated within the main body of the paper. May be you need to explicitly state the preliminary studies in separate subsections.

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We have included brief description about the two studies in the methods section (highlighted in yellow)

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- 3) Method section is too verbose with not sub-sections or figures or tables. Is there a way to bring out the methodology of this research more explicit?

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In this revision we have introduced subheadings (highlighted in yellow) to reduce the level of abstraction and have also removed some of the text.

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- 4) The results are too descriptive. Is there a better way to present the findings?

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As explained in the results section it is paramount for us to introduce the four main layers of the architecture as those layers are core outcomes. As we expect to provide some guidance for the system designers to understand the functionality and link between these

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3 layers, it is very important for us to elaborate the structure and the  
4 contents of the four layers. Whenever possible we have tried to  
5 include some level of visualization using figures and tables to cut  
6 down the text (e.g. graphical representation of the Networks layer and  
7 table for technological components). However we could realise that  
8 amount of text used for the data Manipulation layer and HCI layers is  
9 somewhat lengthier and therefore in this new version we removed  
10 some of the text from those two subsections. However, we believe  
11 that it is very important for us to keep the remaining description  
12 communicate the components and functionality of the proposed  
13 architectural layers to our readers.  
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21 5) Clearly state in separate sub-sections under conclusion -  
22 implications to theory and practice, limitations and future research  
23 recommendations/avenues.  
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27 We have included the subheadings in the Conclusions section as  
28 highlighted in yellow  
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