Applications of Wireless Sensor Technologies in Construction

by

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ABSTRACT

The construction industry is characterised by a number of problems in crucial fields such as health, safety and logistics. Since these problems affect the progress of construction projects, the construction industry has attempted to introduce the use of innovative information and communication technologies on the construction site. Specific technologies which find applicability on the construction site are wireless sensors, and especially radio-frequency identification (RFID) technology. RFID tagging is a technology capable of tracking items. The technology has been applied on the construction site for various applications, such as asset tracking. There are many problems related to health, safety and logistics on the construction site which could be resolved using RFID technology. In the health and safety field, the problems which exist are the monitoring of dangerous areas on the construction site, such as large excavation areas, the collisions between workers and vehicles, between vehicles and equipment and between vehicles, the detection of hazardous substances on the construction site when the construction work has been completed and the collection of hazard notifications from specific areas of the construction site as feedback for the prevention of future accidents. In the logistics field, the tracking of a material during its delivery on the construction site, its transportation to specific subcontractors and its future utilisation as well as the monitoring of the rate of use of materials on the construction site, the checking of the sequence of steel members and the monitoring of the temperature of porous materials are issues which can be realised using RFID technology. In order to facilitate the use of RFID technology for the specific health, safety and logistics problems, a system has been developed. The operation of this system is based on the combined use of hardware and software elements. The hardware elements of the developed system are a wireless local area network, RFID readers and tags. Its software elements are a software development kit based on which, a number of graphical user interfaces have been created for the interaction of the users with the RFID tags, and Notepad files which store data collected from RFID tags through the graphical user interfaces. Each of the graphical user interfaces is designed in such a way so that it corresponds to the requirements of the health, safety or logistics situation in which it is used. The proposed system has been tested on a simulated construction site by a group of experts and a number of findings have been produced. Specifically, the testing of the proposed system showed that RFID technology can connect the different stages which characterise the construction supply chain. In addition, it showed the capability of the technology to be integrated with construction processes. The testing of the system also revealed the barriers and the enablers to the use of RFID technology in the construction industry. An example of such a barrier is the unwillingness of the people of the construction industry to quit traditional techniques in favour of a new technology. Enablers which enhance the use of RFID technology in the construction industry are the lack of complexity which characterises the operation of RFID tagging and the relatively low cost of RFID tags. In general, RFID technology is an innovative sensor technology which can help the construction industry through its asset tracking ability. However, further research should be done on the improvement of RFID technology on specific characteristics, such as its inability to provide location coordinates and the resilience of the electromagnetic signal emitted by the RFID reader when there are metallic objects around the reader.

KEYWORDS: sensors, wireless, RFID, reader, tag, health, safety, logistics, enablers, barriers

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LIST OF ACRONYMS/ABBREVIATIONS

AC	Address-Centric
ADC	Analog-to-Digital Converter
AGK	Department of Applied Geology
ARM	Advanced (previously Acorn) RISC Machines
ASDMCon	Advanced Sensor-Based Defect Management at Construction Sites
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
AUC	Authentication Center
BS	Base Station
BSC	Base Station Controller
BSS	Base Station Subsystem
BTS	Base Station Transceivers
CAD	Computer-Aided Design
CALIT2	California Institute for Telecommunications and Information Technology
CDMA	Code-Division Multiple Access
CDPD	Cellular Digital Packet Radio
CLR	Common Language Runtime
COM	Component Object Model
3D	Three-Dimensional
4D	Four-Dimensional
DC	Data-Centric
EAN	European Article Numbering
EAS	Electronic Article Surveillance
ePC	Electronic Product Code
EIR	Equipment Identity Register
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GUI	Graphical User Interface
HLR	Home Location Register
HSE	Health and Safety Executive
HVAC	Heating, Ventilation and Air-Conditioning

IFF	Identity Friend or Foe
IITB	Institute for Information and Data Processing
ISAPI	Internet Server Application Programming Interface
ISM	Industrial, Scientific, Medical
ISO	International Standard for Organisation
LEACH	Low-Energy Adaptive Clustering Hierarchy
LED	Light-Emitting Diode
MCU	Microcontroller Unit
MHz	Mega Hertz
MIPS	Microprocessors without Interlocked Pipeline Stages
MRT	Department of Measurement Control
MSC	Mobile Switching Center
OMSS	Operation and Maintenance Subsystem
PAMAS	Power Aware Multi-Access Protocol with Signalling
PC	Personal Computer
PCMCIA	Personal Computer Memory Card International Association
PDA	Personal Digital Assistant
RFID	Radio-Frequency Identification
SAR	Sequential Assignment Routing
SDK	Software Development Kit
SHERPA	Stent Handheld Electronic Roving Piling Assistant
SHM	Structural Health Monitoring
SIGF	Secure Implicit Geographic Forwarding
SMR	Specialised Mobile Radio
SMSS	Switching and Management Subsystem
SPIN	Sensor Protocols for Information via Negotiation
SPM	Scanning Probe Microscope
TDMA	Time-Division Multiple Access
UCC	Uniform Code Council
UHF	Ultra-High Frequency
US	United States
VB	Visual Basic
VLR	Visitor Location Register
Wi-Fi	Wireless Fidelity
W-LAN	Wireless Local Area Network

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The PhD Thesis is dedicated to my family

*"I thank whatever gods may be
for my unconquerable soul.*

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*I am the master of my fate.
I am the captain of my soul"*

From the poem "Invictus"
by William Ernest Henley

*"As you set out on your journey
to Ithaca, pray that the road is
long, full of adventure, full
of knowledge"*

From the poem "Ithaca"
by Konstantinos P. Kavafis

Chapter 1 : Introduction

1.1 Introduction

There have been significant attempts in the integration of innovative information and communication technologies with the construction process. This chapter provides an overview of the use of information and communication technologies in the construction industry and the needs of the construction industry that require the realisation of more research in the construction industry about the use of information and communication technologies on the construction site. Furthermore, it evaluates the current situation of health and safety as well as logistics on construction sites. The chapter also provides the aim and objectives of the research, the research process which was followed and gives an overview of the structure of the thesis.

1.2 Wireless Communication Technologies in the Construction Industry

A variety of wireless communication technologies have been used successfully in the construction industry. These technologies include circuit-switched cellular modems, specialised mobile radio using packet-switched wireless data systems, packet-switched cellular modems, wireless local area networks [Beyh & Kagioglou, 2004], paging systems and satellite-based data communications [de la Garza & Howitt, 1998]. Tablet and wearable computers are also used on the construction site and they offer advantages related to the access to construction data [Elvin, 2003].

Circuit-switched cellular modems are technologies in which the mobile user uses a laptop connected via a wireless cellular link to the mobile telephone switching office. The specialised mobile radio (SMR) includes base station transmitters, antennas, and mobile radio units. The packet-switched cellular modems are cellular digital packet data (CDPD) systems which provide non-interfering data services [de la Garza & Howitt, 1998].

Paging systems are wireless networks capable of transmitting only data. Their main characteristics are the two-way paging and the ability to send alphanumeric messages [Maxim & Pollino, 2002]. Wireless local area networks allow the use of radio waves instead of wires [Sybex, 2002]. Every computer which is part of a wireless local area network communicates with other computers by using a radio modem and an antenna [Gast, 2002]. Satellite systems are capable of providing communication services to vast geographic areas [Harte et al., 2002].

Tablet and wearable computers are used in the construction industry for the purpose of improving the communication between the construction personnel on the construction site and their off-site collaborators [Elvin, 2003]. An example of how tablet and wearable computers are used on the construction site is the Stent Handheld Electronic Roving Piling Assistant (SHERPA) system. This system is used for piling works and consists of a server-site database which contains data about the construction of piles, a Wireless Local Area Network (W-LAN) and tablet PCs which are used by the construction personnel in order to access the database through the wireless LAN [Ward et al., 2004].

COSMOS is an EU-funded project which has been undertaken by a consortium of nine organisations in different European countries. The project was completed in 2001 and produced an integrated system for mobile operations support in the construction industry. This system allows continuous updating of construction data and the efficient communication within the construction site through the use of different types of devices [Beyh & Kagioglou, 2004].

Wireless sensors are used successfully in applications on the construction site. Examples are the Advanced Sensor-Based Defect Management at Construction Sites (ASDMCon) project developed at Carnegie Mellon University [Akinci, 2004] and the use of wireless sensors for structural health monitoring [Lynch, 2004]. The ASDMCon project uses embedded sensors in order for the history of a construction project to be captured and analysed. The project allows the use of laser scanners and embedded sensing systems for the provision of accurate and frequent as-built information [Akinci, 2004]. Wireless sensing units can be applied for the monitoring of the health of structures. These units may include sensors such as Micro-Electromechanical System (MEMS) accelerometers, MEMS gyroscopes, or linear displacement transducers. Sensing interfaces are used in order to collect the outputs of the sensors [Lynch, 2004].

The construction industry is characterised by trends which enhance the use of mobile communication technologies and especially sensor technologies, such as radio-frequency identification (RFID) tagging. Björk(1999) mentions that the construction industry was always characterised by the desire to use machines for the purpose of automating the processes of material and information elaboration. In addition, the construction industry has as vision the integration of the construction processes using mobile technologies. In this case, the cooperation between the people of the construction team will be more effective [Aziz et al., 2003]. The desire of the construction industry to explore innovative technologies can be shown by the organisation of conferences and workshops related to such technologies and by the realisation of research related to such technologies from civil engineering departments and research organisations [Turk, 2006].

1.3 Current Situation of Health & Safety in Construction

Health and safety are issues of major importance for any industry and especially for the construction industry. The major causes of accidents on the construction site are falls, falling materials, the wrongful use of mobile plants and electrical shocks [Health & Safety Executive, 1996].

The majority of construction activities are characterised by the high risks of accidents and health problems. Knowledge of the risks which exist on the construction site remains limited [Confederation of International Contractors, 2002]. Even though the rate of accidents in the UK construction industry is the second lowest in the European Union, the health and safety records in the UK construction industry are poor in comparison to the other UK industries. However, a large number of workers in the construction industry are wounded fatally in contrast to other industries, such as the agricultural and the manufacturing industries, where the number is significantly lower [Bourn, 2004].

1.4 Current Situation of Logistics in the Construction Industry

Logistics constitute a significant element of the construction process, which affects the progress of the construction project. Construction logistics are defined as the movement of materials and equipment in order for a construction project to be supported [Salim & Timmerman, 2001]. The logistics process for a construction project can offer a number of benefits (eg. low construction project cost), if it is conducted appropriately. However, the reality reveals that there is a number of problems which characterise the logistics process in the construction industry.

These problems may be related to delays in the delivery of materials to the construction site and bad inventory management. In addition, the construction industry is reluctant to address the problems associated with construction logistics. This is because the nature of the construction industry is fragmented with every construction project faced differently under different requirements specified by contractual arrangements. Furthermore there is lack of understanding of the requirements of a modern construction supply chain [Construction Products Association & Strategic Forum for Construction, 2005].

1.5 Research Questions

A number of research questions were formulated for the specific PhD research and were the basis for the realisation of the research. These questions are listed below:

- How can wireless sensor technologies be used in an innovative way in the construction industry?

- How can wireless sensor technologies improve health and safety on construction sites?

- How can wireless sensor technologies improve construction logistics?

- Barriers/Enablers to the use of wireless sensor technologies and especially to the use of Radio-Frequency Identification (RFID) technology in the construction industry.

1.6 Research Aim and Objectives

The main aim of this research project is to investigate the potential for enhancing the integration of wireless sensor technologies with construction processes by focusing on their application to the resolution of crucial problems related to health, safety and logistics on construction sites. The specific objectives of the research project are:

a) To examine key features of wireless sensor technologies, such as the possible architectures of such technologies, the devices which comprise them, and the networking protocols and standards used for their deployment.

b) To identify barriers and enablers through the thorough examination of the applications of wireless sensors in other industries, such as medicine, computer-integrated manufacturing, chemical engineering and food industry.

c) To focus on a specific wireless sensor technology (namely RFID – Radio-Frequency Identification), identify its characteristics and show how these characteristics can benefit the construction industry.

d) To design, implement and evaluate an RFID-based system for a number of scenarios related to health and safety, and logistics on the construction site.

1.7 Justification for the Research

There are many reasons which explain the realisation of this research thesis. These reasons can be identified in the problems which characterise the construction industry and which are related to health, safety and construction logistics and also in the problems faced by the construction personnel to use information and communication technologies on the construction site.

The construction industry is characterised by a large number of accidents which result in deaths, injuries and cost [Cotton et al., 2005]. The European Agency of Health and Safety at Work (2004) reported that the incidence rate of non-fatal accidents in construction is double the average rate. Also, the incidence rate is especially high for small and medium-sized construction sites. The reason for this is that health and safety standards are not maintained properly on these sites [European Agency for Safety and Health at Work, 2004]. The use of specific wireless sensor technologies such as Radio-Frequency Identification (RFID) tagging could provide solutions in health and safety problems which exist on the construction site. The ability of RFID tags to transmit data wirelessly from a distance to a host system which uses an RFID reader is significant in the development of a warning system which will warn construction personnel from possible dangers.

Construction logistics is also an important field and this is shown by the fact that the costs associated with materials in the construction industry cover 39% of the overall cost of a construction project. Specific factors which have been underlined as critical for construction logistics are the cooperation between construction workers and subcontractors, the adherence to timetables and the material and information flow. Even if these factors are satisfied, there is still need for improvement through the use of high-level technology [Jang et al., 2003]. Wireless sensors and especially RFID technology can improve the cooperation between construction personnel since it allows the quick and easy reading/writing of data from/to the RFID tags. In addition, RFID tags can be used for the better monitoring of the construction work, thus achieving reduction of possible time losses. Since they allow asset tracking, they can be attached to materials so that material tracking is achieved throughout the progress of a construction project.

Hedgeperth Sr et al. (2006) mention that a key issue in construction logistics is to know every minute where a specific material is found in the construction supply chain. This will help in the transportation of the material to the correct location at the right time. This can only be achieved through the tracking ability offered by RFID tags [Hedgeperth Sr et al., 2006].

Brilakis (2006) mentions that modern construction sites are characterised by increased complexity, an intense need for construction project control and problems related to cost. Remote construction sites lack the technology and this makes the work of the construction site manager and the workers difficult [Brilakis, 2006]. Construction personnel uses modern information and communication technologies at a low level while the introduction of Personal Digital Assistants (PDAs) is useful only when the PDAs are combined with mobile telephones and laptop computers [Magdic et al., 2002]. Wireless sensors and especially RFID technology are characterised by simplicity in their use while they can be combined with a number of mobile devices, such as laptops and PDAs.

The main construction logistics and health and safety issues which the specific research aims to resolve are shown in Table 1.1.

Table 1.1 Issues which the research aims to resolve

Field	Health & Safety	Logistics
Problems	Monitoring of Hazardous Substances on the Construction Site Collection of Hazard Notifications as Feedback to Possible Accidents Protection of vehicles against falls to 'dangerous' areas on the construction site, such as large excavation areas Monitoring of Collisions between Vehicles and Workers, between Vehicles and between Vehicles and left equipment	Material Delivery Material Circulation Material Utilisation Monitoring of the Rate of Use of Materials Checking of the Sequence of Steel Members Monitoring of the Temperature of Porous Materials

1.8 Justification for the Development of the RFID System

The choice of RFID technology for the realisation of the scenarios which were presented in Chapter 5, was based on the capabilities offered by the technology which are the quick exchange of data between users and the tracking of items. Especially for the proposed scenarios, RFID technology provides automation which results to better health, safety and logistical conditions on the construction site. This automation is expressed through the electronic exchange of information between the users of the proposed system. The system developed for the PhD thesis is characterised by multiple functionality and this results to the integration of the processes on the construction site. Additionally, by using the proposed system, reduction of the time for the completion of a specific task is achieved. This is explained in detail in the following paragraph.

Especially for the proposed scenarios and for example, for the monitoring of the existence of chemical substances on the construction site, the construction site manager has to search with other members of the construction personnel whether there are any chemical substances left on the construction site when the construction work has been completed. This task requires time. By using RFID technology, the time required to find any chemical substances left on the construction site is minimised drastically since the construction site manager has only to login to the appropriate graphical user interface and initiate a scanning for tags placed on the storage mediums of chemical substances. This applies for the scenario related to the collection of hazard notifications. In the case of the 'Monitoring of Collisions between Workers and Vehicles, between Vehicles and between Vehicles and Equipment", the driver of the vehicle has to check all the time if a worker, a vehicle or equipment is close to his vehicle. In this case, he is disorientated from his work. In contrast, by using RFID technology, the driver can be informed for the existence of any worker, vehicle or equipment close to his vehicle through the emission of a sound emitted to his headphones as a warning. A sound is emitted to the headphones of the driver when the RFID reader of his vehicle detects from a small range from the vehicle, the tag which is placed at a worker, another vehicle or equipment. In the "Protection against 'dangerous' areas on the construction site' scenario, the use of RFID technology enables the automatic identification of the existence of a 'dangerous' area (eg. a large excavation area). Currently, the protective measure which is taken on construction sites for the protection from the falls of vehicles into large excavation areas is the placement of barriers with warning signs in these areas.

In the logistics scenarios, the use of the RFID system can provide better organisation in the delivery, distribution and utilisation of materials on the construction site. The use of the proposed system enables the automatic recording of the delivery of materials on the construction site and the organised distribution of the materials on their specific destinations on the construction site. Specifically, when a material arrives on the construction site, its arrival is recorded automatically even if the construction site manager or any other member of the construction personnel is not present at the moment of the arrival at the gate of the site. The time and date of arrival are also recorded electronically. Also, the driver of a boom-truck knows exactly when he/she should go and collect the material because this information has been stored on the RFID tag of the vehicle. In this case, there is not the possibility that the information related to the arrival of the material will not be seen by the driver of the vehicle as it could happen in the case this information was recorded on paper. Furthermore, the proposed system allows the construction site manager to be informed at any time about the delivered material(s)'s future use since the subcontractor can include this information on the RFID tag of the delivered material. The proposed system uses different graphical user interfaces integrated in such a way so that the user does not have any difficulty in finding which graphical user interface he/she should use depending on the situation. Each of these interfaces has different operation and allow the user to collect data in a classified way. For example, the construction site manager can collect data from a specific subcontractor on the rate of use of a specific material and then quickly switch to the graphical user interface related to the measurement of the temperature of porous materials and initiate a temperature measurement of a specific porous material. For all the proposed scenarios, the developed system allows the wireless collection of data. For example, for the measurement of the temperature of porous materials, the fact that temperature measurements are collected wirelessly along with the time and date of the measurements and the classification and storage of these measurements to different files depending on the type of the porous materials, is very useful since it saves valuable time.

1.9 Scope of the Research

The specific research is concerned with the examination of sensor technologies and specifically of the Radio-Frequency Identification (RFID) tagging and its implementation in the resolution of specific problems related to health and safety and logistics on construction sites.

1.10 Overview of Research Process

The research was based on a number of steps which are literature review, scenario development, scenario validation, system design, system development and system evaluation. These steps are described in detail in Chapter 2. Each of these steps is also based on the use of a number of a research methods.

Literature review was based on the use of academic journals, papers published in conference proceedings and books. Opinions from experts were also collected through interviews with them and methodologies which are followed by leading wireless sensors companies have been examined in the form of case studies. The results which were drawn helped in the identification of the capabilities of the wireless sensor technologies and how these capabilities can benefit the construction industry.

Scenario development was based on the use of specific techniques dedicated to scenario creation. The selection of these techniques occurred after the analysis of the features of each of them. Also, the development of the scenarios was based on the in-depth examination of specific problems faced by the construction industry. Publications from well-known organisations in the field of construction were used and visits to construction sites took place. A number of scenarios were developed which actually suggest ways on how specific problems on the construction site could be solved. A specific wireless sensor technology is a core part of these scenarios. Scenario validation included the examination of the proposed scenarios from a group of experts from the construction industry.

The next step was the design of a system based on the wireless sensor technology which is suggested for use in the proposed scenarios. A number of companies were identified as potential providers of the technology. The selection of the company from which the specific wireless sensor technology would be provided from was based on a number of criteria. Also, the exact type and number of elements of the selected technology were identified while an architecture of the system was created based on the requirements of the proposed scenarios.

Also, specific programming languages were selected for the development of the system for this thesis. These programming languages were used in combination with the provided wireless sensor technology and their selection was based on their flexibility they offer and their compatibility with the specific technology.

System evaluation was the final step of the research. During system evaluation, a number of experts tested the proposed system and provided their feedback. Based on the feedback of the evaluators of the system, a number of conclusions were produced.

1.11 Thesis Structure

The thesis consists of a number of chapters which examine the implementation of innovative wireless sensor technologies for specific problems in the field of Construction Logistics and Health and Safety.

Chapter 2 examination of the existing research approaches. The quantitative and qualitative approaches are analysed and there is also examination of the triangulation method. There is focus on the research approaches which are followed for the Information Systems research and also for the Construction Information Technology. In addition, the methodology which was followed for the specific research is presented and the different stages which are followed from the initiation of a research until the testing and evaluation of the proposed research system are presented.

Literature Review consists a major part of the research. Chapters 3, 4 and 5 are dedicated to literature review. Chapter 3 provides a definition of wireless sensors and concentrates on the analysis of the wireless sensor networking technology. Parameters such as the communication between the nodes of a wireless sensor network, the energy consumption of a wireless sensor network, the fault-tolerance and the performance of the technology are presented. Also, the applications of wireless sensor network technology in a variety of industries are presented and emphasis is given to the applications of the technology in the construction industry.

Chapter 4 focuses on the examination of a specific wireless sensor technology which is the Radio-Frequency Identification (RFID) technology. A definition of the technology is provided, its history is presented and the different components of the technology, such as the RFID readers and tags are analysed. Specific issues related to the technology such as security and energy consumption are also presented. There is a detailed comparison between RFID technology and other tracking technologies, such as bar-coding, Wi-Fi tagging and the Global Positioning System (GPS). Furthermore, the applications of RFID technology in various industries, such as the retail and aeronautical industry, are discussed while specific emphasis is placed on the applications of the technology in the construction industry.

Chapter 5 is related to the examination of the health and safety conditions and the logistics processes which characterise a modern construction site. The chapter examines the different types of accidents which occur on a construction site and the causes which provoke these accidents. The chapter also examines the field of construction logistics and presents innovative techniques which characterise it. In addition, a number of proposed scenarios related to the use of RFID technology for health, safety and logistics on the construction site which were developed by the researcher, are presented in detail. The chapter also analyses how the specific proposed scenarios have been developed and presents each of them separately in a detailed manner. In addition, it provides the results of the validation of the proposed research scenarios from a group of experts.

Chapter 6 presents the development environment for the proposed system. This chapter analyses the architecture of the system with specific reference to its hardware and software elements. Specific emphasis is given to the characteristics and the operations of the various graphical user interfaces which consist of a significant element of the proposed system.

Chapter 7 presents the testing of the proposed system. Specifically, it shows how the proposed system was tested under the requirements of each of the research scenarios. The objectives of the testing of the system are presented and the conditions under which the testing of the system occurred, are analysed. The steps of the testing of the proposed system are also provided.

Chapter 8 focuses on the analysis of the results of the evaluation of the proposed system. The specific aspects of the system which were evaluated are the effectiveness and the efficiency of the proposed system, its graphical user interfaces, the scenarios in which the proposed system was examined, and its usefulness to the construction industry. Feedback provided by the evaluators about the problems which characterise the proposed system, its best features, ways for improving the proposed system and ways for improving the graphical user interfaces are presented.

Chapter 9 provides a list of conclusions which can be useful for the expansion of the existing knowledge on wireless sensors and their use in the construction industry. The limitations of the research are also presented, along with recommendations for future research.

Chapter 2 : Research Methodology

2.1 Introduction

This chapter introduces a number of qualitative, quantitative and triangulation research methods. In addition, it presents a number of methods which are used in information systems research and focuses on the research approaches which are followed in construction informatics. The research methodologies which have been followed for this research are presented with specific emphasis on literature review, scenario development method, scenario validation, system design, development and evaluation.

2.2 Definition of Research

Research is undertaken in most disciplines and it is defined as "a way of thinking: examining critically the various aspect of your profession; understanding and formulating guiding principles that govern a particular procedure; and developing and testing new theories for the enhancement of your profession" [Kumar, 1999, pp. 2]. Research can be classified into different categories depending on the researcher's viewpoint :

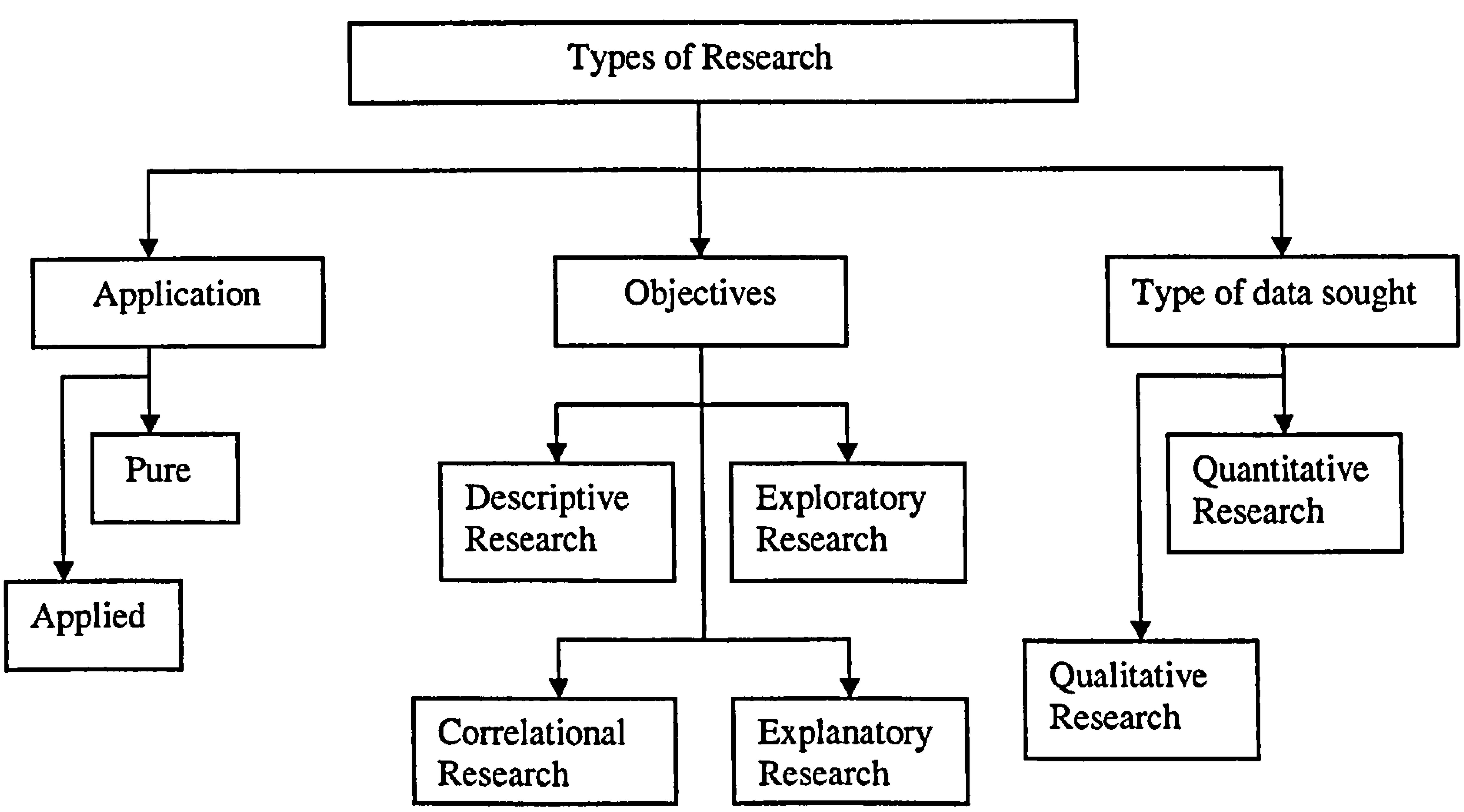


Fig. 2.1 Classification of different types of research [Kumar, 1999]

Pure research refers to the development of theories and theoretical models which can be the basis for an application while applied research refers to the development of practical applications [Nickerson, 2005].

Descriptive research attempts to describe a situation, problem or phenomenon. Exploratory research tries to examine the possibilities of developing a particular research study. Correlational research examines possible relations between two or more facts which describe a specific problem [McKnight, 2001] while explanatory research examines the reason of such a relationship [Kumar, 1999].

Qualitative research is the research method in which the aim is the collection of qualitative data, such as specific situations and events [Maxwell, 1996]. In contrast, in quantitative research, the researcher is focused on a specific problem, specifies a number of variables related to it and selects and measures relevant variables accurately [Reswick, 1994].

2.3 Research Methods

Research is a dynamic process. It involves the creation of connections between problems which may be theories, previous findings or methods [Fellows & Liu, 1997]. The steps followed during the research process are shown in Figure 2.2.

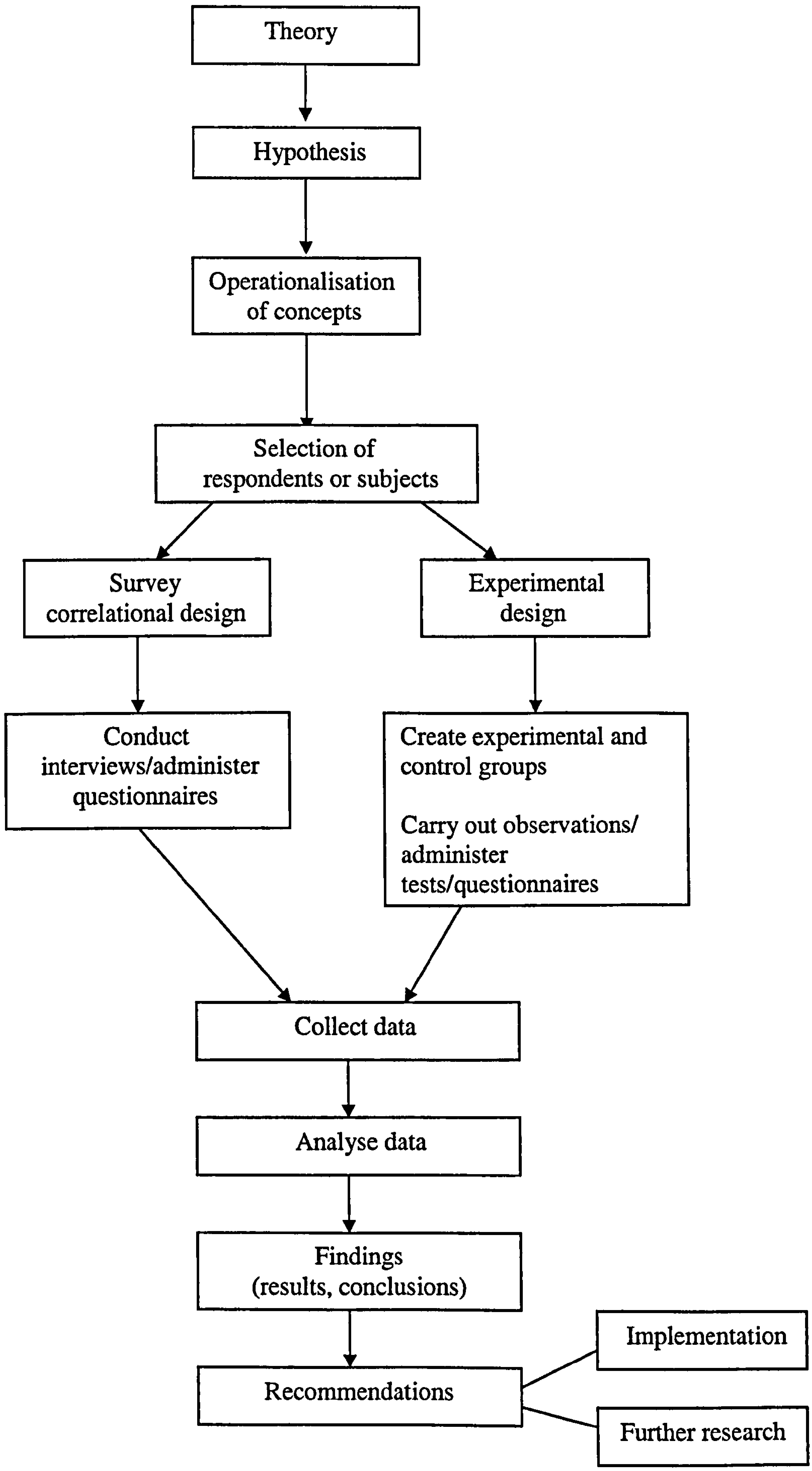


Fig. 2.2 The research process [Bryman & Cramer, 1994]

According to Figure 2.2, during the research process, a theory is introduced and based on this theory, a number of hypotheses are created [Creswell & Plano Clark, 2006]. A number of concepts are outlined together and their capabilities are assessed. This is referred to as the operationalisation of concept [Saith, 2001]. A number of subjects are selected and the researcher either uses qualitative research methods, such as surveys and interviews or he/she uses quantitative research methods, such as experiments. Creswell & Plano Park (2006) mention that the collection and analysis of data results to a number of findings. Based on these findings, a number of recommendations are made which either lead to implementation of the findings of the research or require further research to be made. These specific research methods will be the focus of this chapter.

2.3.1 Qualitative Research

Qualitative research is an activity that locates the observer in the world. It involves the careful use and collection of various empirical materials, such as case studies, interviews, cultural, observational, historical, interactive and visual texts. Furthermore, qualitative researchers produce a number of interconnected practises, thus attempting to get a better comprehension of the examined field [Denzin & Lincoln, 2005]

Qualitative research methods were developed in social sciences in order to enable researchers to comprehend the social and cultural contexts in which they live [Gittins, 2006]. The methods which are followed in the qualitative research are action research [Iosifides, 2003], case study research [Lloyd-Jones, 2003], ethnography and grounded theory [Tatnall & Gilding, 1999]. In addition, the sources of data for a qualitative researcher are interviews and questionnaires [Labuschagne, 2003], fieldwork, texts and the reactions of the researcher [Gittins, 2006].

Action research contributes to the resolution of problems through the comprehension of a specific social situation [Hult & Lenning, 1980]. Case studies are used in order to provide descriptions of one or more cases. Specifically, they examine one or more selected examples of a specific subject [Hakim, 1987]. Ethnography refers to the description of a group or a culture [Fetterman, 1998] while grounded theory supports the idea that theories can be produced from theories [Huehls, 2005].

Qualitative research can be positivist, post-positivist, interpretive or critical [Gittins, 2006]. These four approaches are analysed below :

• *Positivist Qualitative Research*: Positivists believe that reality can be observed by specific measurable properties which are independent of the observer [Tatnall & Gilding, 1999]. They attempt to test theory in order to enhance the predictive comprehension of phenomena [URL4, 2006].

• *Post-positivist Qualitative Research*: Post-positivists believe that researchers are affected by their own subjective selves in their research. As a result, any conclusions drawn about reality reflect both the researcher and the research subject. For post-positivist researchers, the research is valid if it is based on logical facts, generates a new theory and acknowledges the influence of the researcher or the research methods to the results [Schulze, 2003].

• *Interpretive Qualitative Research* : This type of qualitative research assumes that truth is not absolute but is determined by human judgement and the use of non-scientific methods. The philosophical base for interpretive research consists of hermeneutics and phenomenology. Hermeneutics refer to the extraction of truth through detailed study of free-flowing texts while phenomenology focuses on the direct observation of phenomena [Bernard, 2000].

• *Critical Qualitative Research* : In critical qualitative research, there is examination of how social and political forces affect the ways in which individuals perceive the reality [Merriam & Associates, 2002].

2.3.2 Quantitative Research

Quantitative research is the type of research which quantifies the change of a phenomenon, situation or problem [Kumar, 1999]. Quantitative research can also be defined as an inquiry to a social or human problem based on the testing of a hypothesis or a theory which includes variables. This testing uses statistical processes in order to evaluate the validity of the hypothesis or the theory [Naoum, 1998].

During quantitative research, the following approaches can be followed :

•Asking questions especially through:

-surveys: Surveys aim to identify the characteristics of a large population from a smaller sample of it. For the purpose of data collection, they use questionnaires or interviews [Dobbin & Gatowski, 1999].

-questionnaires: Questionnaires are written lists of questions, the answers to which are recorded by the respondents. Respondents read the questions, comprehend what they ask and then answer them. A good questionnaire is characterised by clear and easy to understand questions. The sequence of the questions must be easy to follow [Kumar, 1999].

•Execution of experiments: Experiments are based on the use of experimental controls and the development of experimental conditions for the testing of specific subjects [Dobbin & Gatowski, 1999].

•Personal interviews: Personal interviews are a mean of acquiring high quality data [Research Councils UK, 2005]. They can be classified as structured, semi-structured and unstructured. Structured interviews use a pre-defined group of questions [Vatrapu & Perez-Quinones, 2004]. In semi-structured interviews, the sequence of questions may vary. The questions which are used in a semi-structured interview are often more general in comparison to the questions used in structured interviews [Bryman, 2001]. Unstructured interviews are more like conversations and their subject may change as the interview progresses [Leech, 2002]. Interviewees can understand a question more easily since the interviewer is with them so he/she can explain to them any difficulty related to a specific question [Keller & Warrack, 2003].

•Telephone interviews: Telephone interviews are less personal in comparison to personal interviews and they are characterised by a lower response rate. This is because many people refuse to be interviewed by telephone [Keller & Warrack, 2003].

•Self-completion on paper: In this quantitative research approach, longer questionnaires can be used but better responses are received when the questionnaires are short [Research Councils UK, 2005].

•Self-completion through electronic means, such as email and Internet: In this case, only people with Internet access can participate. The interviewer can send additional materials, eg. pictures, to the interviewees in order to help them respond [Research Councils UK, 2005].

2.3.3 Comparison between Qualitative and Quantitative Research

Qualitative and quantitative research differ mainly in their analytical objectives, the types of questions they pose, the types of instruments they use for data collection, the type of data they generate and the level of flexibility which characterises a specific research [Mack et al., 2005]. Table 2.1 underlines the main differences between qualitative and quantitative research.

Table 2.1 Qualitative vs. Quantitative Research

Comparison Criteria	Qualitative Research	Quantitative Research
General Framework	Attempts to explore phenomena, thus it is explanatory [Smith, 1983] Use of semi-structured methods, such as focus groups and interviews [Labuschagne, 2003]	Attempts to confirm hypotheses about phenomena, thus it is descriptive [Smith, 1983] Use of highly structured methods, such as surveys [Grossnickle & Raskin, 2001] and questionnaires [Eyler et al., 2003]
Analytical Objectives	Description of change and interpretation of possible relationships and of individual experiences [Mack et al., 2005]	Quantification of change, prediction of relationships and description of characteristics of a population [Mack et al., 2005]
Question Format	Open-ended [Mack et al., 2005]	Closed-ended [Grim et al., 2006]
Data Format	Textual [Pope et al., 2000]	Numerical [Mack et al., 2005]
Flexibility	Flexible study design. It only corresponds to what has been learned [Mack et al., 2005]	Stable study design but is only affected by statistical conditions [Mack et al., 2005]

Comparison Criteria	Qualitative Research	Quantitative Research
Nature of Data	Variables [Johnson & Christensen, 2004]	Word, Images, Categories [Johnson & Christensen, 2004]
DataAnalysis	Identification of statistical relationships [Johnson & Christensen, 2004]	Identification of patterns between the data and holistic features [Johnson & Christensen, 2004]
Results	Generalized [Johnson & Christensen, 2004]	Particularistic [Johnson & Christensen, 2004]
Nature of Reality	Objective [Smith, 1983]	Subjective [Smith, 1983.]

2.3.4 The Triangulation Method

Triangulation can be considered the combination of two or more research strategies in the study of the same subject [Denzin, 1970]. There are four types of triangulation and these are the following: methods triangulation, data triangulation, triangulation through multiple analysts and theory triangulation [Hoepfl, 1997].

Method triangulation uses more than one quantitative and/or qualitative methods in order for a specific field to be examined. Data triangulation involves time, space and observers while triangulation through multiple analysts requires that the researcher combines a number of different observers, theories, data sources and methodologies. Theory triangulation considers the use of more than one theoretical perspectives in the examination of a phenomenon [Guion, 2002].

2.4 Research Methods Applied in Information Systems

There is a variety of research approaches which are the following: laboratory and field experiments, surveys [Pinsonneault & Kraemer, 1993], case studies, grounded theory, action research, subjective/argumentative research and longitudinal research [Venkatesh & Vitalari, 1991].

The above mentioned research approaches are analysed in detail below:

• *Laboratory and Field Experiments*: Experiments are the best way for the collection of knowledge through the identification of specific parameters and the control of the remaining ones [Balnaves & Caputi, 2001]. Experiments conducted in a laboratory environment are characterised as laboratory experiments [Palfrey, 2006] while experiments conducted in the natural setting are characterised as field experiments [Goodman et al., 2004]. The basic experimental designs are between-subjects and within-subjects designs. If variables are received by two or more separate groups, then this is a between-subject design while if variables are received by the same group of people, then this is within-subject design [Balnaves & Caputi, 2001].

• *Case studies:* A case study attempts to describe real events so that the researcher can comprehend the complexities faced by the decision makers in the case. The aim of case studies is the extraction of useful information, the identification of problems and their possible solutions and the development of strategies for action [Stone & Redmer, 2006]. The different types of case studies are described below :

(1) Descriptive case studies: This type of case study tries to identify how frequently a specific reply is given by the participants [Naoum, 1998].

(2) Analytical case studies: This type of case study tries to identify possible relationships between specific attributes of the case [Naoum, 1998].

(3) Explanatory case studies: This type of case studies attempts to explain the relationships between the objects of a specific study [Fisher & Ziviani, 2004].

• *Surveys*: Surveys are a way of collecting information about the features and actions of a group of people. Surveys are characterised by three distinct features. Firstly, surveys allow the creation of quantitative descriptions for specific aspects of the examined group of people in order to develop conclusions about possible relationships between data. Secondly, surveys are based on structural and predefined questions. Thirdly, they allow the development of conclusions for the whole population, especially when the data sample is large and allows statistical analysis [Pinsonneault & Kraemer, 1993].

• *Grounded Theory*: Grounded theory is based on the discovery of new theories from a set of data [Fellows & Liu, 1997]. Glaser (1978) characterises grounded theory as a source of good ideas. The theory involves early data collection and analysis and further theoretical sampling [Goulding, 1998]. Theoretical sampling involves data collection for theory generation in a way that the researcher decides what data to collect next and then develops the new theory [Glaser, 1978]. The next step is the examination of the data from the perspective of the issues which will be the focus of the research, and the identification of the data categories. In this case, a number of hypotheses can be tested by additional field work and the use of the method of analytical induction. During this method, there is definition of the examined issue, instances of which are examined and possible relationships between data are developed [Fellows & Liu, 1997].

• *Action Research*: Action Research is carried out by a group of people which consists of a professional action researcher and participants. The researcher together with the participants define the problems to be examined, generate knowledge related to the problems, take action and interpret the results of the actions based on what they have learned [Greenwood & Levin, 1998].

• *Subjective/Argumentative Research*: This type of research requires from the researcher to adopt a creative stance rather than being just an observer. It is a useful technique since new theories could be generated. However, since it is subjective, it is possible that mistakes will occur from the researcher which can mislead the research. Examples of such type of research are hermeneutics and phenomenology [Davison, 1998].

• *Longitudinal Research*: Longitudinal research examines the behaviour of processes and the existence of any changes of critical parameters over specific time periods. Longitudinal research allows the recording of events in chronological order. In the case of information systems, these events are interrupted by the intense development of information technology followed by long or short periods of use, maintenance and termination [Venkatesh & Vitalari, 1991].

2.5 Research Methods in Construction Information Technology

The scope of use of Information Technology in the Construction Industry is multi-disciplinary. Among its many roles, information technology in the construction industry needs to support the integration of information during the construction process. Information technology is used during the design of the product, the project organisation carrying out the design and construction, and the process to carry out the design [Fischer & Kunz, 2004].

Specific research approaches are used in construction information technology. These research approaches are action research, ethnographic research, surveys, case studies and experiments [Fellows & Liu, 1997]. Crook et al. (1996) suggest that research in construction information technology should be orientated to the sensing of the world by the researchers and the comprehension by them of the information provided by people.

There is a number of features of the research approaches suggested by Fellows & Liu (1997) which explain their appropriateness for construction information technology. Specifically, action research allows the direct involvement of the researcher with the research setting [Nunes & McPherson, 2003]. In addition, action research is characterised by learning in and through action and reflection [McNiff & Whitehead, 2002]. Ethnography attempts to see the world from the optical view of the people it examines. The ethnographer uses observation, participant-observation and interviews [Prus, 1996]. Surveys are characterised by the fact that they allow the collection of results at the level of a person and also at the level of a sample of a population or even the whole population [Li et al., 2005]. Case studies are useful because they allow the development of a theoretical basis for the adaptation and use of information technology. Case studies could be used to comprehend the reasons for implementing information technology in the construction industry and how this implementation can be done [Lubbe, 2003].

2.6 Research Methodologies Adopted

A number of research approaches were used for the development of the specific research. Specifically, these research approaches are literature review, scenario development method, scenario validation, system design, system development and system evaluation. Additionally, each research approach which was followed during the research consists of different stages. Table 2.2 represents the research approaches followed and all the stages included in them:

Table 2.2 Research Methodologies Adopted

Literature Review	Data collection from books and published papers Interviews with Experts Production of Technical Reports Examination of Innovative Technologies
Scenario Development Method	Identification of the problems of the Construction Industry Interviews with Experts Identification of potential uses of innovative technologies for specific problems Scenario Generation
Scenario Validation	Examination of the proposed scenarios by a number of experts
System Design	Design of the topology of the proposed system
System Development	Programming Tasks for the realisation of the System
System Evaluation	Testing of system by a group of evaluators Evaluators Feedback collection and analysis

2.6.1 Literature Review

Literature review for the specific research was based on the examination of a number of academic journals, papers in conference proceedings and books. Data collection occurred also through the attendance to a number of workshops related to innovative technologies used in the construction industry. The purpose of the literature review was the examination of specific innovative technologies, such as wireless sensors and the current and potential uses of these technologies in the construction industry. There are many advantages of using academic journals, papers in conference proceedings and books as sources for extracting information about a research topic in comparison to other sources, such as websites or technical papers produced mainly by universities or companies. Specifically, the information which appears in these sources has been developed by scientists and has been reviewed by leading academics. Also, the content of a website is dynamic and can change any time. The data which appear on a website have not been reviewed by any experts before they appear on the website. Telephone interviews were also conducted with experts from a number of industries other than the construction industry in order to identify how wireless sensor technologies are used in these industries. An extended visit to a large construction site and two short visits to smaller construction sites took also place in order to identify problems related to health, safety and logistics which exist currently on construction sites. Since there was only one extended visit to a construction site, it is not possible to consider that the health, safety and logistics problems which were identified on this construction site, characterise the whole construction industry. However, this visit allowed the collection of data through interviews from a number of people who had different responsibilities on the specific construction site and these data were helpful in the verification of the facts about health, safety and logistics which are presented in journal papers and papers included in conference proceedings. The literature review for this specific thesis included only a limited number of websites and technical papers. These papers were produced by recognised organisations. The literature review which has been done for the specified research is presented in detail in Chapters 3, 4 and 5.

2.6.2 Scenario Development Method

During the research process, scenario development is a significant part of it since it allows the examination of new possibilities and challenge long-held internal beliefs. In addition, it enables the re-evaluation of the hypotheses which have led to the development of the current situation and also allows also the detection of any problems or discontinuities in the current processes [Mietzner & Reger, 2005].

In order for scenarios to be developed, specific scenario development methods can be applied. These methods are presented in detail in this section.

2.6.2.1 Definition of the terms 'Scenario' and 'Scenario Planning'

Scenarios can be defined as the descriptions of sequences of events that represent specific parts of a setting and an activity [Gruen, 2000]. Alspaugh and Anton (2001) define scenarios as sequences of events which achieve a specific target. Scenarios can also be considered as a synthesis of different strategies that lead to possible futures [Mietzner & Reger, 2004]. Godet and Roubelat (1996) define scenarios as descriptions of future situations which allow someone to move forward from the original situation to the future.

Scenario planning is a semi-structured method which is used for the identification and comprehension of the forces which formulate the future of a specific domain by creating in a systematic way scenarios for the future of that domain [Björk & Börjesson, 1998]. Peterson et al. (2003) suggest that scenario planning is based on the use of a number of scenarios in contrast to each other so that the uncertainty which characterises the future consequences of a decision are analysed. Scenario planning is mainly related to the definition of a clear strategy through the analysis of possible future situations and their impact on today's decisions. Scenario planning firstly aims to generate new concepts about the future. The scenarios which are generated in this case are characterised as prospective scenarios [Laperrouza & Pigneur, 2004]. In addition, scenario planning aims to develop reasonable future situations and to define strategies on how to cope within these situations. In this case, the generated scenarios are characterised as context-aware scenarios [Dewulf & Van der Schaaf, 2004].

2.6.2.2 Scenario Design Methods

The following three approaches can be followed for effective scenario design:

• *the Inductive Method* : This method is based on the use of specific event and the gradual addition of data [Ogilvy & Schwartz, 1998]. Van der Heijden (1996) defines the inductive method as a step-by-step building of data, thus allowing the structure of the new scenario to emerge by itself.

• *the Deductive Method* : This method is based on a framework to which data are placed [Walsh, 2005]. In this case, data are combined in natural groups. The creation of these groups is based on the identification of a small number of key events, key trends or two or three key driving forces [Ogilvy & Schwartz, 1998]. The deductive method is similar to the scenario matrix method which is based on the identification of important issues and key factors. A scenario matrix is created by selecting the most significant forces. Two significant forces generate four scenarios. The important issue in each scenario is identified and parameters which show to which direction the environment is heading to, are gathered [Björk & Börjesson, 1998].

• *the Incremental Method* : According to Van der Heijden (1996) this method is applied in cases in which the concept of scenario planning has been dismissed. This method uses as a starting point the future situation. In this case, there is identification of the flaws which characterise the future situations with the aim of creating alternatives. There is also examination of new models of the future environment [Dewulf & Van der Schaaf, 2004].

Furthermore, Peter Schwartz suggested eight steps for scenario development which are listed below:

• identification of the issue which must be examined

• underlining of the key factors which may affect the success or the failure of the examined issue

• identification of the key forces which affect the wider world

• distinction of the identified key forces depending on their uncertainty and importance

• selection of the scenario logics and creation of the scenario matrix

• creation of the scenarios by referring to the key factors

• identification of how each decision affects each scenario

• identification of leading indicators and signposts [Schwartz, 1996]

Ute von Reibnitz (1988) has also suggested eight steps towards scenario creation. Specifically, he suggested that a detailed examination of strengths and weaknesses must be conducted. The next step is the acquisition of knowledge related to the system dynamics of the associated area. The third step is the examination of different areas of influence while in the fourth step a consistency matrix is used in order for future developments to be checked against each other for consistency. The fifth step is the interpretation of the scenarios, their description in an imaginative way and also the analysis of the system dynamics and changes [Von Reibnitz, 1988]. The sixth step involves the analysis of the consequences and the deduction of possible opportunities and risks. Measures are taken on how these opportunities can be used and how risks can be converted to opportunities. During the seventh step, there is diagnosis of trends. Events which are unlikely to occur, are not considered during the planning process [Mietzner & Reger, 2004]. The eight step is related to the evaluation of the strategies which were developed in the sixth and seventh step [Schwab et al., 2003].

Godet (2000) distinguishes nine phases in the development of scenarios in an organisation. Phase 1 analyses the problem posed and defines the system which is under examination. Phase 2 is based on a complete analysis of the organisation while phase 3 identifies the key variables of the firm and its environment by means of structural analysis. During phase 4, there is an attempt to understand the dynamics of the organisation in relation to its environment while during phase 5, there is reduction of the uncertainty which characterises the key questions for the future. Phase 6 underlines the strategic options which are compatible both with the identity of the organisation and the most probable scenarios for its environment. The next phase includes an evaluation of the available options while in phase 8, the objectives of the system are put in an hierarchy. In phase 9, a plan of action is created and implemented [Godet, 2000].

2.6.2.3 Selected Scenario Design Method

During the creation of scenarios for the proposed research, a number of features from the inductive and deductive scenario design methods which were presented in Section 2.6.2.2, were combined. Specifically, there was use of specific events as a starting point and then gradual addition of data occurred. As Van der Heijden (1996) defined it, the gradual addition of data which occurs in inductive method allows the structure of the new scenarios to emerge by themselves. Specifically, the inductive method allows the scenario developer to check better the different stages of the developed scenario, define the boundaries of each stage and how each stage is connected to the other stages of the developed scenario. In this case, if the scenario developer wants to make any changes to any of the stages of the developed scenario, he/she will be able to see how these changes affect the other scenario stages and the whole scenario. There was also identification of a number of key driving forces. This identification allowed the researcher to understand the requirements of each of the scenarios and as a result formulate them appropriately. The incremental method was not selected as a scenario planning method for this research since it allows the development of new scenarios based on the possible existence of flaws of a specific process.

Based on the eight steps proposed by Peter Schwartz, the first act during the development of the research scenarios, was to identify specific areas which present great importance for the construction industry. Literature review was used in order to exactly identify the current problems of the UK construction industry and the current approaches for resolving these problems. Also, a number of interviews were conducted with experts from different industries in order to comprehend how wireless sensors are used in other engineering fields. In addition, the knowledge acquired through the review of the literature was used for the identification of the key forces which characterise the examined issues. A distinction of the key forces depending on their significance was followed and based on these factors, a sequence of scenario steps was formulated. A number of alternatives "What-If" situations were also used in order to test each formulated scenario.

2.6.3 Scenario Validation

Scenario validation allows the examination of each scenario not in an isolated way but in connection to all the other proposed scenarios. In this case, possible combinations of scenarios can be identified or specific steps for the execution of a scenario will be considered in order not to intervene with the other scenarios [Glinz, 2000]. In addition, scenario validation is useful for the checking of how realistic the proposed scenarios are. This is especially important for scenarios developed for the construction industry since the scenario developer must consider a variety of different parameters, such as the needs of the contractors and the way the construction project is realised. Also, scenario validation allows the identification of possible weaknesses in the proposed scenarios. This allows the researcher to correct these weaknesses before he/she can proceed to the development of a system for the realisation of these specific scenarios. Furthermore, scenario validation allows the generation of new ideas which can form the basis for the development of more scenarios or the enhancement of the proposed ones.

The research scenarios which were developed for this research, were examined by a group of experts which included academics and construction analysts from large construction companies. The aim of this examination was to identify whether the proposed research scenarios are realistic and how successful the use of sensor technologies on the construction site, could be. A variety of conclusions were formulated and these conclusions were focused on a number of areas, such as the cost of using the technology on a construction project and its advantages in comparison to other similar technologies. The validation of the scenarios occurred through the provision of a report to each one of the experts which presented in detail each proposed research scenario. Each of the experts had to read the report and write his remarks at the end of the report. Questions from the experts were expressed to the researcher when they were providing back their report with their comments. The use of a report than an oral presentation of the scenarios from the researcher is better because there is not the risk that the researcher will forget any detail and also the experts have more time to examine the proposed scenarios. The validation of the proposed research scenarios is presented in more detail in Section 5.5 of Chapter 5.

2.6.4 System Design

System design is a significant part of the research. It involves the analysis of the requirements of the proposed scenarios and the development of the appropriate architecture based on these requirements. The development of the right architecture is important because it affects the overall success of the research. The correct system design allows more efficient implementation of the system and it reveals the true capabilities of both the software and hardware elements.

System design was based on the analysis of the requirements of the proposed research scenarios and the results of the validation of these scenarios from a group of experts. The requirements analysis included the identification of the hardware and software needs for the realisation of the proposed scenarios. The conclusions extracted from the validation of the proposed research scenarios were the basis for the formulation of the hardware and software requirements in such a way so that possible problems to be avoided.

In addition, the architecture of the system had to be designed and this architecture should follow the procedures which describe the proposed research scenarios and in a way that would integrate all the aspects of the scenarios. The design of the architecture of the system was based not only on the identification of the needs of the proposed scenarios but also on the identification of the users' needs. Cultural issues related to the level of knowledge of Information and Communication technologies in the construction industry were considered so that the system could be as friendly as possible to the users.

2.6.5 System Development

System development is the next step after system design. During this stage, the appropriateness of the selected system architecture is tested. Any flaws in the design are shown and appropriate measures to correct them are taken. The difficulty of this stage is found on the fact that the data models which have been developed during system design have to take the form of a computer program in a specific programming language. During system development, specific programming tasks were realised. The first step was the selection of the appropriate programming languages which would enable the realisations of these tasks. In addition, the necessary programming techniques were identified in order to adjust the designed system to the requirements of the proposed scenarios.

2.6.6 System Evaluation

System evaluation is necessary to be ensure that a working system has been developed [Anderson, 2001]. The feedback which is collected by a group of experts is necessary in order for the capabilities of the system to be clarified and their possible weaknesses to be underlined.

During system evaluation, the participants used the proposed system under the instructions of the researcher and they provided their feedback through a questionnaire. The use of a questionnaire for the evaluation of the system was preferred because it allowed the system evaluators to provide a clear rating of many aspects of the examined system. Harvey (1998) considers questionnaires more objective than interviews since they gather responses in a standardised way. The questionnaire which was used for this thesis, contained not only questions where the evaluators had to tick an answer but it also provided questions which gave to the evaluators the opportunity to express their opinion about the proposed system and its different aspects.

The purpose of system evaluation is to check the effectiveness and efficiency of the proposed system, the easiness which characterises its use and its usefulness to the construction industry. Also, specific aspects of the proposed research scenarios were examined while the system evaluators were able to propose their suggestions for the improvement and future implementation of the proposed system.

2.7 Summary

Research methodology is an important element of the research process. It involves the steps taken in order for a desired outcome to be achieved. The division of the research process into many stages which are connected to each other through a specific sequence allows better analysis of the problems examined during the research. There are two categories of research methods: qualitative and quantitative. Qualitative research involves action research, case studies, ethnography and grounded theory. Tools which are used by qualitative researchers are interviews, questionnaires, fieldwork, texts and the reactions of the researcher. Quantitative research involves surveys, questionnaires, experiments, personal interviews, telephone interviews, self-completion on paper and self-completion through electronic means. The combined use of quantitative and qualitative techniques is referred to as triangulation. Additionally, a number of quantitative and qualitative research methods, such as surveys, action research and longitudinal research, are applied in Information Systems. Especially for Construction Information Technology, the research methods which are applied are action research, ethnographic research, surveys, case studies and experiments. The different stages of this PhD research were based on the use of a variety of research tools, both qualitative and quantitative. Specifically, during the review of the literature, qualitative and quantitative data were collected and analysed through the use of papers published in journals and conference proceedings, books, and publications by well-known organisations of the construction industry. The data collected from the review of literature were useful in the development of scenarios in the construction industry to which specific wireless sensor technologies can be applied. Specifically, based on the knowledge acquired by literature review and using specific scenario planning methods, such as the inductive and deductive methods, gradual development of a number of scenarios has occurred. Figure 2.3 provides an overview of the research methodology.

Fig. 2.3 Overview of Research Stages

Chapter 3: Wireless Sensor Technologies

3.1 Introduction

This chapter presents the innovative technology of wireless sensors. A definition of the technology is provided as well as a focus on wireless sensor networking technology is done. Wireless sensor networking is actually the integration of many sensors together which communicate wirelessly between each other and then to a central wireless node which transfers all the data to a central processing system. The key features of the technology are presented and specific issues related to the communication between sensor nodes in a wireless sensor network, its energy consumption, its fault-tolerance and performance are examined. The applications of the wireless sensor networking technology to a variety of industries, such as automotive, medical/biomedical, chemical, computer-integrated manufacturing, and food industry are examined and specific emphasis is given to the applications of the technology in the construction industry.

3.2 Definition of Wireless Sensors

Sensors are small devices which are equipped with communication subsystems, storage and processing resources. Sensors are able to observe phenomena such as thermal, acoustic, optic, seismic and acceleration events, while the processing and other elements analyse the data and develop answers to specific user requests [Megerian et al., 2003]. Park et al. (2000) defines wireless sensors as small devices which are capable of performing a sensing task. Wireless sensor networks are networks of such devices which can perform a cooperated sensing task [Domdouzis et al., 2004].

A taxonomy of the main categories of wireless sensors can be shown in Table 3.1.

Table 3.1 Taxonomy of Wireless Sensors

Types	*Specification*	*Categories*	*Features*	*Applications*
Acoustic	Detection of acoustic signals [Boser et al., 2005]	Hydrophones [Alcocer et al., 2006], Ultrasonic Transducers [Teng & Hariz, 2006]	Deployment in a single or array form [Chen et al., 2003]	Marine, Biological [Akyildiz et al, 2005]. Military [Römer & Mattern, 2006]
Analytical	Quantitative analysis of chemical substances [Vlasov et al., 2005]	Microelectrodes [Stulik et al., 2000], Ion Selective Electrodes [Tymecki et al., 2006], Photometers [Zhao et al., 2001]	Robustness, High Performance, Low cost [Lucas et al., 2006],Small size [Stulik et al., 2000]	Biochemical [Bolger et al., 2006]
Biochemical	Detection of changes in chemical properties of a substance [Thievenot et al., 1999]	Biosensors [Vadgama, 2004]	Ultra-sensitivity, Low-cost [Andreescu & Sadik, 2004]	Environment-al, Medical [Rodriguez-Mozaz et al., 2004]
Displacement	Measure displacement of the position of a point [Weber et al., 2003]	Linear Encoders [Korhonen & Kalantari, 2001], Optical Sensors [Aydinli et al., 2004], Position Sensors [Nezuka et al., 2002]	Measurement range [Furutani et al., 1999], Accuracy [Ibbett et al., 1994], Sampling Rate	Biosensing, Atomic Force Microscopy [Suh et al., 2005]
Environmenta l	Measurement of Environmental Parameters, such as population of birds [Martinez et al., 2004]	Photometers [Chen, 2001], Seismic Sensors, Weather Sensors [Hart & Martinez, 2006]	Use of a number of technologies, such as gamma rays or X-rays [Krimchansky et al., 2004]	Environment-al Monitoring [Martinez et al., 2004]
Fibre-Optic Sensors	Detection of Vibration, Strain [Lau, 2003],	Fibre-Optic Refractometer [Sheeba et al., 2005]	Use of optical fibres [Thomas Lee, 2003]	Biomedical Sciences [Wolfbeis, 1987], Constructio n Industry [Lau, 2003]
Flow Sensors	Determination of flow rate	Flow Meters	Thermal	Microfluidic

	[Kersjes et al., 1996]	[Lindh & Brownlee, 2003]	transfer [Van Baar et al., 2001], Torque transfer [Svedin et al., 2001], Pressure distribution [Lofdahl et al., 1996]	applications [Meng & Tai, 2003],
Gas Sensors	Detection of gas [Zee & Judy, 1999]	Gas Chromatographers [Hinshaw, 2004]	Voltage [Simakov et al., 2006], current [Tian et al., 2005] outputs	Environment-al Monitoring [Getino et al., 1999], Health & Safety Monitoring [Hooker, 2002]
Humidity & Moisture Sensors	Detection of humidity and moisture [Beigl et al., 2004]	Humidity Measurement Instruments [Déry & Stieglitz, 2002]	Network of small wires on a material. These wires measure the resistance of that material which varies with the humidity [Beigl et al., 2004]	Weather Monitoring [Awtrey, 2000]
Level Sensors	Measurement of level of liquids [Bukhari & Yang, 2006]	Externally mounted displacers, Gamma ray sensors, Ultrasonic Transducers [Bukhari & Yang, 2006]	Use of optical fibre [Betta et al., 1996] or microwave [Sovlukov & Viktorov, 2006] technology,	Oil Industry [Bukhari & Yang, 2006]
Linear Position Sensors	Detection of change of linear position [Kohvakka et al., 2005]	Laser Displacement Sensors [Song, H.X. et al., 2006], Linear Encoders, Inductive Position Transducers, Capacitive Position Transducers [Nyce, 2004]	Consideration of linear measurement range [Seco et al., 2005]	Precision Positioning Application s [Guckel et al., 1996]
Pressure Sensors	Detection of pressure changes [Sidhu, 2005]	Pressure Gauges [Pressey, 1952]	Display types can be digital or graphical [Simpson,	Medical Application s (blood pressure,

			1994]	bladder pressure, spinal fluid Pressure Measureme nts [Judy, 2000]
Temperature Sensors	Detection of temperature changes [Beigl et al., 2004]	Temperature Probes [Schuderer et al., 2004]	Very small, easy to use [Beigl et al., 2004]	Medicine [Fang-Chung et al., 2004], Nuclear Facilities Monitoring [Kimura et al., 2001]
Vibration Sensors	Detection of possible vibrations [Dinev, 1995]	Piezoelectric Actuators [Wu & Janocha, 2004], Inertial Gyros [Bernstein, 2003]	Consideration of frequency range [Zhang et al., 2000], use of transducers [Greaves & Sawyer, 1983]	Geophysical applications [Bernstein et al., 1999]

3.2.1 Definition of Wireless Sensor Networking Technology

Wireless Sensor Networks are groups of sensor nodes which co-operate with each other in order to produce a larger sensing task [Park at al.,2000]. Mhatre and Rosenberg (2004) define wireless sensor networks as networks of wireless nodes which are deployed over a specific area in order to monitor specific phenomena of interest.

The wireless sensor nodes are dispersed in a sensor field as shown in Figure 3.1.

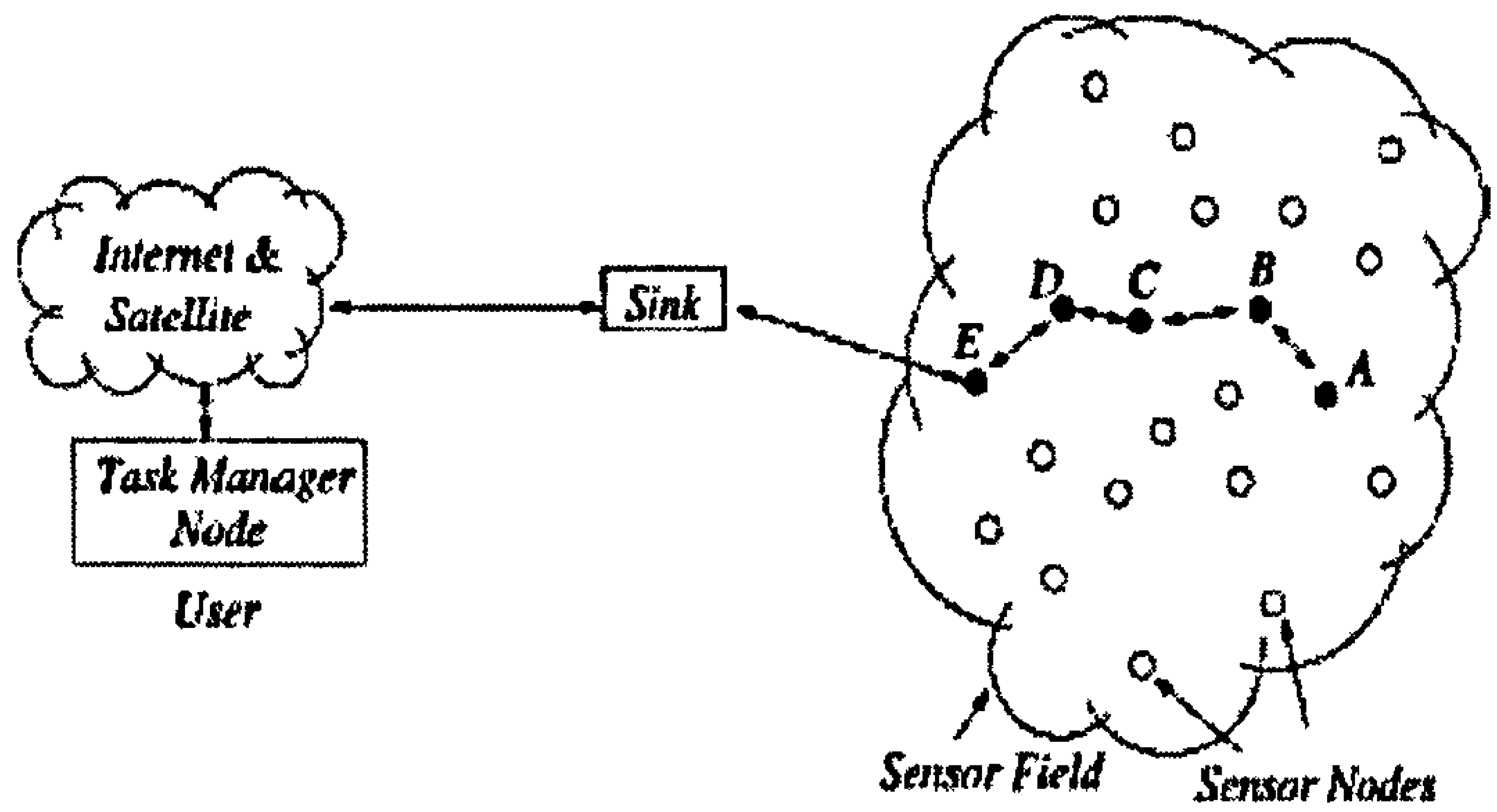


Fig. 3.1 A diagram of a wireless sensor network [Akyildiz et al., 2002]

Each of the scattered sensor nodes is characterised by the ability to gather data and route them back to the sink and the end user. Data are routed back to the end user by a multi-hop infrastructure architecture through the sink. The communication between the sink and the task manager is achieved through the Internet or a satellite [Akyildiz et al., 2002].

3.2.2 Key Features of the Wireless Sensor Networking (WSN) Technology

According to Wadaa et al. (2005), a sensor node is characterised by three main capabilities which are the sensory, data elaboration and wireless communication capabilities. The sensory capability is used for the acquisition of data from the environment while the data elaboration capability is used for data aggregation and control information processing. The wireless communication capability is used for the transmission and reception of data from other nodes or the sink [Wadaa et al., 2005].

A sensor node consists of a sensing unit which is used for the sensing task, a processing unit which is used for the elaboration of the sensing data, a communication unit which is used for the communication with the sink node and/or the other nodes and a power unit which is used for the provision of power [Cheng et al., 2004].

The elements of the sensor node can be shown in Figure 3.2.

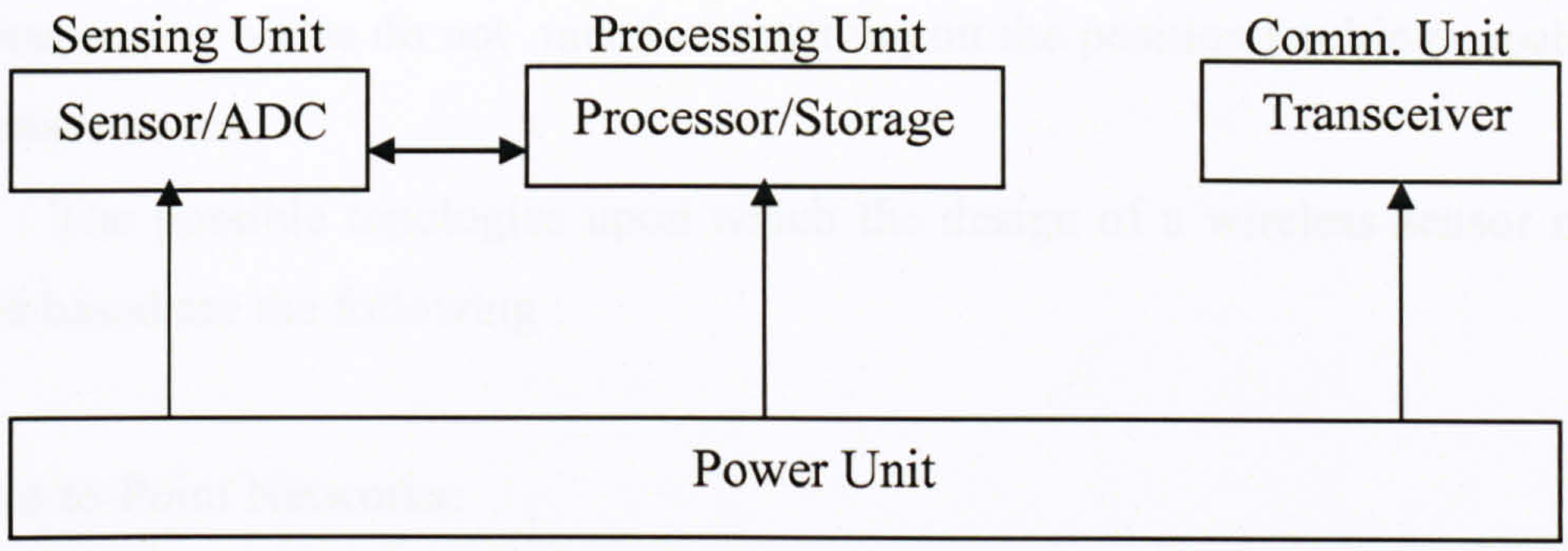


Fig. 3.2 Elements of a sensor node [Cheng et al., 2004]

Al-Karaki and Kamal (2004) mentions that a sensor node includes a number of units which are the sensing, processing, transmission and power unit. In addition, they consist of a position finding system, a mobilizer and a power generator. The anatomy of a sensor node is provided in Figure 3.3.

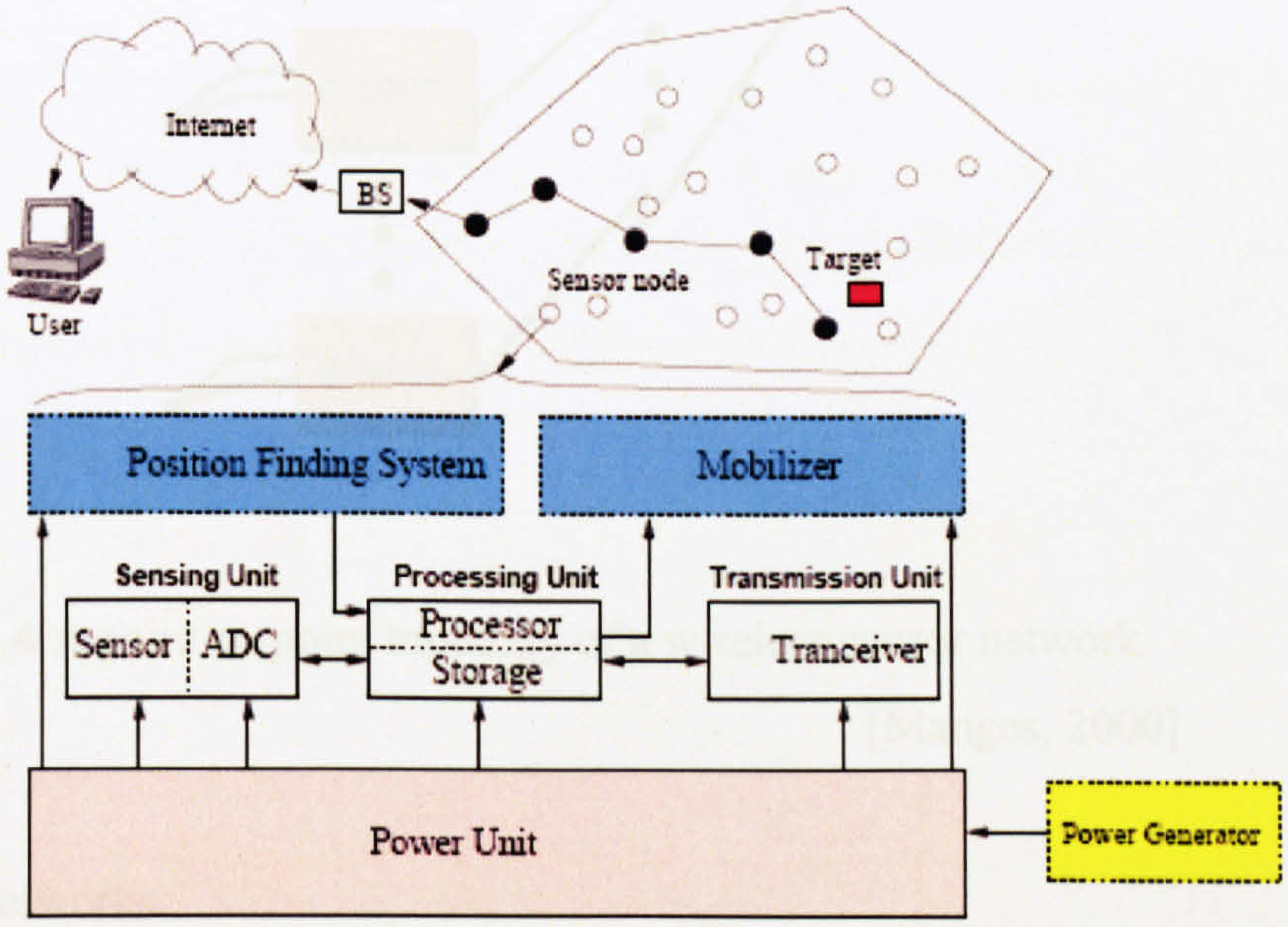


Fig. 3.3 Anatomy of a wireless sensor node
[Al-Karaki & Kamal, 2004]

Some of the elements which are shown in Figure 3.3 may be optional and not included in all the nodes [Al-Karaki & Kamal, 2004]. The definition provided by Al-Karaki and Kamal is more advanced in comparison to the previous definitions which were presented. In addition, this definition presents as an integral part of each sensor node, a position finding system. This fact is important because most definitions for wireless sensor nodes do not mention anything on the position tracking capability of the sensor nodes.

The possible topologies upon which the design of a wireless sensor network can be based are the following :

• Point-to-Point Networks:

In this sensor topology, numerous sensor nodes transmit sensor readings to a base station or aggregation point in the network [Karlof & Wagner, 2003].

A schematic representation of a point-to-point network is shown in Figure 3.4.

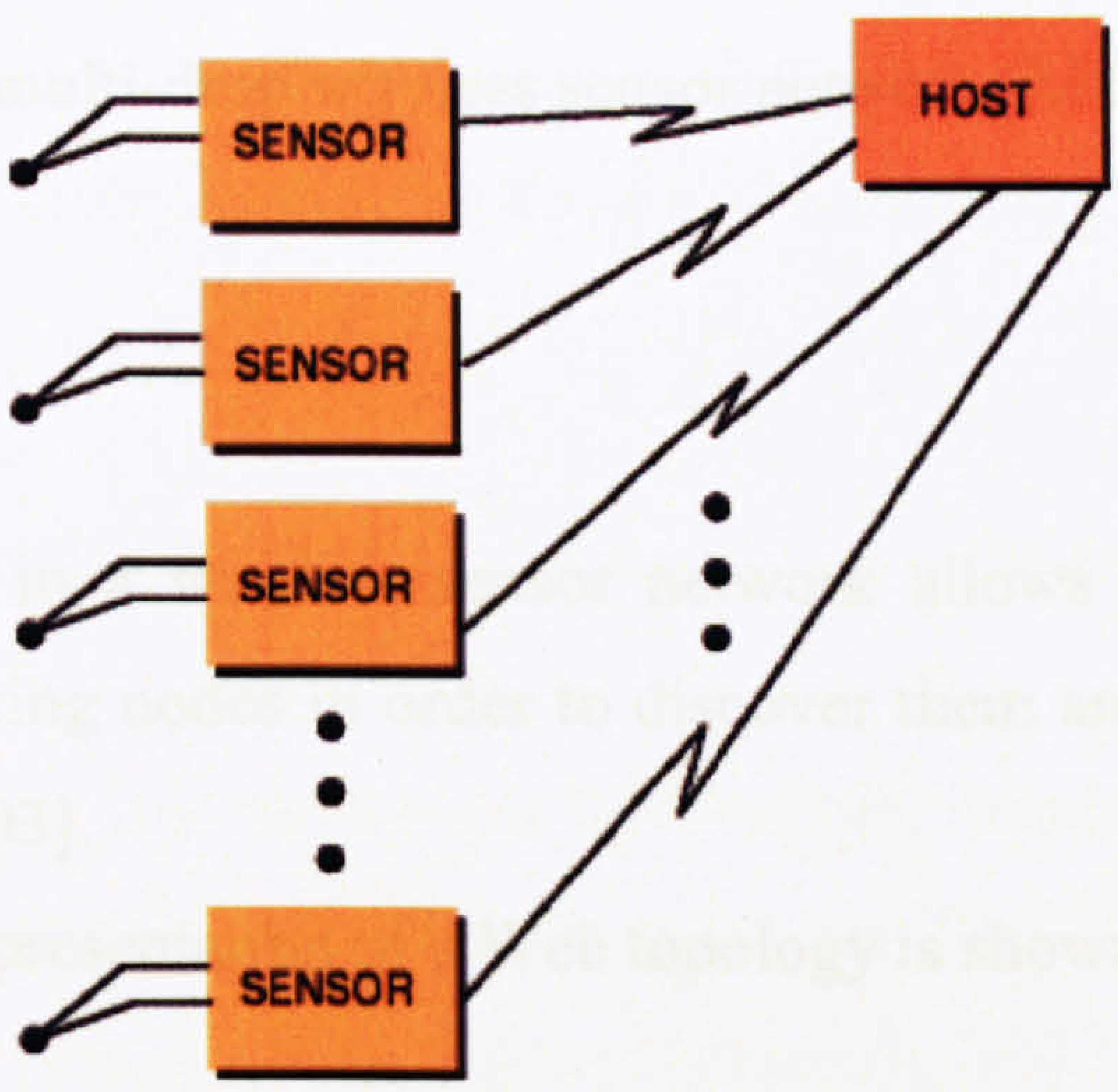


Fig. 3.4 A point-to-point topology of a wireless sensor network

[Manges, 2000]

• Multi-drop Networks:

Multi-drop (or many-to-one) wireless sensor networks are sensor networks in which multiple sensor nodes transmit sensor readings to a base station in the network [Karlof & Wagner, 2003].

A schematic representation of a multi-drop network is shown in Figure 3.5.

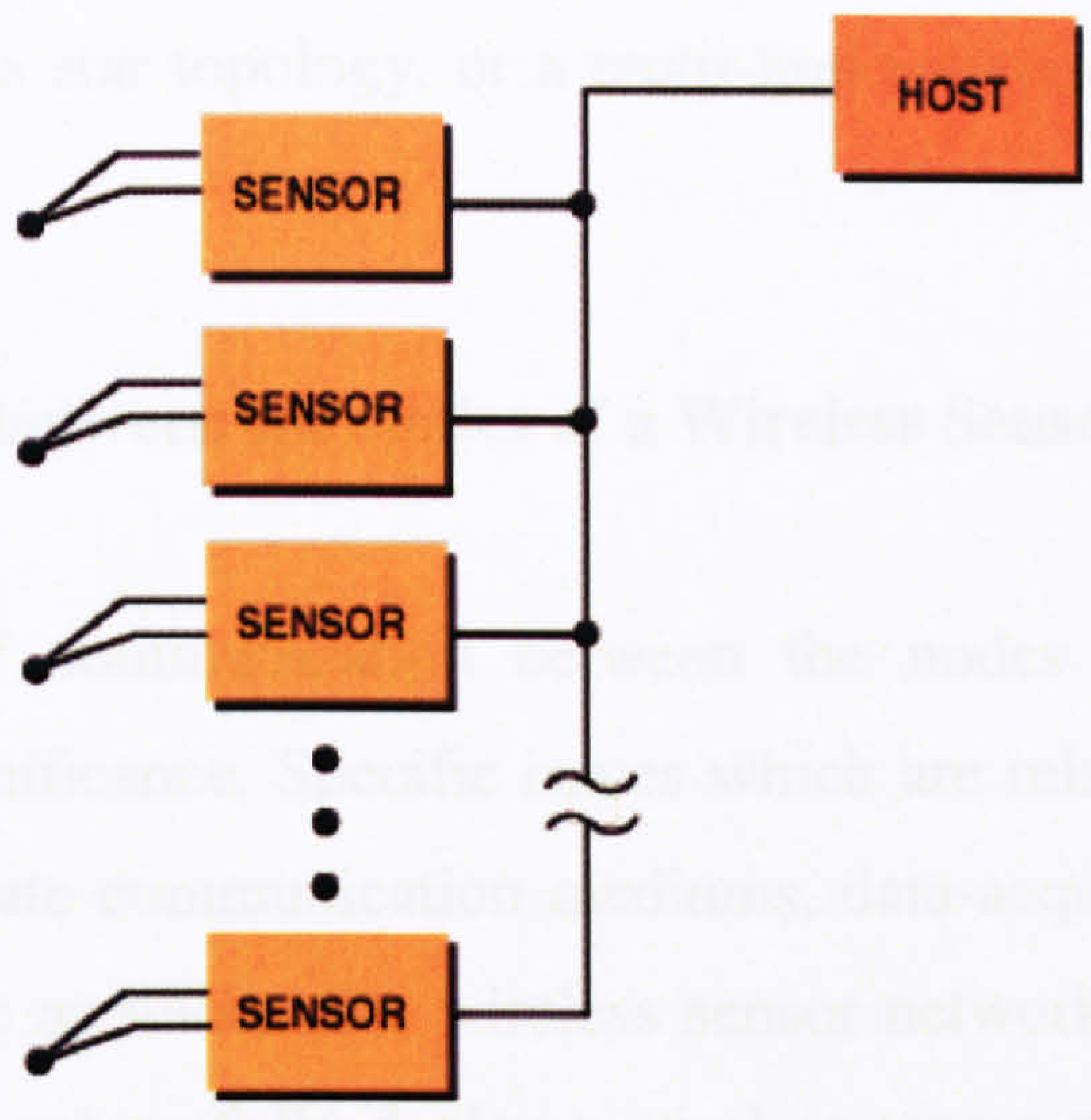


Fig. 3.5 A multi-drop wireless sensor network [Manges, 2000]

• Web Topology:

Web topology in a wireless sensor network allows a sensor node to send messages to neighbouring nodes in order to discover them and coordinate with them [Karlof & Wagner, 2003].

A schematic representation of a Web topology is shown in Figure 3.6.

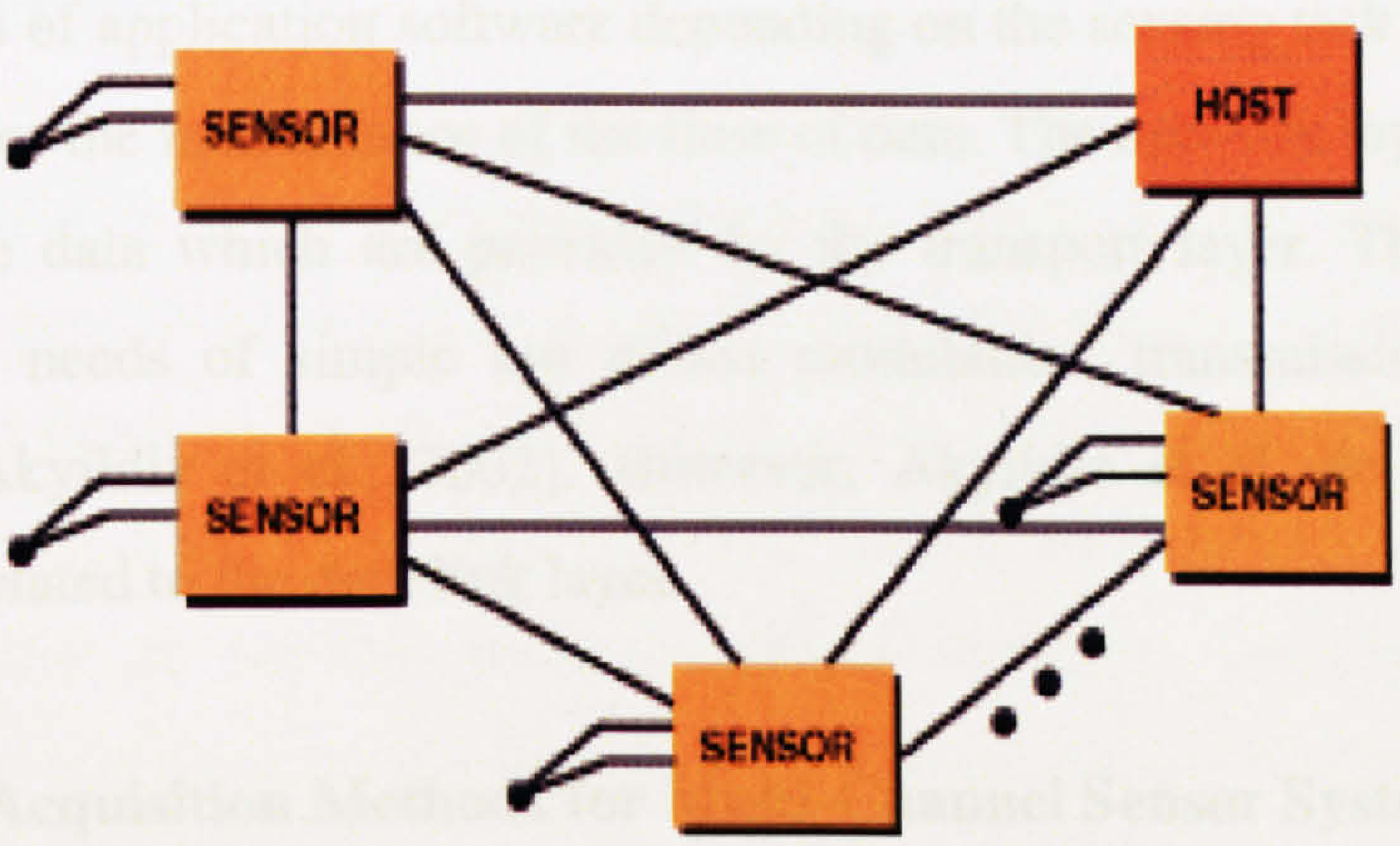


Fig. 3.6 A web topology of a wireless sensor network [Manges, 2000]

Römer and Mattern (2004) suggest that a wireless sensor network can have the form of either a single-hop network in which every sensor node communicates directly with every other node, an infrastructure-based network in which the base station is the centre of a star topology, or a multi-hop network which may create an arbitrary graph.

3.2.3 Communication between the Nodes of a Wireless Sensor Network

The subject of communication between the nodes of a wireless sensor network is of great significance. Specific issues which are related to this subject are the use of the appropriate communication mediums, data-acquisition techniques and routing algorithms. The architect of a wireless sensor network must be aware of all these issues in order to successfully deploy a wireless sensor network. Any failure in the comprehension of these issues will affect other important aspects of the wireless sensor networking technology, such as its performance and its tolerance against any possible faults.

3.2.3.1 Requirements for Effective Communication in Wireless Sensor Networks

In order for the communication between the wireless sensor nodes to be effective, a protocol stack is used. This protocol stack includes the following layers: application, transport, network, data link and physical. The application layer can use different types of application software depending on the sensing task and the transport layer is used for the maintenance of the flow of data. The network layer is used for the routing of the data which are provided by the transport layer. The physical layer addresses the needs of simple but robust modulation, transmission and receiving techniques [Akyildiz et al., 2002]. However, Akyildiz et al. do not provide any information related to the data link layer.

3.2.3.2 Data Acquisition Methods for Multi-Channel Sensor Systems

The methods which are used for data acquisition in multi-channel sensor systems are divided to time-division channelling and space-division channelling methods. The first type of methods is based on the transformation of the frequencies of multiple sensors to a binary code by counting the frequencies during quantization time or by measuring the impulses of the high reference frequency during one or many periods. The second type of methods is based on the simultaneous acquisition of data from all the sensor nodes while the conversion of frequencies occurs simultaneously across different channels [Deynega et al., 2002].

3.2.3.3 Transmission Mediums Used in Wireless Sensor Networks

The communication of sensor nodes in a multi-hop sensor network is established through a wireless medium. The connections of the sensor nodes to the wireless medium can be achieved through the use of radio and infrared mediums [Akyildiz et al., 2002]. A number of possible choices are listed below :

• ISM bands:

One option for radio links is the use of industrial, scientific and medical (ISM) bands, which offer license-free communication in most countries. A number of frequency bands are available from the International Table of Frequency Allocations. A typical sensor node uses a radio-frequency transceiver which is analogue and runs in the high frequency range of ISM bands (300 MHZ to 2.4 GHz) and a MCU which is digital and runs in a low-frequency range, usually in kilohertz [Rhee et al., 2003].

• Infrared Communication:

Another way of communication between wireless sensor nodes is by infrared. Infrared communication is robust to interference from electrical devices. In addition, infrared-based transceivers are cheaper and easier to build [Akyildiz et al., 2002]. A large number of today's laptops, personal digital assistants (PDAs) and mobile telephones offer an infrared data association interface. The main disadvantage however is the requirement of a line of sight between the transmitter and the receiver [Carruthers, 2002].

3.2.3.4 Routing in Wireless Sensor Networks

Routing protocols which are used in a wireless sensor network are the following:

(A) Address-Centric/Data-Centric Routing Protocols :

Simple models of routing schemes are the data-centric and address-centric schemes which are presented below:

• Address-Centric Protocol (AC): Each source separately transmits data along the shortest path to the sink based on the route which the queries took ("end-to-end routing") [Krishnamachari et al., 2002]. The address-centric protocol can be shown in Figure 3.7.

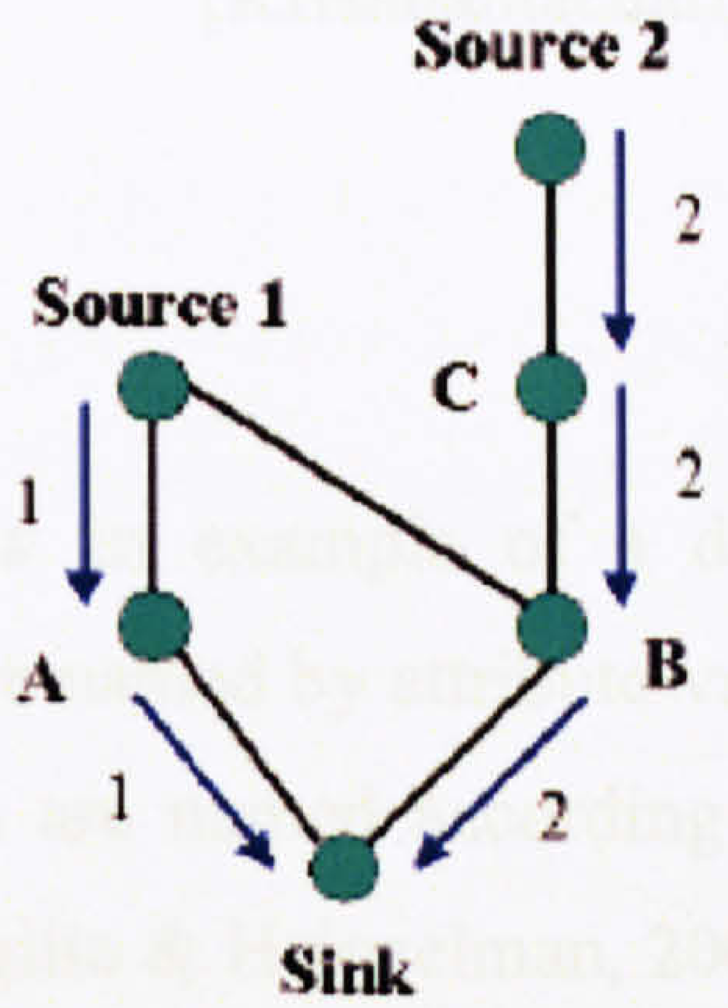


Fig. 3.7 Address-Centric Protocol

[Krishnamachari et al., 2002]

• Data-Centric Protocol (DC): In data-centric routing, the sink node transmits queries to certain regions and waits for data from the sensors placed on that regions. Attribute-based naming is used by the sensor nodes in order for the properties of the data to be specified [Akkaya & Younis, 2005]. The data-centric protocol can be shown in Figure 3.8.

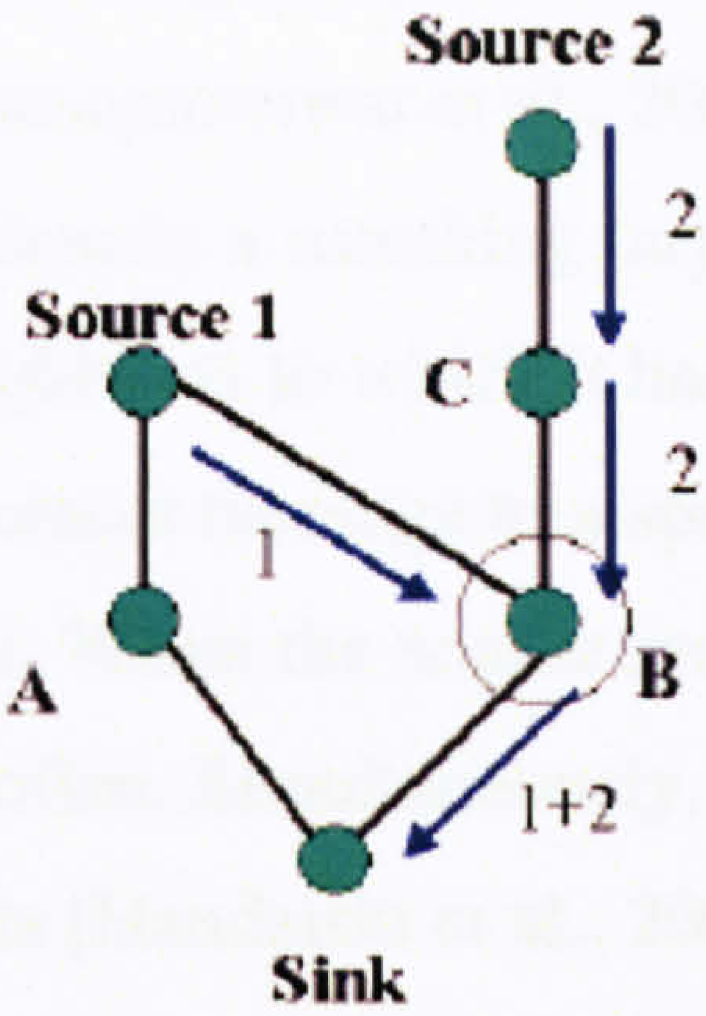


Fig. 3.8 Data-Centric Protocol
[Krishnamachari et al., 2002]

(B) Directed Diffusion:

Directed diffusion is an example of a data-centric routing scheme. Data produced by sensor nodes are named by attribute-value pairs. A node requests data by transmitting interests which are named according to the characteristics of the data which have to be sensed [Perillo & Heinzelman, 2005].

In directed diffusion, task descriptions are named by a list of attribute-value pairs that describe a task. The task description specifies an interest for data matching the attributes. Therefore, such a task description is called an interest. The data transmitted in response to interests are also named using a similar naming scheme [Heidemann et al., 2001].

An interest is usually inserted randomly into the network at a specific node. The term sink is used to denote this node [Intanagonwiwat et al., 2003]. The sink node periodically broadcasts an interest message in order to request data from its neighbours. When this occurs, gradients are created which contain as much as possible of the requested data. Also, when a sensor node receives the interest, it immediately creates a gradient towards the nodes from which it receives the gradient [Al-Karaki & Kamal, 2004].

A sensor node which receives a message from its neighbours, searches its interest cache for a matching interest entry. If no match exists, then the data message is silently discarded. If a match is found, the sensor node checks the data cache which is related to the matching interest entry. If no match in the cache is found, the data message is discarded. If a matching entry is found, the sensor node will re-transmit the data to its neighbours [Intanagonwiwat et al., 2003].

When a sensor node detects a matching target, it becomes a source and starts transmitting data to all its neighbours to which it has gradients. After the sink receives these data, it sends a reinforcement message to a specific neighbour and especially the one which sent first data to it. When the source receives a reinforcement message, it starts transmitting data more often. Simultaneously, the source transmits data to all the nodes to which it has gradients [Handziski et al., 2004].

(C) LEACH (Low-Energy Adaptive Clustering Hierarchy):

LEACH is a self-organising, adaptive clustering protocol which distributes amounts of energy evenly to the sensors of the network [Heinzelman et al., 2000]. The operation of LEACH is based on a number of rounds. Each round begins with a set-up phase, when there is organization of the clusters. This phase is followed by a steady-state phase when there is transfer of data to the base station. In order to reduce overhead, the steady-state phase is compared to the set-up phase [Wang et al., 2004]. The phases which describe the LEACH protocol are shown below:

(1) Advertisement Phase:

When clusters are created, each node decides whether or not to become a cluster-head for the current round [Li et al., 2005]. This decision is based on the suggested percentage of cluster heads for the network and the number of times the node has been a cluster-head so far [Balakrishnan et al., 2000]. Each node can become a cluster depending on a certain probability. This probability for a node n in round r is defined as follows :

$$T(n)=\begin{cases}\dfrac{P}{1-P\left(r \bmod \dfrac{1}{P}\right)} & \text{if } n\in G, \\ 0 & \text{otherwise}\end{cases}$$

where P is the percentage of sensor nodes that could become cluster heads, and G represents the nodes that have not been cluster heads in the last 1/P rounds [Khan et al., 2003].

Each node which has chosen a cluster-head for the current round transmits an advertisement message to the rest of the nodes [Li et al., 2005]. The non-cluster head nodes must maintain their receivers on in order to hear the advertisements of all the cluster-head nodes [Balakrishnan et al., 2000]. After the completion of this phase, each non cluster-head node decides the cluster to which it will belong for this round. This decision is based on the received signal strength of the advertisement [Heinzelman et al., 2000].

(2) Cluster Set-Up Phase:

After each node has decided to which cluster head it belongs, it informs the cluster head that it will be its member [Hussain & Matin, 2006].

(3) Schedule Creation:

During this phase, each cluster node creates a Time-Division Multiple Access (TDMA) channel for the nodes which are found in their cluster and informs all the other sensor nodes [Voigt et al., 2003].

(4) Data Transmission:

During this phase, each cluster head receives packets of data from the other sensor nodes in the cluster, fuses these packets and transmits the result of the fusion to the sink node [Wang & Xiao, 2005].

(5) Multiple Clusters:

The transmission in one cluster will affect the communication in a nearby cluster. In order for this type of interference to be reduced, each cluster communicates through the use of different Code Division Multiple Access (CDMA) codes. When a node decides to become a cluster-head, it selects randomly from a list of spreading codes [Saha et al., 2005]. In this case, it informs all the nodes in the cluster to transmit using this spreading code. There is filtering of all the received energy by the cluster head using the provided spreading code. Also, the radio signals generated by the neighbouring clusters will be filtered and will not affect the transmission of nodes in the cluster [Balakrishnan et al., 2000].

(D) SPIN (Sensor Protocols for Information via Negotiation):

SPIN is a family of adaptive protocols which distribute data among sensors in a wireless sensor network with limited energy resources. The nodes which use the SPIN protocols, name their data using high-level data descriptors, called meta-data [Heinzelman et al., 1999]. In the SPIN protocols, the sensor node which has new data, advertises these data to its neighbouring nodes by using meta-data. If a neighbouring node wants these data, it sends a request to the sensor node which contains these data. Then this sensor node sends data to the sink nodes [Qi, 2002].

(E) Sequential Assignment Routing (SAR):

The Sequential Assignment Routing (SAR) protocol creates numerous routes between a sink and a node, thus it reduces the time and cost associated with the development of new routes during failures. Each node belongs to multiple paths and each sensor node can control which one-hop neighbour of the sink to use for messaging. The SAR algorithm re-computes routing paths in order to re-adjust in possible changes of the sensor network topology [Andrews et al., 2004].

3.2.4 Energy Consumption in Wireless Sensor Networks

Energy consumption is considered one of the most significant aspects for wireless sensor networks. In the following paragraphs, the issue of the total energy consumption in a wireless sensor network is analysed and the parameters which affect it are also presented.

3.2.4.1 Total Energy Consumption in a Wireless Sensor Network

Gao J.L. (2002) mentions that in a wireless sensor network which is developed in a uniform manner over a region S and produces traffic (ρ), the total energy which is required in order for all data to be relayed to a single node which is located at a point c of the region S, is given by the following equation:

$$E\,total(c) = \sum_{S} \overline{Eb}(|s-c|) \cdot \rho \cdot ds$$
$$= \tau H^* \rho \sum_{S} |s-c| \cdot ds \quad \text{joules}$$

where H* is the watt-per-meter metric. This is a random variable which depends on the distance to the base station, the bearing Θ ($-\pi/2 < \Theta < \pi/2$) and the distance R. $\overline{Eb}$ is the energy for the transmission of a single bit over a distance d between a sensor node and the base station during time τ, and is calculated by the following relationship: $Eb(d) \approx \tau \cdot d \cdot H^*$ joules/bit [Gao, J., L , 2002].

Niebeng et al. (2003) suggested that the energy consumption of the battery of a wireless sensor node is the sum of the energy which is spent during the different states of the battery of the node. The energy consumption within a state Sj can be measured using a simple index Tj while the energy spent for the transition from a state to a different state is measured by using the matrix STij which shows the number of times the battery of the node switched from state Si to Sj. The total energy consumption for a sensor node in this case is given by the following equation:

$$E_{consumed} = \sum_{j=1}^{k} Tj\,Pj + \sum_{i,j=1,\, i\neq j}^{k} STij\,Eij$$

where Pj is the power which is required in state Sj and Eij is the energy consumption when switching from state Si to state Sj [Nieberg et al., 2003].

3.2.4.2 Reasons which cause Energy Consumption in a Wireless Sensor Network

There are several reasons which may cause energy dissipation in a wireless sensor network. These reasons are related to the way a wireless sensor network operates and are listed below:

- Energy Consumption caused by Different Modes of Operation of Wireless Sensor Nodes:

The amount of energy spent by the battery of the wireless sensor node during the time of operation is given by the following equation:

$$\text{Battery Capacity (A*H)} = \sum_{to+td}^{to} I(t)dt$$

where I(t) is the instantaneous current which is drawn from the sensor node during the time of operation t. If the value of the discharge rate is high, then the capacity of the battery is reduced. In these cases, the current of the battery may be reduced significantly. As a result, the discharge rate starts to decrease and the battery can recover its lost capacity [Savvides et al, 2003].

- Energy Consumption caused by Routing:

A wireless sensor network can be modelled as a directed graph G = (V,E) while each of the links of the network can be represented as e = (v ,w). The energy consumption of a routing y which is the same for all the sensor nodes is estimated by the following function:

$$f^{T}(y) = \max_{v\in V}\{\sum_{t=1}^{T}(\sum_{e\in I^{v}} \rho y_e^t + \sum_{e\in O^{v}} \tau y_e^t)\}$$

where t is each iteration in which every node transmits a packet to the base node, ρ is the cost for the reception of one packet, I^{v} represents the set of incoming links of v and O^v is the set of outgoing links of v. $f^T(y)$ is the maximum energy which is used by nodes when transmitting and receiving according to routing y [Alonso et al, 2003].

• Energy Consumption caused by Overhearing:

Energy consumption in a wireless sensor network occurs because of overhearing. Overhearing occurs when a wireless sensor node picks up a data packet which is destined for another node. In this case, energy is wasted in order for the transmitting node to re-transmit the data [Basu & Redi, 2004]. Furthermore, during the transmission process, all the nodes which are neighbours to the transmitting node overhear the transmission of the data packet. In this case, they consume energy even though the packet is not directed to them [Gao Q. et al, 2002].

Wireless sensor nodes have to listen to the radio link in order to receive any possible traffic which may however not be sent. This is called idle listening and it may consume large amounts of energy [Bachir et al., 2006] which may reach half the level of energy required for the reception of data [Gao Q. et al, 2002].

3.2.4.3 Ways of Reducing Energy Consumption in a Wireless Sensor Network

There are many ways in order for the energy which is consumed by a wireless sensor network to be reduced. These are listed below :

• Use of Data Aggregation Methods on a Wireless Sensor Network:

Data Aggregation is the technique of combination of sensor readings in intermediate nodes during the transmission of data packets towards a specific destination. This process reduces the amount of data which must be transmitted and thus, conserves energy. When aggregation occurs, then instead of transmitting a message to the data sink, intermediate nodes delay messages until they have received all the messages from their children nodes. The next step is to combine all these messages and transmit an aggregated message to the sink node [Karl et al, 2003].

• Implementation of Ultra-Low Energy Pico-Radio Wireless Sensor Networks:

Advances in the technological field have enabled the development of dense wireless networks of heterogeneous nodes capable of processing a wide range of data [Rabaey et al, 2000]. A significant factor in the success of these networks is the use of small, low-cost and lightweight network elements which are called Pico-Nodes [Willig et al., 2002]. These nodes are smaller than one cubic centimetre, have a weight of less than 100 grammars and cost less than one dollar [Shah & Rabaey, 2002]. In addition, these nodes use low power [Arslan et al., 2006].

• Implementation of Energy-Aware Techniques:

In order for the lifetime of a wireless sensor network to become maximum, the system must ensure that there is energy awareness not only into individual sensor nodes but also into the entire wireless sensor network. Specific energy-aware techniques such as data-centric dissemination, reinforcement-based adaptation and data aggregation and directed diffusion enable queries to extract data with minimum number of transmissions, thus decreasing energy consumption [Xu, Y., 2003].

• Use of specific Energy Conservation Methods:

The reduction of energy consumption in a wireless sensor network can be achieved through specific energy conservation techniques, such as the Power Aware Multi-Access Protocol with Signalling (PAMAS). PAMAS requires from a wireless sensor node to switch itself off when it has no packets to transmit and a neighbour node begins transmitting a packet which is not destined for it [Raghavendra, 2003]. Also, the protocol specifies that a node can switch itself off when it has no packet to transmit and also its neighbour nodes do not have any data packet to transmit [Marín et al., 2005].

3.2.5 Fault-Tolerance for Wireless Sensor Networks

Fault-tolerance is of major importance for Wireless Sensor Networks. This is because wireless sensor networks operate in harsh environments. In addition, since the applications in which wireless sensor networks are implemented are mission critical and the complexity of the structure of sensor and actuators in comparison to the structure of semiconductor integrated circuits-based systems, the subject of fault tolerance becomes even more significant.

3.2.5.1 Techniques for achieving Fault-Tolerance in Wireless Sensor Networks

There are a number of techniques which facilitate the achievement of fault tolerance. Lee et al. (2006) suggest that a wireless sensor network should be able to configure itself and also heal itself in possible changes of its topology. A method for sensor recovery has been suggested by Gupta and Younis (2003). Specifically, they suggested that in order for sensors to be recovered by a cluster failure, the cluster heads should periodically exchange information related to the condition of other cluster heads. Each cluster head uses these information in order to decide whether there are any malfunctioning cluster heads [Gupta & Tounis, 2003]. However, this method attempts to diagnose whether there is any problem with any node of a wireless sensor network and face it accordingly but it does not mention what measures are taken when this problem has already affected the operation of the wireless sensor network.

A significant technique which can ensure fault tolerance in a wireless sensor network is multi-sensor fusion. This technique involves the combination of the outputs of a large number of sensors for the provision of more accurate data [Luo et al., 2002]. An example of the use of multi-sensor fusion is the detection of defects on pipelines systems. The German project "Sewer-Assessment with Multi-Sensors" uses different sensor systems for the characterization of the state of the examined pipe system, the testing of sensor equipment for the detection of filtration in sewer and water mains, the development of an information system for taking maintenance decisions and the quantification of the damage in pipelines with the combined help of sensor-based methods [Eiswirth et al., 2001]. Figure 3.9 describes the specific project.

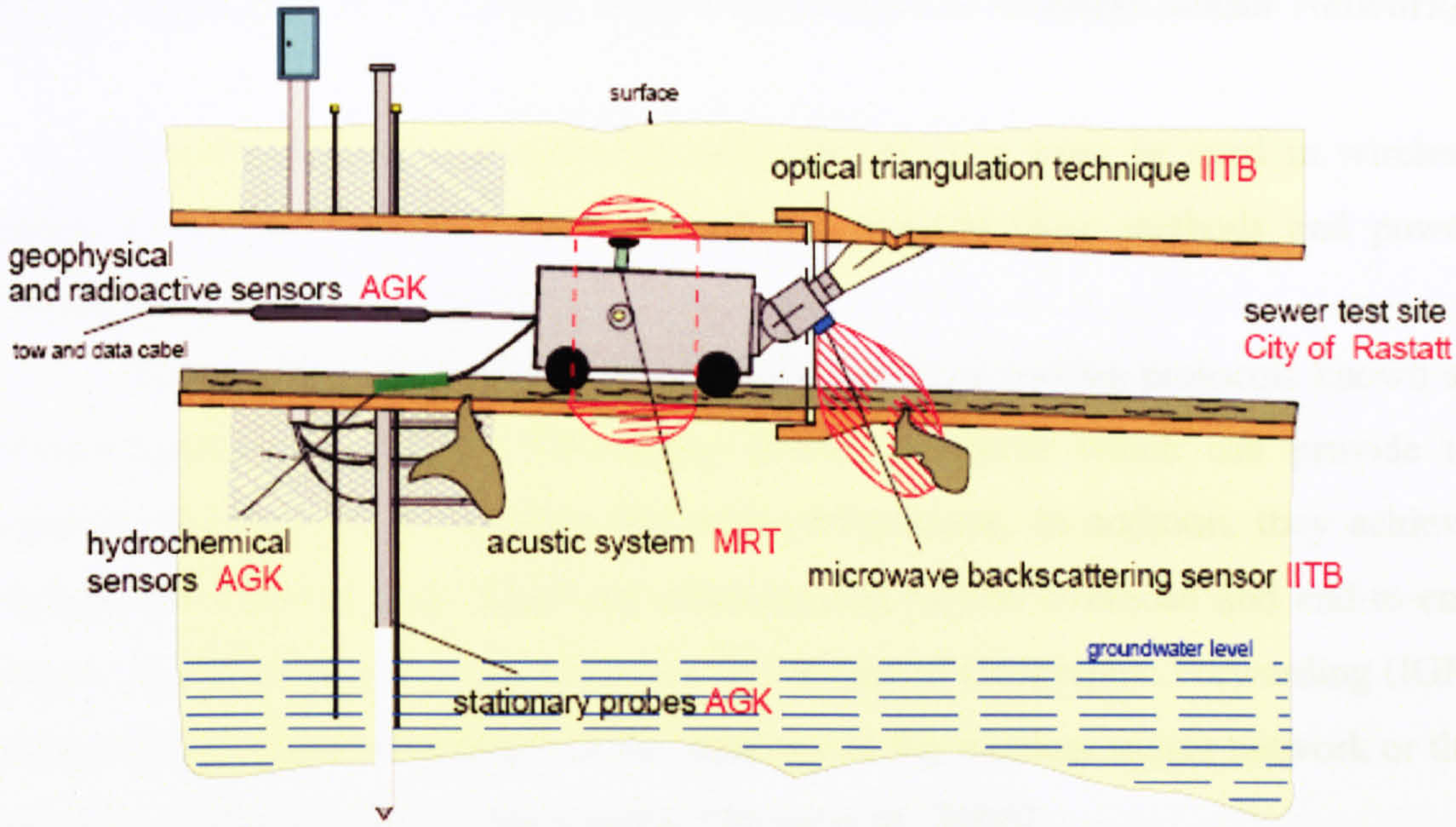


Fig. 3.9 Detection of pipeline defects using multiple sensors
[Eiswirth et al., 2001]

The advantages of multi-sensor fusion are numerous. First of all, it provides robustness [Van Laerhoven & Gellersen, 2004]. The use of multiple sensors reduces the possibility of an error done by an individual sensor while the observation of a phenomenon becomes more accurate. Also, the examination of a specific phenomenon may require the use of multiple sensors distributed across multiple spatial locations and this is offered only by multi-sensor fusion [Megalooikonomou & Yesha, 2004].

3.2.6 Performance of Wireless Sensor Networks

The subject of performance is significant for every new technology. Wireless sensor networks consist of a new technology and it is expected that they will be characterized by better performance than traditional networks. Specific techniques are analyzed in the following paragraphs which show how the performance of a wireless sensor network can be enhanced without affecting other critical aspects of their operation, such as their energy consumption.

3.2.6.1 Techniques for achieving High Performance in Wireless Sensor Networks

Specific methods for achieving high performance must be used in wireless sensor networks but there must be a balance between these methods and power consumption [Lin et al., 2004].

Wood et al. (2006) suggest the use of a family of routing protocols known as Secure Implicit Geographic Forwarding (SIGF) protocols which can provide to wireless sensor networks security and high performance. In addition, they achieve high packet delivery rates which are characterised by low overhead and end-to-end delays. The SIGF protocols are based on the Integrated Geographic Forwarding (IGF) protocol which does not depend on the topology of the wireless sensor network or the presence or absence of any sensor nodes [Wood et al. 2006].

Another technique for the improvement of the performance of a wireless sensor network is the relocation of the sink node. Specifically, the sink node could be relocated in order to improve some performance metrics, such as the network energy consumption and its throughput. The relocation of the network is to a location which is close to the sensor nodes which are capable of transmitting data directly to the sink node and not via other nodes [Akkaya et al., 2005b]. The relocation of the sink node does not mean necessarily the enhancement of the performance of a wireless sensor network. Especially in the case in which a sensor node is damaged, the relocation of the sink node close to this node will not enhance the performance of the sensor network.

3.3 Applications of Wireless Sensor Networking Technology

Wireless sensor networks are implemented to a variety of fields, such as medicine, chemical technology and mechanical engineering. There is also a number of potential applications of the wireless sensor networking technology in the construction industry. In the following sections, these applications are introduced giving particular emphasis to the applications related to the construction industry. Opinions of experts from various fields giving details of the use of the specific technology are also included.

3.3.1 Applications of Wireless Sensor Networks to various Industries

Wireless sensor networks are implemented in a variety of problems. These applications cover a wide range of industries and are listed below. In addition, telephone interviews have taken place with experts from these industries in order to examine how wireless sensor networking is currently used in the UK industries. These interviews were based on a set of questions related to the type of sensors used by the research institute or the company of the interviewee, the type of the application in which the sensors are used, the number of sensors used, their topology and the cost for the deployment of the whole application. Specific ethical considerations were considered prior to the realisation of the telephone interviews. Specifically, the interviewees were informed about the type of the research realised by the author of this thesis and that their responses would be recorded and presented on this thesis. The responses of the interviewees were clearly presented in this thesis.

3.3.1.1 Automotive Industry

Wireless sensor networks can be implemented in the automotive industry. Sensors are used in adaptive control systems in order to adjust the speed of vehicles. Specifically, if a vehicle is ahead of another vehicle and moves at a low speed, then onboard sensors placed on this vehicle can inform a central station through wireless communications which is responsible for the processing of data related to traffic and weather conditions. The station will then transmit these data to the vehicle which is behind the vehicle with the low speed and its speed is adjusted appropriately [Bulusu & Jha, 2005].

The managing director at Campbell Scientific Ltd., a company which is involved to the use of the sensor networks in automotive industry and which is based on Shepshed, Leicestershire, was interviewed by the researcher. The director gave a detailed image of how sensors could be deployed for an application related to vehicle testing. For such an application, a number of 100 or more sensor nodes would be required. All sensor nodes are connected to a data logger and this connection is achieved by wire. The cost for the deployment of such a system depends on the exact number of sensor nodes which are used and the type of the data logger. The data logger uses a specific operating system which is proprietary to Campbell Scientific. A

Windows platform software is then used in order for data to be transferred from the data loggers to a PC. The advantages of using sensor technology even if it employs wires is its speed of operation and the ease of use while no significant problems were encountered during the deployment of the technology [Saffell, 2003].

3.3.1.2 Chemical Industry

Arrays of chemical sensors are used in a number of chemical engineering applications. Each sensor of the array has its own signal processing circuit and is connected to an intelligent processor. This processor collects the individual outputs and examines the response pattern in order to extract useful data [Forster R.J., 1998].

A schematic representation of an array of chemically intelligent sensors is shown in Figure 3.10.

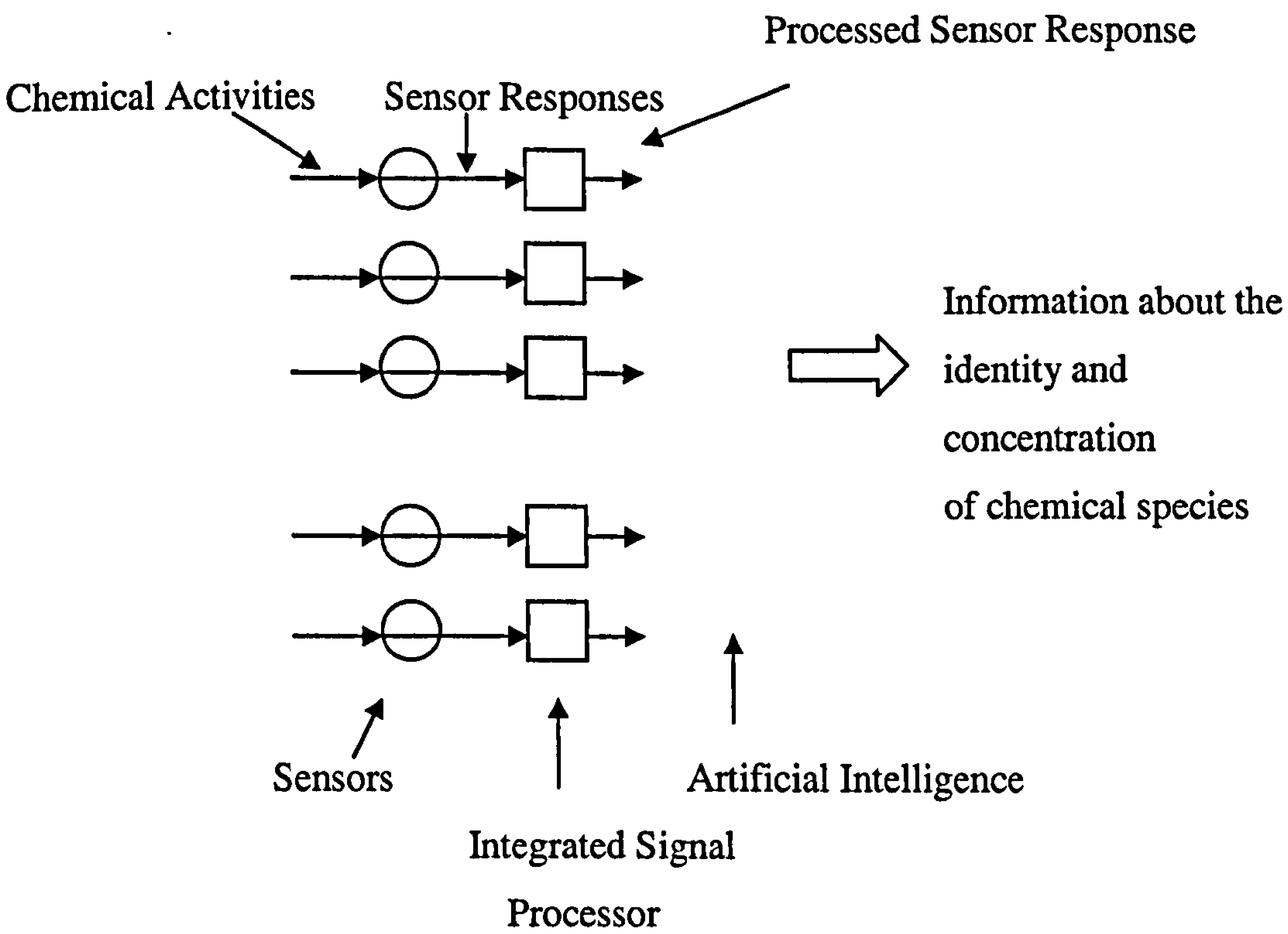


Fig. 3.10 A chemically intelligent sensor array [Forster R.J., 1998]

The array of sensors may include a number of identical sensors while the artificial-intelligence units collect all the outputs produced by the sensors. If the output of a sensor is not similar to the majority of the outputs, then it is assumed that this sensor is not working properly. Sensor arrays can be used in the emission monitoring around factories as well as to the detection of different chemical species in a chemical sample [Forster R.J., 1998].

3.3.1.3 Food Industry

An example of the use of wireless sensor networks in the food industry is their use in the production of wine. In this case, wireless sensor networks can be used for the control of the temperature during the transformation of grape juice into wine. In addition, wireless sensor networks can play a significant role in the fermentation process in which temperature must vary between specific ranges. Also, during the storage process, wireless sensor networks can be used in the detection of humidity levels [Connolly & O'Reilly, 2005].

3.3.1.4 Computer-Integrated Manufacturing (CIM)

Wireless sensor networks can be used in the monitoring of the health condition of machines. Specifically, they could be used for the monitoring of vibrations on machines in order for bearing problems to be prevented. These are problems which characterise industrial machines and can cause the interruption of the work of essential production equipment [Conant, 2006].

3.3.1.5 Habitat Monitoring

Wireless sensor networks can be used for the monitoring of plants and animals in a specific region. The deployment of sensors can occur before the beginning of the breeding season or when the ground is frozen. The monitoring of plants and animals is necessary since continuous human disturbance affects a number of parameters, such as their behaviour and their breeding. The data collected by the sensor nodes will be compared with previous studies which ignored human disturbance [Mainwaring et al., 2002]. An example of a wireless sensor network for habitat monitoring can be seen in Figure 3.11.

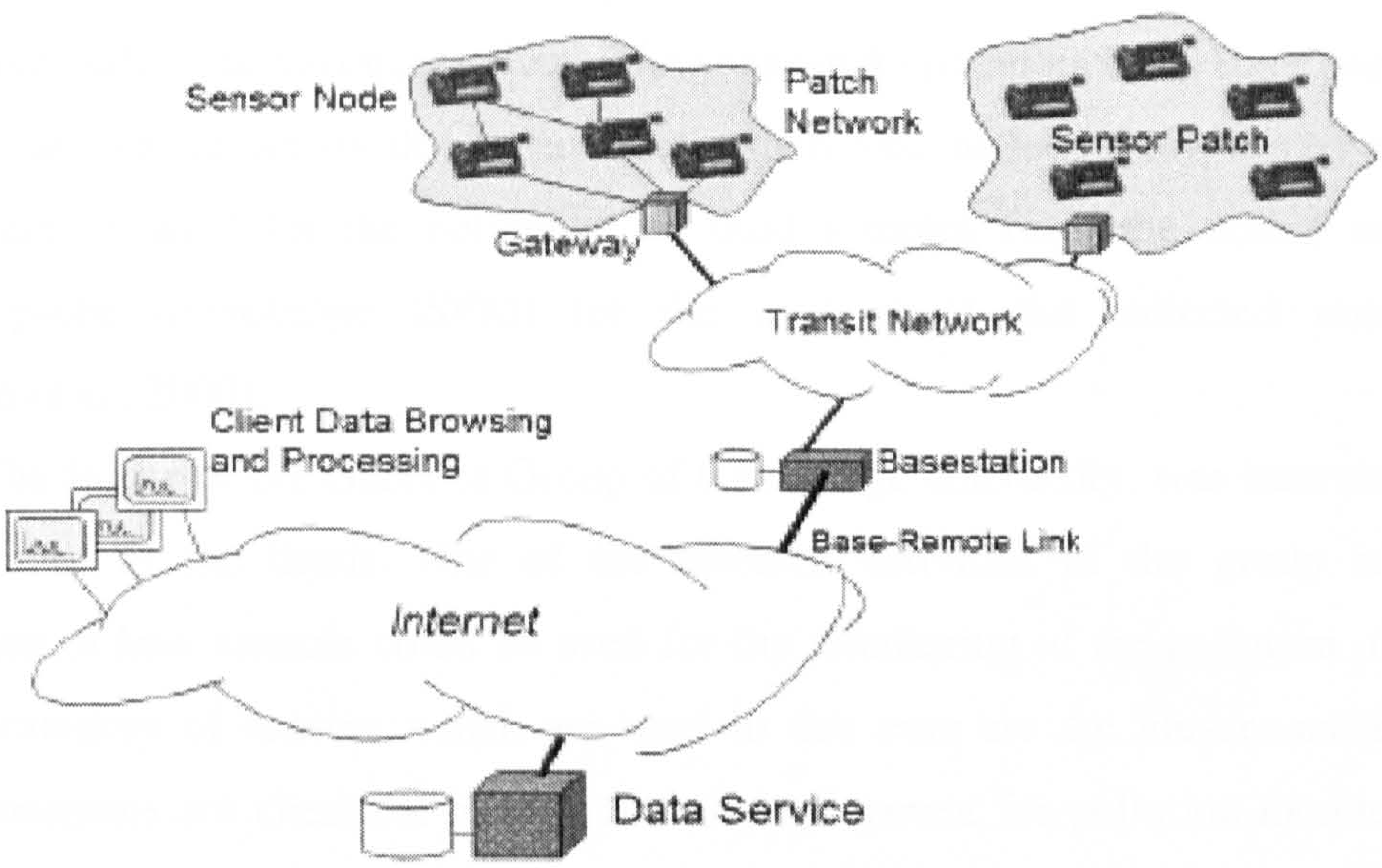


Fig. 3.11 Habitat Monitoring using wireless sensor networks [Mainwaring et al., 2002]

The wireless sensor network of Figure 3.11 consists of sensor nodes which collect data about their immediate surroundings. These nodes form groups which are called patches. The sensor nodes transmit their data through the sensor network to the gateway. The gateway transmits the sensor data through a transit network to a base station which is connected to databases which are found across the Internet. Sensor data are then available to scientists through graphical user interfaces [Mainwaring et al., 2002].

3.3.1.6 Marine Monitoring

The collection of environmental data and their comparison with populations of different organisms is significant for the marine research. It would also be interesting to examine how humans respond to organisms which exist in coasts [Sukhatme et al., 2000].

A combined research from the Universities of Southern California and California at Los Angeles, analyses the problem of monitoring ocean water in metropolitan areas, such as Los Angeles. There is a number of monitoring stations along the coast of the Los Angeles river. Each station performs measurements and transmits them to the other stations through a radio link. The off-shore stations can be used as water-safety monitoring stations. The suggested system includes three parts: a set of sensors placed across the ocean front which also include GPS, a system of robots which is used for the collection of fluid samples from the ocean, and a scanning probe microscope (SPM) for the analysis of the collected samples [Sukhatme et al., 2000].

The leader of the Genetics Group of Cambridge University, was interviewed by the author of the thesis. One of the research activities of the group is the examination of how sensors could be used for the monitoring of the pollution of the sea. The category of sensors which are used in this case are the biosensors. Even though biosensors are chemical in nature, their deployment for pollution monitoring applications requires the use also of electrical equipment, eg. alluminometers for signal detection. Mr Archer explains that a full cell of biosensors could be deployed in a cost and the benefits in this case are that the cell can carry out all the stages of the chemical procedure of environmental filtering. However, the disadvantage of such a system is that it can find that pollution exists but not the quantity of it. Also, a cell of biosensors could be characterised by the problem of the lack of signal stability. The cost of such a system depends on the needs of the market as well as the application [Archer, 2003].

3.3.1.7 Medical/Biomedical Engineering Industry

Wireless sensor networks find great applicability in medicine. Malan et al. (2004) have introduced CodeBlue, a wireless sensor network-based infrastructure for use in the emergency medical care. CodeBlue allows sensors to transmit signs, locations and identities which can be accessed by physicians through laptops or PDAs. In order for network congestion to be avoided, CodeBlue filters and aggregates events. This enables physicians to specify the type of data they want to receive in their laptops or PDAs. Furthermore, authentication is used in order for patient data to be accessed by physicians [Malan et al., 2004]. The architecture of the CodeBlue is shown in Figure 3.12.

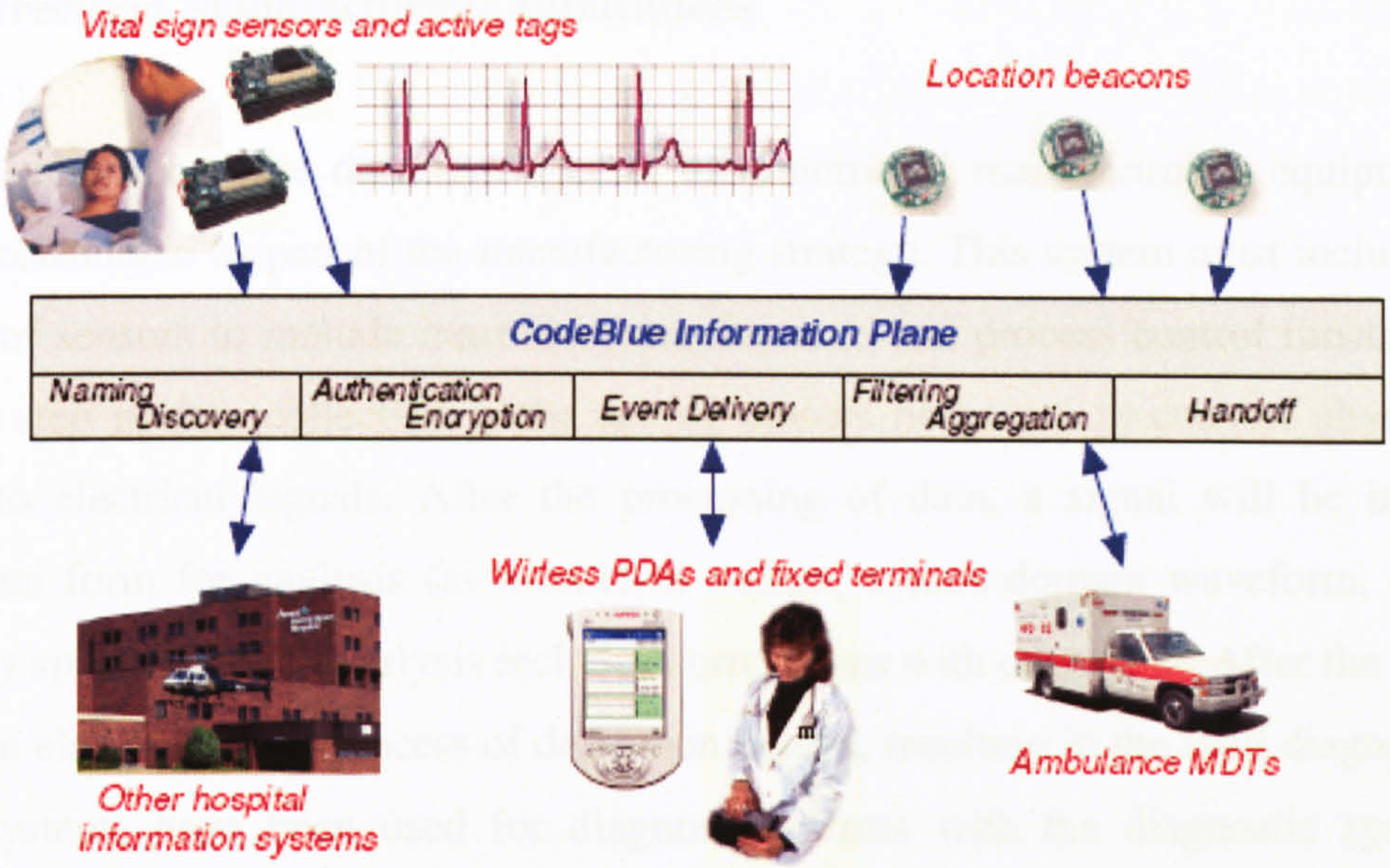


Fig. 3.12 The Code-Blue system

[Malan et al., 2004]

3.3.1.8 Military Applications

Wireless sensor networks can be used for the detection and tracking of military targets such as tanks. In this case, fatalities caused by the surveillance in enemy territory can be reduced.

Bokareva et al. (2006) have suggested a wireless sensor network which can be used for such a purpose. It is based on a large number of low power micro-sensor nodes and also on a limited number of cluster-heads called micro-servers. The tracking of a target is based on the spatial differences of measurements of the strength of the signal produced by the target and collected by sensor motes placed at different locations. The architecture of the system is actually based on the use of sensor motes which measure acoustic and magnetic signals produced by different military targets, micro-servers which are responsible for data aggregation and analysis, and data fusion algorithms for handling the noise generated by the environment [Bokareva et al., 2006].

3.3.1.9 Precision Manufacturing Applications

A comprehensive detection system for automated manufacturing equipment must be considered as part of the manufacturing strategy. This system must include a network of sensors to include machinery maintenance and process control functions. The first step in data collection is the use of sensors necessary to convert physical states into electrical signals. After the processing of data, a signal will be in an appropriate form for analysis (as a table of values, a time-domain waveform, or a frequency spectrum). The analysis includes correlations with other data. After the data have been elaborated, the process of deduction begins, resulting in the fault diagnosis. Expert systems have been used for diagnostic efforts with the diagnostic system presenting either a single diagnosis or a group of possibilities [Soloman S., 1999].

3.3.2 Potential Applications of the WSN Technology in the Construction Field

Wireless Sensor Networks can be applied successfully to the Construction Industry. Even though the Wireless Sensor Networking Technology is found in an early stage, it has shown that it can produce a number of innovative results. The applications of Wireless Sensor Networks to the Construction Field are listed below.

• Damage Detection using the Structural Health Monitoring (SHM) System:

The Structural Health Monitoring (SHM) System is another important example of wireless sensor network applications. The scope of the SHM System is damage detection and estimation of its extent. The Wisden Project at the University of Southern California is an example of a Structural Health Monitoring System. It includes wireless nodes which are placed at various parts of a large structure forming a tree structure. They send vibration data through multiple hops to the root of the tree structure which is the sink node. The addition of more sensor nodes can provide higher resolution in the monitoring of small areas of a building while it enables the monitoring of large areas [Chintalapudi et al., 2006]. Since vibration data are transmitted through multiple hops to the sink node, it is possible that the structural health monitoring system consumes lot of energy.

Glaser (2004) suggests the development of a structural health monitoring system which will be based on the use of inexpensive sensor nodes. These nodes in cooperation with peer-to-peer networks, collect estimates related to hazardous motions of the ground, estimate damages and provide emergency information. This system is especially useful after earthquakes. In this case, a building will use this system to evaluate whether it is capable of tolerating a new earthquake. The data related to the evaluation of the system will be provided to the residents of the building through networks and personal digital assistants (PDAs) [Glaser, 2004].

Holroyd Instruments is a UK company which is involved in acoustic monitoring of buildings. The managing director explained to the researcher during a telephone interview, how the company implements acoustic sensors for its applications. An acoustic monitoring application could use up to 2000 sensors. Specifically, groups of eight sensor nodes are created and communicate with a central station. Each group of sensor nodes can communicate with another group. The central station forwards the data on a specific computer through GSM. The cost of the system is approximately 2500 pounds and it includes the cost of the sensors, the distributed processing between the group of sensor nodes and the daisy-chaining with the central station. The factor which affects the deployment of such a network is the position of the sensors on the site or building. Their position depends on the attenuation which is different depending on the material. The advantage of the use of such technology is that energy released from the construction is recorded. The disadvantages are that it can be very expensive as the past has shown, it requires the constant presence of an expert and it is sensitive to noise [Holroyd, 2003].

• Wireless Sensor Networks for Gas/Fire Detection in Houses:

Sensors can be used in order to alert the owner of a building when there is emission of large amount of gas [Kanoun et al., 2001] or if there is smoke [Arampatzis & Lygeros, 2005]. In this case, they can alert the owner of the house by triggering the alarm. The detection of smoke can be done by the use of optical and ionisation detectors. Gas detection is achieved by the use of gas sensors which are capable of sensing different gas particles. An array of gas sensors which consists of semiconductor metal oxide sensors for the detection of CO, H_2 and NH_3, can be used on this case. A signal-processing method is also used in order to distinguish situations of fire and non-fire [Kanoun et al., 2001].

• Alerting the Security Services during Intrusion Detection:

A distributed, two-dimensional sensor network can be developed for the purpose of the surveillance of a specific area. Such a network offers detection of targets over a specific area. In this case, there is elaboration of intrusion data in each sensor node, sharing of these data with neighbouring nodes and their transmission to a gateway which offers wide area networking capabilities. Collaborative signal processing allows the network to reduce the existence of possible noise and also increases sensitivity [Arora et al., 2005]. This application shows the high potential of wireless sensor networks. Collaborative signal processing resembles the method of multi-sensor fusion which provides fault-tolerance in wireless sensor networks.

• Monitoring the Living Conditions inside the house:

The monitoring of the living conditions inside a house is important for its residents. Wireless sensor networks can be used in order to monitor the light, the temperature and the indoor air pollution so that useful conclusions are extracted about the quality of the indoor environment. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has deployed a wireless sensor network in a part of the Pacific Northwest National Laboratory at Washington in order to examine the advantages and disadvantages of the technology in heating, ventilation and air conditioning (HVAC) systems [Arampatzis & Lygeros, 2005].

• Use of Sensors in order to monitor the condition of elderly or disabled people:

Wireless sensors networks can be applied in order to monitor the condition of elderly or disabled people and alert paramedics if something goes wrong. In this case, the use of sensors reduces significantly the cost of medical care.

An example of the use of sensors for the monitoring of the condition of elderly people is the ALARM-NET project which was developed for the monitoring of the living conditions of elderly people. This project uses heterogeneous devices, mobile body networks, emplaced sensor networks and IP-network elements [Virone et al., 2006]. The architecture of the project is shown in Figure 3.13.

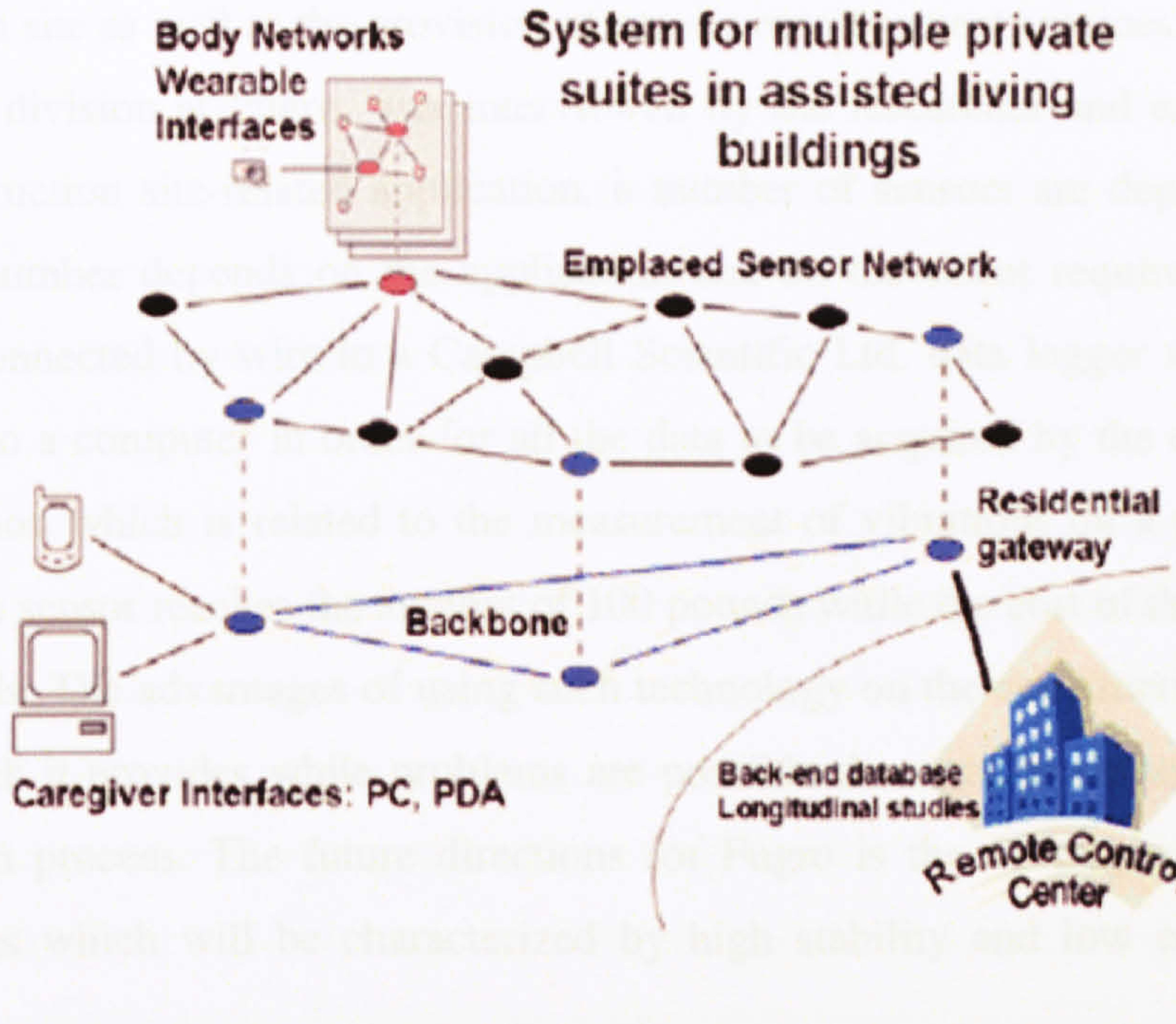


Fig. 3.13 The ALARM-NET project [Virone et al., 2006]

The mobile body networks are wireless sensors which are worn by elderly people and are capable of providing physiological sensing. Emplaced sensors are used in order to monitor the living conditions, such as temperature and light. A backbone network links the emplaced sensor network to PCs and PDAs. It also consists of nodes which are used as databases. These databases are used for real-time processing of medical data. Databases also exist in the medical centre and are used for the storage of medical data and the updating of old medical records [Virone et al., 2006].

• Tracking of Items on the Construction Site:

Wireless Sensor Networks can be implemented for the purpose of tracking of items on the construction site. In addition, they are capable of gathering data, either for the purpose of monitoring the site or for reasons of item identification [Furlani et al., 2000]. Wireless sensor networks are able to provide security on the construction site, either by constantly monitoring the site or by alerting the engineers when an item has been stolen.

Fugro Limited is a UK company which specializes in the implementation of sensor technology on the construction site. Some of the applications in which Fugro Limited is involved is the geo-technical and geo-environmental survey of the construction site as well as the provision of on-site measurement services. The head of monitoring division at Fugro, was interviewed by the researcher and explained that for a construction site-related application, a number of sensors are deployed on the site. This number depends on the application and on the client requirements. Each sensor is connected by wire to a Campbell Scientific Ltd. data logger which is then connected to a computer in order for all the data to be acquired by the engineer. For an application which is related to the measurement of vibrations on a structure, the cost of each sensor reaches the amount of 100 pounds while the cost of the data logger is 40 pounds. The advantages of using such technology on the construction site is the safety which it provides while problems are possible damages to sensors during the construction process. The future directions for Fugro is the development of sensor technologies which will be characterized by high stability and low cost [Dougan, 2003].

• Traffic Surveillance in Motorways:

Wireless Sensor Networks could be deployed successfully for the monitoring of traffic in roads and motorways. Cheung et al. (2005) present a wireless sensor network which can be used for traffic surveillance. This sensor network consists of small sensor nodes which are placed on the pavement. Each of these nodes includes a magnetic sensor, a processor, a radio and a battery. The nodes collect data and transmit them to an access point which is placed on the side of the road. Sensor data are then transmitted through GPRS to the traffic management center [Cheung et al., 2005].

3.4 Enablers for the Wireless Sensor Networking Technology

There is a number of enablers which enhance the use of wireless sensors networks. These enablers are listed below:

• Egan/Latham Reports: Sir John Egan (1998) and Sir Michael Latham (1994) developed separate reports in which they both refer to the need for modernisation of the UK construction industry through the use of new technologies.

• Economic, Social and Political Advances: The economic progress of Western countries has enabled the development of many research projects related to innovative technologies [Committee to Assess the Capacity of the U.S. Engineering Research Enterprise & National Academy of Engineering, 2005]. For example, the California Institute for Telecommunications and Information Technology (CALIT2) has dedicated huge funds to pioneering research in wireless sensor networks [Peggs, 2006]. Globalization has also enhanced the use of new technologies, such as wireless sensor networks [Conant, 2006].

• Need for Integration of Processes realised on a Construction Site: Wireless sensor networks can perform different tasks simultaneously. As the application of wireless sensor networks for the monitoring of the health of a building which was presented in Section 3.3.2, showed, a wireless sensor network can be used for three different tasks which are the monitoring of hazards related to ground motions, the evaluation of the danger and the provision of emergency information [Glaser, 2004]. A wireless sensor network can handle these processes simultaneously, therefore reduction of possible loss of time and cost is achieved.

• Need for Security on the Construction Site: The deployment of wireless sensor networks on the construction site enables better monitoring of the construction site and this is based on the ability of the wireless sensor networks to track lost or stolen items [Cho & Youn, 2006].

3.5 Barriers to the Use of Wireless Sensor Networks

There are several barriers to the implementation of wireless sensor networks in the construction industry. These barriers are listed below:

• Cost: Since wireless sensor networks are a new technology, there are many questions related to the cost of deployment of wireless sensor networks in the construction industry. The needs of a construction project affect specific parameters of the deployment of a wireless sensor network on the construction site, such as the topology of the network and the number of sensor nodes which must be used.

• Reliability: Wireless sensor networks are a new technology, therefore there are many questions about their reliability. Specific techniques which are applied in wired and wireless networks, such as routing techniques, are different in wireless sensor networks and this fact enhances the cautiousness against the wireless sensor networking technology.

• Lack of Knowledge: The people who work on the construction site may not have the required knowledge in order to use wireless sensor networks. The review of the relevant literature which was presented in Section 3.3.2, shows that there are not many applications of the wireless sensor networking technology on the construction site. As a result, the construction industry may be unwilling to adopt a technology for which there is not much knowledge.

• Fear of Employers for Lower Productivity and Higher Cost: Employers are afraid of using a new technology on the construction site because they believe that the lack of knowledge of the details of the specific technology from the construction personnel will reduce the productivity and increase the cost associated with the construction project. Additionally, any training for use of the specific technology could be costly.

3.6 Summary

Wireless sensor networking involves the transmission of data between sensor nodes and towards a sink node. The technology is characterised by a number of advantages, such as the quick collection and elaboration of information, the accuracy in data collection and elaboration and the ease of deployment since no wires are required.

Wireless sensor nodes communicate with each other through the transmission of electromagnetic waves. The comparison of the available transmission mediums shows that the most appropriate communication mediums are ISM bands. However, the use of ISM bands is characterised by disadvantages related to power and the existence of noise. There are also specific routing schemes which can be applied in a wireless sensor network, such as the address-centric and the data-centric scheme. The data-centric routing scheme and especially directed diffusion, uses data aggregation techniques which are useful for energy conservation and fault tolerance. Address-centric routing is based on the transmission of data to the sink via the shortest path while data-centric routing is based on the dispersion of data to certain regions in which sensors exist from the sink node. Other routing schemes which are used are the Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol, the Sensor Protocols for Information via Negotiation (SPIN) and the Sequential Assignment Routing (SAR) protocol. These techniques are all energy efficient.

The subject of energy is extremely significant during the operation of a wireless sensor network. There is a variety of operations of the wireless sensor networks which require significant amounts of energy. Examples of such operations are the routing of data packages to the sink node of the network and the different states which characterise the battery of a sensor node. A number of techniques and conservation methods are used in order for the amount of energy which is spent in a wireless sensor network to be reduced. A common characteristic of some of these techniques is the aggregation of sensor data. Other techniques are based on the use of tiny sensor nodes or the interruption of the operation of a sensor node which it is thought not to contain any data packets for transmission.

Fault-tolerance is an important factor which must be considered when the deployment of a wireless sensor network is planned. The most characteristic technique which ensures fault-tolerance on wireless sensor networks is the technique of multi-sensor fusion which allows the combination of a large number of sensor outputs for the provision of more accurate data. Especially for the construction industry, fault-tolerance of wireless sensor networks is necessary. If a wireless sensor network is vulnerable to any damage caused to any of its sensor nodes and its operation is halted because of this damage, then this will affect the whole construction project.

The issue of performance in wireless sensor networks is very important because it may affect the success of the application in which these networks are implemented. Especially for complex applications, performance is a crucial factor which affects the way the application is realised. Techniques which provide high performance in a wireless sensor network are the Secure Implicit Geographic Forwarding (SIGF) protocols and the relocation of the sink node of the network. The first technique is not affected by the topology of the wireless sensor network to which it is applied while the second technique has as main scope to improve specific performance metrics, such as energy consumption.

Wireless sensor networking has wide applicability in many scientific and technical fields. The variety of these applications demonstrates the usefulness of the technology. Examples of such applications include the use of wireless sensor networks for the control of temperature in the food industry; the monitoring of the health condition of machines; the monitoring of plants and animals; the monitoring of the structural health of buildings; the monitoring of the living conditions inside houses; the tracking of items on construction sites, and the surveillance of traffic on motorways. The applications of wireless sensor networks in fields, such as medicine and manufacturing and their existing applications in the field of construction can form the basis for the development of further applications for the construction industry. To assess the capabilities of wireless sensor networks in different industries, a number of telephone interviews were conducted with experts from various industries. These interviews were based on a specific set of questions which are included in the Appendix. Specific ethical issues, such as the recording of the replies of the interviews, were considered prior to the realisation of the specific interviews. Wireless sensor networks are used widely because of their capability to process and exchange data wirelessly often using tiny sensor nodes. However, their accuracy depends on the number of sensor nodes they use. This number depends on the complexity of the application on which a wireless sensor network is used. For complex applications, such as the acoustic monitoring of buildings, the use of a large number of sensor nodes is required. The increment of the number of sensor nodes increases the cost of the deployment of a wireless sensor network for a specific application. In addition to the number of sensor nodes which are used by a wireless sensor network, their topology is also important in the success of the development of an application. Problems which are associated with wireless sensor networks are the lack of signal stability, the sensitivity of the sensor nodes to noise and the damaging of nodes. Wireless sensor networks can also be easily integrated with other software technologies, such as artificial intelligence, the Internet and databases, for better manipulation of the acquired data. For construction-related applications, factors such as the number of the sensor nodes, their topology are parameters which must be considered.

There are a number of enablers and barriers that affect the use of the wireless sensor networking technology in the construction industry. Such enablers are the Egan/Latham reports which suggest the use of innovative technologies in order for the

UK construction industry to be modernised and the economical, social and political advances which have enhanced the use of innovative technologies through the realisation of research projects. Additionally, the need for integration of the construction processes and the need for security on the construction site have imposed the use of technologies, such as wireless sensor networking. Barriers for the use of wireless sensor networks in the construction industry are the cost of the deployment of wireless sensor networks and doubts about their reliability since wireless sensor networks are a new technology. There is also lack of knowledge about how wireless sensor networking can be used on construction sites and fear from the employers that this lack of knowledge will delay the progress of construction projects. The identification of the enablers and barriers of the use of wireless sensor networks in the construction industry occurred through the study of journals, magazines and the proceedings of symposiums and also the realisation of telephone interviews with experts. Personal knowledge also contributed to the formulation of the specific enablers and barriers.

Chapter 4: Proposed Wireless Sensor Technologies for the Construction Industry

4.1 Introduction

In this chapter, an introduction to a specific wireless sensor technology called Radio-Frequency Identification (RFID) technology is presented. The main elements of an RFID system are described and parameters which affect their function are analysed. Moreover, the integration of RFID technology with other technologies, such as Wireless Local Area Networks (W-LANs) is presented and the significance of specific programming tools for the integration of RFID with these technologies as well as its adaptation to modern scientific and technical situations is underlined.

4.2 Definition of RFID

Radio-Frequency Identification (RFID) technology is a wireless sensor technology which is based on the detection of electromagnetic signals [McCarthy et al., 2003]. A typical RFID system includes three components: an antenna or coil, a transceiver (with decoder) and a transponder (RF tag) electronically programmed with unique information. When an RFID tag is found into the electromagnetic zone of the reader, the tag detects the activation signal of the reader. The reader decodes the data which are encoded in the integrated circuit of the tag and the data are transferred to the host computer for processing [URL2, 2004].

A typical RFID system can be seen in Figure 4.1.

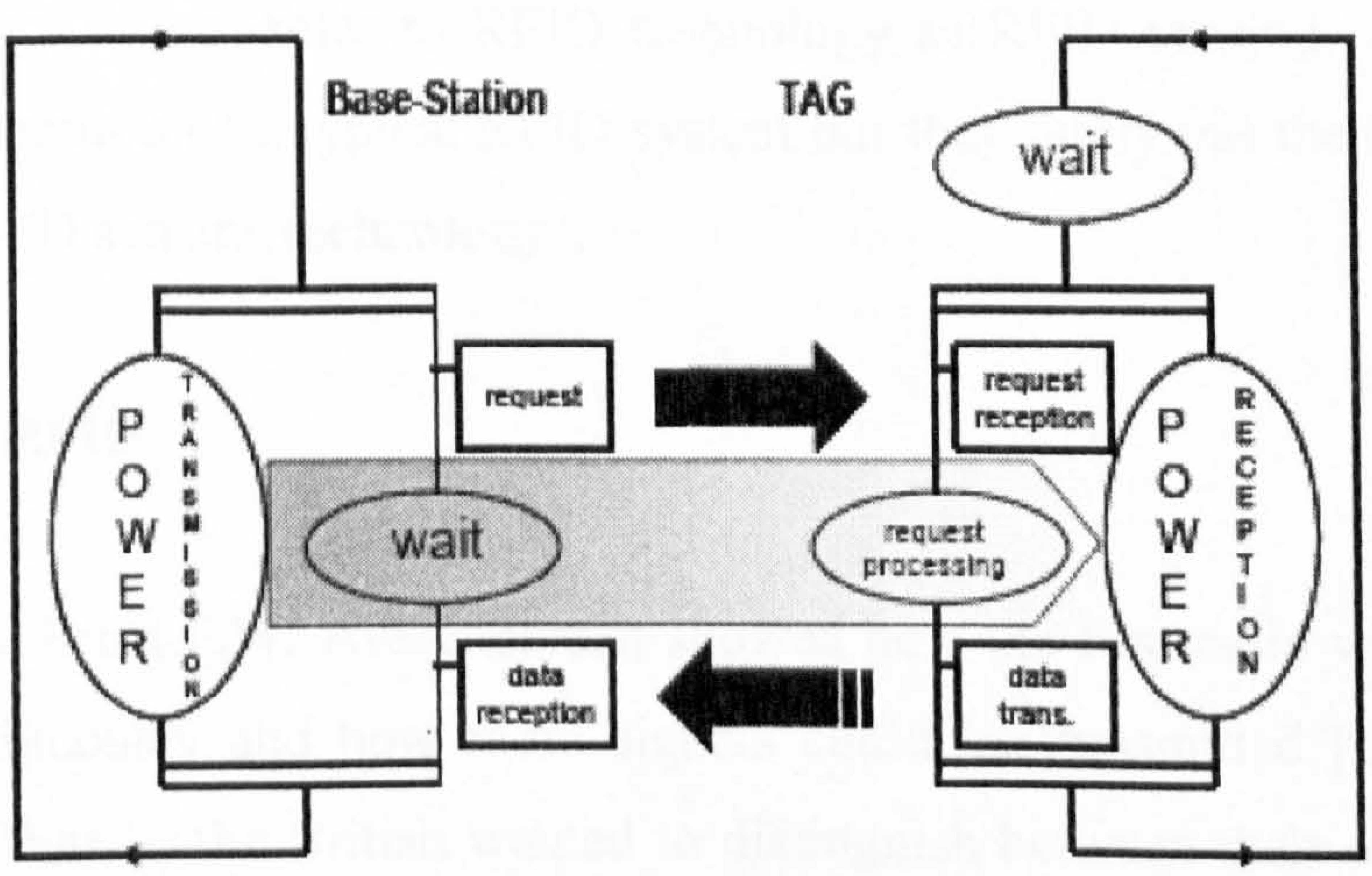


Fig. 4.1 Typical RFID system [Tedjini et al., 2005]

Phillips et al. (2005) suggest that an RFID system consists of RFID readers, a host computer which controls these readers and back-end enterprise information systems that apply business rules. This definition can be shown in Figure 4.2.

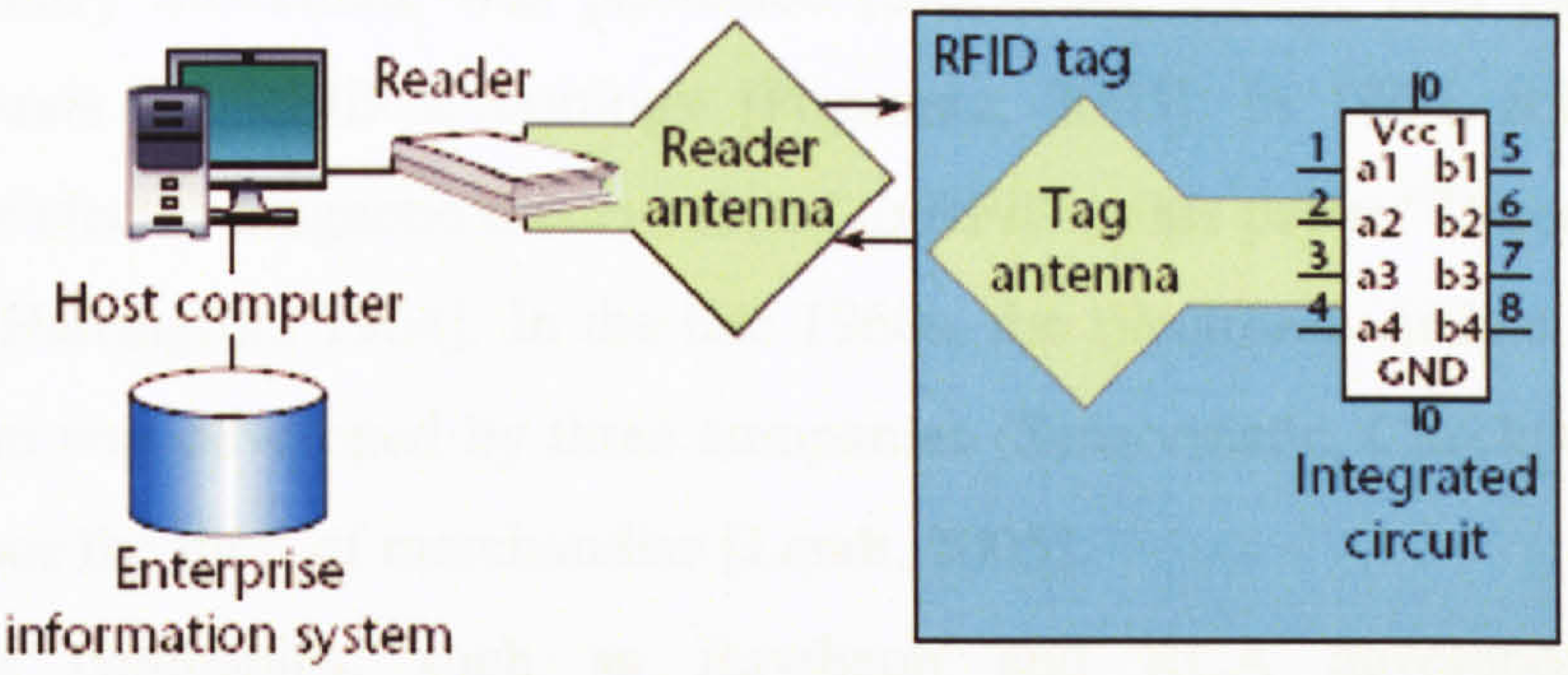


Fig. 4.2 Structure of RFID Systems

[Phillips et al., 2005].

The author of the PhD thesis has developed a definition for RFID systems. According to this definition, RFID technology is part of the wider field of wireless sensor technologies. The characteristic of the technology is the exchange of data between an RFID reader and one or more tags which is achieved through the transmission and sensing of electromagnetic waves. Appropriate software techniques can be used in order for the data received from the RFID tags to be transferred to a host computer system.

The consideration of RFID technology as a sensor technology is not very common in definitions of the technology. Most authors who are involved to the use of RFID technology do not refer to RFID technology as RFID sensing. They usually describe the operation of a typical RFID system but they rarely use the terms "RFID sensors" or "RFID sensing technology".

4.3 History of RFID

In 1906, Ernst F.W. Alexanderson showed how the first radio wave could be generated continuously and how radio signals could be transmitted [Landt, 2005]. During World War II, the British wanted to distinguish between their own returning aircrafts and those of the enemy. For this reason, they placed transponders on their aircrafts which would be able to respond appropriately to interrogating signals from base stations. This was the Identity: Friend or Foe (IFF) system which is considered the first use of Radio-Frequency Identification (RFID) [Dittmer, 2004].

In 1948, a paper entitled "Communication by Means of Reflected Power" written by Harry Stockman, was published [Stockman, 1948]. This paper was the theoretical basis for RFID technology [Poganatz, 2005]. In 1964, R.F.Harrington examined the electro-magnetic theory related to RFID in his paper "Theory of Loaded Scatterers" [Harrington, 1964]. In the late 1960s, the Electronic Article Surveillance (EAS) system was developed by three companies (Sensormatic, Checkpoint, Knogo) in order to face the theft of merchandise [Landt, 2005].

Large companies, such as Raytheon and RCA developed electronic identification systems in 1973 and in 1975 respectively [Landt, 2005]. In 1978, R.J. King wrote a book about microwave homodyne techniques which was used as the basis for the development of the theory and practice which are used in backscatter RFID systems [King, 1978]. In 1987, Norway applied RFID in toll stations [Poganatz, 2005]. During the 90s, IBM developed an ultra-high frequency (UHF) RFID system. IBM did some pilot tests of the system with Wal-Mart but they never developed a product. Eventually, the RFID system was sold to a bar-code systems provider, Intermec. This company used the RFID system for applications related to warehouse tracking but since there were not many sales of the system, it was expensive [RFID Journal, 2006].

In the 21st century, the smallest RFID tags have been constructed. RFID tags are built in the form of labels and placed on the objects which are going to be managed [Landt, 2005].

4.4 RFID Readers

RFID readers are fixed or mobile hand-held scanners. They are usually connected to a computer and can read up to 200 tags simultaneously. The reader uses also an antenna in order to broadcast and receive messages. The antenna which is connected to the RFID reader activates the RFID tags and transmits messages through the emission of wireless pulses [Gerst et al., 2005].

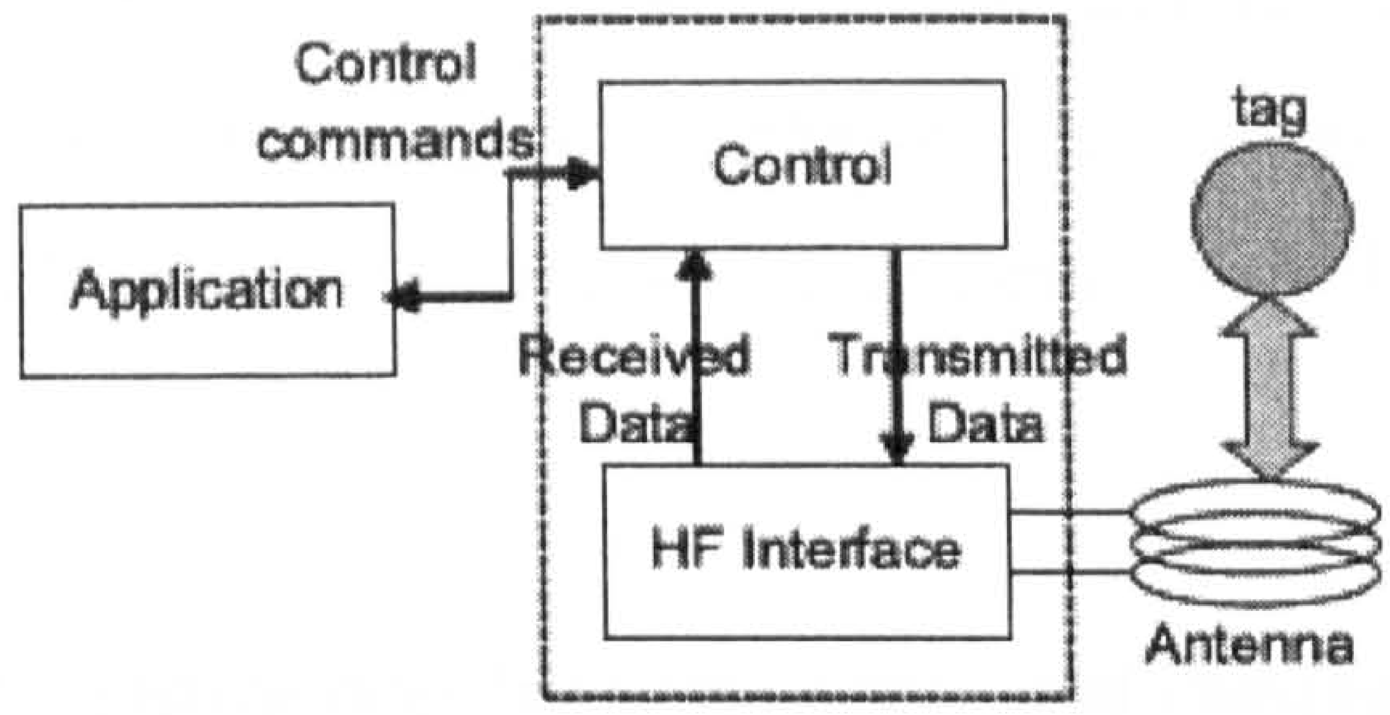


Fig. 4.3 Anatomy of an RFID Reader

[Wang & Liu, 2005]

An RFID reader includes a control and a high-frequency interface block. The control block receives control commands by the application and then the control block controls the high-frequency interface in order to read the RFID tags. The read data of the tag are sent back to the application through the control block [Wang & Liu, 2005]. Readers can be a handheld device or fixed at a specific location [Knospe & Pohl, 2004].

4.5 Types of RFID Tags

RFID tags include two main elements : an integrated circuit and an antenna [Juels & Pappu, 2003]. The integrated circuit consists of the microprocessor, memory and an antenna. The role of the antenna is to define the read range of the tag [Bassi, 2003].

RFID tags can be distinguished into two main categories depending on their data storage capability : Read-Only and Read/Write Tags. Most Read-Only tags don't have data storage capacity. They only have a unique ID pre-written to them which points to a database, thus providing information about the object the tag is attached to [Bassi, 2003]. Read/Write tags have larger data storage capacity than Read-Only tags. In addition, a user of such type of tags can re-write data to the tags [Henrici & Müller, 2004].

RFID tags can also be distinguished as active and passive. Passive tags depend on the electromagnetic field generated by the RFID reader in order to get activated. Active tags have built-in batteries and this increases the range of the system as the tags do not depend on the electromagnetic field of the reader in order to get activated

[Kinoshita et al., 2005]. The power however of the tags may be reduced by the actual size of the tags as well as the local radio licensing regulations [Bassi, 2003].

The main differences between active and passive RFID tags can be shown in Table 4.1.

Table 4.1 Differences between Active and Passive RFID Tags

	Active RFID Tags	Passive RFID Tags
Tag Power Source	Internal to tag [Nambi et al., 2003]	Energy transferred from the reader [Nambi et al., 2003]
Availability of Tag Power	Continuous [Rieback et al., 2005]	Only when found in the field of the reader [Peris-Lopez et al., 2006]
Required Signal Strength from Reader to Tag	Low [Hsiao, 1999]	High [Auto-ID Labs, 2006]
Available Signal Strength from Tag to Reader	High [Auto-ID Labs, 2006]	Low [Auto-ID Labs, 2006]
Communication Range	Long range [Nambi et al., 2003]	Short range [Nambi et al., 2003]
Data Storage	Large [Maier, 2005]	Small [Rieback et al., 2005]

4.6 Physical Principles of RFID Systems

This section examines the physical principles which characterise the function of RFID systems.

4.6.1 Radio-Frequency Detection

The radio-frequency procedure is based on the use of LC resonant circuits adjusted to a specific resonant frequency [Nambi et al., 2003]. In modern RFID systems, coils are placed in foils in the form of labels [Finkenzeller, 1999]. A magnetic field is created by the reader and if the LC resonant circuit is close to the field, energy from the field can be transferred to the resonant circuit through its coils [Sorrels, 2000]. The current which is flowing in the resonant circuit causes a small change in the voltage of the transmitter's coil and as a result it reduces the strength of the magnetic field [Finkenzeller, 1999]. The process of radio-frequency detection on a system used for electronic article surveillance and which uses coils in the form of labels can be shown in Figure 4.1.

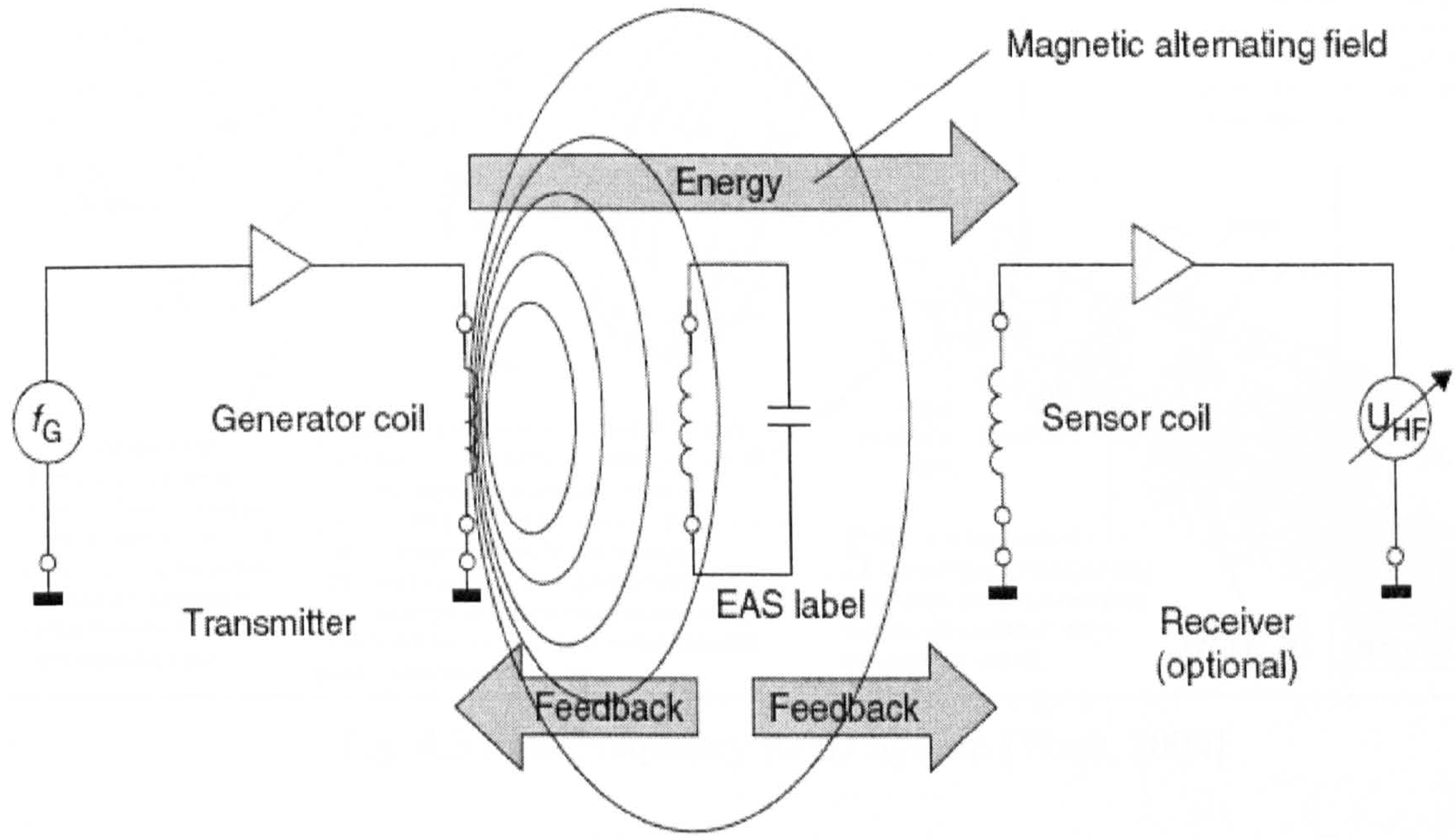


Fig. 4.4 Radio-Frequency Process on an Electronic Article Surveillance System [Finkenzeller, 1999]

Want (2004) describes the function of an RFID system on low and high frequencies. This description is shown in Figures 4.5 and 4.6 respectively.

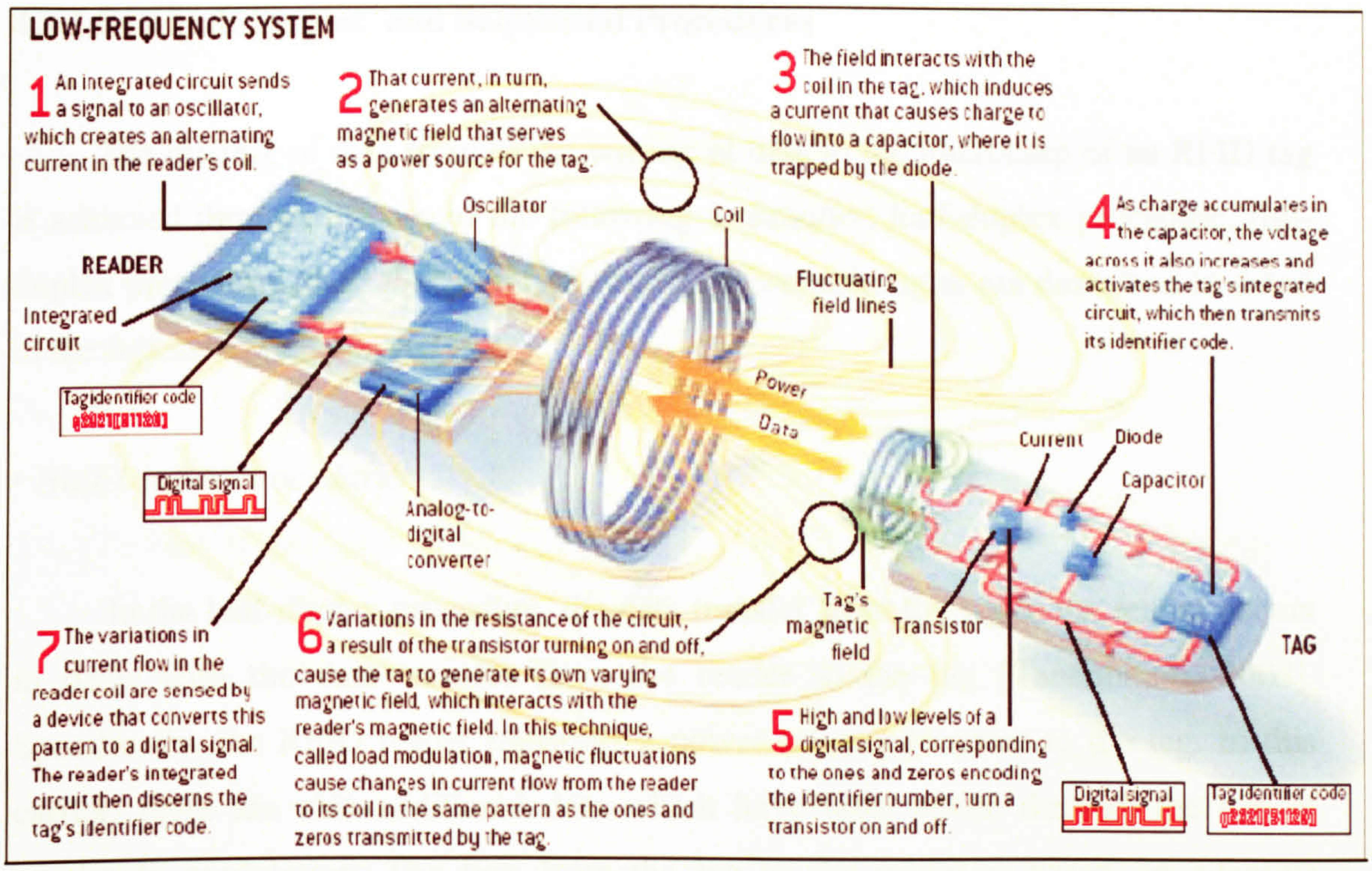


Fig. 4.5 Low-Frequency RFID System [Want, 2004]

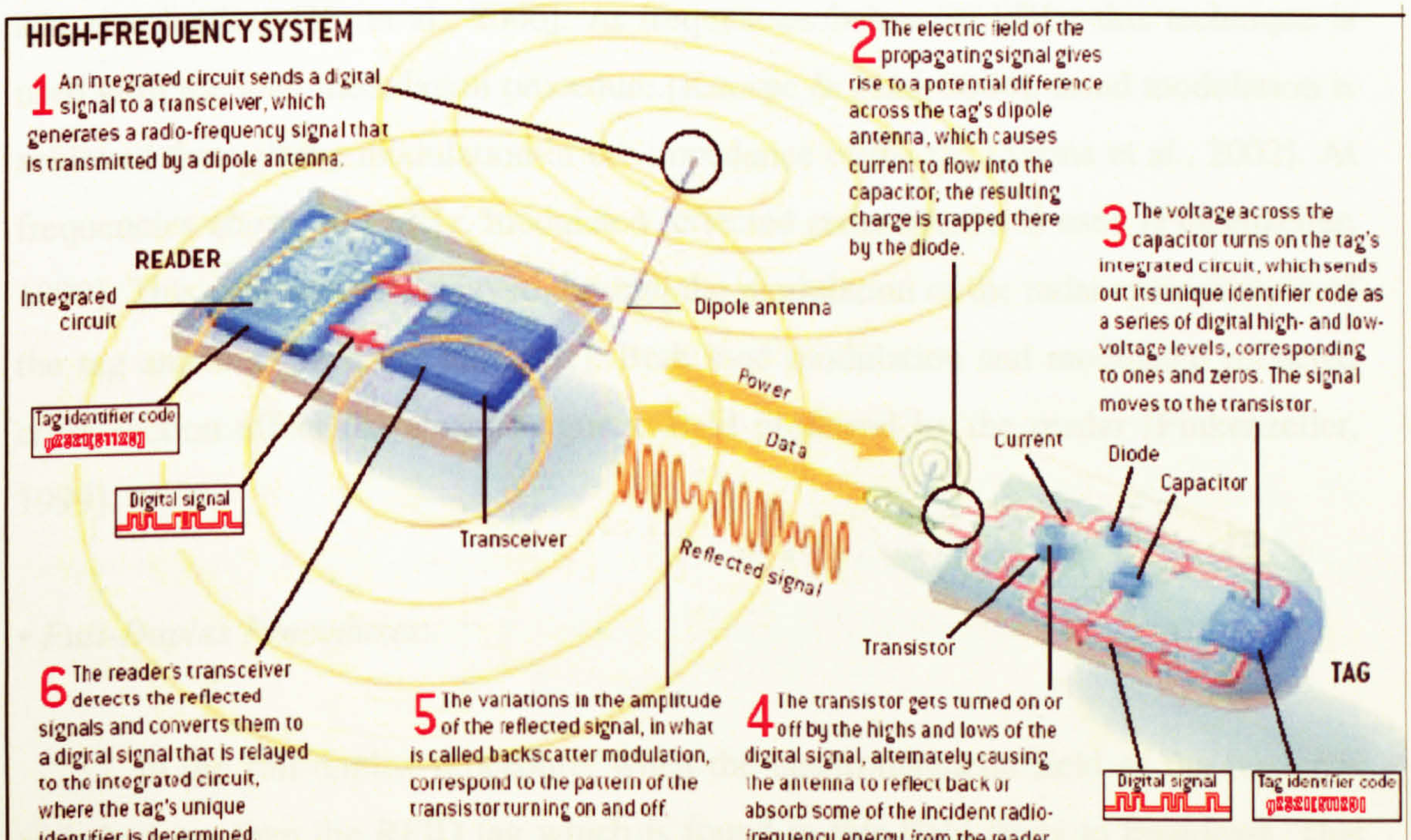


Fig. 4.6 High-Frequency RFID System [Want, 2004]

4.6.2 Full/Half Duplex and Sequential Procedures

The reading of data from or the writing of data to the microchip of an RFID tag is achieved through the use of the following techniques: half-duplex procedure, full-duplex procedure, and sequential procedures. These techniques are described in detail in the following paragraphs:

• *Half-Duplex Procedures*:

In the half-duplex procedure, the data transfer from the tag to the reader occurs in turns with the data transfer from the reader to the tag [Tanenbaum, 2003]. Specifically, the RFID reader transmits a power-enhanced carrier to the tag. In this carrier, there are also additional data which have been added through the use of amplitude modulation. The link from the tag to the reader is based on adaptive reflection (backscatter) of the phase of the incoming radio-frequency carrier or on adaptive loading [Yu et al., 2006]. At frequencies below 30 MHz, this technique is used with the load modulation procedure [Knospe & Pohl, 2004]. Load modulation is achieved through the modulation of the impedance of the tag [Sarma et al., 2002]. At frequencies above 100 MHz, modulated reflected cross-section is used [Finkenzeller, 1999]. This technique is achieved through the modulation of the radar cross-section of the tag antenna [Sarma et al., 2002]. Both load modulation and modulated reflected cross-section affect the electromagnetic field produced by the reader [Finkenzeller, 1999].

• *Full-Duplex Procedures*:

In the full-duplex procedure, when the electromagnetic field of the reader is switched on, then the RFID tag which is found in this field starts to broadcast. This procedure is appropriate for applications in which the detection of numerous tags by the reader is necessary [Wang & Liu, 2005]. In the full-duplex procedure, the data transfer from the tag to the reader occurs simultaneously to the data transfer from the reader to the tag [Tanenbaum, 2003]. The transfer of power from the reader to the tag is continuous [Finkenzeller, 1999].

• *Sequential Procedures*:

In sequential mode, the electromagnetic field of the reader is switched off for a small period at regular intervals. The tag in this case recognises the gaps and responds to the reader [Wang & Liu, 2005]. The function of sequential systems is based on inductive coupling and the use of frequencies below 135 kHz. In sequential systems, the reader's transmitter does not operate on a continuous basis [Finkenzeller, 1999].

4.6.3 Frequencies of the RFID Systems

The frequencies of use of RFID systems are analyzed below :

• *125 – 134 kHz*: This is the low frequency [Dziadak et al., 2006] and allows the detection of RFID tags in a range of less than 0.5 meter [Ward & Van Kranenburg, 2006]. The typical data transfer rate is less than 7.8 kilobit per second [Juels & Pappu, 2003] and in this frequency the electromagnetic waves penetrate water but not metal [Dziadak et al., 2006]. This frequency is used for animal identification [UK Parliamentary Office of Science and Technology, 2004].

• *13.56 MHz*: This is the high frequency [Dziadak et al., 2006]. This frequency allows the detection of RFID tags for a distance between 1 and 2 meters [Floerkemeier, 2004]. The tag-to-reader data transfer rate for this specific frequency is approximately 50 kilobits per second [Juels & Pappu, 2003] and in this frequency, the electromagnetic waves can penetrate water but not metal. This frequency is used for applications related to access and security [Ward & Van Kranenburg, 2006].

• *433 – 960 MHz*: This is the ultra-high frequency [Dziadak et al., 2006]. The frequencies which are found in the range from 433 to 864 MHz allow the detection of RFID tags for a distance of up to 100 m [Ward & Van Kranenburg, 2006] while the frequencies at the range from 860 to 960 MHz allow the detection of RFID tags for a distance of seven meters while in reality it is usually less [Floerkemeier, 2004]. Dressen (2004) specifies that the detection range of RFID readers in the frequencies between 868 and 928 MHz is 3 meters. There is clear difference in the opinions of the different authors on the exact detection range for the frequencies between 860 and

864 MHz and between 868 and 928 MHz. For all the frequencies in the range between 433 and 956 MHz, the data transfer rate is 100 kilobits per second [Ward & Van Kranenburg, 2006]. The generated electromagnetic waves cannot penetrate water or metals [Lahiri, 2005]. The frequencies at this range are used for applications in logistics [Wyld, 2006].

• *2.45 GHz*: This is the microwave frequency [Sopensky, 2005]. This frequency enables an RFID reader to detect a tag from a distance of twelve meters [Curty et al., 2005]. The data transfer rate for this specific frequency is up to 100 kilobits per second [Ward & Van Kranenburg, 2006]. The electromagnetic waves generated in this case cannot penetrate water or metal [Lahiri, 2005]. The specified frequency is used for applications related to mobile vehicle toll [Wyld, 2006]. The U.S. Federal Communications Commission (FCC) has allocated spectrum in the 5.9 GHz band [Landt, 2005].

The following table summarizes the frequencies of use of RFID systems for a variety of countries :

Table 4.2 Frequencies of Use of RFID Systems in different countries [RFID Working Group, 2005]

Frequency	Countries
125 – 134 kHz	USA, Canada, Japan, Europe
13.56 MHz	USA, Canada, Japan, Europe
433.05 – 434.79 MHz	In most of USA and Europe and under consideration in Japan
868 MHz	Europe [Sopensky, 2005]
866 – 869 and 923 – 925 MHz	South Korea
902 – 928 MHz	USA
952 – 954 MHz	Japan (for passive tags after 2005)
2400 – 2500 and 5.725 – 5.875 GHz	USA, Canada, Japan, Europe

There are different regulations among different states on how radio-frequency devices should be used. These regulations are specified by specific organisations, such as the Federal Communications Commission (FCC) [Van Eeden, 2004] and the European Telecommunications Standards Institute (ETSI) [Collins, 2005]. Full regulations on the harmonization of the use of radio-frequency devices among different states have not been developed, therefore there are differences in the use of radio-frequency devices among different states. For this reason, the operation of RFID is closely associated to local regulations [Paret, 2005].

4.7 RFID Standardisation

Standards for the RFID technology have been developed through the International Standard for Organisation (ISO) [Tsunaka, 2006]. These standards are categorised below according to the different RFID operations :

• *Animal Identification*: The ISO standards 11784, 11785 and 14223 are used for the identification of animals using RFID systems in the frequency band below 135 KHz [Peris-Lopez et al., 2006].

ISO 11784 defines the data bits which are used for the specification of the identification code [Phillips et al., 2005].

ISO 11785 specifies the transmission method for the data of the reader and the reader specifications for the activation of the RFID transponder [Finkenzeller, 1999].

ISO 14223 defines the high-frequency interface and allows the use of large memory from transponders [Finkenzeller, 1999].

• *Contactless Smart Cards*: There are three ISO standards for the contactless smart cards and these are ISO 10536 which corresponds to close coupling, ISO 14443 which corresponds to proximity coupling and ISO 15693 which corresponds to vicinity coupling [Metras, 2005].

ISO 10536 describes the parameters for smart cards with contact-less integrated circuits [Bennett, 2000].

ISO 14443 standard is used in applications related to credit cards and electronic passports. The RFID systems which are designed to use this standard operate at a range between 5 and 10 cm [Kirschenbaum & Wool, 2006].

ISO 15693 allows the development of software which enables the interfacing with passive RFID tags and also it enables RFID readers to interface with passive RFID tags from different manufacturers [Goodrum et al., 2006].

• *Item Management*: There are a number of standards developed for item management and these are ISO 10374 [Hodges & Harrison, 2003], ISO 15961, ISO 15962, ISO 15963, ISO 18000 and ISO 18001 [ITU, 2005].

ISO 10374 is a standard which is used as an automatic identification system for containers based on microwave transponders [Finkenzeller, 1999]. ISO 15961 specifies a set of features, such as types of tags and data storage independent of transmission media and air interface protocols. ISO 15962 specifies the procedures used for the exchange of data in an RFID system which is used for item management [ITU, 2005]. ISO 15963 introduces the use of uniquely identifiable tags [Tsukada, 2006]. It also addresses the anti-collision when multiple tags are detected by the same reader [Hodges & Harrison, 2003].

ISO 18000 is a series of standards which specify the air interface, collision detection mechanisms and the communication protocol for item tags in a range of frequency bands [Knospe & Pohl, 2004].

ISO 18001 is a protocol used for item management [Hodges & Harrison, 2003].

The Auto-ID Centre has created the EPCglobal [Tsukada, 2006]. The EPCglobal is a joint venture by the European Article Numbering Association (EAN International) and the Uniform Code Council (UCC) and its responsibility is to oversee the development of the EPC standard [Department of Defence, 2005].

The European Article Numbering (EAN) Association is an international organisation which is responsible for the bar-codes in the retail industry. The Uniform Code Council (UCC) is a US-based organisation which manages bar-codes [Tsukada, 2006].

The structure of the EPC standards is based on the use of two classifications: the 'Class' classification which shows how data are programmed in the tag and the 'Generation' classification which specifies the amount of data that can be written to the device [Data Systems International, 2005]. The EPC standards are the following :

• EPC Class 0: This standard refers to read-only passive tags [Garfinkel & Holtzman, 2005] that support the storage of up to 56 bits of data [Data Systems International, 2005] and operate in the 860-930 MHz frequency range [Dobkin & Wandinger, 2005].

• EPC Class 1: This standard refers to the Write-Once-Read-Many technology [Garfinkel & Holtzman, 2005] and supports 96 bits of data storage [Roussos, 2005]. The EPC Class 1 standard operates at the 860-960 MHz frequency range [Dobkin & Wandinger, 2005].

• EPC Class 1 Generation 2: This standard refers to the Write-Once-Read-Many technology [Data Systems International, 2005] and also to the Read-Write technology [Phillips et al., 2005]. The operation of this standard is at frequencies between 800 and 960 MHz [Duc et al., 2006]. The standard allows increased data storage (up to 1028 bits) [Data Systems International, 2005].

4.8 Energy in RFID Technology

The energy requirements of RFID tags are distinguished depending on the type of tags. Active tags use lithium batteries with a varying lifetime (5 to 10 years) [Ergen et al., 2006] while passive tags depend totally on the electromagnetic field generated by the RFID reader [Sopensky, 2005].

Energy conservation is of great significance for RFID technology. In order for energy to be conserved, the tag can enter a 'sleep' state in which the radio reception is disabled. Communication protocols which will ensure the energy conservation for RFID tags must be used in this case in order to address the time in which RFID tags are active. An example of such a protocol uses a pseudo-random number generator which determines whether an RFID tag is on 'sleep' state or not [Chlamtac et al., 1997].

4.9 RFID Economics

Goodrum et al. (2006) mention that the active tags they used for their research cost $75 in 2003 while the same tags in 2002 cost $150. Juels & Pappu (2003) mention that the cost of an RFID tag in its simplest form which consists of a small silicon integrated circuit and an antenna is approximately $50. This cost is expected to be reduced in the next years. Smith & Konsynski (2003) mention that there is a fall in the prices of RFID equipment, however the cost still remains a barrier for the implementation of the technology. Also, RFID technology is more expensive than bar-codes [Smith & Konsynski, 2003]. Even though there is a small difference in the prices of RFID tags between Goodrum et al. and Juels & Pappu, the specific authors agree that the prices of RFID tags are low.

4.10 Comparison of RFID with other Location Tracking Technologies

There are a number of wireless technologies except RFID, which can be used for asset tracking and identification. Examples of such technologies are bar-coding and Wi-Fi (Wireless Fidelity) tagging.

• *Bar-coding* : Bar-coding is a language which is composed of bars and spaces which are arranged in a predetermined manner. The bars and spaces can be vertical, square or hexagon. The most common type of bar-codes especially for retail food in the USA is the Universal Product Code (UPC) [LaMoreaux, 1998].

Table 4.3 summarises the main differences between RFID tagging and bar-codes.

Table 4.3 Differences between Bar-codes and RFID technology

Bar-coding	*RFID*
Human intervention is required [Bailey & Juels, 2006]	RFID tags can be detected without the need of human intervention [Ilie-Zudor et al., 2006]
Scanning of one item per time is required [Intille et al., 2003]	Simultaneous scanning of many items is achieved [Chachra, 2003]
The bar-code reader and the bar-code must be in straight line in order for the bar-code to be read by the reader [Furness, 2000]	No line-of-sight is required [Chachra, 2003]
Barcodes do not provide unique codes for each product but only for a group of products, thus making it impossible to have detailed information for each product separately [Garfinkel, 2002]	RFID technology allows the use of electronic product codes which are unique for each product and allow the retrieval of detailed information about a specific product [Wyld, 2006]

Bar-coding	*RFID*
Barcode communication is affected by the existence of objects [Peris-Lopez et al., 2006]	Communication between the RFID reader and the tags can be achieved through cardboard or paper [Peris-Lopez et al., 2006]. Also, RFID systems are not affected by dirt or dust [Uchida et al., 2005]
Minimum storage Capacity [Strassner & Schoch, 2002]	Storage capacity larger than bar-coding's capacity [Wing, 2006]

• *Wireless-Fidelity (Wi-Fi) Tagging* :

Wi-Fi tags are used for the tracking of the location of items [URL5, 2004]. An example of a company which constructs Wi-Fi tags is the Finnish company Ekahau. Based on facts collected by this company, the following table summarizing the differences between different types of RFID tags and Wi-Fi tags has been created.

Table 4.4 Differences between RFID and Wi-Fi technologies [Domdouzis et al., 2005]

Description	Active RFID Tag	Passive RFID Tag	Wi-Fi Tag
Energy derived from :	Battery-powered	Reader's signal	Battery-powered
R/W Ability	Read/Write	Read-Only	Read-Only
Read Range	Up to 100 m	Up to 3 m	30 – 100 m
Data Storage	128 Kbytes	128 Bytes	Very small
Weight	Heavier	Lighter	Lighter
Size	Larger	Smaller	Smaller
Cost	Higher	Lower	Lower

• *Global Positioning Systems (GPS)*: The Global Positioning System (GPS) is an advanced location tracking system operated by the United States Department of Defence. This system enables the acquisition of a position anywhere on earth in the form of three-dimensional coordinates under any weather conditions and at any time. This is achieved through a GPS receiver which determines the distances to a number of orbiting GPS satellites and a computer then calculates the three dimensional coordinates of the position of the user [Uren et al., 2006].

The space segment consists of 24 satellites in six orbital levels. These satellites are responsible for broadcasting time signals. The satellites orbit in such a way so that five of them can be viewed by GPS receivers globally. The control segment includes a control centre and access to control stations which are located throughout the world. The control segment tracks the GPS satellites and provide corrections to possible clock-bias errors. The user segment consists of GPS receivers and additional equipments such as antennas [Pace et al., 1995].

The main differences between GPS and RFID technologies is that GPS is more expensive to use than RFID [Karali, 2004]. Also, GPS accuracy in positioning objects is sometimes doubtful depending on the positioning method that is followed [Kopf et al., 2006] . GPS can provide coordinates of the tracked objects [Hightower & Borriello, 2001]. In contrast, RFID technology cannot provide location coordinates. Also, an RFID reader has to be in a relatively close distance from the tagged item. In contrast, GPS receivers receive data from satellites which are in very large distance [Zeffiro, 2006].

4.11 Applications of RFID in Various Industries

RFID technology has been successfully applied in a number of scientific and technical fields, such as medicine and engineering. In medicine, RFID tagging is used in blood transfusion. For example, an RFID tag can be assigned to each blood bag which arrives at a hospital. The tag contains a unique identification number and information related to the type of the contained blood. These information are stored in a database which contains details about the origin of the blood, its designated purpose of use and its recipient. Patients wear ID bracelets while a PDA with an embedded RFID reader is used to read the contents of the tags and of the patients' bracelets. If the data contained in a blood bag's tag are matched with the data contained on the ID bracelet of a patient, then the blood transfusion for this specific patient can begin [Fuhrer & Guinard, 2006].

RFID technology is applied in the aeronautics supply chain. Specifically, Boeing ships tagged crates which are loaded with aeronautical equipment. Passive Electronic Product Code Class 0 RFID tags are attached to these crates and they contain information such as a unique ID number which can be read by RFID readers at the military depot. Boeing then sends an advance report to the military depot regarding the contents of the tags. This information is related to the type of equipment which is included in the crate, its quantity, its point of origin, and the purchase contract. When the loaded crates are delivered to the military depot, a RFID reader obtains the ID numbers of the tags which are attached to the crates. These numbers point to a database which contains the information included on the advance shipment report sent by Boeing [Swedberg, 2005].

An important element in the construction and maintenance of oil facilities is the correct assembly of the pipe-work systems. An incorrect assembly would create leaks which can affect safety in an oil refinery. RFID tags can be used in order to identify individual pipe-work joints. In this case, a database could be created which would include information about each joint. RFID tags can also be embedded in the valves of the pipelines and record technical information. An RFID reader can be used to scan these tags and identify whether they are placed at the correct location and under an appropriate pressure. In addition, RFID technology is used to trace the movement of fuel tankers [DTI Basic Technologies, 2004].

In the automotive industry, RFID technology is used in the assembly of new cars. Specifically, RFID tags can be attached to parts of a car and track them during the assembly process. In this case, the correct placement of the components of the car can be checked. Since every customer in the automotive industry may have different choices as to how his/her car should be, the use of RFID tags allows faster tracking of the desired components and avoidance of possible errors caused by incorrect placement of these components [Fleisch & Strassner, 2003].

In the retail industry, RFID tags are used to identify and track products along the retail supply chain. The tags can be attached to physical items, such as pens or toothpastes, and transmit an identification signal allowing them to communicate with RFID readers or with each other. An example of a consumer goods tracking system is the Auto-ID system. This system uses a numbering scheme called the electronic Product Code (ePC) which can assign a unique ID to any physical object in the world. In the retail industry, the Auto-ID can assign a unique ID to a specific product through an RFID tag and then the tag transmits this ID to an RFID reader, thus making the product identifiable [Albrecht, 2005].

4.12 Applications of RFID in the Construction Industry

RFID technology has been successfully used for applications in the construction industry. Examples of these applications are briefly presented below :

• Automated Tracking of Pipe Spools:

Pipe spools are of specific interest for a construction project since piping is considered a costly process. However, piping is characterised by uncertainties in the realisation of prerequisite site work. For this reason, the construction project's materials manager relies on large quantities of pipe spools so that any scheduled work on the construction site will not be delayed. These large quantities of pipe spools are placed on the constructor's lay-down yard and they remain there until pipe fitting crews request for new pipe spools. When a request is done by pipe fitting crews, the constructor has to locate the pipe spools in the lay-down yard. However, it is possible that the requested pipe spools are located in a different location than their right location or even located outside the lay-down yard, such as the fabricator's storage area. In this case, the localisation of the requested pipe spools would require lot of time. RFID technology can be implemented in this case in order for the requested pipe spools to be located successfully [Song et al., 2005].

For the specified project, the RFID system is installed on a portal structure which uses 4 RFID readers through which a flatbed trailer could be driven, thus simulating the transport of a pipe spool. For the field tests with the fixed RFID system, 20 RFID tags were placed on pipe spools. These pipe spools were then put on a trailer to be driven under the portal structure. A number of parameters were considered such as the number of tags placed on the trailer, any variance in the amount of data to be captured from the tags, the movement of the trailer under the portal structure and the number of RFID readers activated. The field tests showed that RFID technology could be effective in construction environments where large metal objects are present and long read ranges are required [Song et al., 2005].

The steps which were followed during the field tests are shown in Figure 4.7.

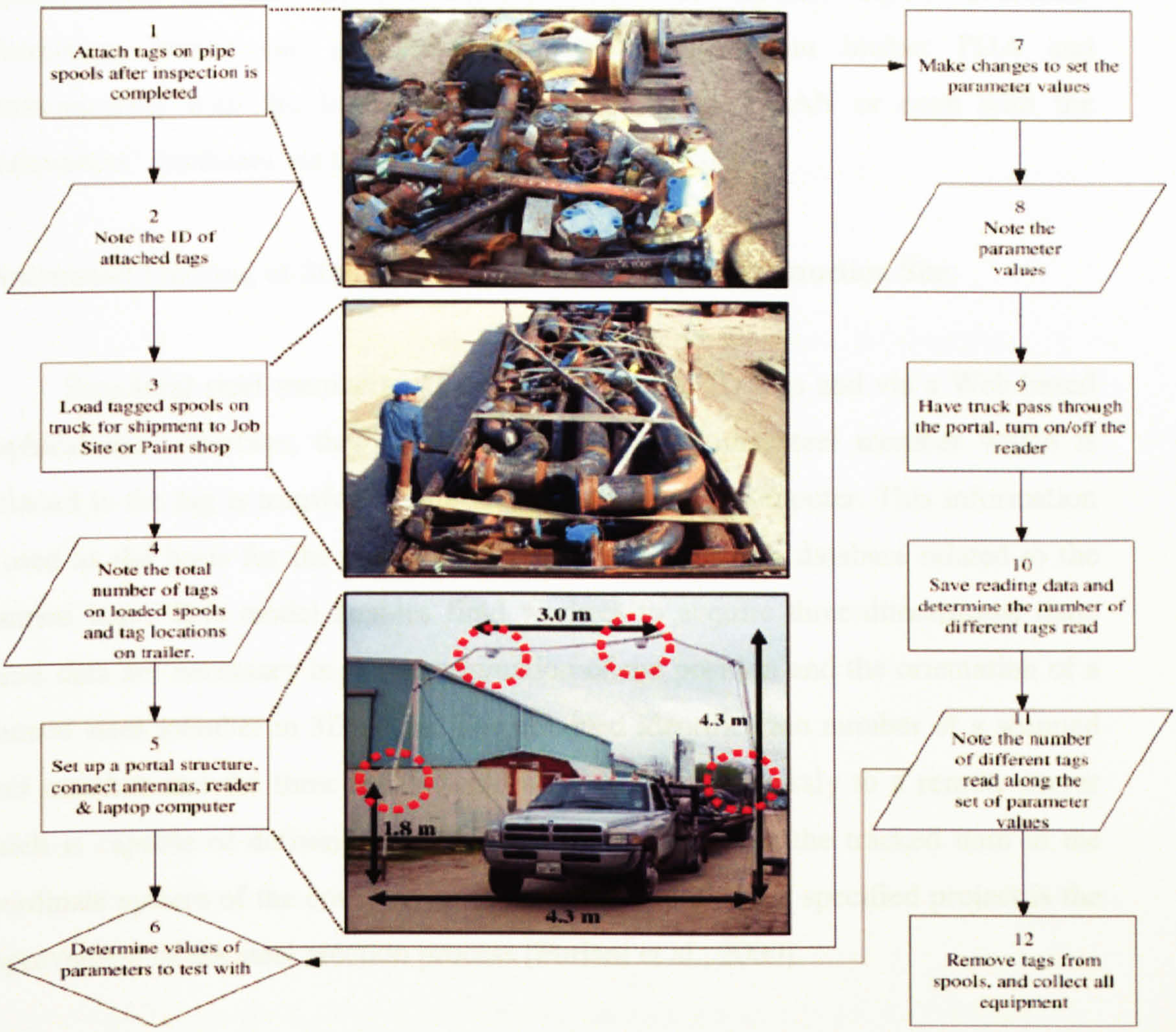


Fig. 4.7 Steps followed during field tests [Song et al., 2005]

• On-Site Inspection Support System Using RFID Tags and PDAs:

RFID tags can be used in combination with Personal Digital Assistants (PDAs) for the inspection of the construction processes. An on-site inspection support system which can be deployed on the construction site, will include an RFID tag system, a PDA connected to the Internet, a voice input/output system, and a digital camera. Each RFID tag is attached to a specific facility and can contain the latest inspection notes, inspection procedures and the latest measured data related to this specific facility. The memory of the RFID tag is 256 bytes but it can be extended to 3 Mbytes if a battery and a microprocessor unit is attached to the tag. In addition, RFID tags can contain an ID for each facility. The PDA contains also data, such as digital photographs and latest inspection routes while the local office includes all the inspected data, document and drawing files. When the inspector requires additional information, he/she can get that information using again his/her PDA and communicating with the local office through a wireless LAN or even with the headquarters' databases via the Internet [Yabuki et al., 2002].

• Automated Tracking of Structural Steel Members at the Construction Site:

Structural steel members can be tagged with RFID tags and via a Web-based graphical user interface, the identification number of the steel member which is included in the tag is transferred directly into a wearable computer. This information is used as the basis for the extraction of data from a project database related to the scanned item. This model enables field workers to acquire three-dimensional data. These data are necessary in the determination of the position and the orientation of a scanned steel member in 3D space. The obtained identification number of a scanned steel member and the three-dimensional data are sent wirelessly to a remote server which is capable of defining the position and orientation of the tracked item in the coordinate system of the construction site. The purpose of the specified project is the improvement of the steel erection process [Furlani et al., 2000].

• Tracking of Items on the Construction Site:

RFID tags have been deployed on a construction site for the purpose of asset tracking. Thus they are able to provide security on the construction site, either by constantly monitoring the site or by alerting the engineers when an item has been taken away from the site.

Goodrum et al. (2006) have developed a prototype system for the tracking of tools on construction sites using active RFID technology. Specifically, they used active RFID tags and an RFID reader which was attached to a type II Personal Computer Memory Card International Association (PCMCIA) slot of a personal digital assistant (PDA). Two sites were used for the testing of the developed system and one site was used as a jobsite. For the needs of this specific application, a portable band saw, a reciprocating saw and a hammer drill were identified as the tools in which the active RFID tags would be embedded. Parameters which were tested during the field trials were the read range of the RFID tags, their ability to store uncorrupted data and their ability to update these data. The field trials took place over a period of three months and they showed that the active RFID technology can provide adequate read range. Specifically, the average field read ranges of the tags was between 3 to 9 meters. The trials also showed that the existence of metals affected the read range and that cold temperatures was reducing it [Goodrum et al., 2006].

4.13 Integration of RFID with other Wireless Communication Technologies

RFID could be combined with a number of wireless communication technologies. Examples of such technologies are the wireless Local Area Networks (W-LANs), Global System for Mobile Communications (GSM) networks, smart-phones and handheld readers. This combined use of the RFID technology with other wireless communications technologies is analysed below.

• *Wireless LANs (W-LANs)*: A wireless Local Area Network (W-LAN) connects computers together through radio technology, thus providing the benefits of a wired network without the need of use of cables [The University of Birmingham, 2003]. The main element of a wireless local area network is the access point while the mobile hosts access the wireless local area network through the access point [Pilosof et al., 2003].

There are two types of wireless local area networks. These types are listed below:

• Ad-hoc networks: these are networks in which a host can connect directly to other hosts.

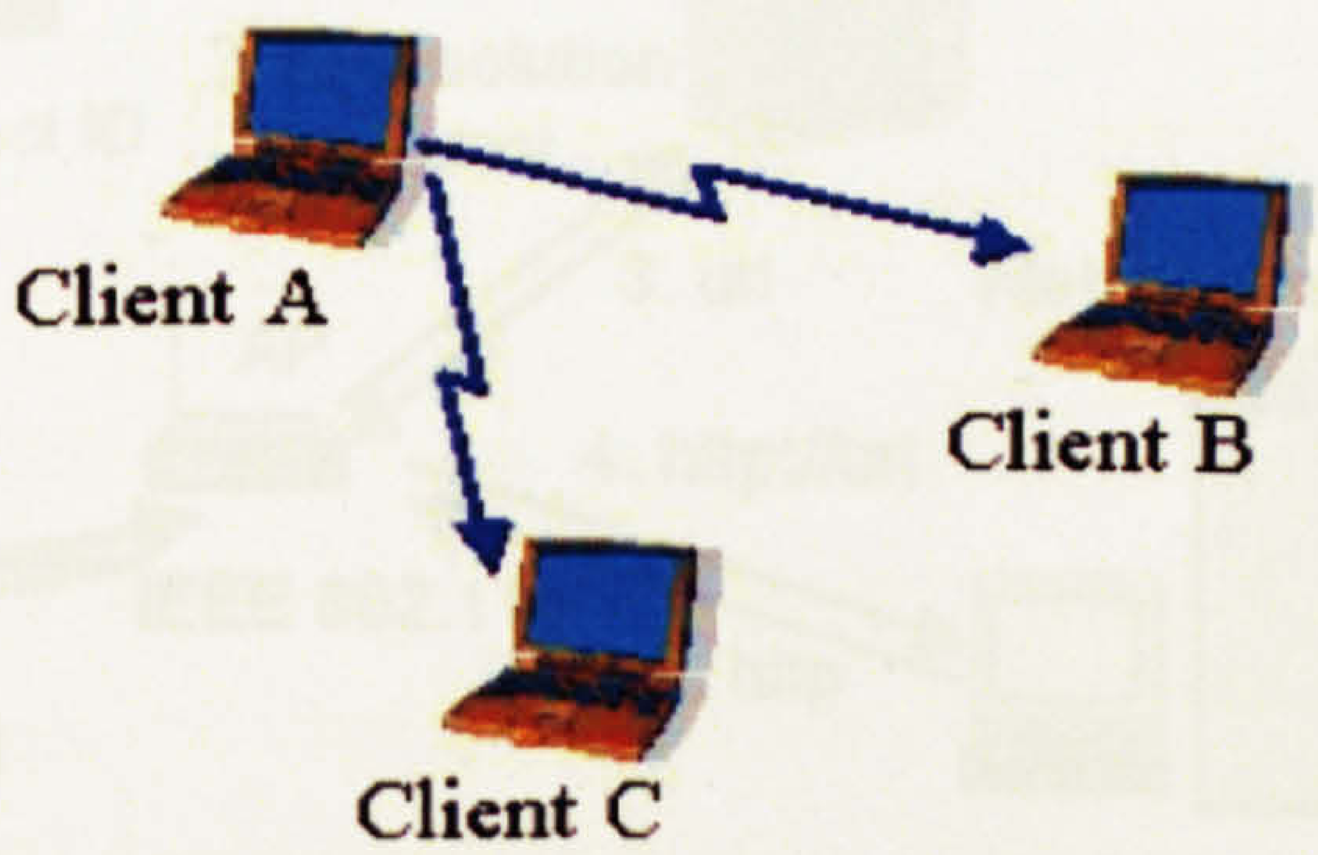


Fig. 4.8 An Ad-hoc Wireless Local Area Network
[Arbaugh et al., 2002]

• Infrastructure networks: these are networks in which each host connects first to an access point which then forwards all the communication traffic to a wired or a wireless network. An example of an infrastructure network can be shown in Figure 4.9.

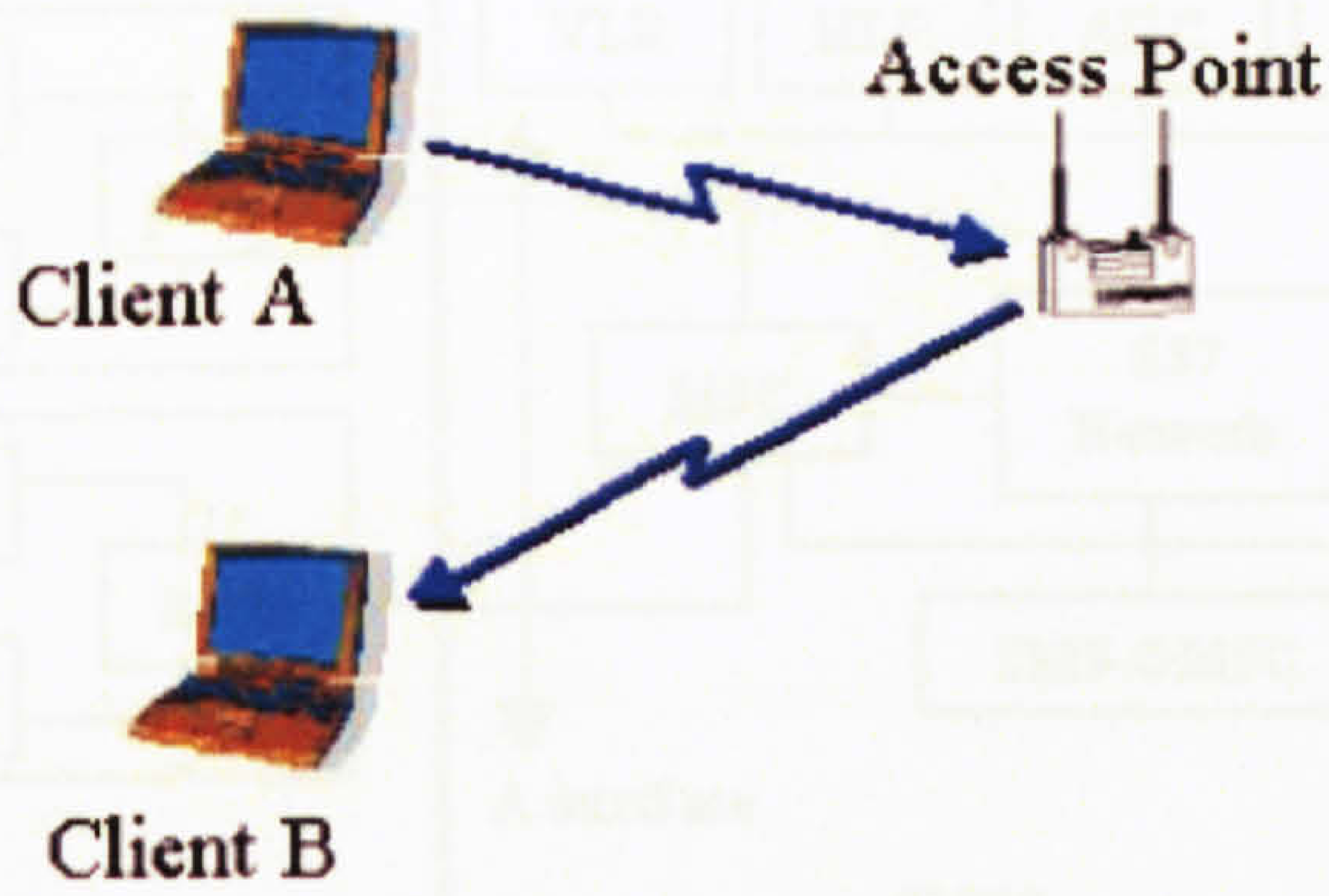


Fig. 4.9 An Infrastructure Wireless Local Area Network

[Arbaugh et al., 2002]

An example of the integrated use of RFID with wireless local area networks is the project CampusSpace developed at the University of Linz. In this project, location data are collected from RFID tags through the access point and stored in a location server. The users can access these data also through a web server. Figure 5 shows the CampusSpace project.

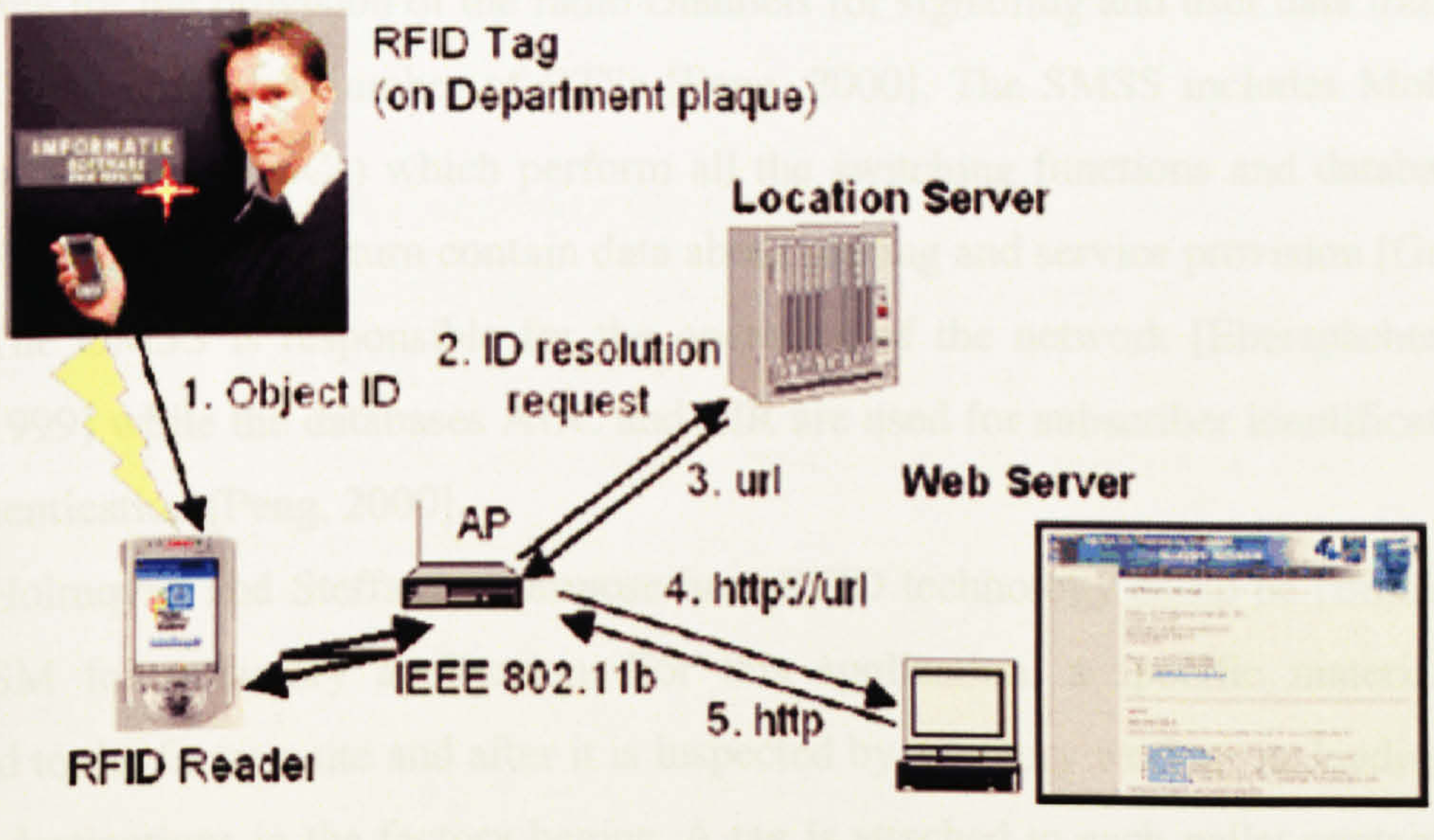


Fig. 4.10 The CampusSpace Project

[Ferscha et al., 2001]

• *GSM Systems*:

A GSM system consists of two major elements : the fixed network and the mobile stations. Figure 4.11 shows the architecture of a GSM network.

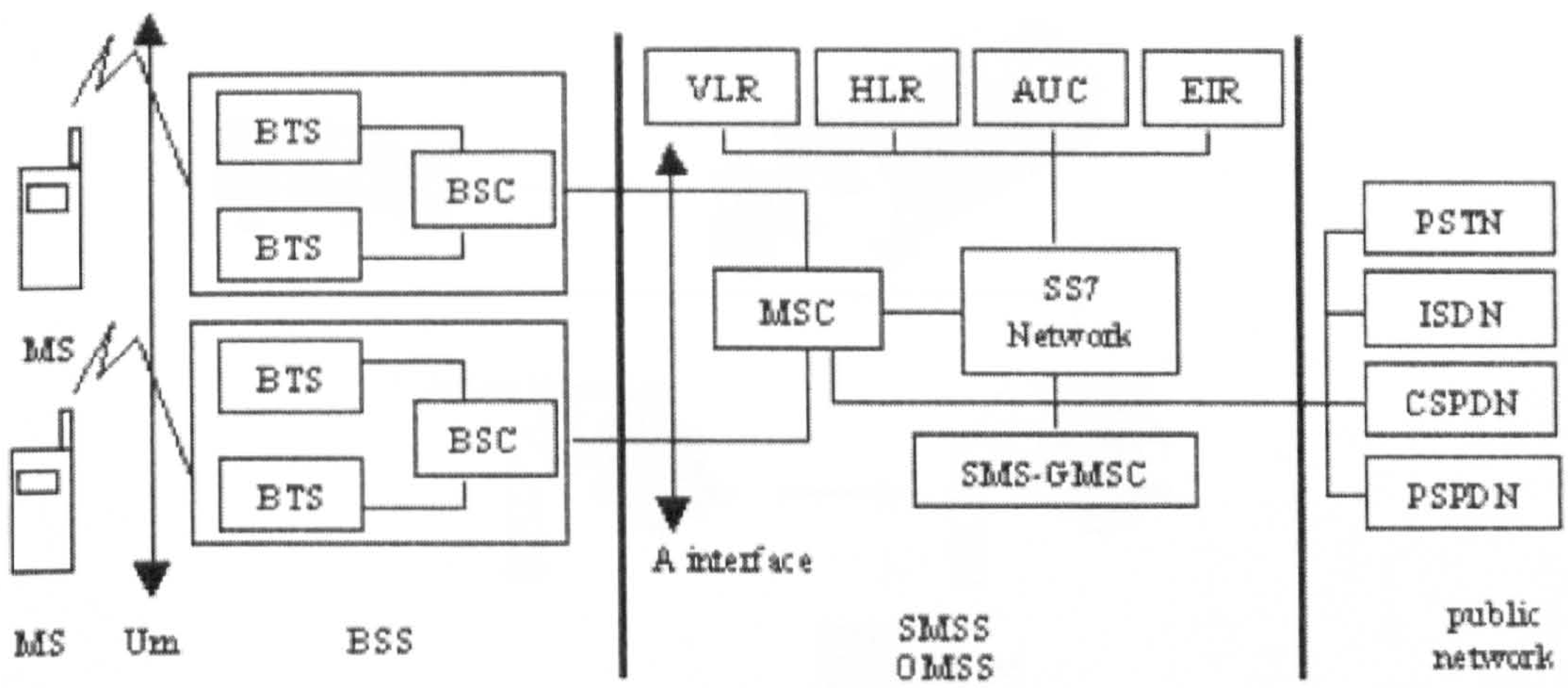
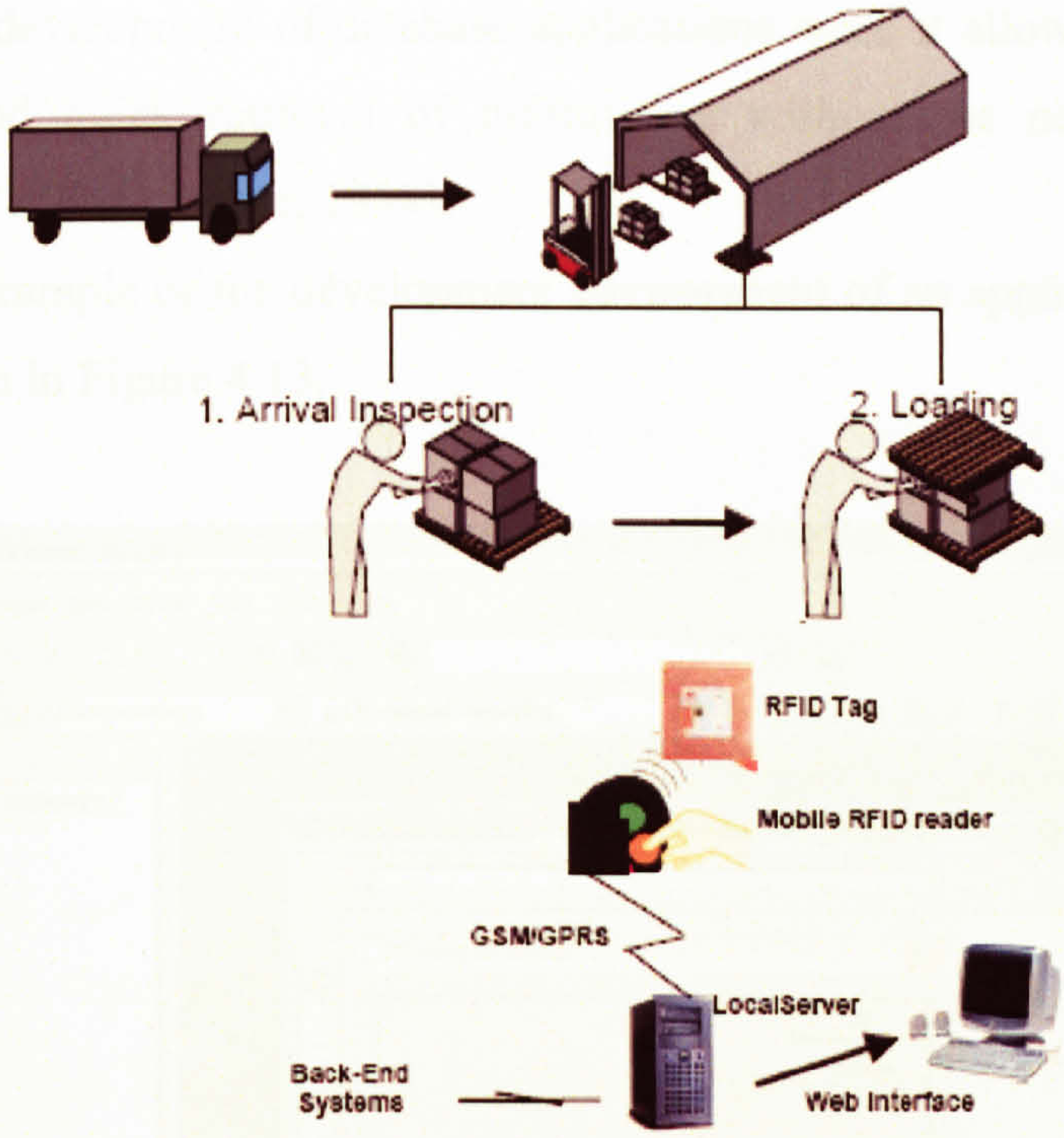


Fig. 4.11 The GSM System

[Peng, 2000]

The fixed GSM network includes the Base Station Subsystem (BSS), the Switching and Management Subsystem (SMSS) and the Operation and Maintenance Subsystem (OMSS) [Eberspächer & Vogel, 1999]. The BSS includes the Base Transceiver Station (BTS) and the Base Station Controller (BSC). The BTS is responsible for the provision of the radio channels for signalling and user data traffic. The BSC can control a number of BTSs [Peng, 2000]. The SMSS includes Mobile Switching Centers (MSCs) which perform all the switching functions and databases (eg. VLR, HLR) which in turn contain data about routing and service provision [Garg, 1999]. The OMSS is responsible for the operation of the network [Eberspächer & Vogel, 1999] while the databases AUC and EIR are used for subscriber identification and authentication [Peng, 2000].

Holmqvist and Steffanson propose how RFID technology could be combined with GSM for a factory application. For this application, a specific material is delivered to the factory site and after it is inspected by a factory worker, its loading to specific destinations in the factory begins. A tag is attached to each pallet containing the material. This tag includes information related to the material and this information is transmitted through GSM/GPRS to a local server. The transmitted data are then available to the users either through a web interface [Homqvist & Stefansson, 2006]. The architecture of the specific application can be shown in Figure 4.12.



4.12 Combination of GSM with RFID
[Homqvist & Stefansson, 2006]

4.14 Mobile Software Technologies

Specific programming languages can be used on mobile environments in order to develop RFID-based data acquisition systems. The use of these languages enables the communication with RFID tags and the development of applications in mobile devices. The mobile software technologies which can be integrated with RFID technology are presented in detail below :

• Visual C++:

Visual C++ allows the development of a number of projects using a flexible integrated development environment (IDE) based on the C++ programming language.

Visual C++ is characterised by many advantages. Specifically, it allows better prototyping by providing enhanced wizards. Also, Visual C++ is considered the ideal environment for writing ActiveX controls along with Internet Server Application Programming Interface (ISAPI) extensions and filters. Furthermore, Visual C++ is good in the development of database applications since it allows easy connection to databases and quick retrieval of information without the need or writing large fragments of code [Mueller, 1999].

An example of the development environment of an application in Visual C++ can be shown in Figure 4.13.

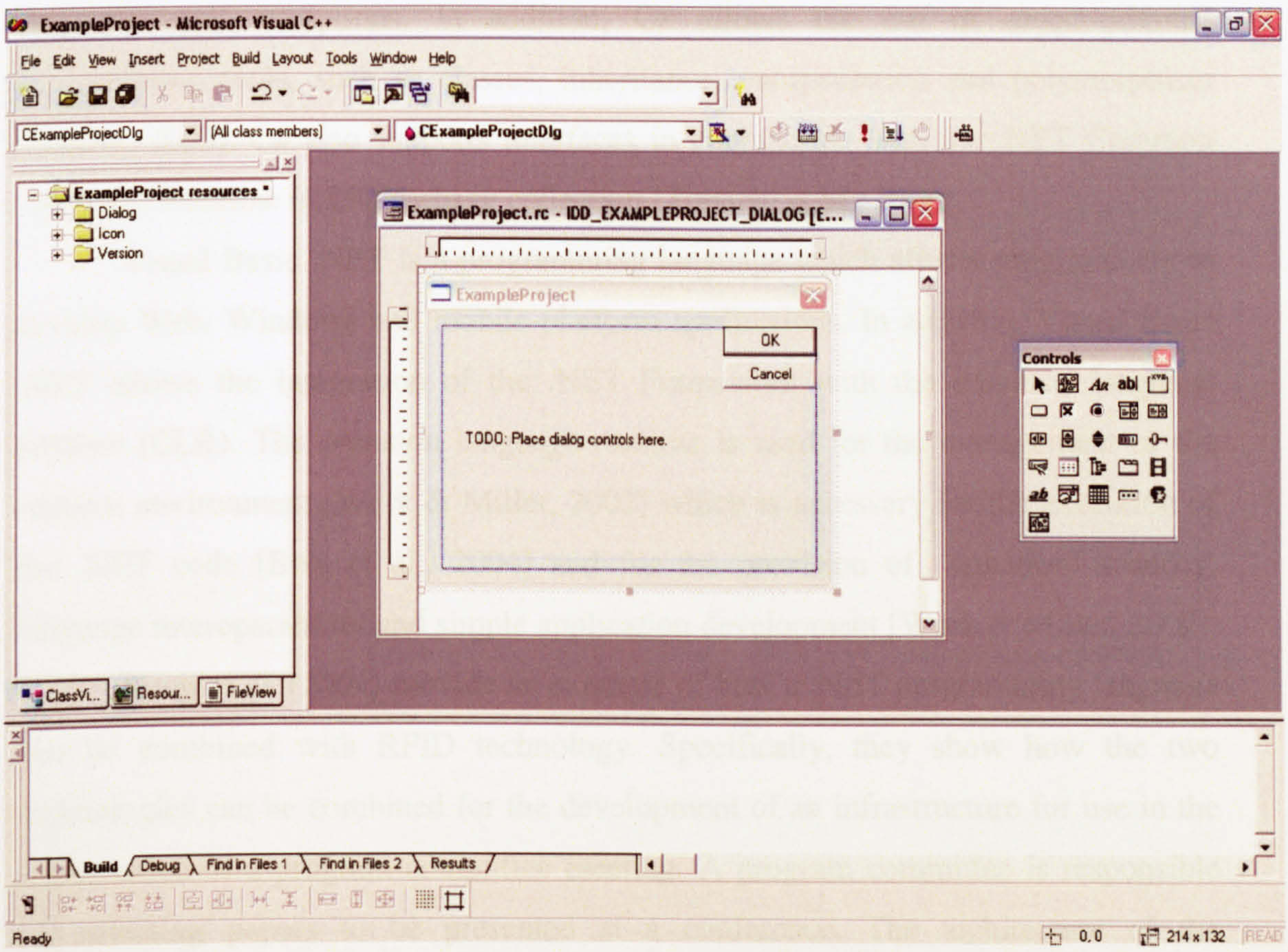


Fig. 4.13 Visual C++ Integrated Development Environment

RFID technology can be combined with Visual C++ in the identification of valves in nuclear power plants for maintenance purposes. A prototype system which is based on the use of augmented reality and RFID tagging has been developed for the Japanese nuclear power plants in order for the task of water system isolation to be executed. This task requires workers to trace specific valves through a huge number of valves. Augmented reality is used in order to navigate the workers to the specific valves while RFID tags attached to the valves are used for the clarification that these tags are the ones which the workers must isolate. The prototype system is based on a number of hardware elements while its software has been developed in Visual C++ 6.0 under Windows 2000 [Shimoda et al., 2004].

• C# and VB .NET Technologies:

RFID applications can be developed using C# and VB .NET technologies. C# is a modern object-oriented language. It supports the use of operators, arrays, properties and exceptions. In addition, C# allows the use of object-oriented programming tools, such as classes, inheritance, encapsulation and polymorphism [Schildt, 2002]. C# also supports interfaces in conjunction with the .NET Common Language Runtime (CLR) garbage collection [Turtschi et al., 2006].

Visual Basic .NET is a programming language which allows programmers to develop Web, Windows and mobile platform applications. In addition, Visual Basic .NET allows the integration of the .NET Framework with the common language runtime (CLR). The common language runtime is used for the management of the runtime environment [Work & Miller, 2002] which is necessary for the execution of the .NET code [Bres et al., 2004] and for the provision of enhanced security, language interoperability and simple application development [Work & Miller, 2002].

Kerer et al. (2004) provide an example of how a .NET programming language can be combined with RFID technology. Specifically, they show how the two technologies can be combined for the development of an infrastructure for use in the organisation of a program committee meeting. A program committee is responsible for selecting papers to be presented at a conference. The architecture of the infrastructure is based on a number of services which characterise the different functions of the infrastructure. The data flow of the services is controlled by the C# programming language [Kerer et al., 2004].

• Embedded Visual C++:

Embedded Visual C++ is a programming language which allows the development of applications for mobile platforms, such as Windows CE [Gopalan, 2002]. Microsoft Embedded Visual C++ offers a flexible Integrated Development Environment (IDE) which supports the testing of applications on many different processor architectures, such as the ARM and the MIPS architecture. Embedded Visual C++ offers also the same level of support for Component Object Model (COM) objects [Lóders et al., 2006]. The MFC and ATL libraries offer new classes but some classes have also been reduced.

An example of the Microsoft Embedded Visual C++ IDE can be shown below:

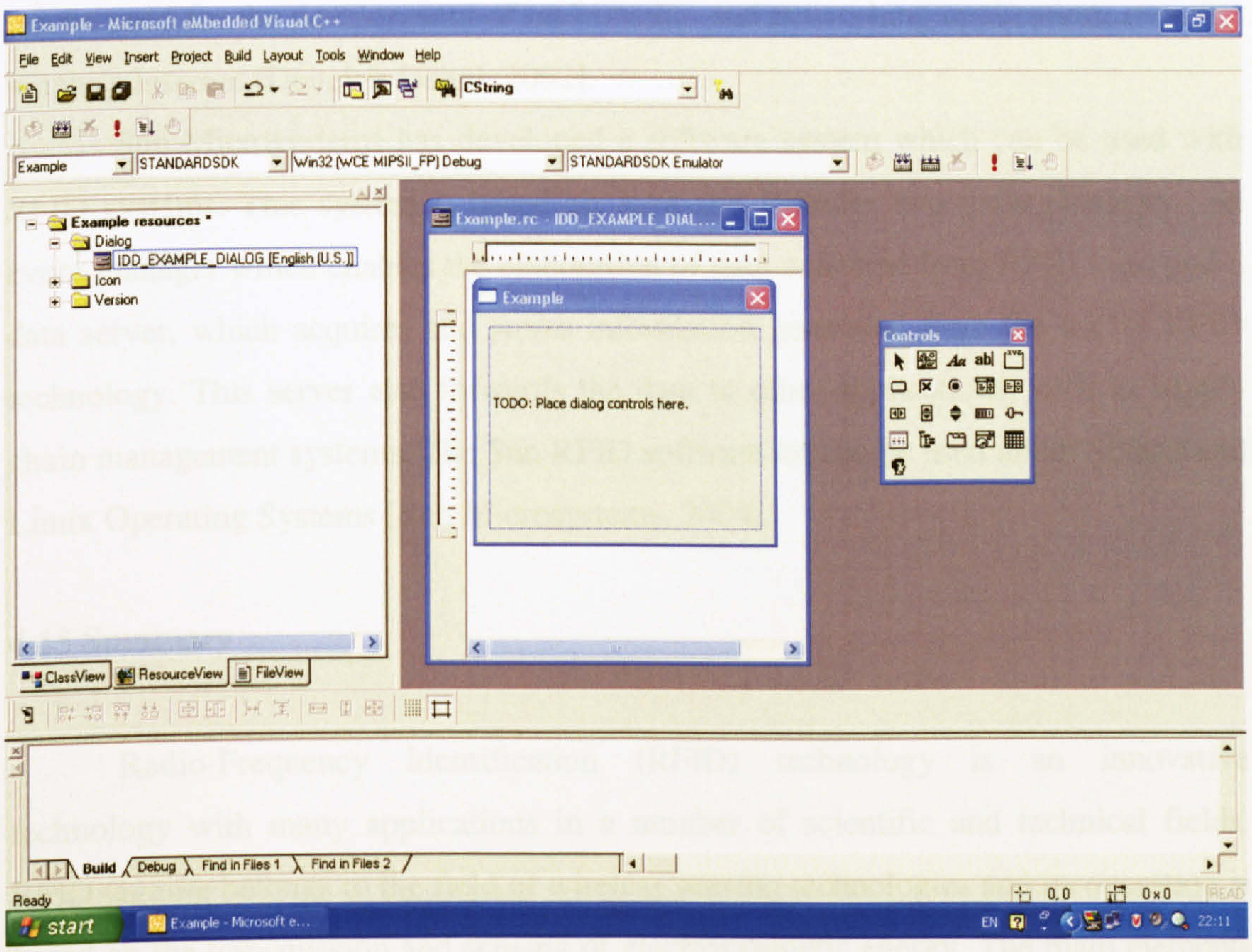


Fig. 4.14 Embedded Visual C++ Integrated Development Environment

Ibach et al.(2005) present a distributed robotics system which shows how Embedded Visual C++ can be combined with RFID technology. The system consists of two types of components: real-time critical logic components and other business components. The first components were developed with Embedded Visual C++ and use application programming interfaces (APIs) under Windows CE. The business components have been developed in C# and execute within the .NET Compact

Framework. The robotics system can be used for indoor and outdoor applications, such as protection of properties, rescue operations and development of smart houses [Ibach et al., 2005].

• Java:

Java is an object-oriented programming language. This language allows the development of web-pages with dynamic content. Java is characterised by the use of class libraries known as Java Application Programming Interfaces (Java APIs). Java can be used for the development of multimedia and networking applications over the wireless Internet [Deitel & Deitel, 2002].

Sun Microsystems has developed a software system which can be used with RFID systems. This system is based on Java and includes two main elements : an event manager which enables the elaboration of data collected from RFID tags, and a data server, which acquires and stores information generated from the use of RFID technology. This server also forwards the data to other applications, such as supply chain management systems. The Sun RFID software kit can be used under Solaris and Linux Operating Systems [Sun Microsystems, 2004].

4.15 Summary

Radio-Frequency Identification (RFID) technology is an innovative technology with many applications in a number of scientific and technical fields. RFID tagging belongs to the field of wireless sensing technologies and its operation is based on the transmission and sensing of electromagnetic energy. The main elements of RFID technology are the readers and the tags. RFID readers can be fixed or mobile hand-held scanners. RFID tags are classified as either active or passive depending on whether they have their own battery or take energy from the electromagnetic field of the RFID reader. Depending on whether they have storage capacity or not, RFID tags are characterised as Read/Write or Read-Only. The reading and writing of data from/to the tags is achieved through specific procedures called half-duplex, full-duplex and sequential procedures respectively. A range of frequencies characterises also RFID systems. These frequencies are characterised as low (125-134kHz), high (13.56 MHz), ultra-high (433-960 MHz) and microwave (2.45 GHz). Additionally, different standards characterise the operation of RFID systems and these standards depend on the different applications of RFID technology. There are many advantages which characterise the technology in comparison to other technologies, such as bar-coding and the Global Positioning System (GPS). Furthermore, the technology is able to integrate with a number of mobile technologies both on a hardware and software level, so that innovative applications can be produced. Even though there are arguments about possible disadvantages of the RFID technology and difficulties on its adoption from the construction industry, there are many characteristics of the technology which prove how useful the technology can be in the resolution of a number of construction industry-related problems. Examples of such characteristics are the asset tracking capability offered by RFID tags and the wireless exchange of data through the use of small tags.

Chapter 5: Development of Scenarios

5.1 Introduction

A number of scenarios have been developed for the use of RFID technology in the construction industry. These scenarios are focused on specific aspects of construction logistics and health and safety. In the following sections, an analysis of the current problems of the UK construction industry in logistics and health and safety is presented. Specific scenarios which have been developed as part of this research, are presented to show how RFID technology could be used for the resolution of specific problems in the fields of construction logistics and health and safety.

5.2 Choice of Research Scenarios

The development of the specific scenarios was based on the identification of specific problems which characterise the logistics and the health and safety in the UK construction industry. These problems reveal the weaknesses of the construction industry in comparison to other industries in which similar problems have been resolved. Furthermore, they show how RFID technology could be used for the effective resolution of these problems. As part of the scenario development process, a number of statistics produced by authorised UK construction organisations were used and visits were made to construction sites to investigate the existing health and safety and logistics conditions to be identified.

Figure 5.1 is provided by the UK National Audit Office and is a refinement of the Egan and Latham reports. It shows what is required in order for the UK construction industry to be modernised. The main points considered in the following diagram are the need for integration between the different stages of the construction process, better cooperation between contractors and clients, and better cost evaluation of the construction project. Two key points, however, are the need for an improvement of the construction supply chain covering all its main actors (materials suppliers, subcontractors, designers, construction consultants) and the need for better health and safety conditions.

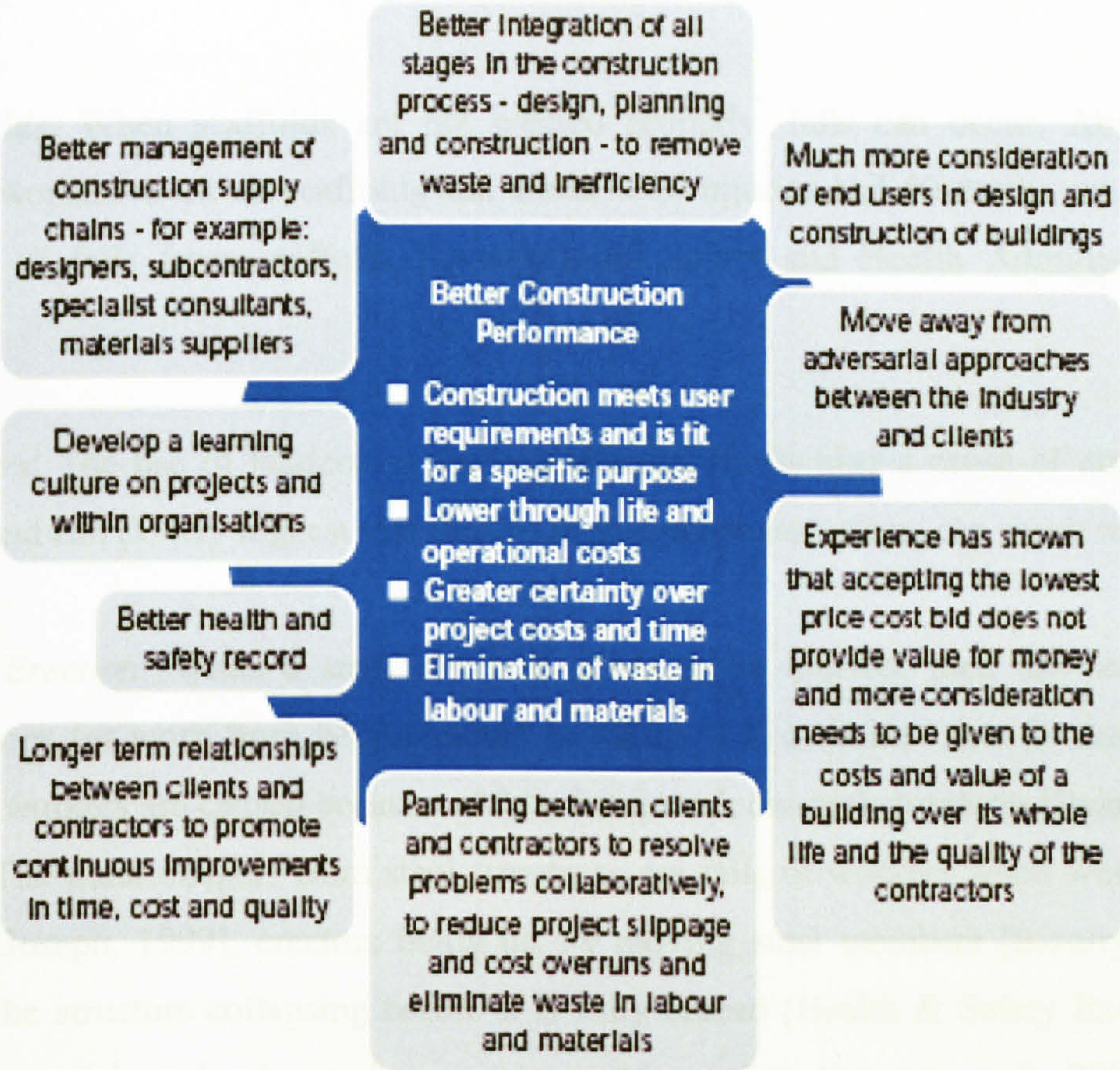


Fig. 5.1 Overall needs of UK Construction Industry

[Bourn, 2001]

5.2.1 Health and Safety in the Construction Industry

Health and safety is a major issue for any industry and especially for the construction industry. The most common health and safety risks in the construction industry are accidents and ill health. Accidents can be caused by falls, falling materials, electrical shocks and moving vehicles. Ill health can be caused by hazardous substances found on the construction site. The health and safety-related issues are analysed further below.

5.2.1.1 Risks on the Construction Site

There are many risks which characterise work on the construction site. These risks are listed below:

(1) Falls

• *Scaffolds*: When scaffolds are not erected properly, falls can occur. About 2.3 million workers work on scaffolds and about 4500 injuries and 50 deaths are caused because of falls from scaffolds [Occupational Safety and Health Administration, 2005].

• *Ladders*: The use of ladders on the construction site is also a cause of accidents. Cohen and Lin (1991) suggest that the use of inappropriate ladders can result to falls.

• *Steel Erection*: When a steel structure needs to be erected, then the necessary precautions for work from height should be taken. It is estimated that 68 deaths per 100000 workers are caused because of falls from work on steel structures [Paine et al., 2004]. The main dangers from steel structures are falls of workers when working at height [Joseph, 1999], erectors being hit by moving steel members [Irizarry et al., 2005], the structure collapsing before it is fully braced [Health & Safety Executive, 2001], materials to be dropped to people working below [Irizarry et al., 2005], and cranes carrying large steel members to be overturned [Health & Safety Executive, 2001].

(2) Groundwork

Many people are killed or injured when working in excavations, or when they contact buried underground services. Groundwork has to be planned in such a way in order to prevent possible accidents.

• *Excavations*: Dangers associated with excavations are the formation of cave-ins, the falls of materials into the excavation and the exposure to underground utilities [Occupational Safety and Health Administration, 2002]. Trenches are excavation areas in which the depth is larger than the width [URL3, 2006]. Trenches can be very dangerous because workers can be buried alive. Cave-ins can also be formed in excavation areas [Centers for Disease Control and Prevention, 2006]. A cave-in is the separation of soil or rock material from the side of the excavation and its sudden movement into the excavation area [Occupational Safety and Health Administration, 2004]. Also, water can be gathered in the bottom of the excavation and flammable and toxic gases from nearby sewer lines, can be accumulated [Centers for Disease Control and Prevention, 2006].

• *Underground Services*: Accidents could be caused by the damage of underground services. Examples of such accidents are wounds caused by heat or fire generated by the striking of an electrical cable, breath problems caused because of escaping gas when a gas pipe is hit, or from flooding when a water pipe is damaged [Health & Safety Executive, 1996].

(3) Work in Confined Spaces

A confined space is an area so large that a construction worker can enter and perform a task. However, this area cannot be used continuously and also it has limited means for entry or exit [Hinze & Baseden, 1999]. Work in confined spaces poses serious dangers for the workers.

Confined spaces can be classified as those with open tops and with a depth that will restrict the natural movement of air, and enclosed spaces with very limited openings for entry [URL1, 2006]. The hazards which are associated with the confined spaces are related to a number of parameters which are analysed below :

• the materials stored in such spaces. For example, damp activated carbon in a filtration tank will absorb the oxygen [National Institute for Occupational Safety and Health, 1979].

• the activity which is carried out. Fermentation of molasses creates ethyl alcohol vapours and decreases the oxygen in the atmosphere [National Institute for Occupational Safety and Health, 1979].

(4) Drowning

There is a risk of drowning when people work beside or above water. Drowning can occur into confined spaces and the percentage of accidents caused by drowning in confined spaces is 21%, after asphyxiation [Manwaring & Conroy, 1990].

(5) Moving, Lifting, and Handling Loads

• *Hoists*: Hoists are used to move equipment or materials to successive levels as the construction progresses [Health & Safety Authority, 2006]. The main dangers created by hoists are strikes by the platform of the hoist or being hit by materials falling down the hoist way [International Labour Organisation, 1996].

• *Cranes*: Cranes are very useful in lifting and moving loads. However, there are some parameters which may affect the operation of a crane and as a result, an accident to occur. Such parameters are the type of crane and the bad weather conditions. Reasons which can cause an accident related to crane operation are overloading, overturn, killer hooks, confusion shown by crane operator and unintentional power line contact [Neitzel et al., 2001].

(6) Moving Vehicles on the Construction Site

Workers and vehicle drivers can be killed when a vehicle falls into an excavation area because it is close to the edge of the excavation area and the driver is not able to see the edge [International Labour Organisation, 1996]. Especially for road construction sites, a percentage of 60% of all the accidents which occur on such a site characterises the accidents caused when workers are struck by a moving vehicle or mobile equipment [Pegula, 2004].

(7) Hazardous Substances

Any hazardous substances which are found on the construction site or any procedures which will produce hazardous substances, should be identified [International Labour Organization, 1996]. The major hazardous substances which can be found on a construction site are asbestos, cement and lead.

The term "asbestos" describes a family of fibrous minerals with biological effects. Exposure to asbestos is a cause for mesothelioma and pulmonary fibrosis

[Senitkova & Stevulova, 1999]. Cement is also a hazardous substance which can cause serious burns and its chemical components attack nerve endings [Building Safety Group, 2006]. Lead paints, such as metallic lead and calcium plumbate, may cause lead poisoning [Timmins, 1972].

(8) Electricity

There is extensive use of electricity on construction sites. Reasons which can cause accidents related to electricity are the use of damaged electrical equipment and the improper grounding of electrical equipment. Working in wet conditions is hazardous especially when this work involves the use of electrical cables [Ware, 2006]. When dump trucks, cranes or in general conductive materials contact overhead power-lines, then there is a risk for fatal accidents [Sacks et al., 1999].

5.2.1.2 Justification for the Choice of the Health and Safety Scenarios

Health and Safety is an extremely important issue for every construction project. There are many statistics which show the health and safety record in the construction industry. The most reliable statistics in the UK for the health and safety issues in the construction industry are provided by the Health and Safety Executive (HSE). The statistics from HSE show that even though there has been a reduction to fatal injuries in recent years, the rate of accidents in the construction industry is higher than that of other industries, such as the manufacturing industry [Anumba, 1999]. Figure 6.2 shows the main reasons for accidents in the UK Construction Industry.

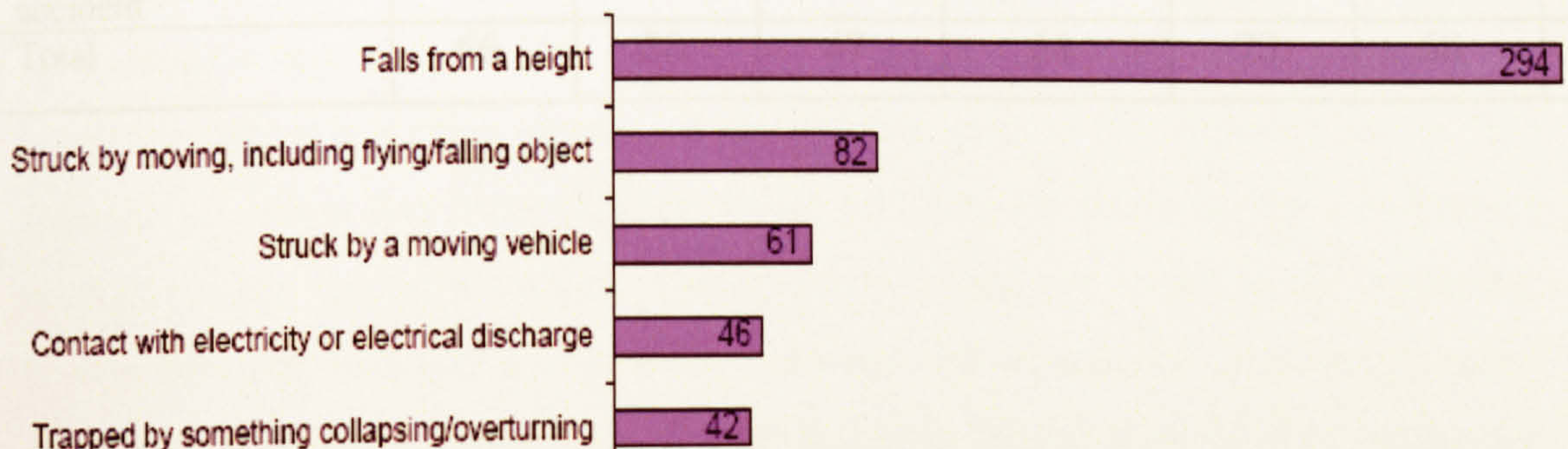


Fig. 5.2 Main causes of accidents in the UK construction industry
[Health & Safety Commission, 2006]

It can be seen that the main cause of accidents in the UK construction industry are the falls from height. These can be mainly falls from scaffolds. The second most important reason is the strike by moving objects, including flying and falling objects. A great number of accidents have also occurred by the collision of workers with moving vehicles. Another reason for accidents is to be trapped by collapsing and overturning vehicles.

Tables 5.1 and 5.2 from the UK Health and Safety Executive specify in detail the number of accidents corresponding to the main causes of accidents over a time period of seven years:

Table 5.1 Percentages for the different accidents on construction sites [Health & Safety Commission, 2006]

Kind of accident	1996/97	1997/98	1998/99	1999/2000	2000/01	2001/02	2002/03
Falls from a height of which:	50%	50%	47%	48%	40%	43%	40%
Up to and including 2 metres	2%	-	-	3%	-	8%	2%
Over 2 metres	47%	50%	45%	39%	40%	28%	33%
Height not stated	2%	-	2%	5%	-	7%	5%
Struck by a moving vehicle	15%	9%	17%	8%	21%	17%	7%
Struck by a moving object	14%	19%	15%	28%	12%	17%	18%
Trapped by something collapsing/overturning	6%	5%	6%	3%	15%	7%	9%
Contact with electricity or electrical discharge	9%	9%	4%	10%	4%	5%	11%
Other kinds of accident	6%	8%	11%	3%	8%	11%	15%
Total	66	58	47	61	73	60	57

Table 5.2 Number of Accidents for specific time periods
[Health & Safety Commission, 2006]

Kind of accident	1996/97	1997/98	1998/99	1999/2000	2000/01	2001/02	2002/03
Falls from a height of which:	33	29	22	29	29	26	23
Up to and including 2 metres	1	-	-	2	-	5	1
Over 2 metres	31	29	21	24	29	17	19
Height not stated	1	-	1	3	-	4	3
Struck by a moving vehicle	10	5	8	5	15	10	4
Struck by a moving object	9	11	7	17	9	10	10
Trapped by something collapsing/overturning	4	3	3	2	11	4	5
Contact with electricity or electrical discharge	6	5	2	6	3	3	6
Other kinds of accident	4	5	5	2	6	7	9
Total	66	58	47	61	73	60	57

Tables 5.1 and 5.2 show that the major cause of accidents in the construction industry are falls. However, other major causes are the collisions of workers with moving vehicles and the overturning of vehicles possibly by falling in an excavation area. Contact with electricity is also a reason for accidents and especially when people use unsafe equipment and when they come in contact with buried cables or overhead electric lines.

During the visit to a large construction site, a number of issues related to the health and safety conditions of the specific construction site, were analysed. The foreman of a specific subcontractor replied to the questions raised. In addition, the researcher was able to take pictures of the different parts of the construction site. The foreman requested that these pictures should be taken discretely so that construction workers would not be provoked. The questions posed are found in the Appendix. Every question initiated a discussion between the researcher and the foreman. Moreover, the foreman went with the researcher to all the parts of the construction site and introduced the researcher to different persons who had different roles on the construction site. The researcher was able to discuss with these individuals and collect information about their role on the construction site [Emirates Stadium Construction Site, 2004].

Also, during the visit to the specific construction site, specific details were provided about the potential of collisions between moving vehicles and workers. It was noted that the vehicles have a camera that provides the driver a rear view of the vehicle; however, the image generated by the camera is not always of high quality. In addition, excavators use mirrors rather than cameras and thus it is more difficult for their drivers to understand if there is an excavation area when they move backwards [Emirates Stadium Construction Site, 2004]. The Health and Safety Executive (1996) specifies that barriers should be placed in order to prevent vehicles from the inside of an excavation area. These barriers must be marked in order to be visible by the drivers. Stop-blocks should also be used to allow vehicles to leave materials into an excavation area [Health & Safety Executive, 1996].

For the purpose of collision monitoring on the construction site, collision detection methods based on visualisation tools of discrete event simulators could be used. However, these methods are not very accurate since they only visualise the results of the simulation of a collision without considering actual parameters which can cause a collision [Kamat, 2003]. Zhang et al. (2006) proposed the division of space on a construction site in cells. Each cell is considered as a discrete event model which changes its state depending on factors, such as its external environment. A moving item can check the state of a specific cell and if it clarifies that it is occupied by other objects, then collision will be avoided [Zhang et al., 2006]. On the construction site of the future, the trucks will be equipped with laser swath devices in order to detect on-time possible collisions [Julien et al., 2005]. Since the collisions of vehicles with workers is one of the main reasons of accidents on the construction site, it is necessary that an appropriate method should be found in order for such types of accidents to be faced. Julien et al. (2005) attempted to make a prediction of what will happen on the construction site of the future while the use of visualisation techniques in order for the problem of collisions on the construction site, is characterised by inaccuracy.

Another issue which was underlined during the visits of the researcher to the construction sites was the existence of chemical substances on the construction site, such as oil and cement. However, it was noted there was not a huge risk of health problems caused by contact with chemical substances but there was still the possibility for the development of minor health conditions, such as dermatitis. In the case of an accident on the construction site, this would be recorded on paper and a set of guidelines would be formed as a feedback for the prevention of future accidents [Emirates Stadium Construction Site, 2004].

In the intelligent construction site of the future, a site office offers access to archives of data while a worker stands outside a volatile organic compound and uses a sensor to monitor the level of a hazardous material. He/she then warns other workers through a wireless network if this level overcomes a specific limit [Julien et al., 2005].

The focus on the development of the health and safety scenarios was the resolution of such specific problems, such as accidents caused by collisions workers with moving vehicles, collapsing or overturning vehicles into large excavation areas, the collection of hazard notifications and the monitoring of chemical substances on the construction site. These problems are clearly a major risk for construction projects, therefore specific emphasis has been provided to them in this research.

5.2.2 Logistics in the Construction Industry

This section examines the field of logistics and focuses on the logistics in the construction industry. A detailed definition of logistics is provided and details are presented about the different stages of the construction logistics process.

5.2.2.1 Definition of Logistics

Logistics can be considered the combination of material supply, material management and distribution. The field of logistics is closely related to the physical and information flows from raw material through to the final distribution of the completed product. Supply and materials management represent these flows into the production process while distribution represents these flows from the final distribution point to the end user [Rushton et al., 1989].

5.2.2.2 Construction Site Logistics

Logistics consist of a significant part of the construction process. Especially for the construction industry, the knowledge of specific parameters of logistics, such as the real-time location of the materials, their quantity, where they have come from and how are they going to be used are of great significance.

According to Veiseth (2003), a construction site acts as a large production system where a large group of complex activities must be carried out in a specific time interval. In addition, a construction site is characterised by a number of supply chains which deliver the material(s) that go into the site. Construction activities are performed by a group of actors. This group includes the client, the architect, the consulting engineer, the building contractor and the end-user [Veiseth et al., 2003].

Jang et al. (2003) specified construction logistics into two categories: supply logistics and site logistics. Supply logistics are related to supply planning, material delivery to the construction site and control of material storage. Site logistics are related to the control of the processes which occur on the construction site and specifically to the management of handling systems and the specification of the sequence of activities [Jang et al., 2003]. Figure 5.3 shows the supply and site logistics.

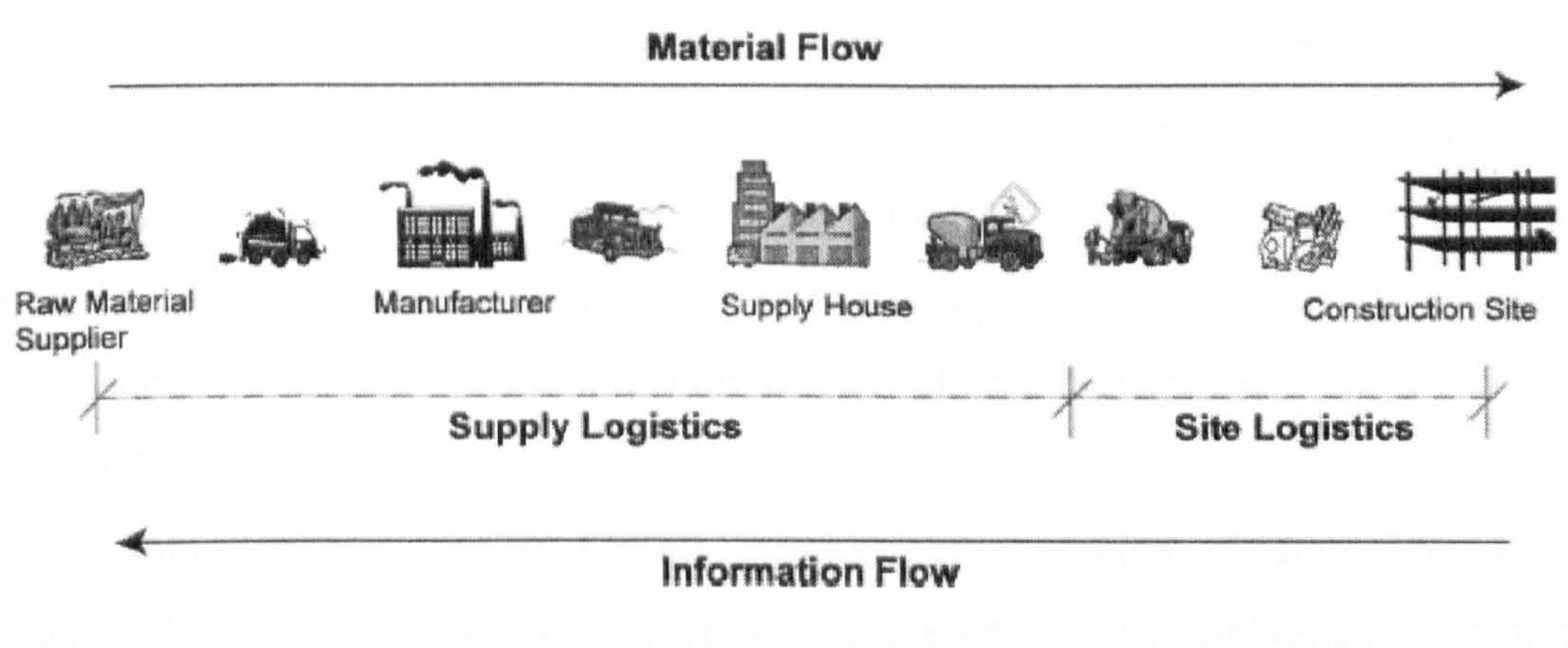


Fig. 5.3 Different Types of Construction Logistics
[Jang et al., 2003]

Cox and Ireland (2002) specify that construction logistics consist of a number of organisational interfaces and this can be shown in Figure 5.4.

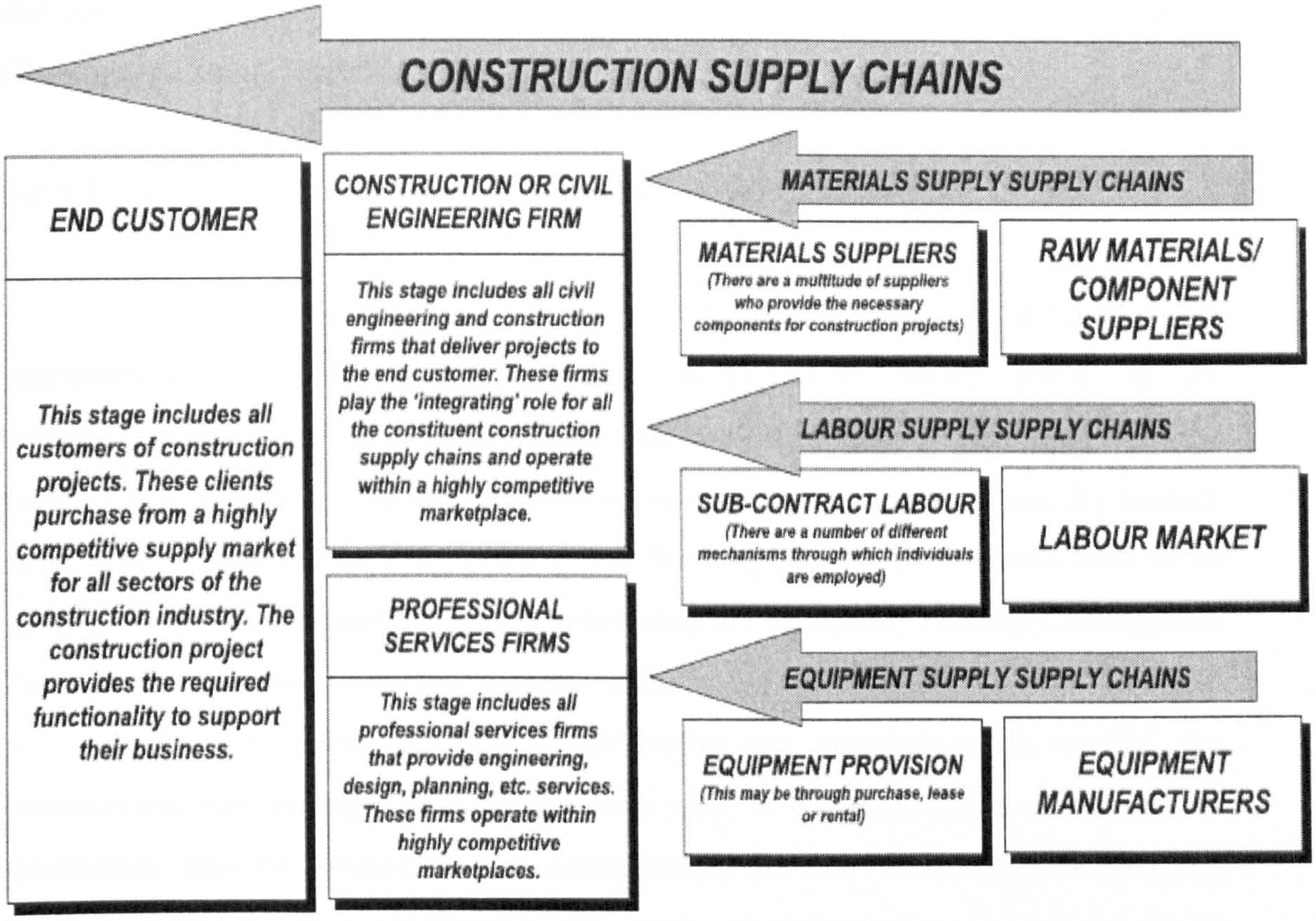


Fig. 5.4 Different interfaces for Construction Logistics
[Cox & Ireland, 2002]

Even though Cox and Ireland (2002) tried to provide with Figure 5.4 a simple image of the supply chains which characterise construction projects, they argue that the reality is quite different. Specifically, it is difficult to identify exactly the number of supply chains which characterise a construction project because the requirements of the end client will define the complexity of the construction project [Cox & Ireland, 2002].

Salagnac and Yacine (1999) provided an overview of how logistics are performed on a construction site. Specifically, the on-site material delivery process is defined by two main participants: the material(s) supplier(s) who distribute(s) materials to the construction site either directly or through a distribution network, and the contractor who is responsible for the assembly of the delivered material(s) and its/their integration with the other parts of the construction project. The contractor orders materials from the supplier and these orders correspond to the specifications of the construction project. The date and time of delivery of the ordered material(s) on the construction site are directly agreed between the supplier and the contractor [Salagnac & Yacine., 1999].

5.2.2.3 Justification for the Development of Logistics Scenarios

According to the Strategic Forum for Construction, construction logistics are characterised by weaknesses. Specifically, many lorries which arrive on the construction site, have to wait for a long time until they deliver their load. A large number of vehicles move around the construction site either empty or partially loaded. Also, construction products are often stored for long periods of time and have to be moved to parts of the construction site when they are eventually needed [Construction Products Association & Strategic Forum for Construction, 2005].

In order to avoid the risk of not having the materials when needed, the construction site manager may order them well in advance. Excessive materials inventories may be created on the construction site and thus materials handling becomes difficult. On a construction site, materials inventories may be monitored either visually or with a spreadsheet application which may be characterised by flaws when the monitoring of the movements of the materials is inconsistent [Ala-Rislu & Karkkhainen, 2006].

Mahdjoubi and Yang (2001) mention that materials management tasks are characterised by the lack of innovative techniques. Hazem and Bell (1995) suggested that materials management tasks should be combined with computer systems. They proposed an object-oriented methodology data structure for a materials management system [Hazem & Bell, 1995]. Wing (2006) predicts that in the future the construction site manager will walk around the construction site where all the items will be tagged. By using an RFID reader, the construction site manager will be able to check the quantities of the materials which have been delivered on the construction site [Wing, 2006]. It can be concluded that the construction industry attempts to introduce the use of innovative technologies in order to face materials management problems on the construction site.

The visit of the researcher to construction sites produced a number of conclusions about current practices in construction logistics. Especially on large construction sites, it was noted that the situation was most of the time chaotic. A visit to a small construction site during which the researcher observed the work of construction workers, it was concluded that the situation was better [Loughborough University Civil and Building Engineering Department Construction Site, 2006]. When materials have to be delivered on the construction site, then most of the times, lorries from different suppliers arrive at the same time at the entrance of the site [Emirates Stadium Construction Site, 2004]. These specific information about construction logistics which were collected during the visit to the construction sites are in accordance with the information collected by the Construction Products Association & Strategic Forum for Construction which were presented before. Wing and Atkin (2002) suggest the use of cyber agents at the gates of the construction site in combination with electronic tags in order to check the deliveries of different materials.

Also, the transportation of materials to the different subcontractors on the construction site is not generally well organised. Mahdjoubi and Yang (2001) note that little has been done to improve material routing on construction sites. The creation of an organised supply chain especially for large construction sites would require a high level of cooperation from all the parties involved. Also, in specific cases, such as the erection of steel structures, the workers place the steel members and the foreman re-checks their sequence based on drawings [Emirates Stadium Construction Site, 2004].

Based on the above facts, there is need for the development of an automated construction supply chain which will cover the main aspects of the materials distribution on site in an organised manner. In addition, a number of specific scenarios such as the monitoring of the rate of use of specific materials on site can help in the overall cost evaluation of the project and the automated checking of the sequence of steel members can be useful for the whole construction logistics process. Chau et al. (2004) suggests the use of 4D visualisation for better organisation of the daily activities which occur on the construction site and specifically provide a link between geometrical models and construction schedule data. In this case, specific processes on the construction site, such as the estimation of the quantities of construction materials and the evaluation of cost can be improved [Chau et al., 2004]. Furlani et al. (2000) describes the use of RFID tags in combination with 3D CAD models during the steel erection process. RFID tags can be attached to steel members and their identification numbers are sent to mobile devices. A 3D CAD model is stored in a database and it is used for the definition of the coordinates of the position of steel members. The coordinates provided by the 3D CAD model and the tags' identification numbers are used for the specification of the orientation and the position of the tracked steel members [Furlani et al., 2000]. Schneider (2003) describes that a number of questions have to be answered when it comes to the placement of steel members. These questions are related to whether a steel member is the correct one for a specific location on the steel structure, what was its final position and orientation, whether there were any problems associated with this specific steel member and whether the construction site manager knows this specific information. This information is currently collected manually on construction sites [Schneider, 2003]. Visualisation techniques can be proven extremely useful for the construction industry as this can be shown by the number of sources which examine the use of such techniques on the construction site.

This research has focused on specific construction logistics issues, such as material delivery, transportation and utilisation. These issues clearly affect the progress of a construction project. The development of scenarios related to these issues is useful because it shows how the construction supply chain can be better organised, thus reducing both the time of completion and the cost of the construction project.

5.3 Health and Safety Scenarios

The health and safety scenarios can be divided into the following sub-scenarios:

• Monitoring of Hazardous Substances on the Construction Site:

The construction work has been completed and the site manager wants to check whether there are any remaining hazardous substances on the construction site. The site manager uses a personal digital assistant (PDA) on which there is embedded an RFID reader.

When a tag is detected, its location appears to the PDA of the site manager. The construction personnel has placed RFID tags on the bags or barrels which contain chemical substances. They have also informed the developer of the graphical user interfaces about the locations of all the tags on the construction site. It is however possible that the location of a chemical substance may change. Because RFID technology cannot provide real-time coordinates of the location of the tagged items, the location which appears on the PDA of the site manager may be wrong. In this case, the site manager can approximately find the real location of any remaining hazardous substances on the construction site. The finding of this location depends on the position of the site manager, the sensitivity of the RFID reader and the orientation of its antenna. Specifically, the site manager can change his/her position during the scanning for tags placed on chemical substances. At a specific position, the tags will be detected. If the sensitivity of the reader has been defined as low by the site manager, then that means that the detected tag is close. The orientation of the antenna of the RFID reader shows to which direction the site manager should look for the detected tag. The scenario can be shown in Figure 5.5.

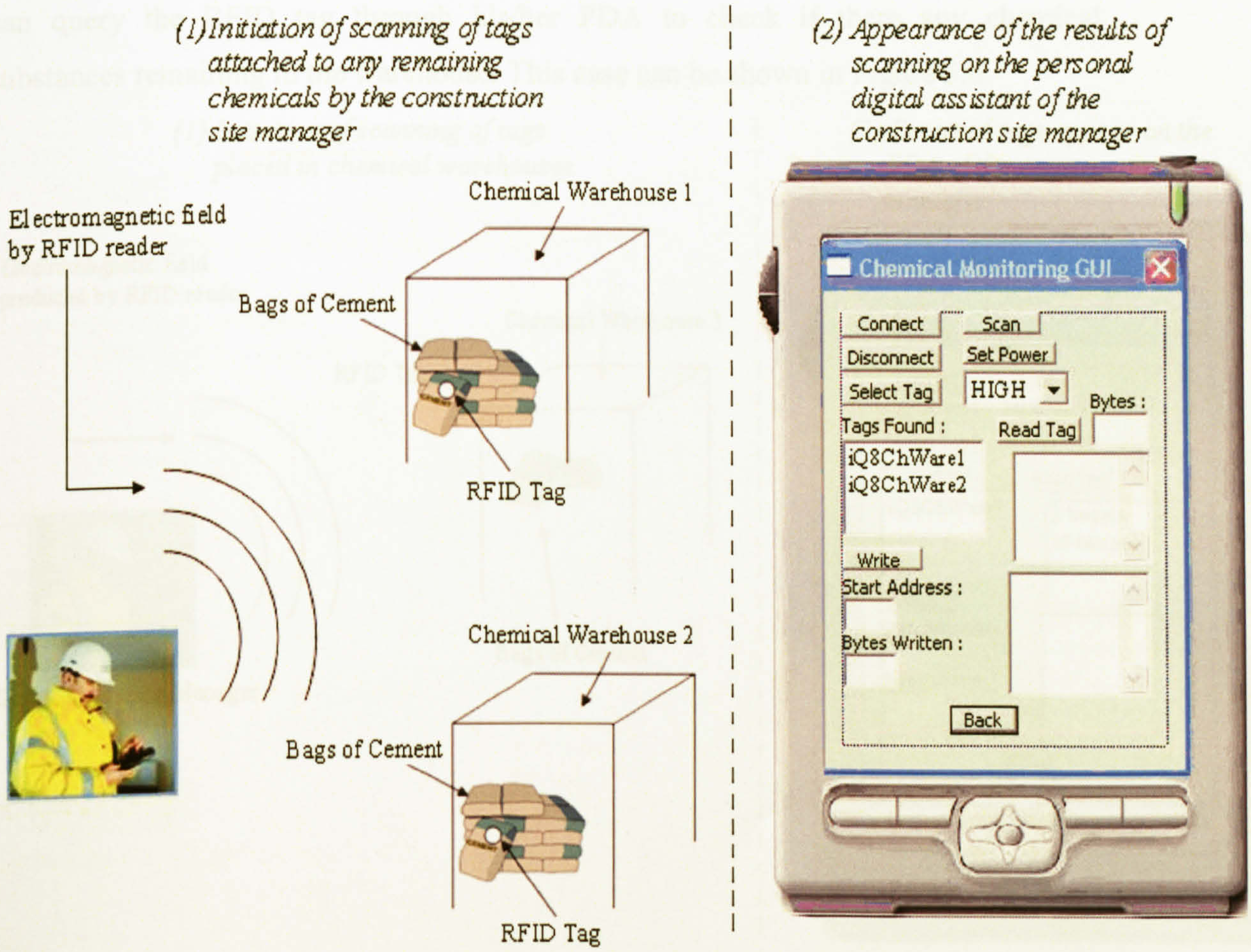


Fig. 5.5 Monitoring of Hazardous Substances on the construction site with RFID tags attached separately to each asset

The steps of the scenario as shown in Figure 5.5 are the following:

(1) The construction site manager does not know whether there are any chemical substances left on the construction site after the construction work has been completed. For this reason, he/she initiates a scanning for tags placed on chemical substances.

(2) The reader detects two tags. The first tag informs the construction site manager that a chemical substance is in chemical warehouse 1 while the second tag informs him/her that a chemical substance is placed in chemical warehouse 2.

An RFID tag could also be placed on a warehouse where chemicals are kept. Information related to the quantities of chemicals used can be stored on the tag and updated regularly. When the construction work has been completed, the site manager can query the RFID tag through his/her PDA to check if there any chemical substances remaining in the warehouse. This case can be shown in Figure 5.6.

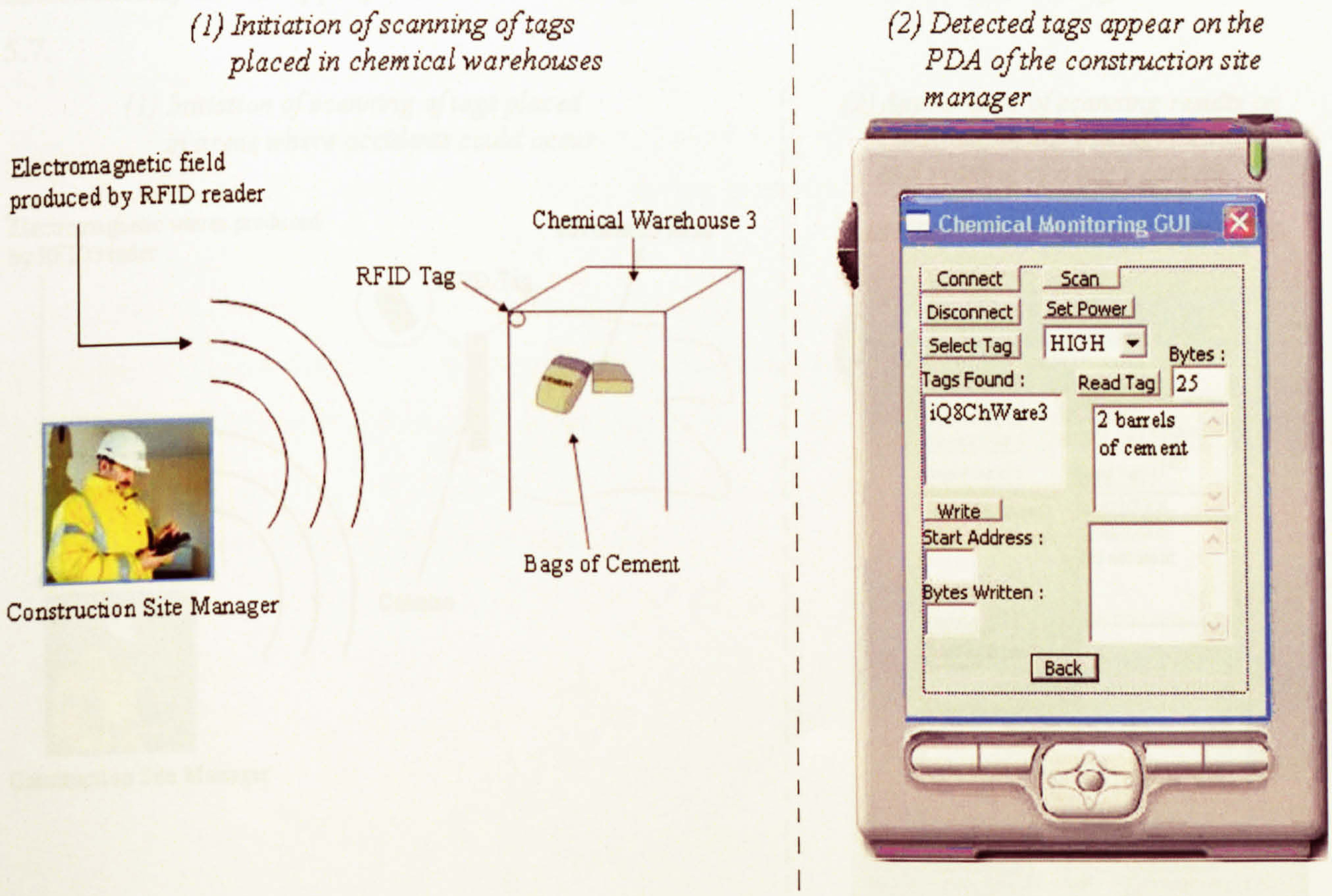


Fig. 5.6 Monitoring of Hazardous Substances on the construction site with RFID tags attached to warehouses

The steps of the scenario as shown in Figure 5.6 are the following:

(1) The construction site manager wants to check if there are chemical substances stored on a specific chemical warehouse. Therefore, he/she initiates a scanning. The tag which is placed in chemical warehouse 3 appears on the PDA of the site manager.

(2) The construction site manager reads the contents of the tags. He/she is informed that there are two barrels of cement in chemical warehouse 3.

• Hazard Notifications as Feedback to Possible Accidents:

Tags can be placed at specific dangerous areas on the construction site. Data related to accidents which have occurred at these locations or possible problems (eg. maintenance problems of vehicles) which may lead to accidents can be stored on the tags. When this information is read by the site manager, it is transferred and stored automatically in the appropriate file for storage. This scenario can be seen in Figure 5.7.

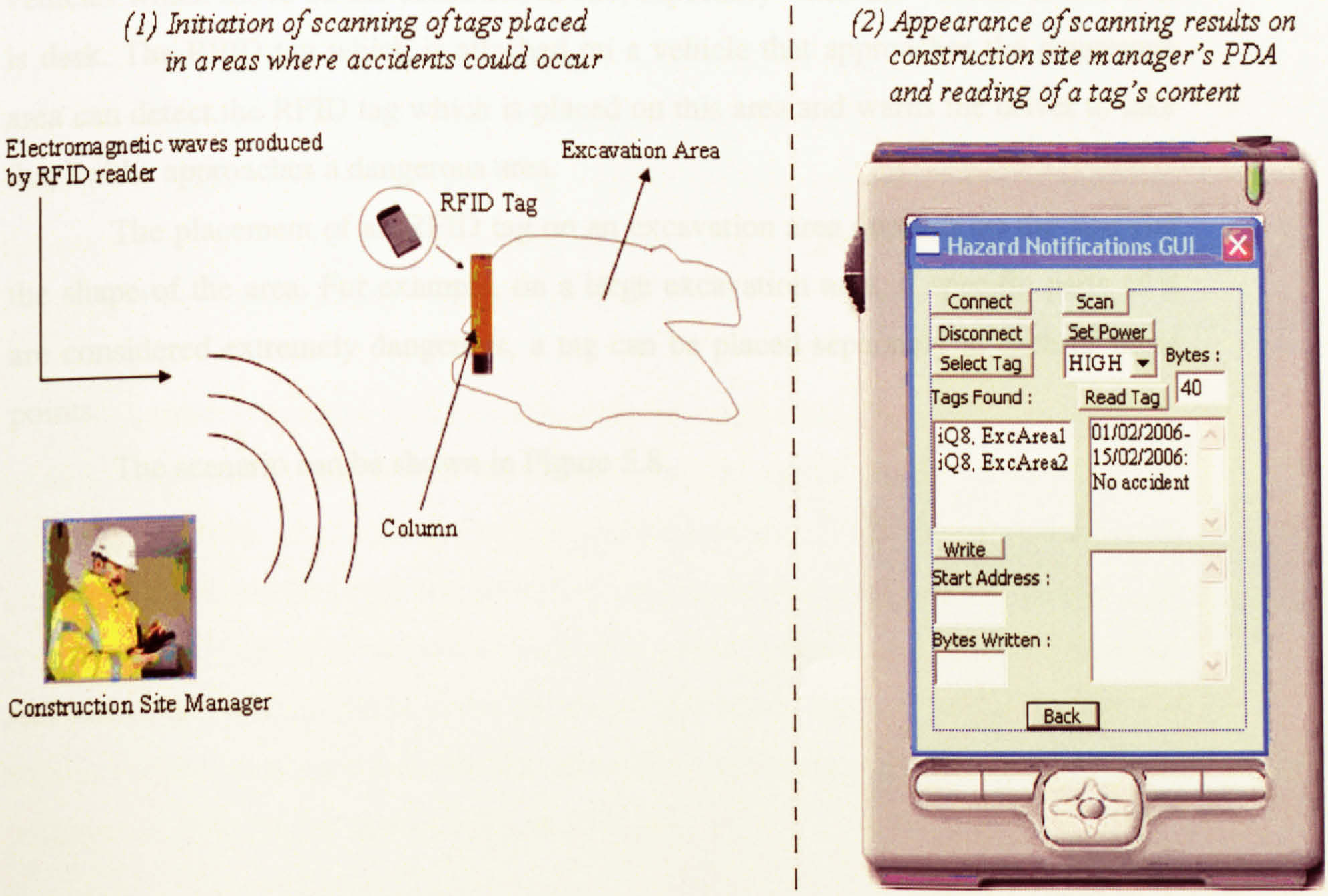


Fig. 5.7 Hazard Notifications as Feedback to Accidents

The steps of the specific scenario as shown in Figure 5.7 are the following:

(1) The construction site manager initiates a scanning for tags placed on specific "dangerous" areas on the construction site, such as large excavation areas or areas in which an electrical shock could occur. He/she does this in order to check of an accident has occurred.

(2) RFID tags on two excavation areas on the site are detected. The construction site manager selects the first tag and reads its contents.

- Protection of vehicles against 'dangerous' areas of the construction site, such as large excavation areas

A worker or a vehicle approaches a specific area of the construction site which is considered "dangerous". Examples of such areas are large excavation areas which are characterised by very steep slopes difficult to be seen clearly by the drivers of vehicles which move on the construction site, especially when the weather is bad or it is dark. The RFID tag which is attached on a vehicle that approaches the dangerous area can detect the RFID tag which is placed on this area and warns the driver to take that he/she approaches a dangerous area.

The placement of an RFID tag on an excavation area depends on the size and the shape of the area. For example, on a large excavation area, if specific parts of it are considered extremely dangerous, a tag can be placed separately at each of these points.

The scenario can be shown in Figure 5.8.

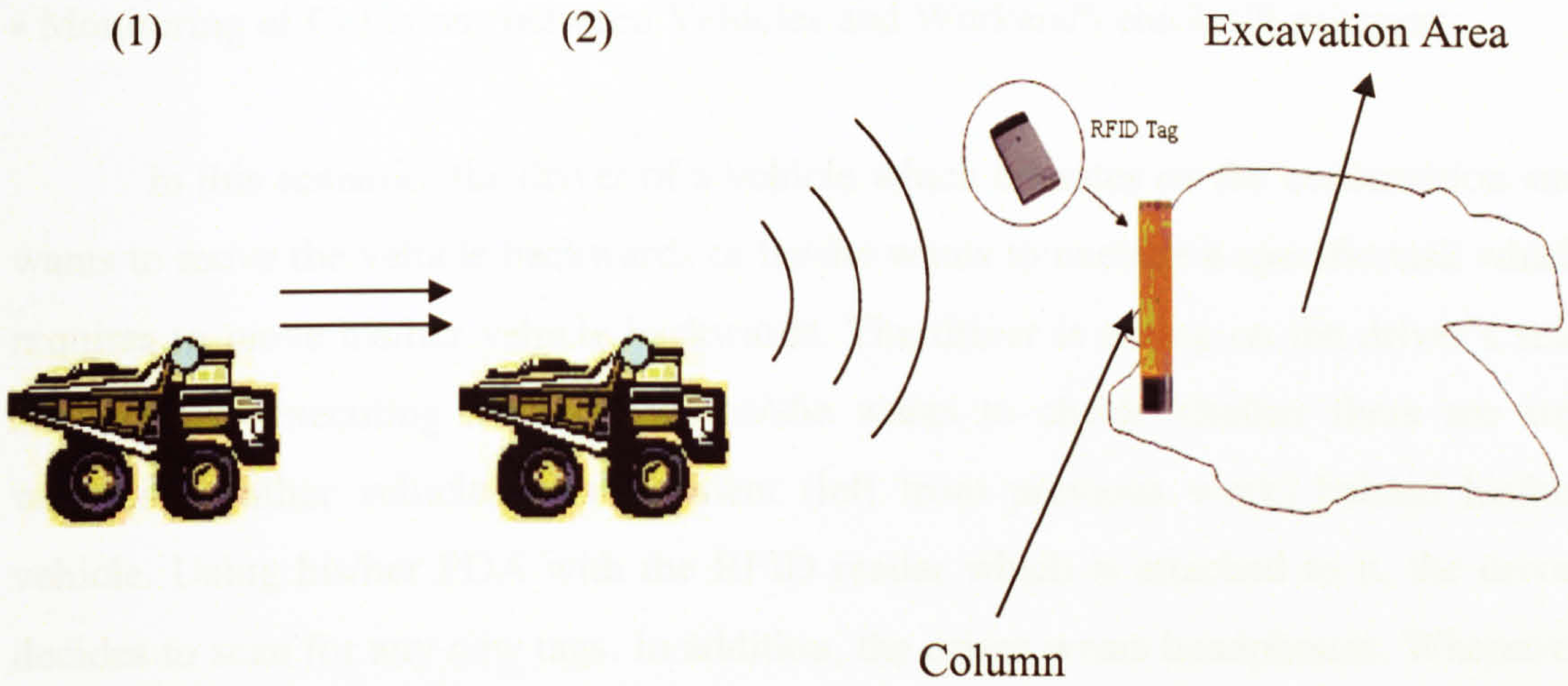


Fig. 5.8 Protection against Dangerous Areas on Site

(1) The driver of a vehicle approaches a large excavation area. The RFID which is attached to the PDA of the driver performs continuous scans in order to detect any RFID tags. The driver of the vehicle uses headphones because any detection of RFID tags placed on forbidden zones will trigger a sound.

(2) When the sensitivity of the RFID reader is adjusted to low, then at a distance of approximately 14 meters from the excavation area, the RFID reader of the driver detects the RFID tag which is placed on a specially designed pole at the boundary of the excavation area. The detection of the specified tag triggers a sound as a warning that the driver is approaching a dangerous area.

The above scenario is useful especially in cases when the weather is bad or it is dark, thus warning labels on the excavation area cannot easily be seen by the drivers of vehicles which operate on the construction site. When the most dangerous points of an excavation area are identified by the site manager and the workers, in order for RFID tags to be placed on them, it is possible that at one of these points an RFID tag could be considered as the tag which also stores daily information about the progress of the work on the excavation area. The site manager could then collect this information from his/her laptop, PDA or tablet PC.

• Monitoring of Collisions between Vehicles and Workers/Vehicles/Equipment:

In this scenario, the driver of a vehicle which operates on the construction site wants to move the vehicle backwards or he/she wants to execute a specific task which requires to move his/her vehicle backwards. The driver is sitting on the driver's seat and prior to executing his/her task, he/she wants to check whether there are any workers or other vehicles or equipment (left from previous work) behind his/her vehicle. Using his/her PDA with the RFID reader which is attached to it, the driver decides to scan for any new tags. In addition, the driver wears headphones. Whenever a tag is detected, a sound is triggered as a warning. The driver can also set the reader to perform continuous scanning for tags while he/she executes his/her task. In this case, if a tag is detected, the driver will be warned by a sound and he/she will immediately stop his/her vehicle before a collision occurs.

The detected tags appear also on the screen of the driver's PDA. The type of these tags will be shown and also the location to which these tags are placed. The location of these tags is pre-defined. This means that the driver does not see any coordinates of the location of the tags. He/she sees the location to which the tags have been placed initially. When a tag is placed at a specific location on the construction site, this becomes known to the developer of the graphical user interfaces which will be used for the interaction with the RFID tags. In this case, when a driver of a vehicle initiates a scanning for RFID tags, this initial location of the tags will appear on his/her PDA. Any change of the location of the tags must become known to the developer of the graphical user interfaces.

In addition, the driver can adjust the radio-frequency sensitivity of his/her reader so that tags which are close to his/her vehicle will be detected while tags which are further away, will not be. Whenever a tag is detected, a sound is triggered as a warning to the driver. The presented scenario can be shown in Figure 5.9.

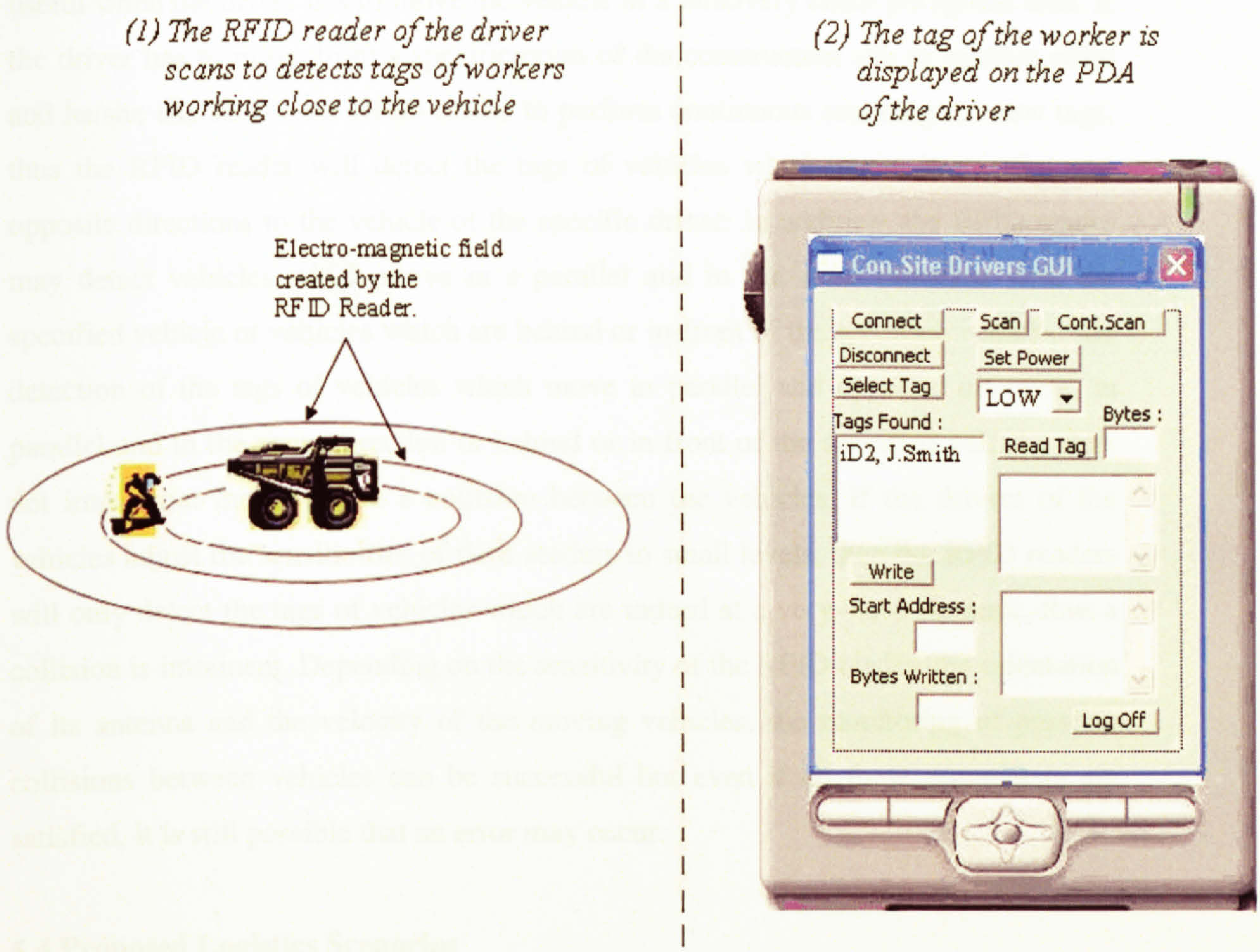


Fig. 5.9 Collision Monitoring between Vehicles and Workers

The steps of the scenario as shown in Figure 5.9 are the following:

(1) A driver of a vehicle want to execute a specific task which requires to move his/her vehicle backwards. The driver doesn't know that there is a worker working close to his/her vehicle. The driver initiates a scanning for tags. At the same time, he/she wears a set of headphones connected to the PDA, so that he/she will be able to hear a warning sound.

(2) The tag of the worker is detected and a warning sound is heard in the headphones of the driver.

It is possible also that the driver of the vehicle will choose for the RFID reader to perform continuous scanning for new tags as the vehicle moves. This is especially useful when the driver has to move the vehicle in a relatively small polygonal area. If the driver has to move from a specific point of the construction site to another point and he/she can set for the RFID reader to perform continuous scanning for new tags, thus the RFID reader will detect the tags of vehicles which move in parallel and opposite directions to the vehicle of the specific driver. In addition, the RFID reader may detect vehicles which move in a parallel and in the same direction with the specified vehicle or vehicles which are behind or in-front of the specified vehicle. The detection of the tags of vehicles which move in parallel and opposite direction, in parallel and in the same direction or behind or in front of the specified vehicle, does not imply that there will be a collision between the vehicles. If the drivers of the vehicles adjust the sensitivities of their readers to small levels, then the RFID readers will only detect the tags of vehicles which are indeed at a very close distance, thus a collision is imminent. Depending on the sensitivity of the RFID reader, the orientation of its antenna and the velocity of the moving vehicles, the monitoring of possible collisions between vehicles can be successful but even if all these parameters are satisfied, it is still possible that an error may occur.

5.4 Proposed Logistics Scenarios

The delivery of materials and their distribution on the construction site is a very significant process which depends on the way the suppliers, the main contractor and the subcontractors have agreed for material distribution on the construction site to occur. The "Logistics" scenario considers that the distribution of materials to the subcontractors occurs through the contractor. The scenario is depicted in Figure 5.10.

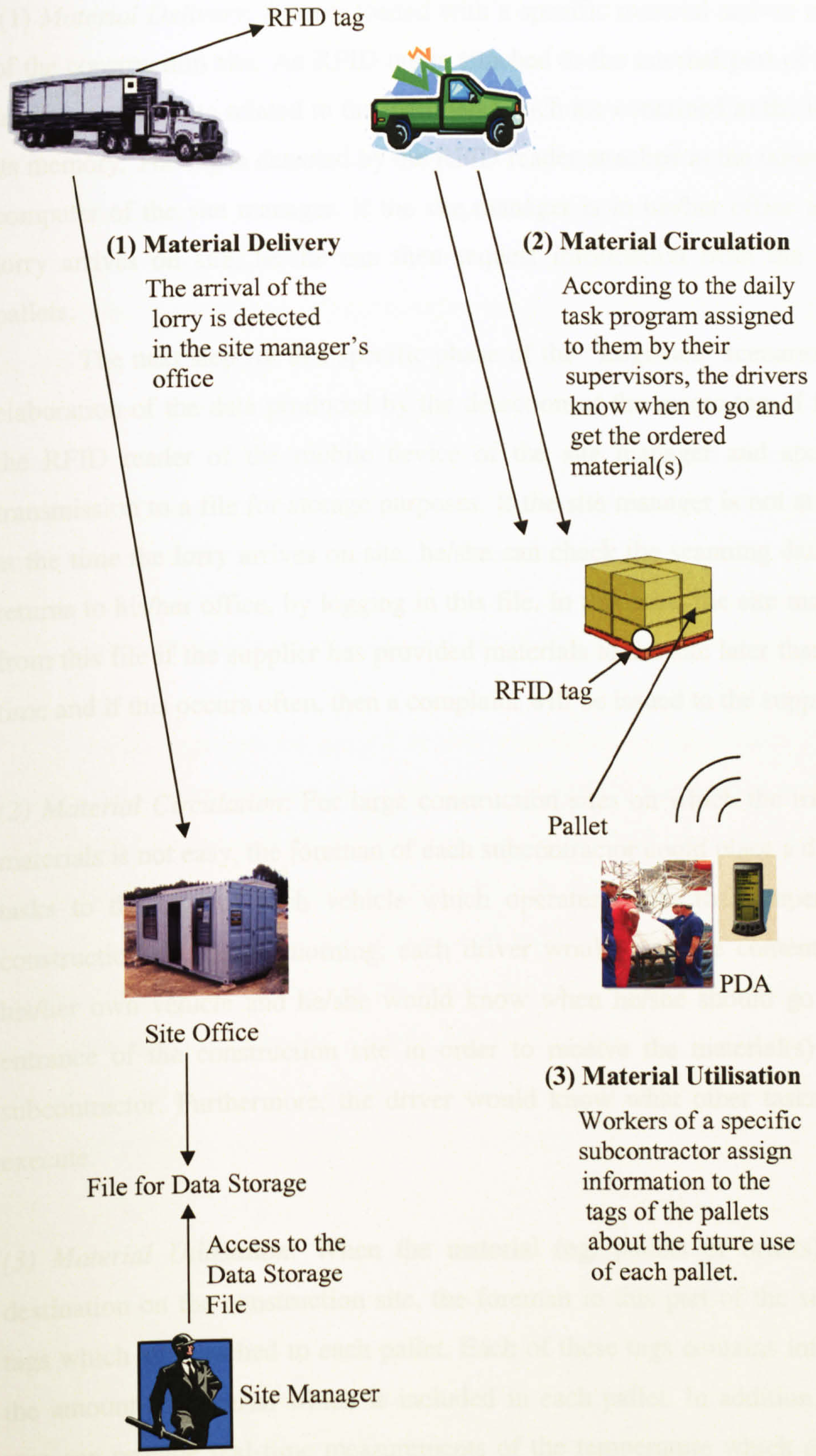


Fig. 5.10 Material Delivery/Circulation/Utilisation

(1) *Material Delivery*: A lorry loaded with a specific material arrives at the entrance of the construction site. An RFID tag is attached to the internal part of the lorry. The tag has a set of data related to the materials which are contained in the lorry, stored in its memory. The tag is detected by the RFID reader attached to the tablet PC or laptop computer of the site manager. If the site manager is in his/her office at the time the lorry arrives on site, he/she can then request information from the tag about the pallets.

The next step for this specific phase of the "Logistics" scenario is the further elaboration of the data produced by the detection of the macro-tag of the lorry from the RFID reader of the mobile device of the site manager and specifically their transmission to a file for storage purposes. If the site manager is not at the site office at the time the lorry arrives on site, he/she can check the scanning data when he/she returns to his/her office, by logging in this file. In this case, the site manager will see from this file if the supplier has provided materials to the site later than the specified time and if this occurs often, then a complaint will be issued to the supplier.

(2) Material Circulation: For large construction sites on which the transportation of materials is not easy, the foreman of each subcontractor could place a daily task list of tasks to the tags of each vehicle which operates under their supervision on the construction site. Each morning, each driver would read the content of the tag of his/her own vehicle and he/she would know when he/she should go exactly to the entrance of the construction site in order to receive the material(s) for a specific subcontractor. Furthermore, the driver would know what other tasks he/she has to execute.

(3) Material Utilisation: When the material (eg. pallets of bricks) arrives at its destination on the construction site, the foreman in this part of the site can scan the tags which are attached to each pallet. Each of these tags contains information about the amount of material which is included in each pallet. In addition, some of these tags can provide real-time measurements of the temperature which characterises the internal part of each pallet since they have a temperature sensor embedded in them. The measurement of the temperature of the internal part of the pallets is important especially for porous materials such as bricks. If the temperature is very low, then materials could be damaged.

Furthermore, the workers can write information to each of the tags about the future use of each pallet of materials or they can place an overall information on a tag which will give a concise picture of how these pallets will be used. For example, an RFID tag could include information about the number of pallets of a specific material which are going to be stored and the number of pallets of the same material which will be used immediately and in which way they will be used. The site manager can either access the information contained on the tag of each pallet or query the RFID tag in order to see how the material will be utilised. It is possible that two different subcontractors use the same material. If one of these subcontractors is going to store pallets of the specific material while at the same time, the same subcontractor needs it immediately, then the site manager can inform the second subcontractor that this material is available from the first subcontractor.

5.4.1 Monitoring of the Rate of Use of Materials

RFID tags can be placed at the warehouses or the places of work of the subcontractors and monitor the quantities of materials spent. This information needs to be stored on the tags by the foreman and be updated regularly. The site manager can select the graphical user interface which is able to scan only for tags which are placed on the warehouses or the places of work of the subcontractors. In this case, he/she can collect information related to the quantities of materials spent from the subcontractors. After he/she collects this information, the site manager can estimate the rate of use of materials on the construction and the overall cost related to material use. The specific scenario can be shown in Figure 5.11.

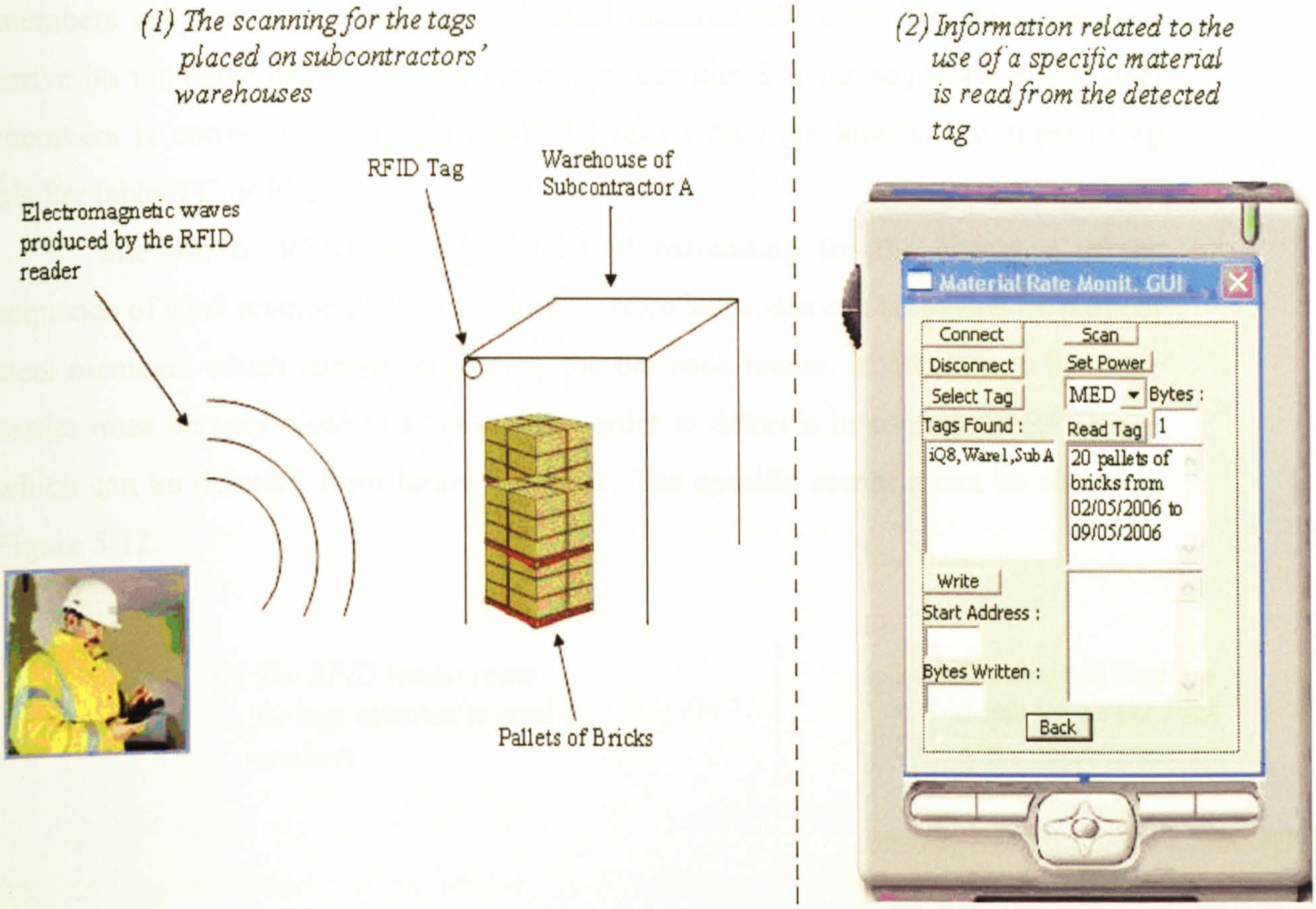


Fig. 5.11 Monitoring of the Rate of Use of Materials

(1) The site manager wants to check the quantity of bricks spent by the subcontractor A. He/she logs in to the appropriate graphical user interface and initiates the scanning of the tags which are placed to the warehouses of the subcontractors.

(2) The tag which corresponds to the warehouse of subcontractor A appears on the graphical user interface. By selecting it, the site manager can read its contents. When the data contained on the tag appear on the graphical user interface, they are automatically transferred and stored in a file for future retrieval along with the date and time of transfer.

5.4.2 Checking of the Sequence of Steel Members

If the materials which arrive on the construction site for a specific subcontractor are steel members that need to be used immediately, then their sequence during their erection must be checked. An RFID tag can be attached by the steel members supplier to the edge of each steel member and when the steel members arrive on the construction site, the supervisor can check if the sequence of the steel members is correct by scanning the RFID tags which are attached to them using his/her tablet PC or PDA.

The use of RFID tagging instead of bar-coding for the checking of the sequence of steel members is more effective since bar-codes can be placed on parts of steel members which cannot be seen by the bar-code reader. In addition, a bar-code reader must be very close to a bar-code in order to detect it in contrast to RFID tags which can be detected from larger distances. The specific scenario can be shown in Figure 5.12.

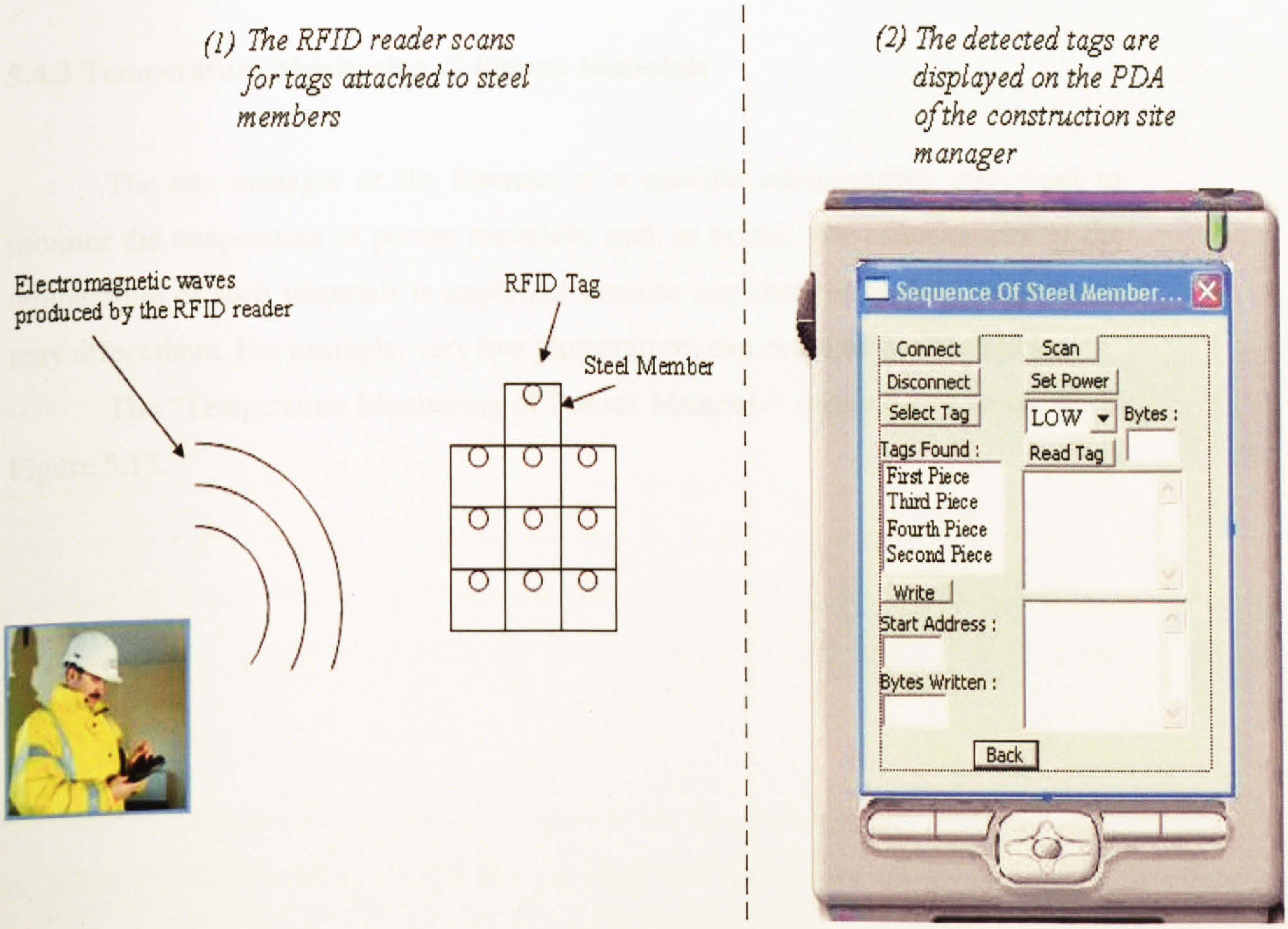


Fig. 5.12 Checking of Sequence of Steel Members

The steps of the scenario as shown in Figure 5.12 are the following:

(1) A pile of steel members arrives on the construction site. At the edge of each steel member there is attached an RFID tag. The foreman of the subcontractor for whom the steel members have arrived, wants to check which steel member is the first in the sequence which must be followed for the erection of the steel structure. He/she logs in to the appropriate graphical user interface and starts scanning in order to identify the first, second, third and so on steel member.

(2) Depending on the positions of the site manager/foreman, the orientation of the antenna of the RFID reader, the site manager or the foreman can approximately identify the location of the first member of the sequence of the steel structure, the second member, the third member and so on.

5.4.3 Temperature Monitoring of Porous Materials

The site manager or the foreman of a specific subcontractor may want to monitor the temperature of porous materials, such as bricks. The measurement of the temperature of such materials is important because any changes to their temperature may affect them. For example, very low temperatures can cause damage to bricks.

The "Temperature Monitoring of Porous Materials" scenario can be shown in Figure 5.13.

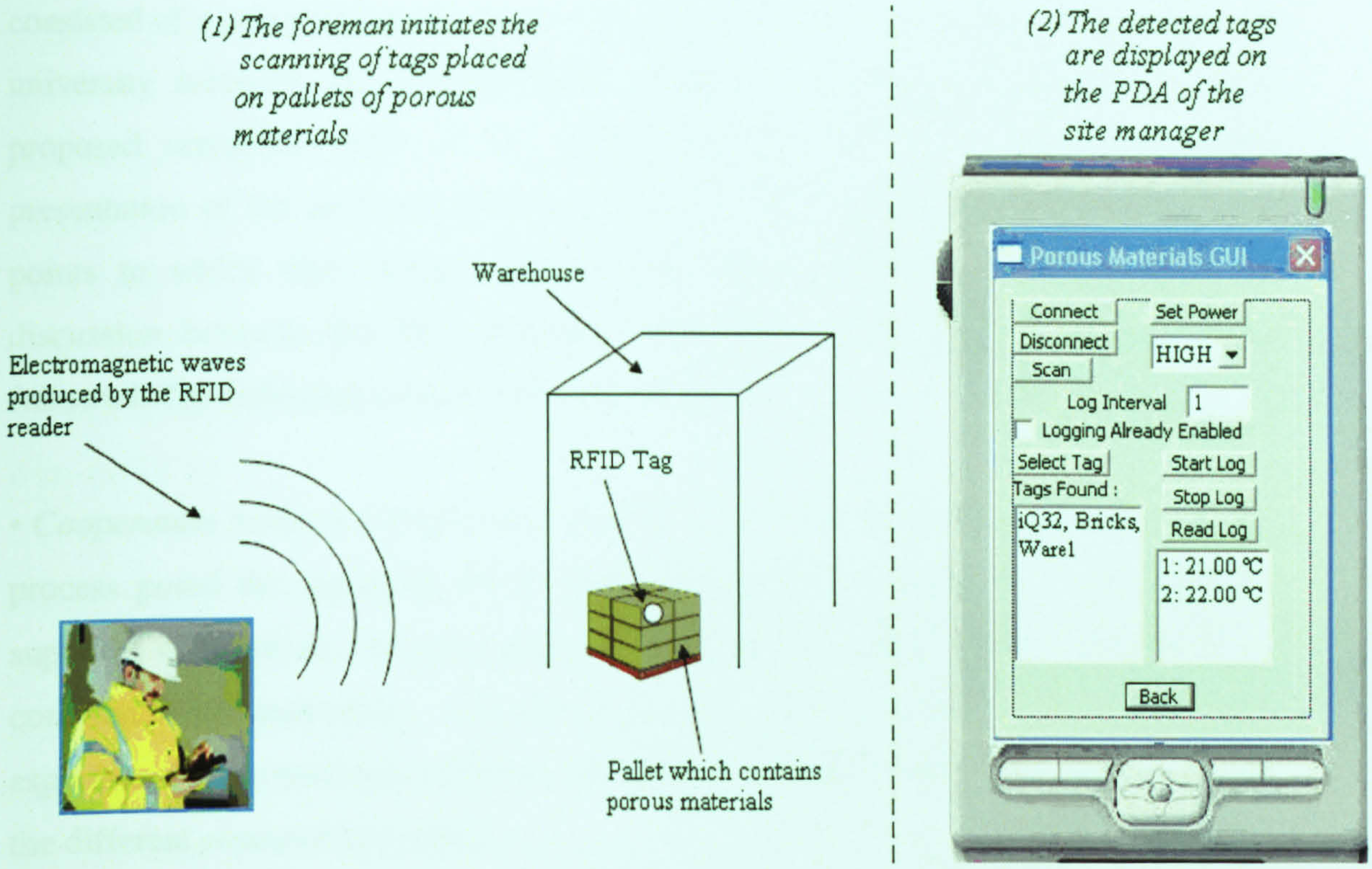


Fig. 5.13 Temperature Monitoring of Porous Materials

The steps of the scenario as shown in Figure 5.13 are the following:

(1) The foreman wants to check the temperature of a pallet of bricks. A very low temperature may affect the bricks. He/she logs in to the appropriate graphical user interface and scans for the tags which are placed on specific pallets of bricks. When the specific tag is detected, he/she can select it and start the measurement of the temperature.

(2) When the temperature information appears on the graphical user interface, it is automatically transferred and stored in a file for future retrieval.

5.5 Validation of Proposed Scenarios

The proposed scenarios have been examined by a group of six experts in order for their validity to be examined. The proposed scenarios have been examined by a group of six experts in order for their validity to be examined. The group of experts consisted of a university professor, post-doctoral researchers some of whom were also university lecturers and a professional engineer. During the validation of the proposed scenarios, each of the expert was provided with a detailed written presentation of the proposed scenarios. Each of the experts made comments to the points to which they thought they had to discuss with the PhD researcher. A discussion between the PhD researcher and each of the experts separately was followed. The following conclusions were derived:

• *Cooperation between Construction Parties*: Two of the participants in the validation process posed the argument that in reality it would be impossible to persuade the suppliers of materials, the main contractor and the sub-contractors to buy and use a common RFID technology. The reason for this is because it would be too costful especially for the materials suppliers who have to buy different RFID technologies for the different construction projects.

The proposed scenarios can be implemented in a way which does not require the materials suppliers to buy RFID products. Specifically, the construction site manager could distinguish the major materials suppliers for a specific construction project. In addition, he/she could cooperate with the materials suppliers in order to identify how many times a specific supplier will have to come to the construction site to deliver materials. In this case, he could give to each supplier a number of RFID tags which would be equal to the number of times each supplier has to come to the site. For example, if supplier A has to come to the construction site five times, the site manager will give to him five RFID tags. Every time, the specific supplier comes to the site, he brings back a specific tag until all the tags are returned to the construction site.

• *Cost*: Three participants raised the issue of the cost of implementation of RFID technology especially on large construction sites. The tagging of many items and the use of RFID readers which require the use also of PDAs and laptop computers is considered very expensive. The proposed scenarios assume that the most significant items on the construction site should be tagged. Also, there are RFID tags which are very small in size and very cheap. Any damage to these tags would not cause significant loss of money.

• *Cultural Issues*: One participant made the remark that it would be difficult for the construction personnel to quit traditional work practices and adopt a very new technology. They wouldn't for example like to quit using notes in order to use a PDA. In addition, the majority of workers are not familiar with modern technology and to train them on a specific technology would be expensive and it would require lots of time. The use of RFID technology is not so complex. In addition, a number of user-friendly graphical user interfaces can be developed for the interaction of the users with the RFID tags. Use of these interfaces would require basic training.

• *Applicability only to Large Construction Sites*: Two participants argued that the proposed scenarios can be applied only to large construction sites. A contractor on a small construction site would not like to spend money for the development of a construction supply chain using RFID technology because this would be expensive and in reality useless as small construction sites could be more organised than larger sites even without the need for use of an advanced technology.

The proposed research scenarios were developed for specific conditions. They do not correspond to all the aspects of the construction site. They are specific for a defined set of problems which occur under specific conditions. They are more applicable to large construction sites as this is where logistics and health and safety-related problems occur more often. This is because large construction sites are characterised by a large number of activities which involve many people.

• *How RFID Technology stands against other technologies such as bar-codes*: One participant argued that barcodes can achieve the same capabilities as RFID technology with less cost.

Unlike bar-coding, RFID technology is a new technology for the construction industry. However, barcodes are characterised by disadvantages in comparison to RFID technology. Specifically, the use of barcodes requires that the bar-code reader is in the line-of-sight of the bar-code. In addition, the reader must be within a distance of millimetres in order to be capable of scanning the bar-code. Bar-codes cannot store information. It is possible that they may act as pointers to specific databases but in this case, any information contained in such databases must be updated regularly and this would require much time. Also, bar-code communication is affected by the existence of metallic and non-metallic many objects. Furthermore, there are very inexpensive RFID tags which can have the form of a label. They can have the form of a bar-code but they can be characterised by more advanced capabilities (eg. storage of data).

5.6 Summary

The research is focused on the implementation of a specific wireless sensor technology to specific health, safety and logistics problems. The choice of construction logistics and health and safety as the fields for the development of scenarios occurred because logistics and health and safety are significant elements of construction projects. Examples of health and safety problems which exist on a construction site are the falls of workers from scaffolds, ladders or steel members, accidents related to excavations and confined spaces, accidents related to moving vehicles, hazardous substances and damaged electrical equipment. In construction logistics, problems exist in delivery of materials to the construction site, the distribution of materials to the different subcontractors on the construction site and the organisation of materials' inventories. The existence of the health, safety and logistics problems on the construction site was identified through the use of statistical results provided by the Health and Safety Executive (HSE), papers published in journals and conference proceedings and the realisation of visits to construction sites. The developed health and safety scenarios are the monitoring of hazardous substances on the construction site, the collection of hazard notifications as feedback to possible accidents, the protection of vehicles against 'dangerous' areas of the construction site, such as large excavation areas and the monitoring of collisions between vehicles and workers, between vehicles and between vehicles and equipment. For construction logistics, the scenarios which have been developed in this PhD thesis, are related to the delivery of materials on the construction site, their distribution to the different subcontractors on site and their future utilisation. Additionally, scenarios have been developed about the monitoring of the rate of use of materials, the monitoring of the temperature of porous materials and the checking of the sequence of steel members. For the proposed scenarios, data flow diagrams has been developed which show how the different roles on the construction site interact with each other and how the distribution of data between the different roles occurs. The validation of the proposed scenarios from a group of experts occurred through specific stages. During the first stage of the validation process, the experts were provided with a written presentation of the proposed scenarios. In the second stage of the validation process, there was a discussion between the PhD researcher and each of the experts related to the scenarios. The way the technology is used on the proposed scenarios shows how specific problems which could lead to fatal accidents could be solved and how the construction logistics process could become quicker and less error-prone combining many functions together. Even though there are arguments expressed about the adoption of RFID technology in the construction industry, there are many advantages which characterise the specific technology and which can benefit the construction process. Specifically, the use of RFID technology can provide automation and better collaboration between the different stages of the construction process.

Chapter 6: System Development

6.1 Introduction

The function of the system which was developed for this thesis, is based on the use of a number of graphical user interfaces which correspond to the different proposed scenarios and which allow communication between the user and the RFID tags. In this chapter, the architecture of the system is presented and the role of each graphical user interface is analysed. Also, the files which are connected to the graphical user interfaces and which store all the data collected from the RFID tags, are presented.

6.2 Choice of Development Environment

The components of the proposed system are hardware and software-related. The choice of the specific components was based on an investigation of a number of providers of RFID products. The main criterion for the selection of the used components was their flexibility for the development of RFID-based applications. The components of the development environment are discussed below.

6.2.1 Identec Solutions RFID Company

In order for the scenarios which were presented in Chapter 5 to be realised, a number of appropriate RFID products have been selected. A detailed analysis of the RFID market took place and a large number of companies were examined in order for the appropriate RFID products to be selected. Specifically, approximately hundred companies involved to the production of RFID technology were examined, among them Mannings, Gemplus, Texas Instruments and Atmel. The criteria which determined the appropriateness of the RFID products were the memory capability of the RFID tags, their cost and the ability of the selected RFID system to be programmed so that it could be adjusted to the requirements of each of the proposed scenarios.

The products which were selected are from an Austrian company called Identec Solutions. These products include a number of active RFID tags as well as RFID readers. The characteristics of the RFID tags used are shown on Table 6.1.

Table 6.1 Types of RFID Tags [Identec Solutions, 2005]

	Tag Name		
Tag Characteristics	**i- Q32T**	**i-Q8**	**i-D2**
- Energy derived from :	Battery powered	Battery powered	Battery powered
- Read/Write Ability :	Read/Write	Read/Write	Read/Write
- Read Range :	Up to100m	Up to100m	Up to 6m
- Data Storage :	32 Kbytes	32 Kbytes	64 bytes
- Frequency of Use :	915 MHz (USA) 868 MHz (UK) Dual Frequency (for transcontinental applications)	915 MHz (USA) 868 MHz (UK) Dual Frequency (for transcontinental applications)	Any
- Weight :	Bit-heavier than i-D2	Bit-heavier than i-D2	Light
- Size :	Bit-larger Than i-D2	Bit-larger Than i-D2	Small
- Lifetime :	Up to 6 years	Up to 6 years	Up to 6 years
- Applications :	Identification Tracking / Tracing Localization Temperature Monitoring	Identification Tracking / Tracing Localization	Identification Tracking / Tracing Localization
- Cost Ratio :	3	2.5	1

As Table 6.1 shows, i-Q32 and i-Q8 tags are characterised by large memory capacity and this makes them appropriate for use for all the proposed scenarios. Furthermore, the i-Q32 tag uses a temperature sensor and this makes possible the realisation of the scenario of the measurement of temperature of porous materials. In addition, all the three types of tags provide a read/write ability, thus it is possible for the user of the RFID system to write information to the tags, read information from them and re-write data to them. The i-D2 tag is characterised by a small tracking the user of the RFID system to write information to the tags, read information from them and re-write data to them. The i-D2 tag is characterised by a small tracking range and thus, they are appropriate for scenarios, such as collision monitoring. The cost of i-Q32 and i-Q8 tags are 69.80 Euros and 49.80 Euros respectively while the cost of an i-D2 tag is 22.20 Euros.

Two types of RFID readers were considered necessary: an i-Card3 RFID reader and an i-Port3 RFID reader. The i-Card3 RFID reader is a mobile RFID reader which can be connected to the PCMCIA slot of a laptop computer or a PDA. This reader is able to receive messages from i-Q8 or i-Q32 tags which are within a distance of 100 meters (300 feet) and from i-D2 tags which are within a distance of 6 meters (20 feet). The cost of the i-Card3 reader is 1140 Euros. The i-Card3 RFID reader with an antenna attached is shown in Figure 6.1.

Fig. 6.1 An i-Card3 RFID Reader [Identec Solutions, 2005]

The i-Port3 RFID reader can be placed at a specific point on a wall and operates continuously. It can collect data from hundreds of RFID tags and uses an anti-collision algorithm in order for hundreds of tags to be recognised simultaneously. Additionally, the i-Port3 reader can communicate serially or wirelessly with a host computer system. The tracking of RFID tags from the iPort3 is achieved through the use of specific antennas which are linearly polarized. Depending on the way these antennas are placed, the field of each of the antennas is either vertically or horizontally polarized. The i-Port3 uses a Real-Time Operating System and an internal Real-Time Clock which allows the accurate time allocation of the data. It can temporarily store up to 2048 data messages. The cost of the i-Port3 reader is 3900 Euros while the price of each antenna is 167 Euros [Identec Solutions, 2005]. The connections between the i-Port3 and its antennas are shown in Figure 6.2.

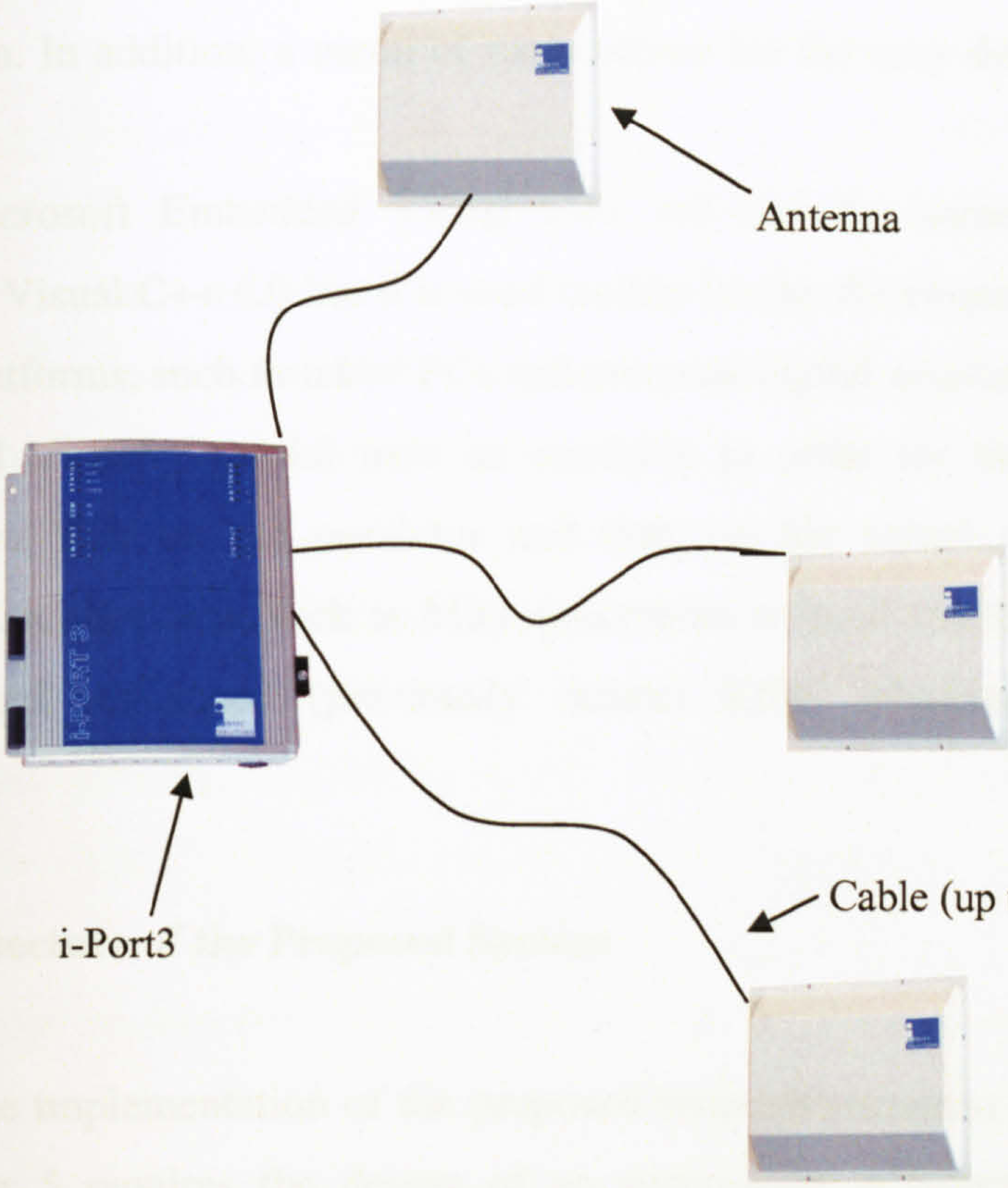


Fig. 6.2 An i-Port3 RFID Reader using three linearly polarised antennas
[Identec Solutions, 2005]

6.2.2 Programming Languages

The development of user applications is achieved through the use of the Identec Solutions Software Development Kit (SDK). This Software Development Kit provides a number of functions which describe many aspects of the data exchange that occurs between the RFID readers and tags. Specifically, these functions may cover aspects such as connection/disconnection to the RFID reader, adjustment of the sensitivity of the reader, types of scan and reading from and writing to the RFID readers. The user is capable of developing a user interface using visual programming languages, such as Visual C++ or Visual Basic .NET and Visual C# and call the functions provided by the Identec Software Development Kit in a way that the requirements of his/her project are covered [Identec Solutions, 2003].

The programming languages which were used during the design of the system are Microsoft Visual C++ 6.0 and Microsoft Embedded Visual C++ 4.0. Microsoft

(IDE) and provides a user-friendly wizard for the development of a specific application. In addition, a menu of tools allows for the easy design of graphical user interfaces.

Microsoft Embedded Visual C++ 4.0 has the same characteristics with Microsoft Visual C++ 6.0 but it is used mainly for the development of applications on mobile platforms, such as tablet PCs and personal digital assistants (PDAs). Microsoft Embedded Visual C++ 4.0 uses an emulator in order for the user to test his/her applications first on the emulator and then on the actual device. A number of processor architectures, such as Microprocessors without Interlocked Pipeline Stages (MIPS) and Advanced (previously Acorn) RISC Machines (ARM), are also supported.

6.3 Architecture of the Proposed System

The implementation of the proposed research scenarios which were presented in Chapter 5 requires the design of an appropriate architecture for the proposed system. This architecture will enable the efficient use of RFID technology in the satisfaction of the requirements of the proposed scenarios.

6.3.1 Components of the Proposed System

The main components of the proposed system are listed below :

- from a hardware point-of-view:

  - RFID readers: either the iCard3 or the iPort3 depending on the scenario
  - RFID tags: either the i-Q32, i-Q8, or i-D2 tags depending on the scenario
  - laptop PC,
  - Personal Digital Assistant (PDA).

- from a software point-of-view:

  - graphical user interfaces corresponding to the various scenarios,
  - Notepad files for the storage and retrieval of RFID tag data.

6.3.2 Topology of the Proposed System

The main elements of the topology of the proposed system are the RFID readers (i-Card3, i-Port3), the antennas of the i-Port3 reader, an Access Point for the development of a wireless network, a Wi-Fi card and the i-Q8/i-Q32/i-D2 RFID tags. The i-Port3 is fixed at a specific point and is connected to its three antennas through cables approximately 2 meters long.

Since the i-Port3 has an IP address and a port number, it can be connected to the access point and form a wireless network. A laptop or tablet PC can be connected to the i-Port3 RFID reader by being connected first to the wireless network. The PDA can also be connected wirelessly to the i-Port3 by being connected to the specific wireless network. Wi-Fi cards can be used by laptops in order to connect to the wireless network.

Based on the requirements of each of the proposed scenarios and considering also the capabilities of each of the selected RFID products, a number of conclusions have been developed on how the topology of the proposed system could be formed :

- i-D2 tags can be placed on the trucks which are used by each sub-contractor.

- An i-D2 tag can also be placed on the shirt or on the helmet of each worker so they can be easily tracked by an RFID reader.

- i-Q8 RFID tags can be placed at the excavation areas and to the areas with major risk for accidents.

- An i-Q8 RFID tag can be placed at each warehouse of the subcontractors. However, the sub-contractor can ask for the placement of one i-Q8 RFID tag to one warehouse and in this tag he can put data covering all his remaining warehouses.

- An i-Q8 RFID tag can be placed at each chemical warehouse. However, if all the chemical warehouses on the construction site are full and there are remaining barrels of chemicals, then these chemicals should be stored at a specific place temporarily and on each barrel, an i-Q8 RFID tag should be fixed.

• For every warehouse which stores only porous materials, such as bricks, an i-Q32 RFID tag should be provided. If the pallets of porous materials are stored with pallets of other materials, then again an i-Q32 RFID tag should be provided which will be placed into the warehouse.

Also, the construction site manager must distinguish the major materials suppliers for the construction site and the times each of these suppliers will deliver materials to the construction site. In this case, he lends each of them a number of i-Q8 RFID tags which are equal to the number of times the specific supplier has to deliver materials to the construction site. Every time each supplier delivers his materials to the construction site, he returns an i-Q8 RFID tag which was given to him by the construction site manager. If a supplier has to deliver porous materials, then an i-Q32 RFID tag should be provided to him.

The topology of the proposed system can be shown in Figure 6.3. This figure represents the topology of the system depicting mainly its hardware elements.

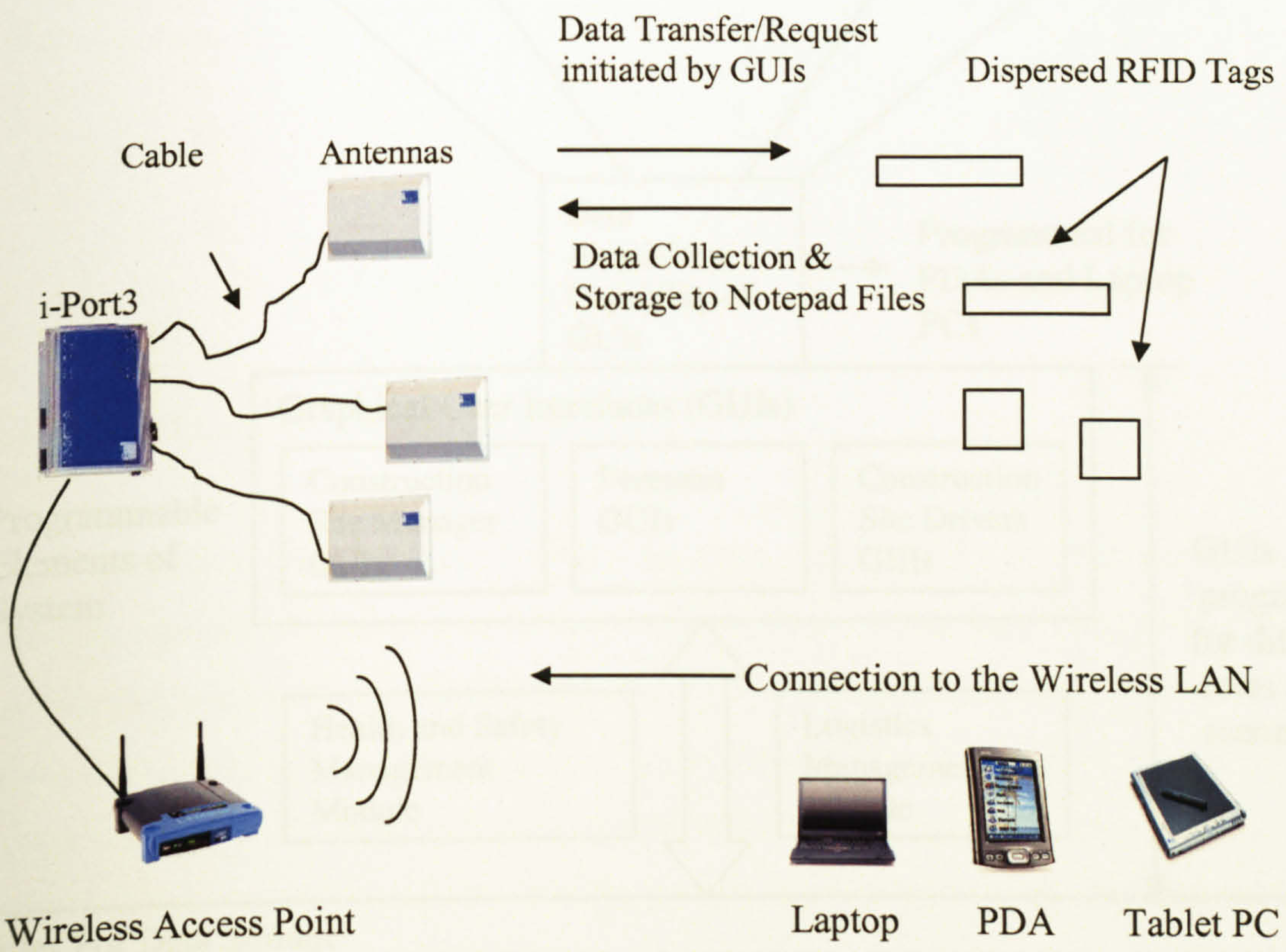


Fig. 6.3 System Topology

The mobile devices (laptop, PDA, tablet PC) shown in Figure 6.3 can use the i-Card3 RFID reader instead of connecting to the i-Port3 RFID reader through the wireless local area network. The use of the i-Card3 reader with laptops and tablet PCs is easy since it requires only the attachment of the reader to the PCMCIA slot of the laptop or the tablet PC. However, especially for the case of PDAs, the proposed system considers that these devices should be connected only to the i-Port3 reader. This is because the use of the i-Card3 reader with the PDA requires an extension PCMCIA slot to be attached first to the PDA. However, this technology is not very popular and thus major companies which construct PDA accessories aim in ending the production any more extension PCMCIA slots for PDAs in the future.

A more comprehensive diagram of the topology is shown in Figure 6.4, which depicts the role of the graphical user interfaces.

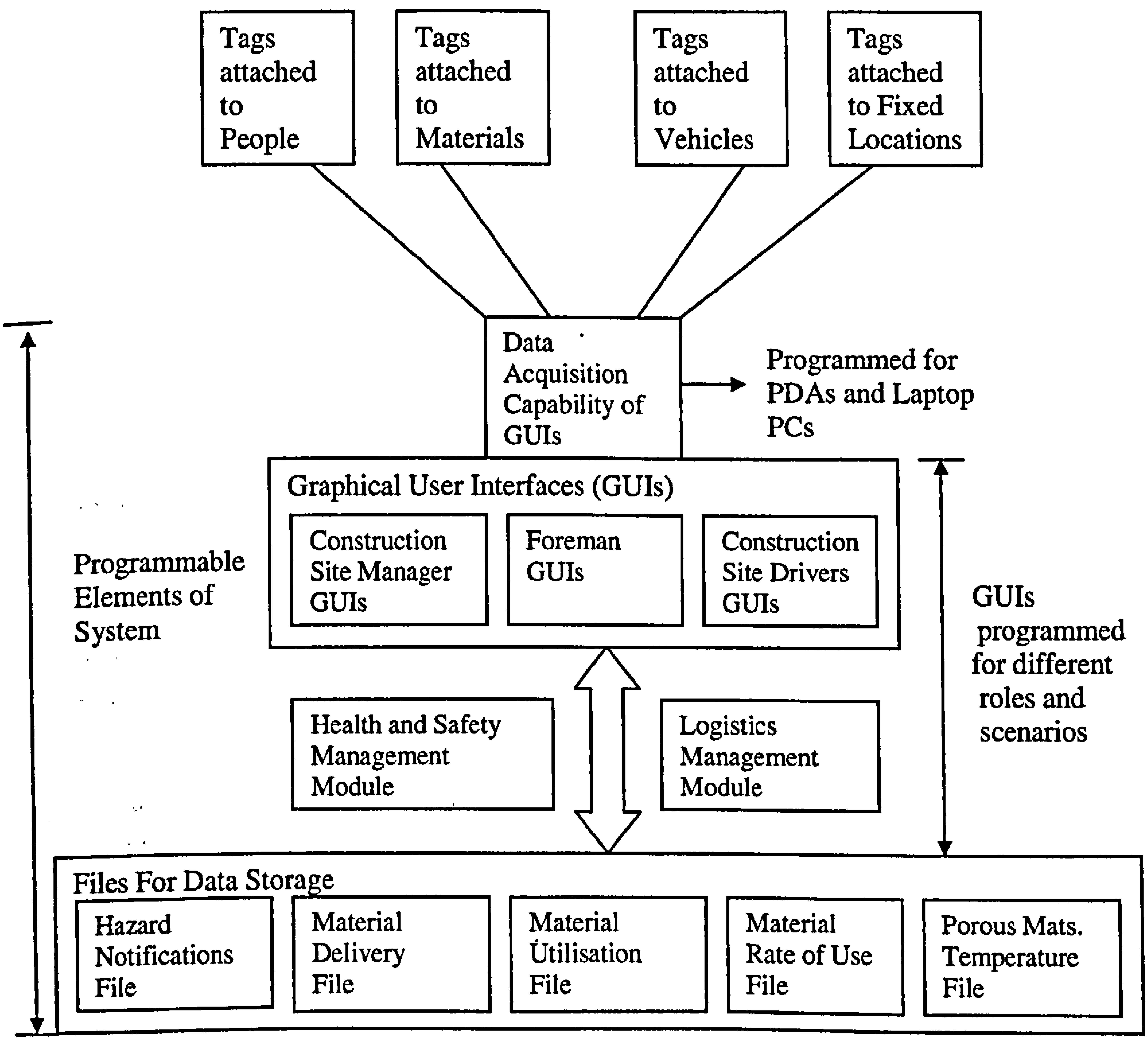


Fig. 6.4 Topology of Proposed System showing its various Software Elements

Figure 6.4 shows the role of the graphical user interfaces and their connection to a number of files for data storage purposes. These files are classified according to the type of data they store. RFID tags are attached to different locations and they are used to transmit data to different graphical user interfaces depending each time on the used scenario.

6.4 Development of Data-Acquisition Software

The data collected from the RFID tags need to be classified and stored depending on the different tasks and operations performed on the construction site. For this purpose, graphical user interfaces (GUIs) and files used for data storage have been designed for use in the specific research. The relationship between the graphical user interfaces and the files for data storage is shown in Figure 6.5.

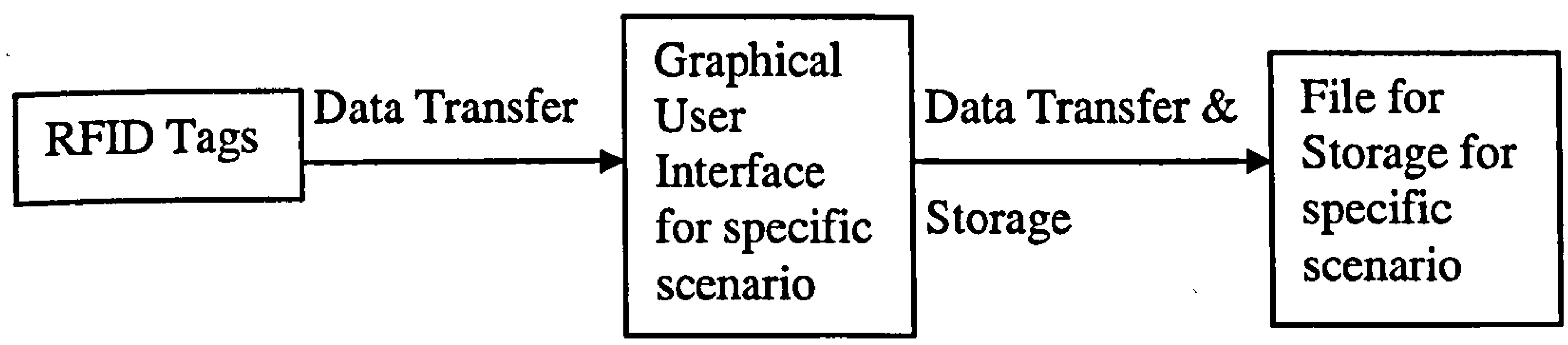


Fig. 6.5 Connection between GUIs and Storage Files

6.4.1 Graphical User Interfaces (GUIs)

Graphical User Interfaces (GUIs) are very significant for the specific research since they enable the interaction of the user(s) with the RFID tags. Especially for the people who work on a construction site, the use of a simplified software system which allows easy access to information is of great importance. For each of the proposed scenarios, a specific graphical user interface has been designed. Although all the graphical user interfaces follow a similar format and use some common buttons, they are programmed to perform different functions.

The graphical user interfaces provide a number of options for the user. The first step is the connection to the reader. The site manager can select the type of reader he/she wants to use - it can be either the iCard3 or the i-Port3. By pressing the button

"Connect", the connection to the reader is established. The disconnection from the RFID reader is also possible by pressing the button "Disconnect". The user can also scan for tags. By selecting the type of scan which can be complete, quick or complete with blink and the type of tags to be scanned which can be i-Q8/32, i-D2 or both, the scanning for tags can occur. Also, the user is capable of changing the sensitivity of the reader by changing the level of electromagnetic power emitted by it, from low to medium or high. Continuous scanning of tags can also occur. Specifically, in this case, the reader scans for tags, then it stops for a minimal period of time and it does a re-scan. Before any scanning or continuous scanning for RFID tags occurs, the type of scan and the type of tags to be scanned must be specified.

The writing of data to the tags is achieved through the specification of a specific address called "Start Address" which is the initial point in the memory of the tag in which information will be written. The user must also specify the number of bytes of memory which are going to be used. The user can then write the data to the appropriate edit box on the graphical user interface and then click the button "Write" in order for these data to be written to the tag. The next time the user intends to write data to the same tag, he/she must define a new start address which will be the point on the memory of the tag in which the last letter of the previously written data is stored. The user can read data from an RFID tag by first defining the number of bytes which he/she wants to read and then by pressing the button "Read Tag Data".

6.4.1.1 Graphical User Interface for the Construction Site Manager

A graphical user interface has been designed especially for use by the construction site manager. The graphical user interface can be used on a laptop or a tablet PC. It can also be used on a PDA providing the same functionality but, in this case, using a different format. The graphical user interface which is designed for the site manager can scan for any tags on the construction site and for tags which correspond to specific scenarios. The site manager acts as the administrator of a computer network. He/she can also access the information contained in them.

• Construction Site Manager 's GUI on a Laptop/Tablet PC

The graphical user interface which is used by the construction site manager and which is installed on a laptop or a tablet PC is shown in Figure 6.6.

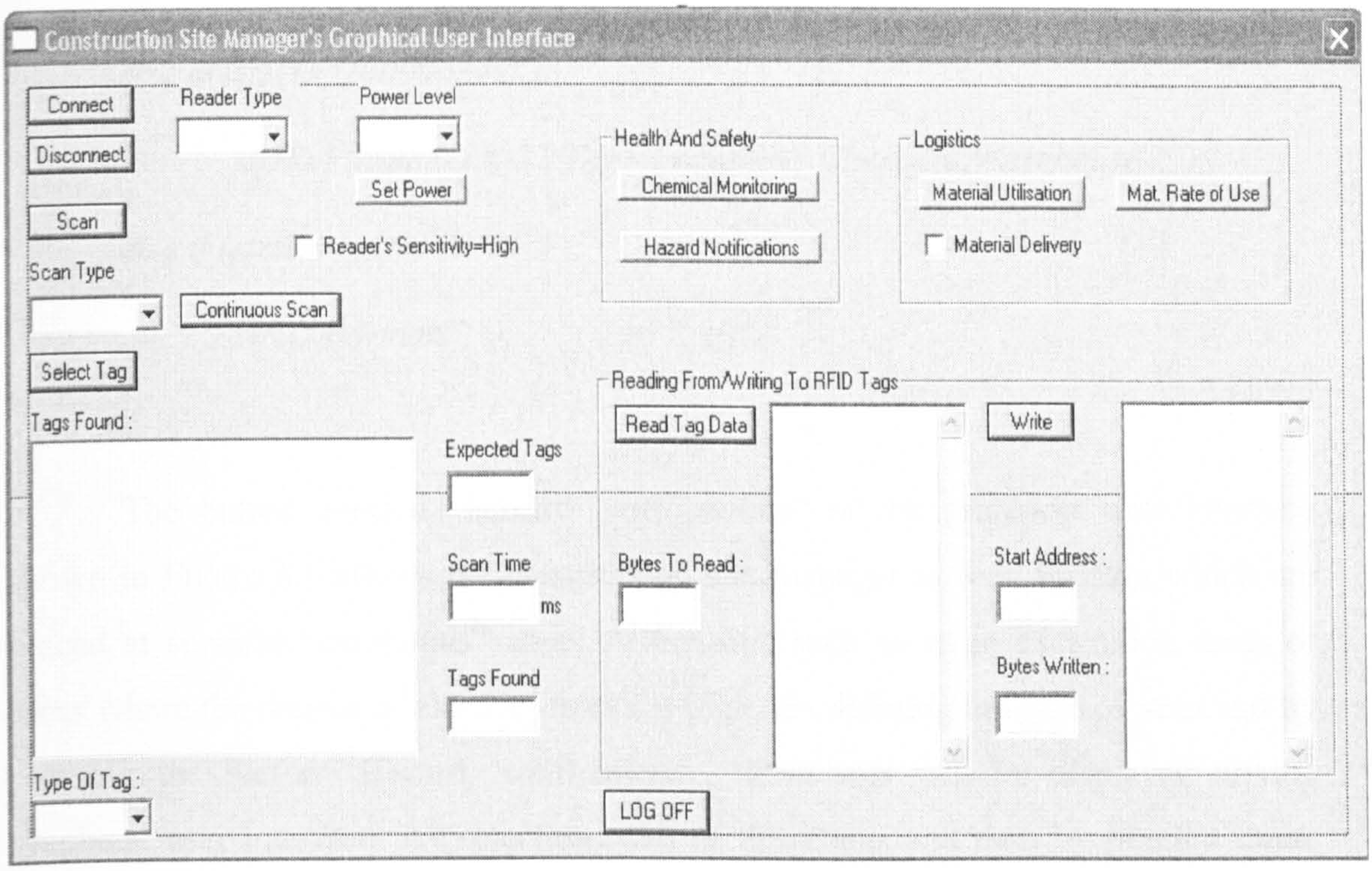


Fig. 6.6 GUI of Construction Site Manager on Laptop/Tablet PC

The graphical user interface of Figure 6.6 shows to the user which buttons correspond to the health and safety scenarios and which buttons correspond to the logistics scenarios. The button entitled "Chemical Monitoring" allows the scanning of the tags attached to barrels of chemical substances forgotten on site and also the scanning of those tags that are placed in chemical warehouses. Specifically, by defining the type of the scan and then by pressing the button "Chemical Monitoring", the RFID tags which are placed on barrels of chemical substances or in chemical warehouses will be displayed. The site manager can then select one of these tags and by pressing the button "Select Tag", he/she can initiate communication with them. In this case, he/she will be able to read the information contained in each tag by using the button "Read Tag Data".

The Visual C++ 6.0 code which shows how the tags which are in chemical warehouses are distinguished from other RFID tags is as follows :

```
if(strID="200111127")
{
        strID.Format("i-Q8 Tag - Location : Chemical Warehouse 1");
}
else if(strID="200096742")
{
        strID.Format("i-Q32 Tag - Location : Chemical Warehouse 2");
}
else if (strID="100092074")
{
        strID.Format(" ");
}
```

The button entitled "Hazard Notifications" of the graphical user interface shown in Figure 6.6 allows the construction site manager to scan for tags which are placed at specific "dangerous" areas on the site, such as large excavation areas or areas where the danger of electric shocks is high. By defining the type of scan and by pressing the button "Hazard Notifications", these tags will be displayed on the graphical user interface. By selecting each of these tags and then by pinging them, he/she will be able to read the information contained in them. When this information is displayed on the graphical user interface, it is automatically transferred to a file entitled "Hazard Notifications.txt".

The box entitled "Material Delivery" and the button "Continuous Scan" in Figure 6.6 enable the RFID reader to perform continuous scans for tags which correspond to materials that have arrived on site. Specifically, by ticking the box entitled "Material Delivery" and by pressing the button "Continuous Scan", the construction site manager will enable the RFID reader to continuously scan for tags attached to materials delivered on the construction site. In this case, when a tag is detected by the reader, its type and its location along with the date and the time of detection are sent and stored in the "Materials Delivery.txt" file. The location of the tag is considered to be static and not dynamic. Since RFID technology is not able to provide coordinates of locations, each tag has a static location. Before the design of the system, the researcher considers where each tag is located and programs the system to display this specific location when the tag is detected by the reader.

The button "Material Rate of Use" enables the RFID reader to scan for tags which are placed in the warehouses of the sub-contractors. By specifying the type of scan and by clicking the button "Material Rate of Use", the tags which are placed in the warehouses of the subcontractors will be displayed on the graphical user interface. The site manager can highlight the name of one of these tags as it appears on the graphical user interface, press the button "Select Tag" and then read its contents which will display the exact quantities of materials which are spent by each sub-contractor. Each subcontractor needs to put these information on the tag before they can be read by the site manager. When these data are displayed on the graphical user interface, they are automatically transmitted to the file "Material Rate Of Use.txt" in which they are stored for future retrieval.

The button entitled "Material Utilisation" enables the construction site manager to check how a material is going to be used when it is delivered to its destination on the construction site. The site manager can request the RFID reader to scan for tags which correspond to materials which have arrived on the construction site and by selecting each of these tags, he/she can read the information which is included in them. When this information is displayed on the graphical user interface, it is automatically transmitted to the "Material Utilisation.txt" file.

- Construction Site Manager's Graphical User Interface for Use on PDAs

When the construction site manager uses a PDA, a menu which consists of options for selecting a number of graphical user interfaces is installed on the PDA. Each of these graphical user interfaces corresponds to different scenarios. Specifically, the options which are included in the menu are the following : Monitoring of Hazardous Substances, Hazard Notifications, Material Rate of Use, Material Delivery, Material Utilisation, and General graphical user interface.

By selecting the option "Monitoring of Hazardous Substances", the following graphical user interface appears (Figure 6.7) :

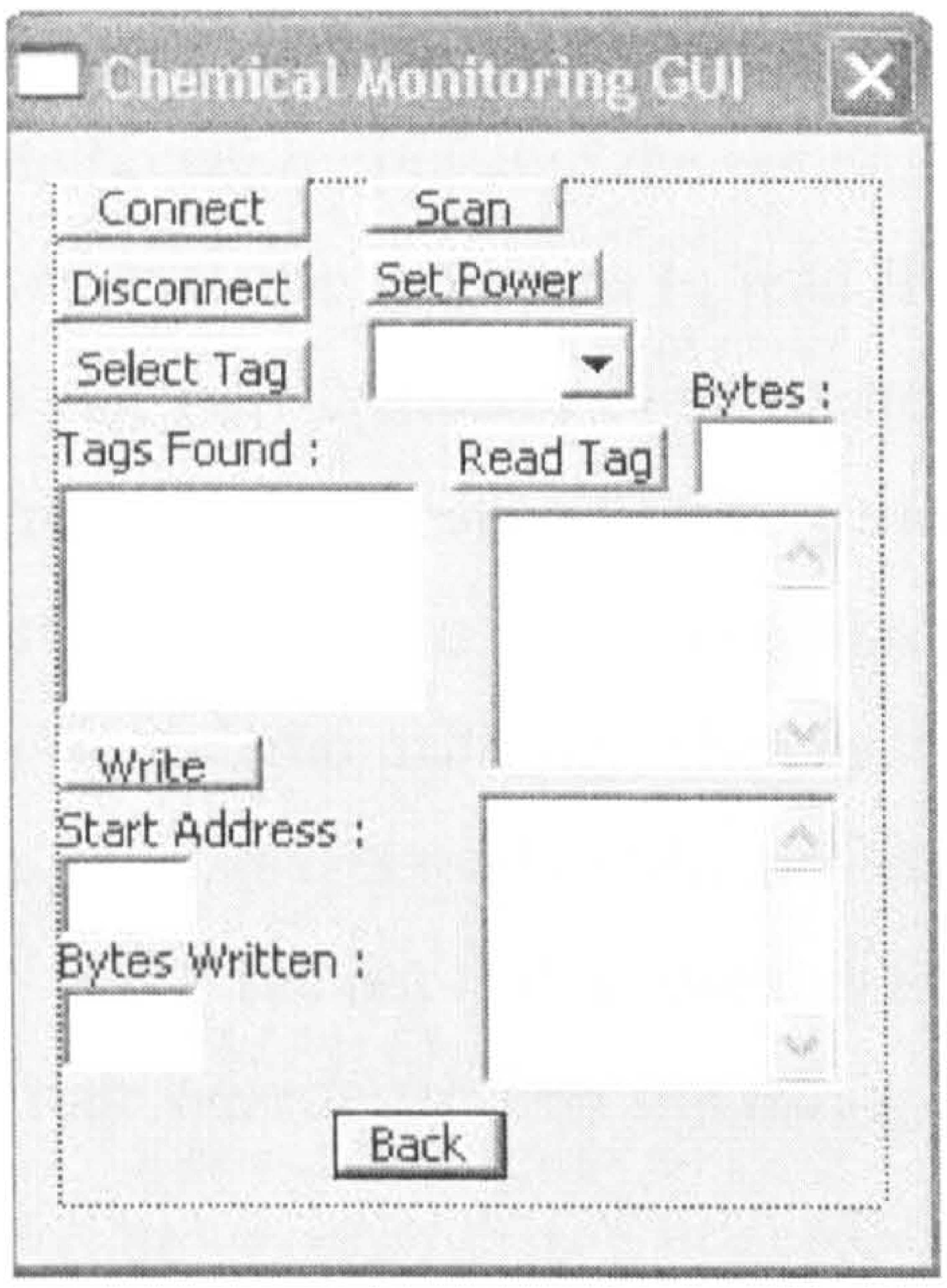


Fig. 6.7 Chemical Monitoring GUI for Construction Site Manager on PDA

The graphical user interface is programmed to scan for tags which are placed on barrels, cans or bags of chemicals or in chemical warehouses. The graphical user interfaces which appear by clicking on the other options of the menu, have exactly the same format as the graphical user interface shown in Figure 6.8. However, each of these graphical user interfaces is programmed to perform a different operation. The purpose of use of each of these graphical user interfaces has been presented in Chapter 5.

When the construction site manager uses the "Hazard Notifications" graphical user interface, a number of tags which are placed on specific "dangerous" areas of the construction site, such as large excavation areas or in areas of the site where there is risk for electric shock, are displayed. By defining the number of bytes, the construction site manager can read the information which is included in the specified tags. By pressing the button "Read Tag", this information will not only appear on the graphical user interface but at the same time a file entitled "Hazard Notifications" will be created and the information which appears on the graphical user interface will be immediately stored in this file.

In order to check the rate of use of a specific material, the construction site manager uses the "Material Rate Of Use" graphical user interface which is programmed to scan for tags which are placed in the warehouses of the subcontractors. In this case, the construction site manager has to initiate the communication with a specific tag by pressing the button "Select Tag". He/she then has to define the number of bytes he/she wants to read from the tag and finally by pressing the button "Read Tag", the contents of the selected tag which will show the quantities of specific materials spent over specific time periods, will be displayed. The information which is included in the tag is stored in a Notepad file entitled "Material Rate Of Use.txt" which is created automatically when the contents of the tag appear. Whenever the construction site manager reads again the data included in the tag, these data will be saved in the Notepad file but in this case this file is not re-created since it has been created the first time the construction site manager read the contents of the tag.

In this Notepad file, the information which is included in the tag is stored along with the time and date of this information appearing on the graphical user interface. The "Material Rate Of Use.txt" file can store unlimited information in a structured way. Specifically, data related to different materials appear in separate lines in the file along with their respective time and date.

The "Material Delivery" graphical user interface is used for the scanning of tags which are placed on lorries that deliver materials to the construction site. In this case, the construction site manager needs to connect to the RFID reader and scan for tags placed in lorries in order to identify when there is a delivery of materials. By pressing the button "Cont. Scan" which is included in this graphical user interface, the reader will be set to execute continuous scans for tags placed on lorries which come to the site to deliver materials. The specific graphical user interface is programmed to scan for tags which are placed on lorries loaded with materials and coming from specific materials suppliers. When such a tag is detected by the RFID reader, the tag type, the label number of the lorry to which it is placed and the time and date of its detection from the reader is stored in the "Material Delivery" database.

6.4.1.2 Graphical User Interfaces (GUIs) for the Foreman

A graphical user interface has been designed especially for use by the foreman. This graphical user interface can be used either on a laptop or a tablet computer. The specified graphical user interface is characterised by the use of fewer buttons in comparison to the buttons used by the graphical user interface of the construction site manager. However, the graphical user interface allows the scanning of all the tags used on the construction site.

• Foreman 's Graphical User Interface installed on a Laptop/Tablet PC:

This graphical user interface is shown in Figure 6.8.

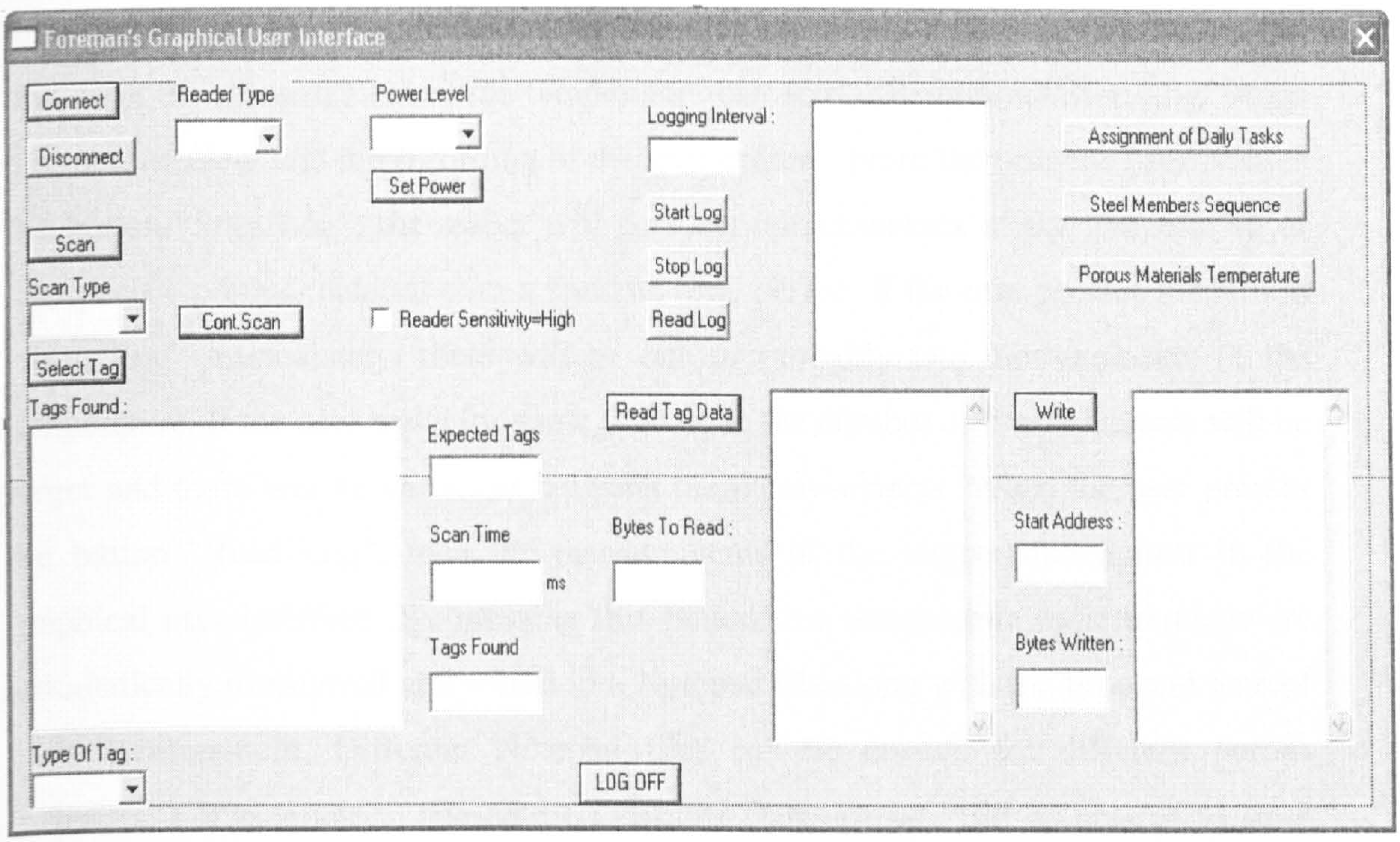


Fig. 6.8 Graphical User Interface for the Foreman

The button entitled "Assignment of Daily Tasks" enables the scanning of tags which are placed on the trucks used by a specific sub-contractor. By defining the type of scan and then by pressing this specific button, the tags on the trucks of the drivers under his/her supervision will be displayed. If the foreman selects one of these tags and pings it, he/she will be able to write information to it, such as the next day's task list for the driver.

The button entitled "Steel Members Sequence" allows the scanning of tags which are placed on steel members. By pressing this button, the reader will scan only for these tags ignoring other tags. The user can adjust the power level so that the reader can scan for more tags which are attached to steel members even over longer distances. When the tags of some steel members are detected, the user can clarify which tags belong to which steel member by selecting a specific tag and by pressing the button "Select Tag". When he/she does this, a small LED on the tag will light for a second.

The button entitled "Porous Materials Temperature" allows scanning for tags which are placed on porous materials. When these tags are displayed, the user can select each of these tags and then press the button "Ping". In this case, communication with the specified tag will be established and the user can start the measurement of the temperature of the porous material. The first step is to press the button "Start Log". In this case, the measurement of the temperature can start. The button "Stop Log" stops the measurement and the recording of the temperature. From the time the user presses the button "Start Log", the reader will perform measurements of the temperature of the specific porous material over a specific time period. If the user presses the button "Stop Log" immediately, there will be one or probably two measurements of the temperature. If the user waits for some time, then the number of measurements will be larger and there will be variances between the measurements. When the user presses the button "Read Log", then the measurements of the temperature appear in the graphical user interface. By pressing this button, the temperature measurements are automatically transferred and stored in a Notepad file along with the time and date of each measurement. Different Notepad files can be created for different porous materials. For example, a file entitled "Bricks Database.txt" can be created to store temperature information for the bricks stored on the construction site.

• Foreman's Graphical User Interface on a PDA:

The graphical user interface for PDAs used only by the foreman is based on the use of a menu. This menu has three options : Assignment of Daily Tasks, Additional Operations (which includes the following two sub-options: Checking of Sequence of Steel Members, Temperature Monitoring of Porous Materials), and General graphical user interface. When the foreman decides to login to a graphical user interface on his/her PDA, he/she sees a menu which offers the previously mentioned options. In this case, by selecting the first option, the "Assignment of Daily Tasks" graphical user interface appears. The graphical user interfaces which are used on the PDA of the foreman have exactly the same functionality as the buttons which are found on the graphical user interface of the foreman's laptop and which have been described in the previous section. Their format is also the same as the format of the graphical user interface shown in Figure 6.8.

6.4.1.3 Graphical User Interface for the Construction Site Drivers

According to the proposed scenarios, the construction site drivers use only PDAs, thus their graphical user interface has been designed using Embedded Visual C++. The format of this graphical user interface is the same as that of the graphical user interface shown in Figure 6.8. The only difference is that the graphical user interface for the construction drivers includes one more button entitled "Cont. Scan" which allows the driver to perform continuous scanning of tags. This is useful especially when the drivers wants to avoid collisions with workers or other vehicles when he/she executes a task on a specific task or drives from one destination to another on the construction site. Also, it is important because by pressing this button, the driver can be warned that there is a "dangerous" area, such as a large excavation area close to him/her.

The accuracy in the detection of such tags depends on the level of sensitivity of the RFID reader which can be defined by the driver of the vehicle. If the driver wants to execute a task on a small area, then it is preferable to set the power level to 'LOW', while if the driver wants to drive the vehicle from one destination to another, then he/she can set the power level to either 'HIGH', 'MEDIUM' or 'LOW'. However, since the tags which are attached to the construction workers and the vehicles which operate on the construction site, are i-D2 tags, the maximum range of detection of these tags from the RFID reader is six meters. It depends on the driver of the vehicle if he/she wants to have this detection range for all the other vehicles and the construction workers or if he/she wants to have a lower detection range.

The graphical user interface of each construction site driver is programmed to scan for specific tags. For example, it is able to scan for the tags of all the vehicles which operate on the construction site, of all the construction workers and of specific "dangerous" areas on the construction site, such as large excavation areas. The RFID reader to which the graphical user interface of the driver is connected, is able to detect other tags also, but these tags do not appear on the graphical user interface.

6.4.2 Connection of Graphical User Interfaces to Notepad Files for Data Storage Purposes

The graphical user interfaces which allow connection to files for data storage purposes are those of the construction site manager and the foreman. These data storage files are important because they allow the safe storage of large quantities of information and the quick and easy retrieval of this information for future use.

6.4.2.1 Connection of the Construction Site Manager 's Graphical User Interfaces to Data Storage Files

The graphical user interfaces which are used by the construction site manager and which can be used on laptops and PDAs respectively, allow the transmission of data related to specific aspects of the construction process. The Notepad files which are connected to each of the graphical user interfaces of the site manager and which are used for data storage are the following : "Material Delivery.txt", "Hazard Notifications.txt", "Material Rate Of Use.txt". These files are analysed below :

- "Material Delivery.txt" Notepad File

This is a file which is used for the storage of information related to the arrivals of materials on the construction site. It is a Notepad file which can store unlimited information and is created automatically when the site manager presses for the first time the button entitled "Material Delivery". The site manager can create this file even before he/she starts using the graphical user interface.

The information which is stored in this file has the following format :

<Type of Tag>, <Material Supplier>
<Date>, <Time>

An example of the Visual C++ 6.0 programming code which describes the creation of the 'Material Delivery.txt' file and the transfer of data to it, is shown below :

```
if(strID=="200111127")
```

```
{
        out1.open("C:\\Material Delivery.txt", ios::app);
        strID.Format("i-Q8 Tag - Location : Lorry AZ2 3HX");
        out1 << "i-Q8 Tag - Location : Lorry AZ2 3HX" << endl;
        out1 << (asctime (timeinfo)) << endl;
        out1.close();
}
```

The respective code in Embedded Visual C++ 4.0 is the following :

```
const char* file_name = "Material Delivery.txt";
FILE* fd = fopen(file_name, "a");

if(strID=="200111127")
{
        strID.Format(_T("iQ8,Supplier1"));
        fprintf(fd, "iQ8,Supplier1", dwID);
        fprintf(fd, "%d", nHour);
        fprintf(fd, "%d", nMinute);
        fprintf(fd, "%d", nSecond)
        fprintf(fd, "%d", nYear);
}
```

• "Hazard Notifications.txt" Notepad File

The "Hazard Notifications.txt" Notepad file is used for the storage of data generated from tags placed on "dangerous" areas of the construction site, such as excavation areas or areas where there is danger of electric shocks. This file can store unlimited amount of data.

The information which is stored in the specific file has the following format :

<Type of Tag>, <Type of Dangerous Area>

<Date>, <Time>

There may be one file which can store all the information from the tags of all the excavation areas or there may be separate Notepad files for each dangerous area.

• "Materials Rate of Use.txt" Notepad File

The "Materials Rate of Use.txt" Notepad file is a file which stores information about the amount of materials used by each subcontractor. This file can store file is the following :

<Type of Tag>, <Type of Material, Storage Area of Material, Name of Subcontractor>

<Date>, <Time>

There may be one file which can store information from the tags attached to the warehouses of all the subcontractors or there may be separate files corresponding to different subcontractors. The second case is better because the information is better organised.

6.4.2.2 Connection of the Foreman's Graphical User Interfaces to Data Storage Files

The graphical user interfaces which are used by the foreman and which can be used either on laptops or personal digital assistants, are each of them connected to a file which is used for the storage of temperature measurements of porous materials. This file is called "Temperature Monitoring of Porous Materials.txt" file.

• "Temperature Monitoring of Porous Materials.txt" Notepad File

The "Temperature Monitoring of Porous Materials.txt" Notepad file is used for the storage of data related to measurements of the temperature of porous materials, such as bricks along with the date and time of each specific measurement. This file can store unlimited amount of data. A separate "Temperature Monitoring.txt" Notepad file can be created for each of the porous materials. The format of data which are stored in the Notepad file is the following:

<Temperature Value> <Time> <Date>

The Visual C++ 6.0 programming code which is used for the creation of the "Temperature Monitoring" file is shown below :

```
out2.open("C:\\Temperature Monitoring of Porous Materials.txt",
        ios::app);
strVal.Format("%d:    %02.2f(Celsius)", i+1, fTemperature);
out2 <<fTemperature << " Celsius" << endl;
out2.close( );
```

The respective Embedded Visual C++ 4.0 programming code is the following:

```
const char* file_name = "Temperature Monitoring of Porous Materials.txt";
FILE* fd = fopen(file_name, "a");
            •
            •
            •

for(UINT i=0; i<iTLog.GetEntryCount(); i++)
{
            iTLog.GetLogEntry(fTemperature, i);
            strVal.Format(_T("%d: %02.2f(Celsius)"), i+1, fTemperature);
            fprintf(fd, "%d: %02.2f(Celsius)", fTemperature);
            m_ListTemperatureLog.AddString(strVal);
}
```

6.5 Summary

The development of the system was based on the identification of the necessary RFID elements, the design of the appropriate topology to the system, and the development of RFID tag data acquisition software. The choice of the hardware and software elements was based on a number of criteria, such as the memory capability of the selected RFID tags and the capability offered by the manufacturer of the RFID products to program the operation of the RFID equipment so that it could be adjusted to the requirements of the proposed scenarios. The products of approximately hundred companies were reviewed and email communication was established with some of them to assess their products. The company which was selected for the provision of RFID equipment was the Austrian company, Identec Solutions. This selection occurred after a month of telephone communication with the company in order for specific issues related to their products to be discussed. The products acquired were two RFID readers, a number of active RFID tags characterised by different memory capabilities and a software development kit which is necessary for the programming of the selected RFID equipment.

The topology of the system had to correspond to the requirements of each of the proposed scenarios. The main elements of this topology are the RFID readers and tags, a number of graphical user interfaces designed appropriately for the requirements of each of the proposed scenarios and Notepad files used for the storage of data from the RFID tags. Depending on the needs of the scenario, each graphical user interface is programmed to scan for specific tags. Additionally, the functionality of each of the graphical user interfaces depends on the role of the person who uses the graphical user interface. The graphical user interface of the construction site manager provides more operations in comparison to the foreman's graphical user interface. Furthermore, the operations associated with the graphical user interface of the construction site manager are more significant to those of the foreman because they involve the whole construction site and not only the area of a specific subcontractor. The connection of each of the graphical user interfaces to a Notepad file allows the quick storage of data received by the RFID tags. Each of the Notepad files stores specific information from specific tags and as a result better classification of the RFID tag data is achieved. Depending on the complexity of the construction project, a large number of Notepad files can exist, resulting in better capture and classification of construction site data.

Chapter 7: System Deployment & Testing

7.1 Introduction

In order for the reliability of the system to be examined, it was necessary to test the system. The testing of the system in reality from a number of participants which act in different roles in each scenario, aims to examine different parameters of RFID technology in a number of construction industry problems.

7.2 Objectives of System Evaluation

The objectives of the system evaluation are listed below :

• *Checking of the Effectiveness/Efficiency of the System*: The evaluation of the proposed system aims to examine whether the use of RFID technology will solve specific construction industry problems and improve specific construction processes. Specifically, the evaluation of the system aims to check whether RFID technology can solve these problems in the right way without causing further problems.

• *Checking of the Graphical User Interfaces*: System evaluation aims to examine how user-friendly the graphical user interfaces used for the communications between the users and the RFID tags. Specific characteristics of the graphical user interfaces which were examined are the ease of use and their flexibility in handling different types of data which may correspond to different areas, such as health and safety and logistics.

• *Checking of the Proposed Scenarios*: In this case, the degree to which the proposed scenarios are realistic is examined. Also, the ability of RFID technology to solve the proposed scenarios is examined.

• *Usefulness to the Construction Industry*: The objective in this case is to examine whether RFID technology as presented through the tested scenarios, can be truly useful for the construction industry. In addition, the willingness for adoption of the technology from the construction industry has to be considered and also the way the deployment of the proposed scenarios enhances this willingness needs to be analysed.

• *How Wireless Sensors facilitate Construction Logistics Management*: The objective is to examine how the use of wireless sensors and especially RFID technology improves the processes involved with construction logistics. Enablers which enhance and barriers which prevent the use of RFID technology in the construction industry need to be identified as well as the technical challenges and benefits from using RFID technology in the construction industry. Also, any cultural issues involved with the use of RFID technology on construction sites need to be clarified.

• *To what extent Wireless Sensors improve Health & Safety on Construction Sites*: In this case, the level of improvement of health and safety conditions from the use of RFID technology has to be examined. As in the case of construction logistics, the enablers, the barriers, the benefits from using RFID technology and the cultural issues associated to its use, need to be identified.

• *What conditions will make the Deployment of Wireless Sensors in Construction more Effective*: The evaluation of the system will help in the identification of what has to be done in order for the deployment of RFID technology on a construction site to become easier and lead to better results.

• *Integration of Wireless Sensors with Existing Systems*: The level of integration of wireless sensors and especially of RFID technology with existing systems and practices, such as Notepad files for the collection of construction-related data, has to be examined. Also, the obstacles which prevent the thorough integration of the technology with other software systems must be identified.

7.3 Simulation of the Construction Site

For the purposes of testing the proposed research scenarios, a large area in the campus of Loughborough University was used as a construction site. This area is next to the Sir Frank Gibb Annexe building. This building was also used during the testing of the scenarios.

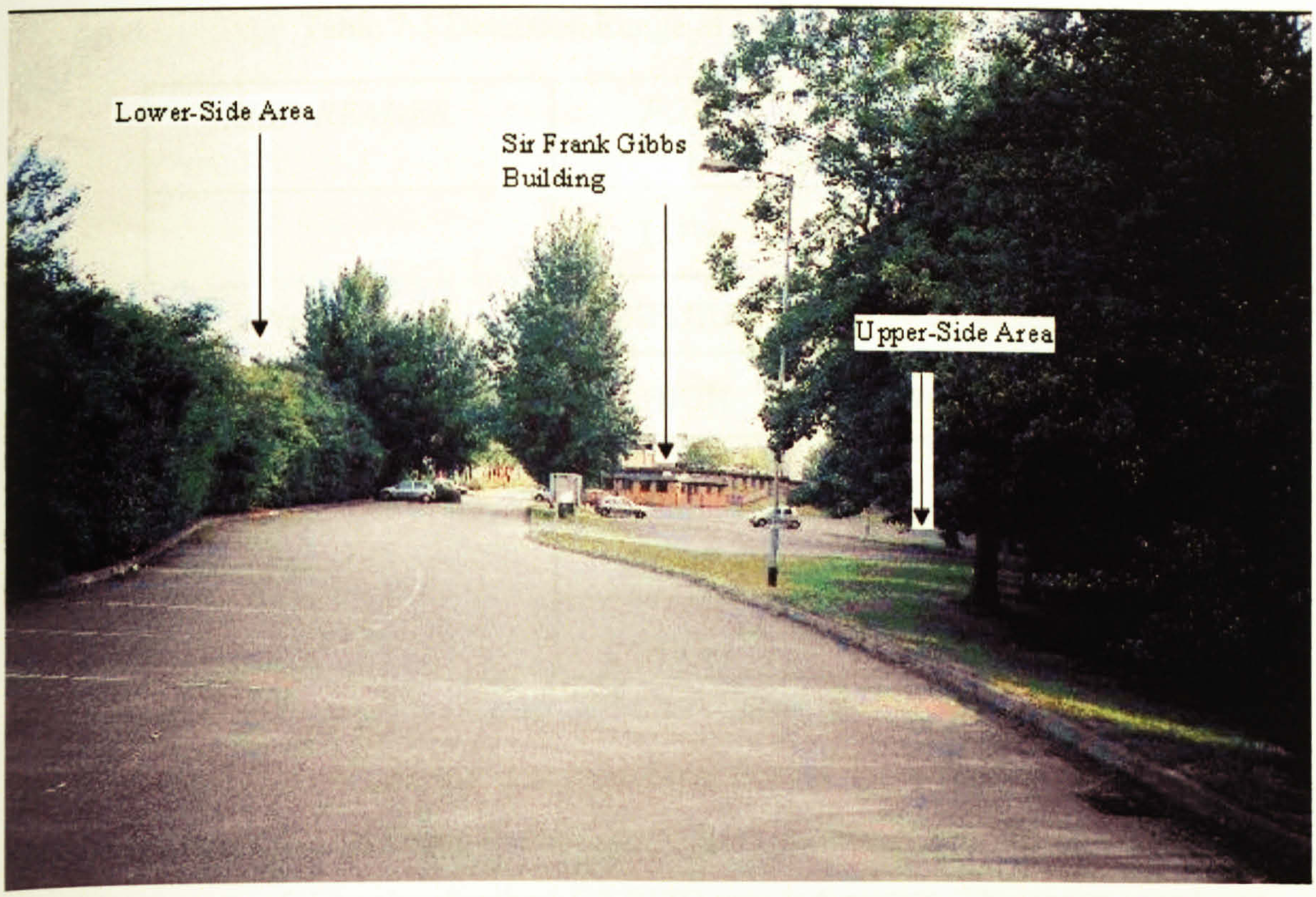


Fig. 7.1 Area of Testing

Figure 7.1 shows the area which was used as a construction site for the testing of the proposed research scenarios. The point from which this photograph was taken, is at a distance of 100 meters from Sir Frank Gibbs building which can be seen at the other end of the area. For the purpose of the testing, this point is considered as the entrance of the construction site.

The proposed health and safety and the logistics scenarios which were presented in Chapter 5, were tested on the area shown in Figure 7.1. Before any testing of the scenarios occurred, a number of experiments took place in order for specific parameters of RFID technology to be examined. Specifically, the range of detection of the i-Q8/i-Q32 RFID tags from the iCard3 and the iPort3 RFID readers under different power levels were examined and the results are shown in Table 7.1.

Table 7.1 Detection Range of Used RFID Readers

RFID READER	*POWER*	*DETECTION RANGE*
i-Port3	LOW	17 meters
	MEDIUM	29 meters
	HIGH	100 meters
i-Card3	LOW	13 meters
	MEDIUM	24 meters
	HIGH	100 meters

Table 7.1 describes the detection capability of the i-Port3 and the i-Card3 readers for the i-Q8/i-Q32 tags. For both the i-Port3 and the i-Card3 RFID readers, the maximum range of detection for the i-D2 RFID tags is 6 meters. This range is reduced to 3 meters when the sensitivity of the reader is adjusted to medium levels and it is reduced even more when the sensitivity of the reader is set to low. Also the existence of many walls between the reader and the tags affects the detection of the tags. In this case, the range of detection of the tags by the reader is decreased.

The use of the iCard3 RFID reader on personal digital assistants (PDAs) requires a PCMCIA expansion slot to be embedded to the PDA. However this expansion slot is considered "old" technology and there will be no future production of it by the relevant companies, thus the RFID reader which was mainly used for the testing of the scenarios was the i-Port3 RFID reader. This reader was placed on a specific location into the Sir Frank Gibb Annexe building along with its three antennas. Furthermore, the i-Port3 RFID reader was connected to a wireless router in order for a wireless local area network to be created.

Because of a problem on the PDA, the date and time on the Notepad files which store data from the RFID tags, are displayed wrongly. This problem does not exist when the proposed system is tested on a laptop computer.

7.3.1 Simulation of the proposed Health & Safety Scenarios

The simulation of the proposed health and safety scenarios required the use of iQ8 and iD2 RFID tags and the use of the iPort3 RFID reader. On the PDA which was used during the testing of the health and safety scenarios, the menu which contains options for logging in to a number of different graphical user interfaces related to the proposed health and safety scenarios was installed. The specific menu with the graphical user interfaces was described in section 6.4.1.1 of Chapter 6.

7.3.1.1 Hazardous Substances Monitoring

During the testing of the "Hazardous Substances Monitoring" scenario, the system evaluator acted as the construction site manager. The purpose of the scenario was to check whether there were any remaining chemical substances on the construction site after the construction work had been completed. Two i-Q8 RFID tags were placed at different locations into the Sir Frank Gibb Annexe building in order to simulate the tag which is attached to a chemical warehouse on the construction site.

After connecting to the i-Port3 RFID reader, the system evaluator set the power level to low and pressed the button "Scan". The result was the following:

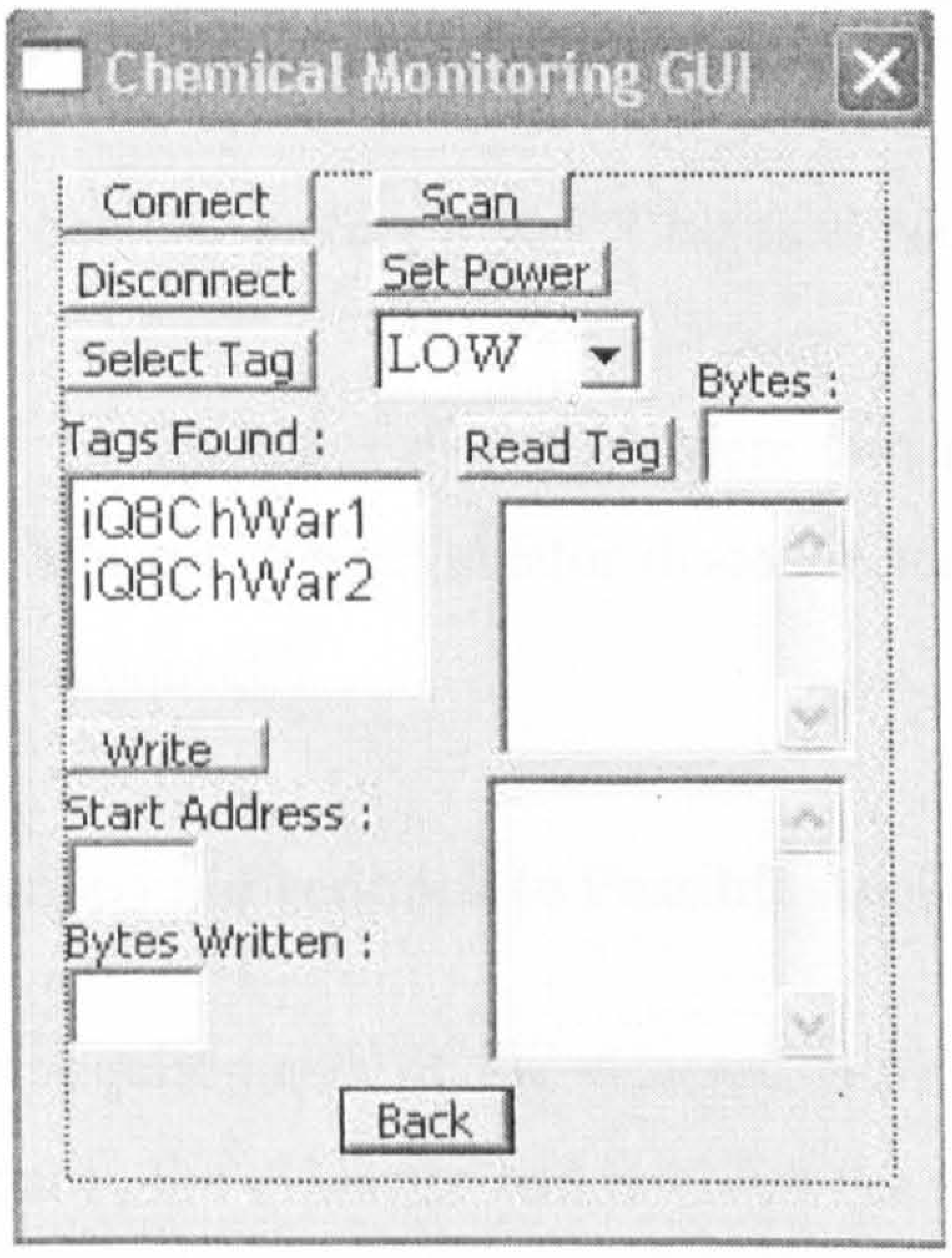


Fig. 7.2 Scanning in the "Chemical Monitoring" GUI

The tags which were detected by the RFID reader were placed in two warehouses used for the storage of hazardous substances and since the power level was low, that meant the evaluator was close to the areas where the RFID tags were placed. As can be seen from Figure 7.3, the first tag is an i-Q8 RFID tag placed in chemical warehouse 1 and the second tag is an i-Q8 RFID tags placed in chemical warehouse 2. The evaluator selected the i-Q8 tag which is placed in chemical warehouse 1. He then pressed the button "Select Tag" and set a number of bytes, eg. 60. He then pressed the button "Read Tag" in order to be able to read the information which was contained in the tag. The result was the following:

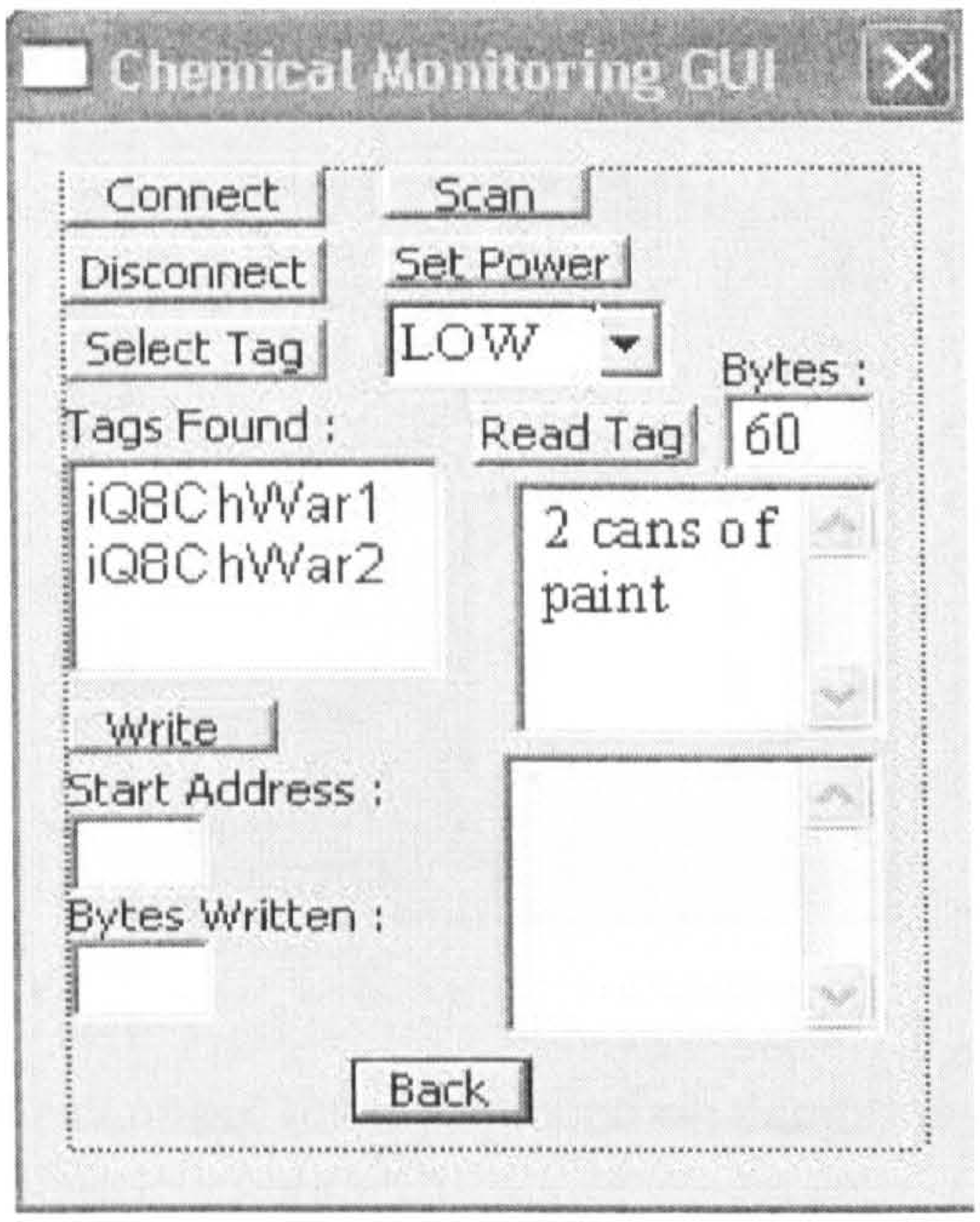


Fig. 7.3 Tag content reading in the "Chemical Monitoring" GUI

The tag informed the evaluator that there were two remaining cans of paint located in chemical warehouse 1. The evaluator disconnected from the RFID reader by pressing the button "Disconnect".

7.3.1.2 Hazard Notifications as Feedback to Possible Accidents

According to the requirements of the "Hazard Notifications as Feedback to Possible Accidents" scenario, the evaluator had to check the content of the tags which are placed at "dangerous areas" on the site. Specifically, he had to check the content of the tags placed on excavation areas or on areas where electric shocks were possible.

For this scenario, the evaluator had to act as the construction site manager and from the menu of choices offered for the construction site manager, to select the graphical user interface entitled "Hazard Notifications". After initiating the connection to the i-Port3 RFID Reader, the evaluator scanned for the tags which are placed at "dangerous areas" on the site. This can be shown in Figure 7.4.

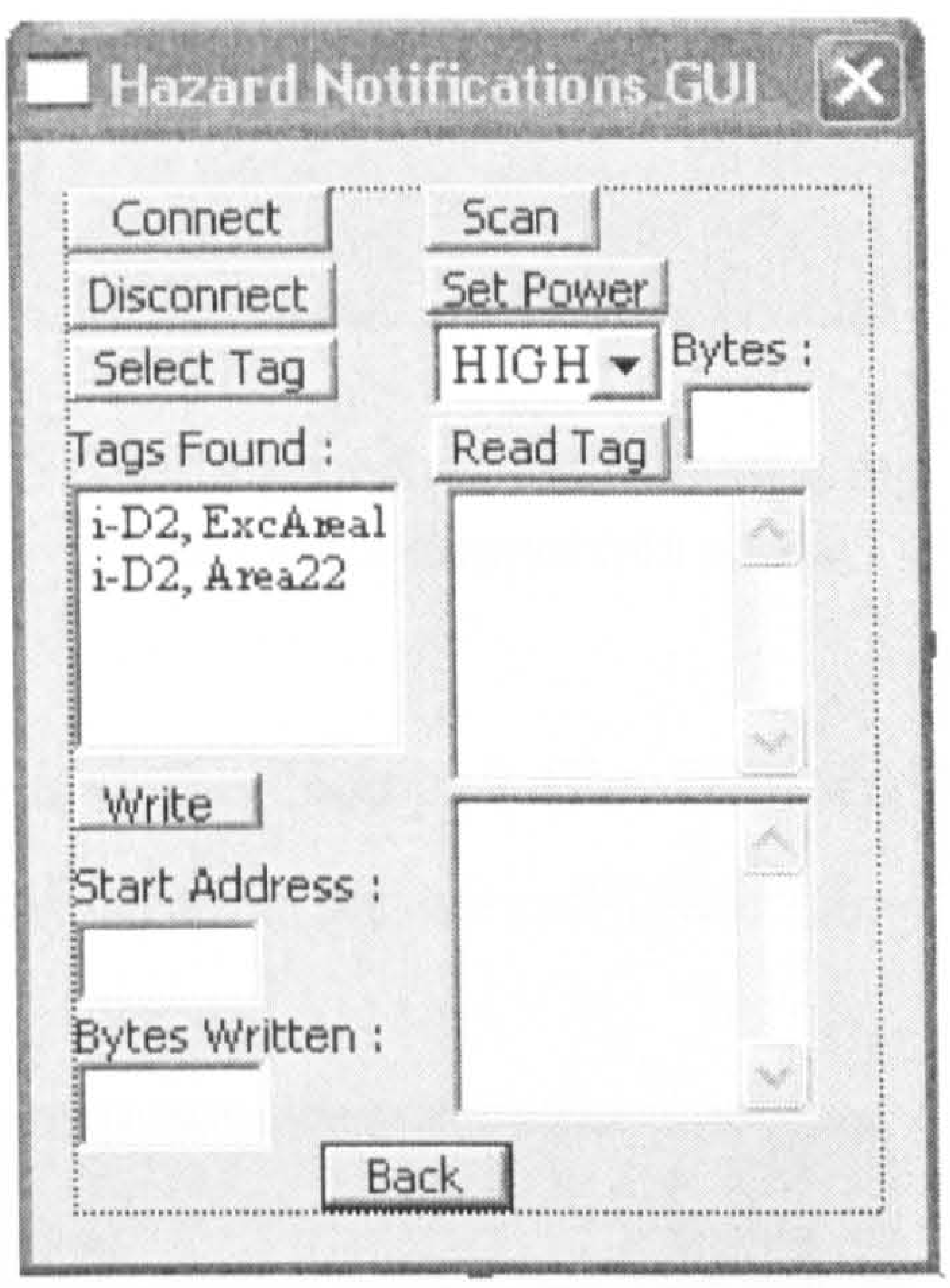


Fig. 7.4 Scanning for tags placed on dangerous areas

The evaluator selected the second tag "i-D2, Area22" and read its contents. The result can be shown in Figure 7.5.

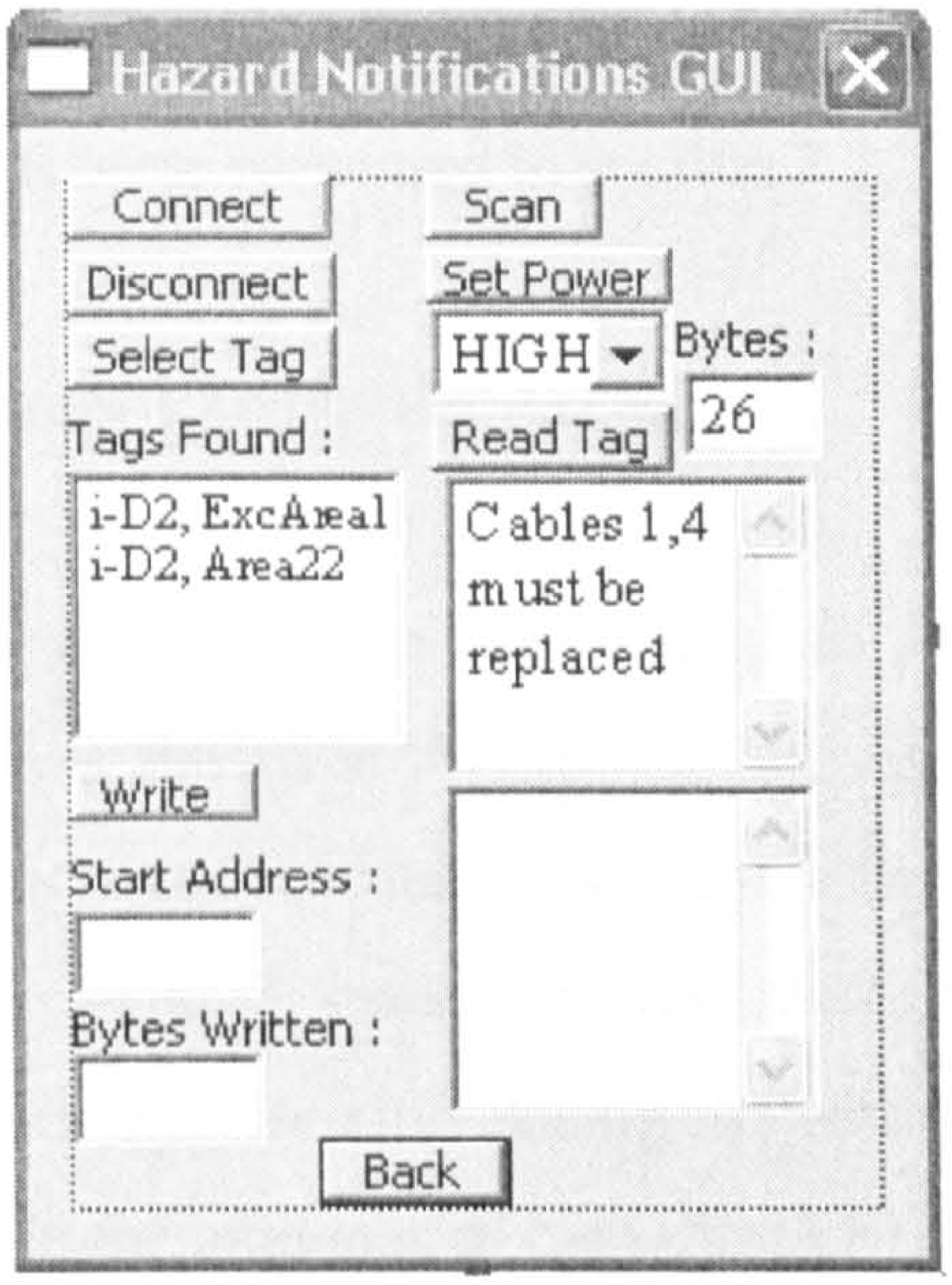


Fig. 7.5 Reading of the contents of a tag placed on a dangerous areas

The evaluator opened the Notepad file "Hazard Notifications.txt" and the contents of the tag were displayed as shown in Figure 7.6.

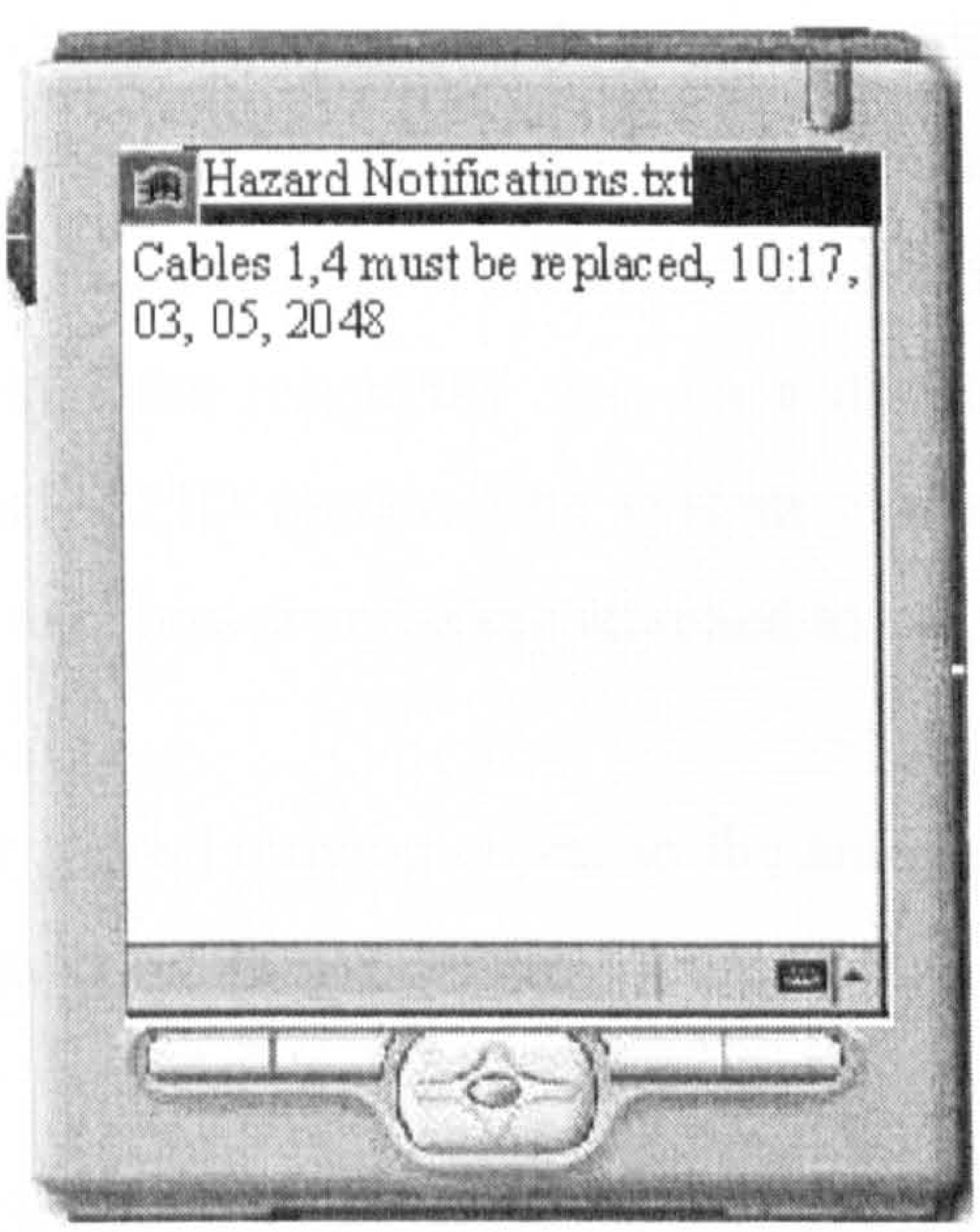


Fig. 7.6 Hazard Notifications File

As it can be seen from Figure 7.6, the time and date are displayed wrongly. The actual time of testing of this specific scenario was different from that shown in Figure 7.6. Also, the date was displayed wrongly. The date '03/05/2048' which was displayed in the file was not the actual date of testing the specific scenario. The reasons for these problems were presented in section 7.2.

7.3.1.3 Monitoring of Large Excavation Areas

For this scenario, the researcher had to hold an i-D2 RFID tag and be on the upper sideline area which is shown in Figure 7.1. Because the i-Port3 RFID reader is fixed at a specific location and because the PDA which was used by the system evaluator cannot use the i-Card3 reader for the reasons which were explained in Section 7.2, the researcher was moving during the testing between a distance from four to twelve meters from the antennas of the i-Port3 RFID reader but only inside the upper-side area which is shown in Figure 7.1.

The system evaluator acted as the driver of a vehicle on a construction site. After logging in to the 'Construction Site Drivers' graphical user interface and connecting to the i-Port3 RFID reader by pressing the button "Connect", he pressed the button entitled "Cont. Scan". The reader started to execute continuous scans for tags. The 'Construction Site Drivers' graphical user interface is programmed to scan for specific tags, however the sound which is emitted when the tags placed at large excavation areas, are detected, is different from the sound which is produced when tags which are attached to vehicles or workers, are detected.

At the beginning, the researcher was on a distance of 12 meters from the antennas of the i-Port3 RFID reader. The system evaluator enabled the reader to perform a continuous scan however the tag attached to the researcher was not detected by the reader.

The researcher started moving closer to the antennas of the RFID reader. The system evaluator pressed again the button "Cont. Scan". The result in this case is shown in Figure 7.7.

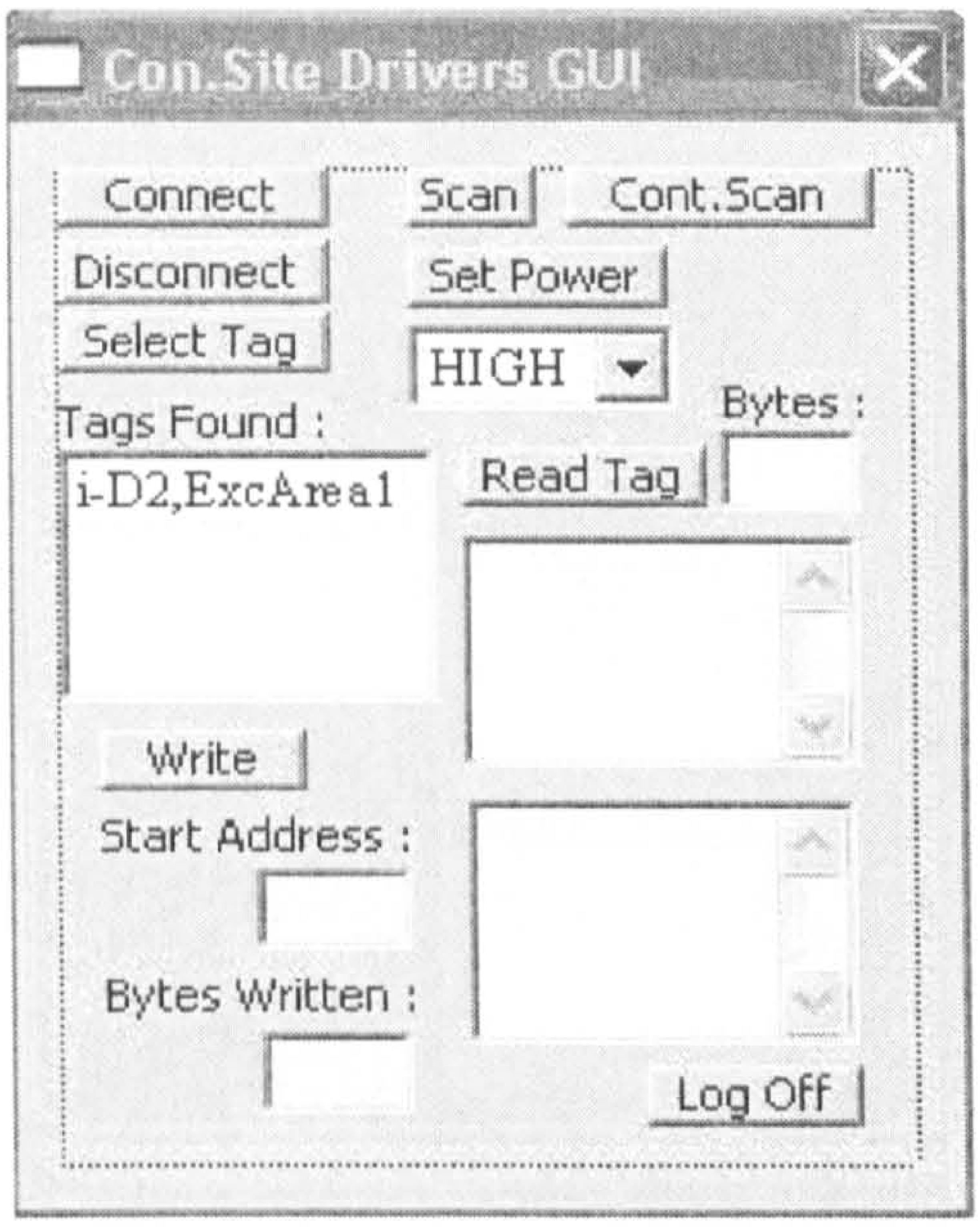


Fig. 7.7 Detection of Excavation Area Tag

It can be seen from Figure 7.7, that the i-D2 tag which was attached to the researcher was detected. A sound was emitted on the headset of the system evaluator as a warning that an excavation area was close to him.

7.3.1.4 Collisions between Workers and Vehicles

For the testing of this scenario, two persons participated: the system evaluator and the PhD researcher. The system evaluator acted as the driver of a vehicle while the researcher acted as a worker. On the shirt of the researcher, an i-D2 RFID tag was placed. The system evaluator used a PDA in which the graphical user interface for construction site drivers was installed. This graphical user interface was described in Section 7.4.1.3.

In addition, the system evaluator used a set of headphones on his ears which were connected to the PDA. The system evaluator connected to the iPort3 RFID reader by pressing the button "Connect". He then set the power level to 'LOW' in order for the i-Port3 RFID reader to detect tags close to its antennas to be detected. The next step for the system evaluator was to press the button "Scan". The result is shown in Figure 7.8.

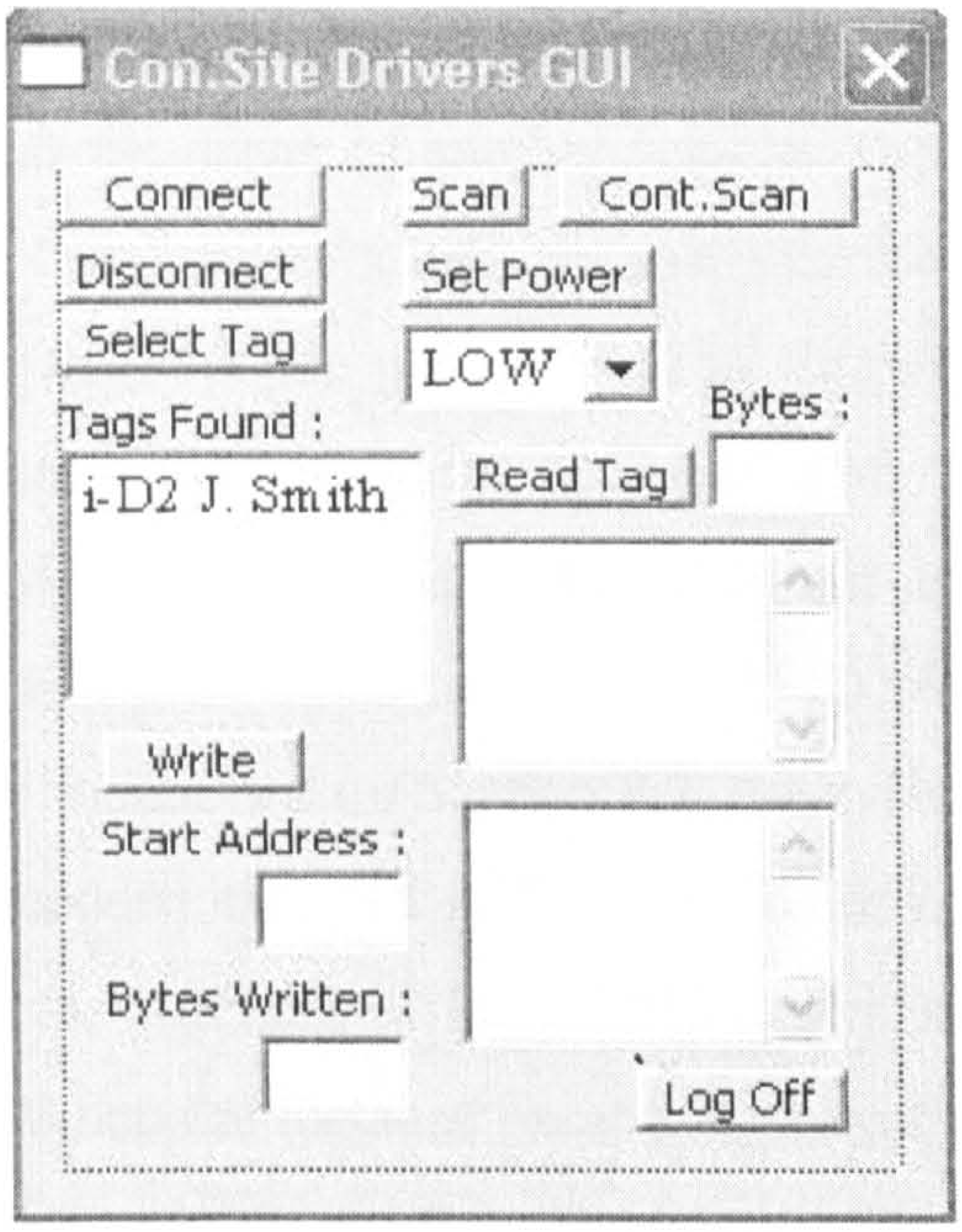


Fig. 7.8 Detection of tag attached to a worker

When the researcher moved to a distance of three meters from the antennas of the i-Port3 RFID reader, the tag which was attached to his shirt was detected. A sound was emitted through the headphones to the system evaluator. This sound was a warning that something was close to him and his vehicle.

The testing of the system showed how the driver of a vehicle can check if something is close to him/her before he/she starts a specific task. The test also explored what happens when the driver executes a specific task in a small polygonal area and wants to check if during his/her work, something is close to him/her. In this case, the system evaluator pressed the button "Cont. Scan" instead of the button "Scan" and the i-Port3 RFID reader was set to perform continuous scans for tags. The researcher (who acted as a worker) moved around. Whenever his tag was detected, a warning sound was heard at the headphones of the system evaluator (who acted as the driver of a vehicle).

7.3.1.5 Collisions between Vehicles

The testing of this particular scenario required the participation of both the system evaluator and the researcher. An iD2 RFID tag was attached to the researcher's shirt while the system evaluator used a PDA and headphones. The researcher acted as the driver of a vehicle operating on a construction site while the system evaluator acted as the driver of another vehicle. The system evaluator logged on to the 'Construction Site Drivers' graphical user interface and connected to the i-Port3 RFID reader. He then set the power level to 'LOW' and pressed the button "Cont. Scan". The system evaluator set the power lever to 'LOW' in order for the i-Port3 RFID reader to detect tags close to its antennas. In addition, the evaluator moved very close to the i-Port3. Since the i-Card3 RFID reader cannot be used with the PDA for the reasons mentioned on Section 8.2, the evaluator needs to be close to the i-Port3 as if it is embedded in the PDA. The researcher with the RFID tag was at a distance far away from the antennas of the i-Port3 reader, thus his tag could not be detected by the reader. When the distance became approximately 3 meters, a warning sound was heard on the headphones of the evaluator with the PDA. The following information was also displayed on the graphical user interface of the PDA and it is shown in Figure 7.9.

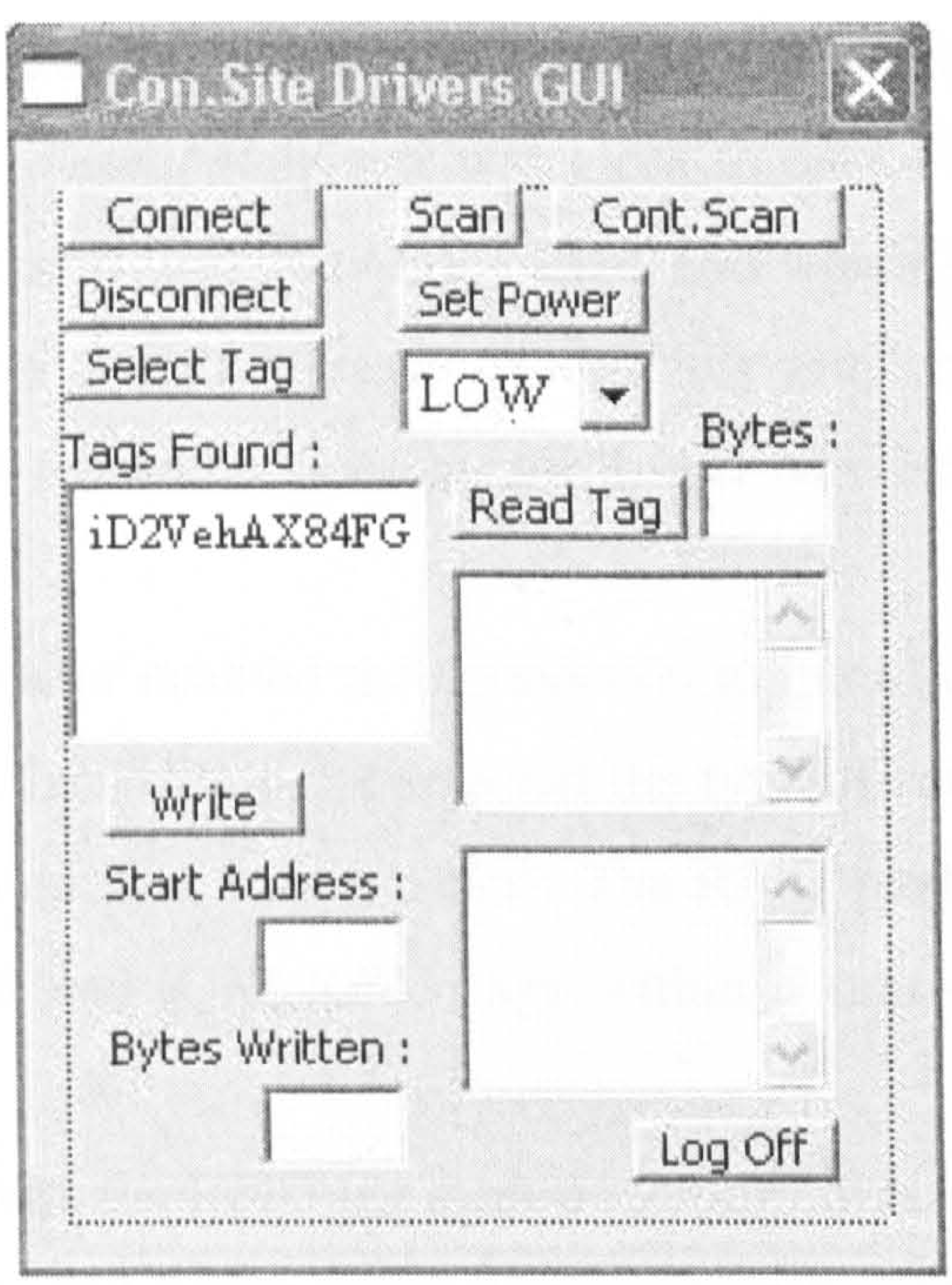


Fig. 7.9 Detection of tag attached to a vehicle

The information which was displayed on the graphical user interface informed the system evaluator, that a vehicle with registration number AX84FG was very close to his vehicle and as a result he should be careful.

7.3.2 Simulation of the Logistics Scenarios

The simulation of the Logistics scenarios required the participation of two persons (system evaluator, researcher) and the use of a PDA and iQ8 and iQ32 RFID tags. The system evaluator acted either as a construction site manager, as a foreman or a construction worker depending on the different scenarios. The three phases of the Logistics scenario which are the material delivery, material circulation, and material utilisation were tested separately. The scenario which is entitled "Checking the Sequence of Steel Members" was tested using structural steel members available in the Loughborough University's laboratories. For the purposes of the "Monitoring the Material Rate of Use" and "Temperature Monitoring of Porous Materials" scenarios, an iQ8 and iQ32 RFID tag were used respectively.

7.3.2.1 Material Delivery

The researcher went to a distance of about 150 meters from the antennas of the i-Port3 reader while the system evaluator was close to the i-Port3 RFID reader and used a PDA. From the menu installed on the PDA and which is designed for use by construction site managers, the evaluator selected the graphical user interface that corresponds to material delivery. This graphical user interface is called "Material Delivery" interface.

The system evaluator enabled the connection to the i-Port3 reader and set the power level to 'HIGH'. In addition, he selected the type of scan to be complete. He then pressed the button entitled "Cont. Scan". The RFID reader was set to perform continuous scan of iQ8 and iQ32 RFID tags within a maximum distance of 100 meters.

The researcher with the RFID tag started moving. At first, the RFID reader did not detect the RFID tag and nothing was displayed on the graphical user interface. When the participant with the RFID tag reached at a distance of about 100 meters from the reader, his tag was detected by the reader as shown in Figure 7.10.

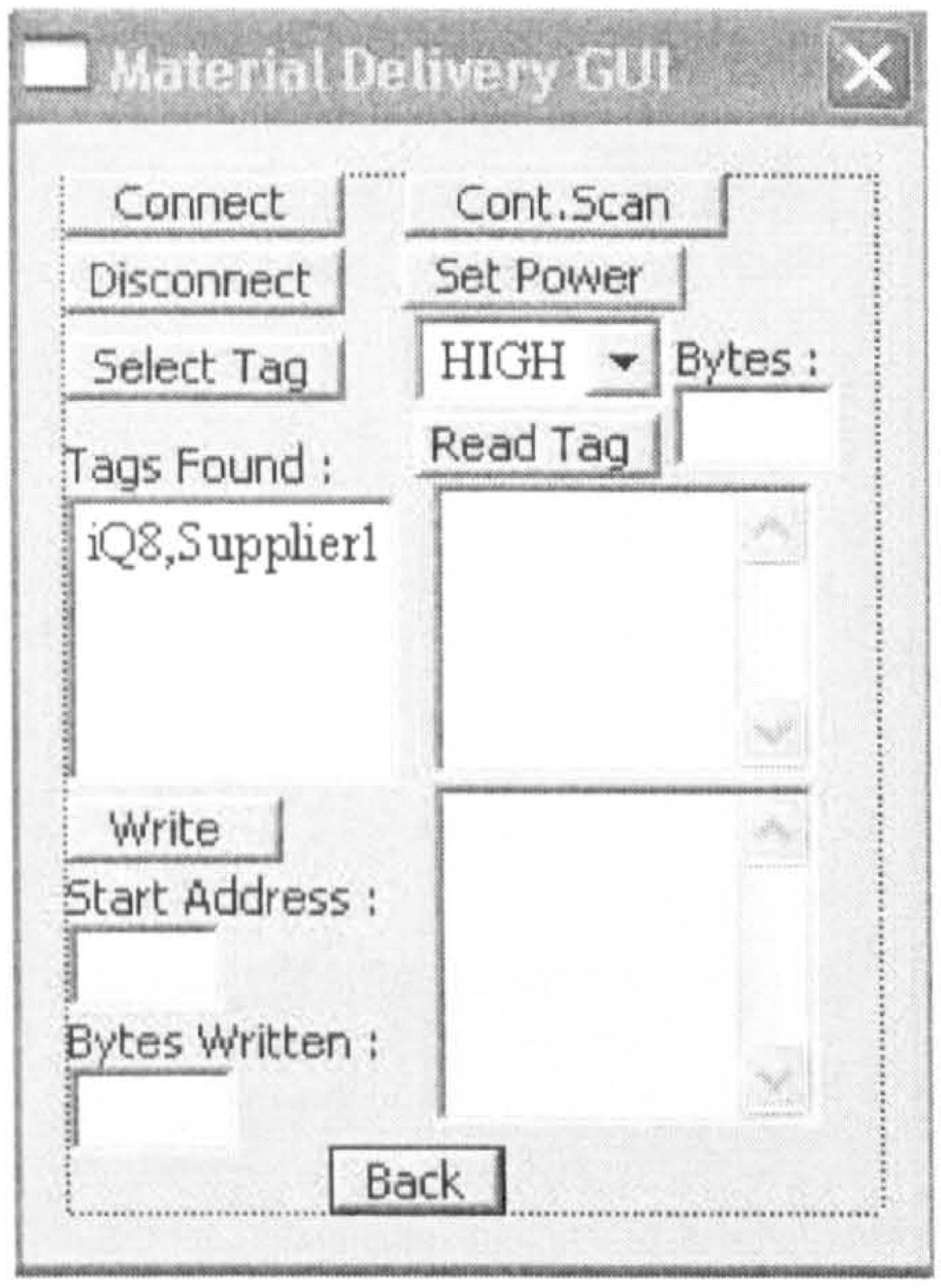


Fig. 7.10 Scanning in the Material Delivery GUI

The first time the tag was detected by the reader, this was displayed on the graphical user interface and the type of the tag, its origin, the time and date of detection were automatically transferred and stored in a Notepad file called "Material Delivery.txt". The user who acted as a construction site manager stopped the continuous scanning by pressing the button "Stop Continuous Scan". He immediately searched on the "My Documents" folder on the PDA for the file called "Material Delivery.txt". He opened the specific file and he saw how many times the reader detected the RFID tag along with the date and time for each detection. The contents of the file "Material Delivery.txt" can be shown in Figure 7.11.

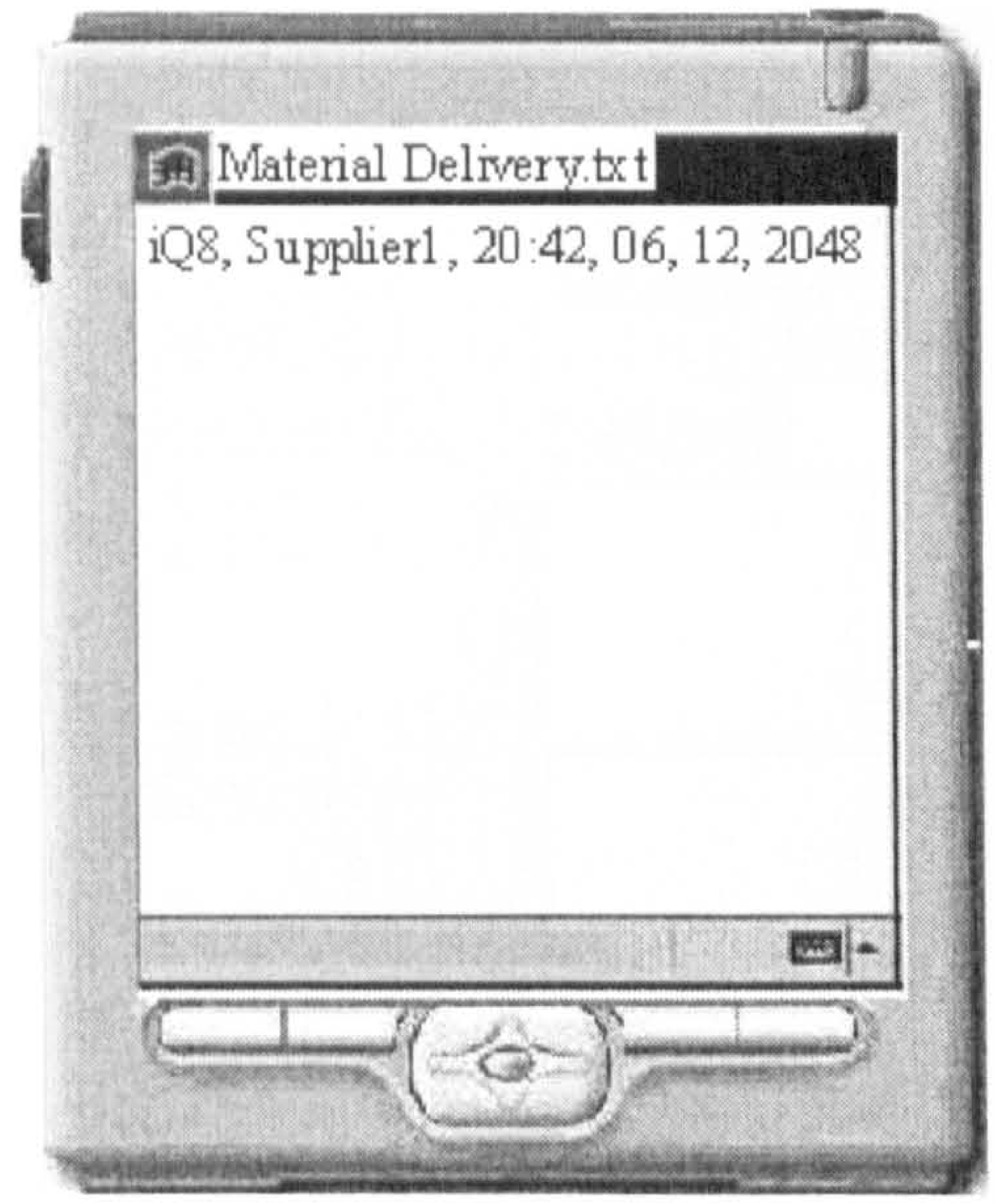


Fig. 7.11 Material Delivery Notepad File

Again the time and date of detection were displayed wrongly.

7.3.2.2 Material Transportation

For the testing of the "Material Transportation" scenario, the system evaluator acted as the foreman of a specific subcontractor. When the system evaluator completed the role of the foreman, he changed role and acted as the driver of a vehicle which operates on the construction site and which is under the supervision of the foreman.

In order to act as a foreman, the system evaluator had to place information on the i-D2 tag of the vehicle which is under his supervision. The researcher acted as the vehicle by just holding the i-D2 tag. By using the PDA, the evaluator connected to the i-Port3 RFID reader through the wireless local area network and then from the menu, he selected the option "Assignment of Daily Tasks".

The evaluator pressed the button "Connect" to connect to the i-Port3 RFID reader and then set the power to a specific level, either low, medium or high. He pressed the button "Scan" in order for the RFID reader to detect the RFID tags which are attached to the boom trucks which are under the supervision of the specific foreman. This resulted in the detection of two tags, as shown in Figure 7.12.

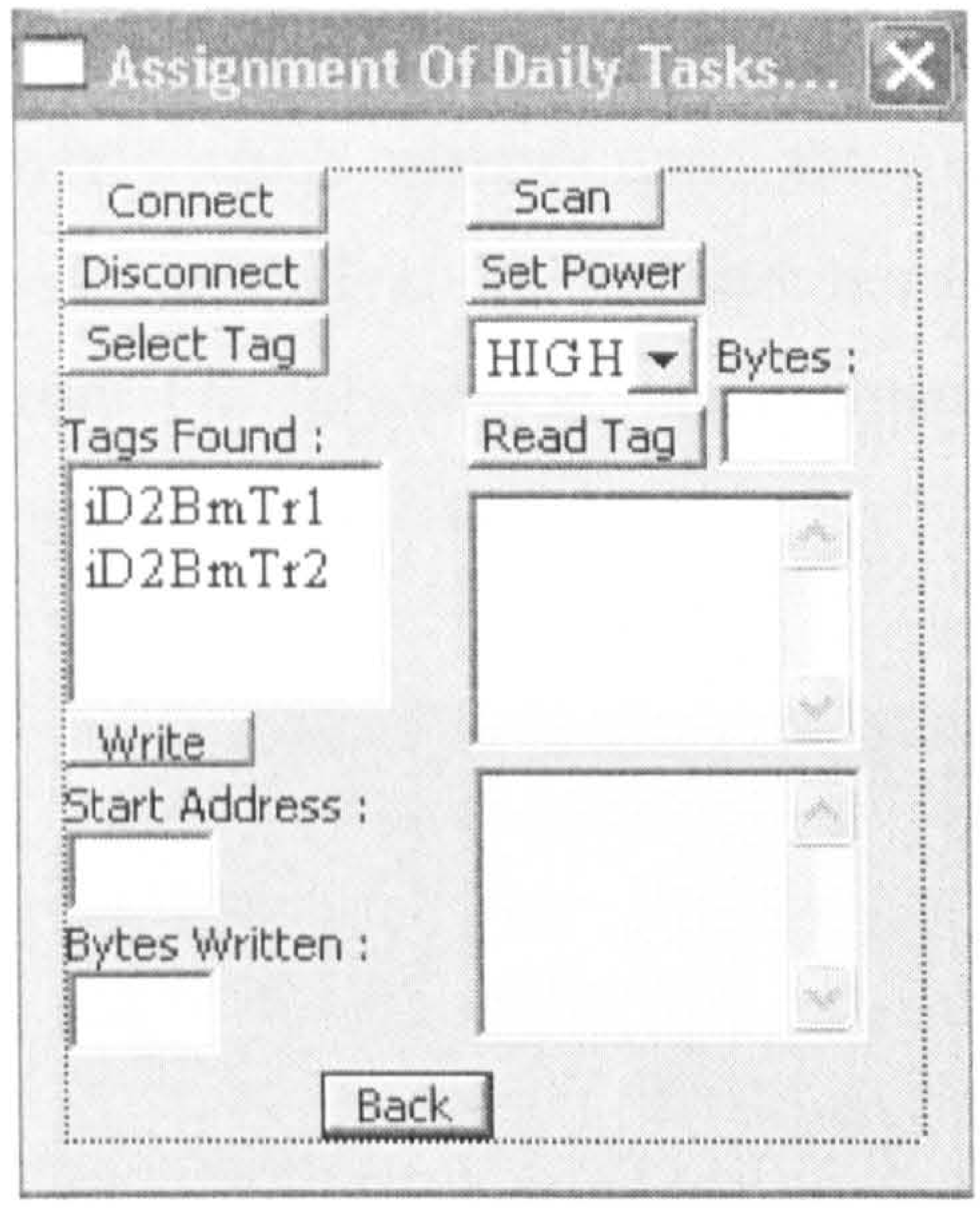


Fig. 7.12 Scanning in the "Assignment of Daily Tasks" GUI

By selecting the tag which corresponded to the one carried by the researcher and by pressing the button "Select Tag", the evaluator initiated the communication with the tag. By setting a specific address, for example 191 from which the writing of data to the tags would begin and by defining the number of bytes which should be written to the tag, he was ready to write a task list which would be read by the driver of the vehicle. This is shown in Figure 7.13.

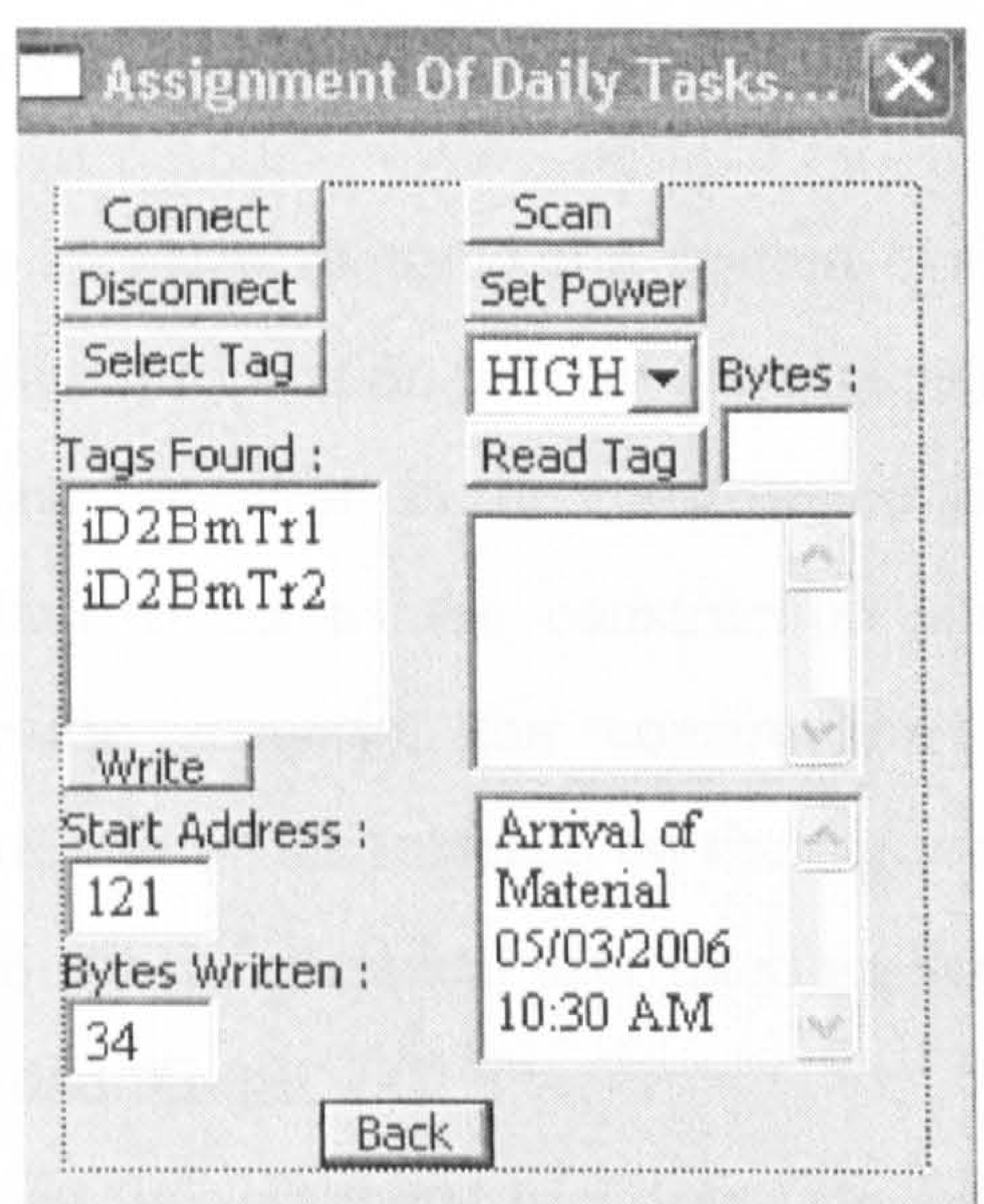


Fig. 7.13 Writing Data to the Tag of a Boom Truck

When the evaluator completed the role of the foreman, he changed his role to driver of a vehicle (eg. BmTr1) which operates under the supervision of the specific foreman. As the driver of vehicle BmTr1, the evaluator needs to check his daily task list assigned by the foreman. For this reason, the evaluator read the information contained in the tag, as shown in Figure 7.14.

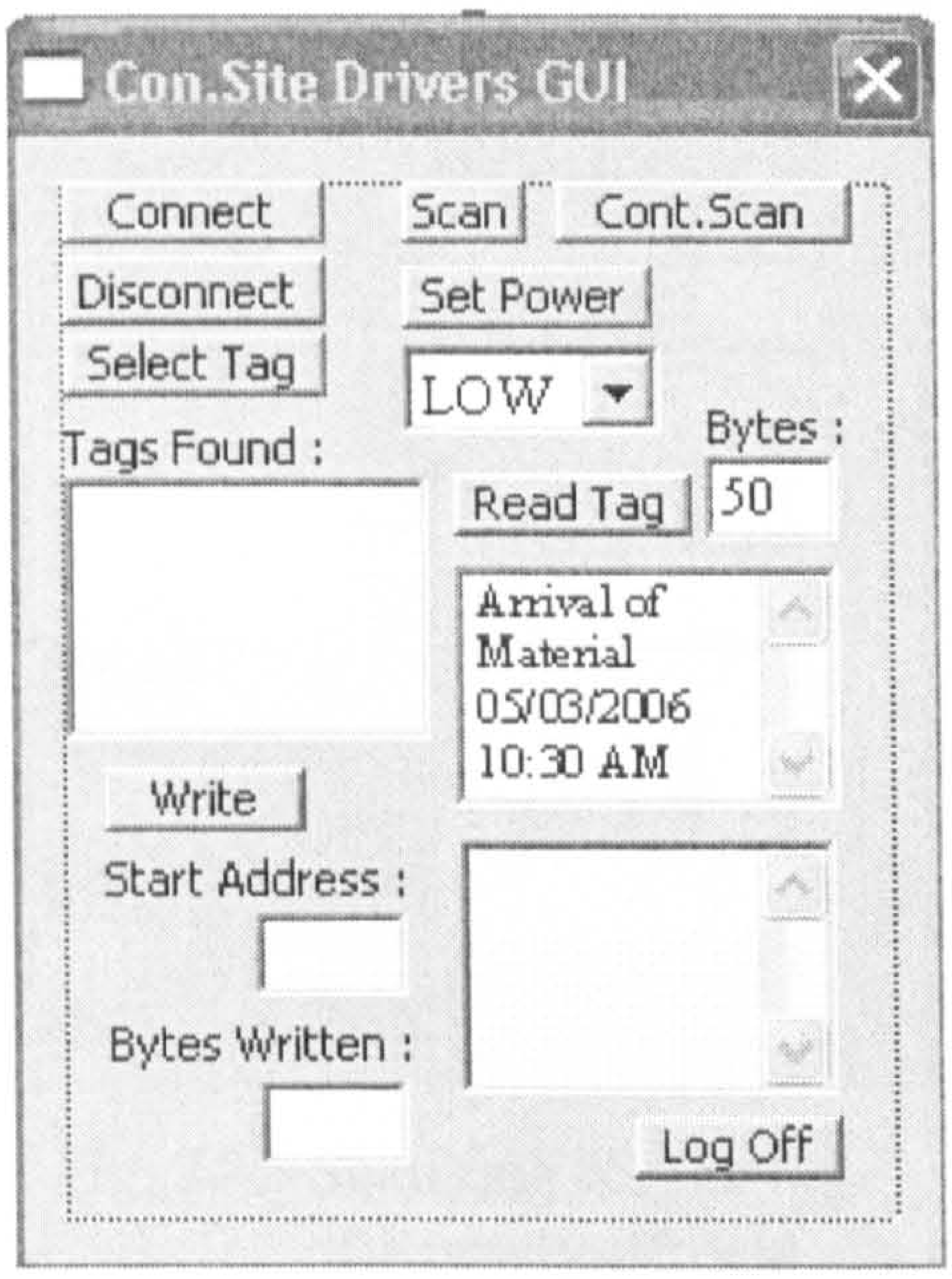


Fig. 7.14 Reading Data from the Tag of a Boom Truck

7.3.2.3 Material Utilisation

The testing of this scenario required the system evaluator first to act as a construction worker who puts information into the tag attached to the material which is delivered to a specific subcontractor on the construction site. When the evaluator completed this role, he had to act as the construction site manager. Under the requirements of the specific scenario, the construction worker had to place information about the future use of the material on the tag which is attached to it. In this case, the worker had to use the graphical user interface which is used by foremen on PDAs and which is entitled "General GUI".

The evaluator opened this graphical user interface and initiated the scanning for RFID tags in order for the tag which is attached to the delivered material to be detected. The ID number of the tag which is attached to the material was displayed.

Before the participant scanned for the tag which is attached to the material, he had to check the ID number which is written on a sticker placed at the exterior of the RFID tag. This is because the graphical user interface which is shown in Figure 7.15, may detect also other tags. Figure 7.15 shows the appearance of the ID number of the tag.

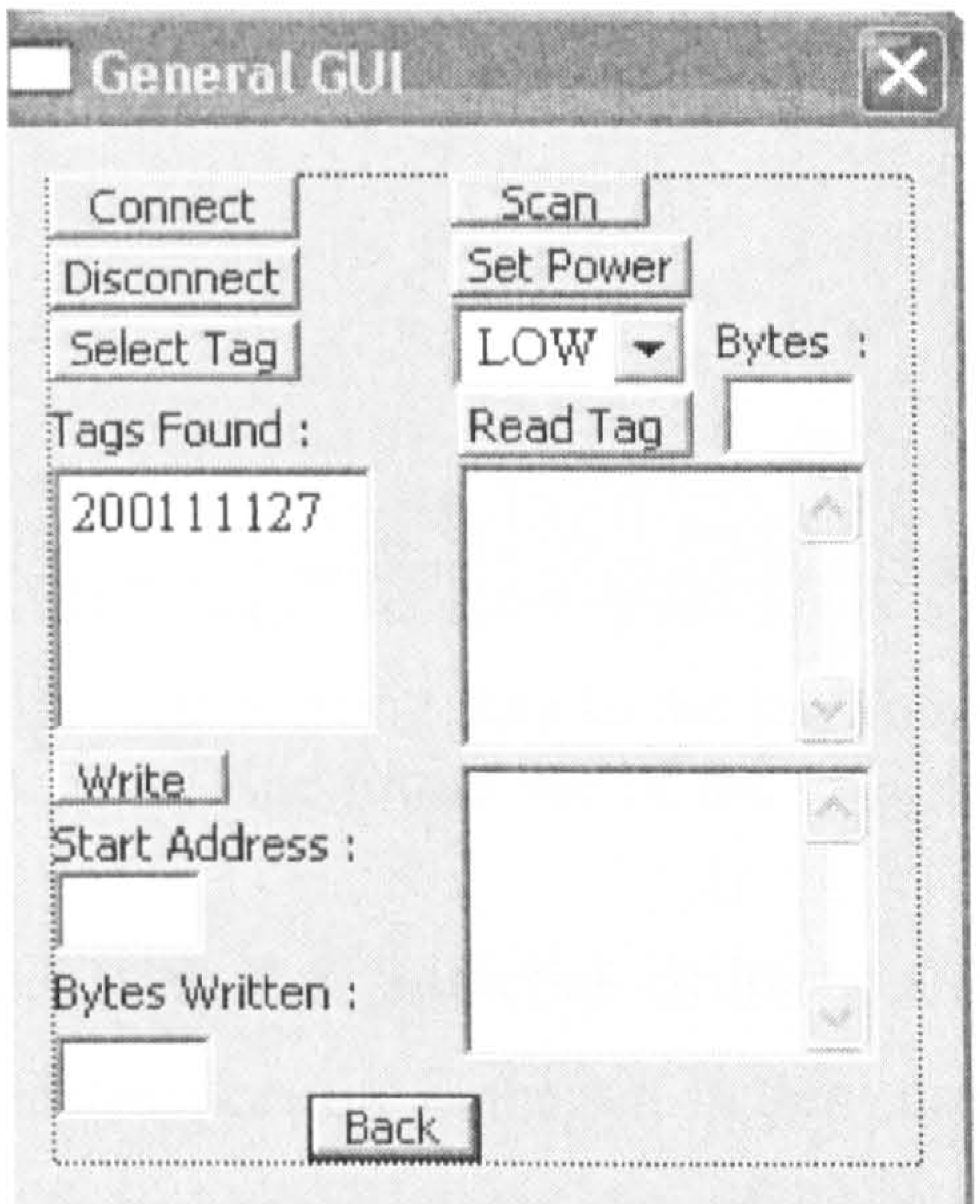


Fig. 7.15 Scanning for the tag of a newly-arrived material

The next step for the evaluator was to put information on the tag about the future use of the material. The evaluator highlighted the ID number of the tag by using the pen of the PDA and then pressed the "Select Tag" button. Communication with the RFID tag was established and the evaluator acting as a construction worker wrote the information to the tag as shown in Figure 7.16.

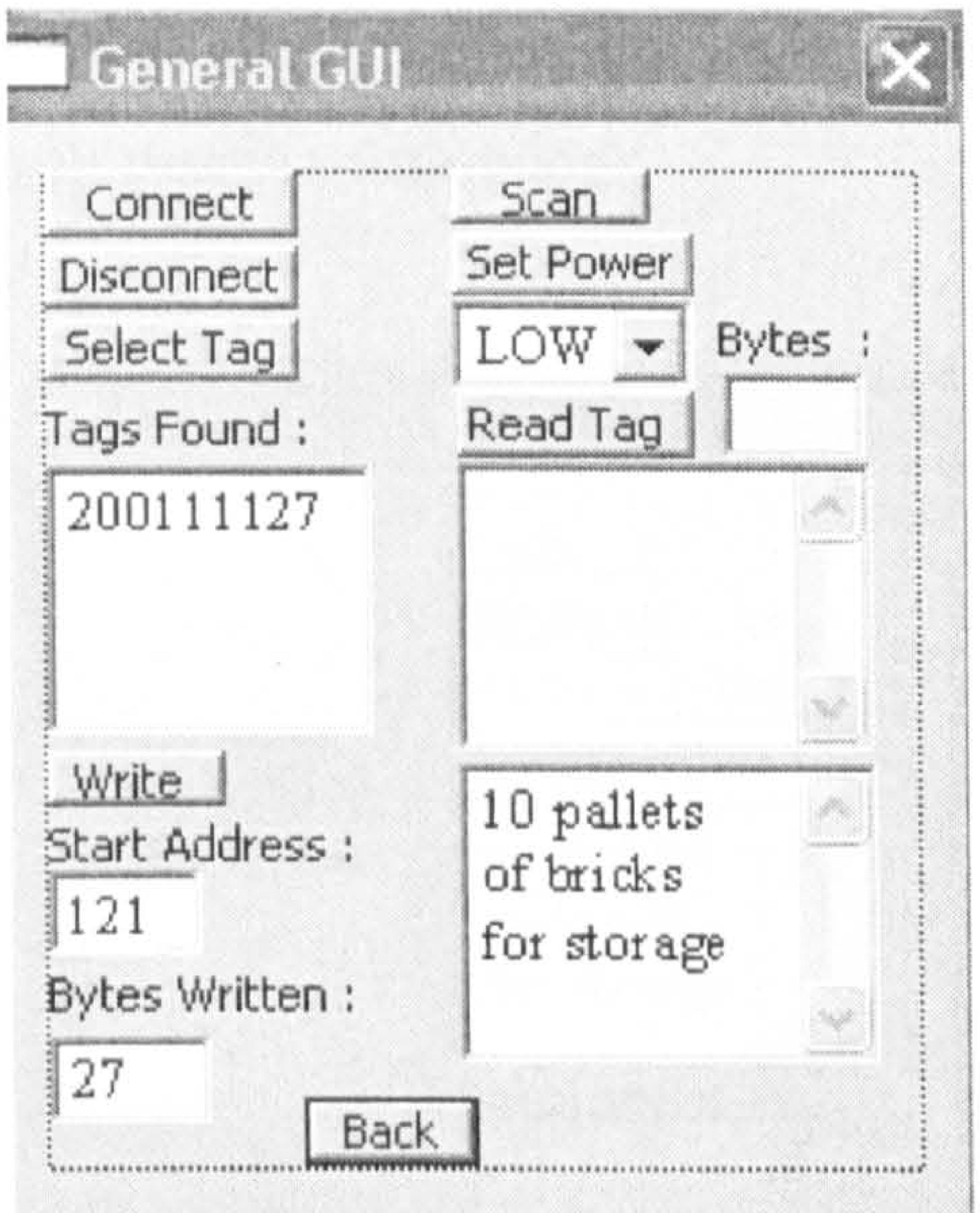


Fig. 7.16 Writing data to the tag about the future use of the material

For the purpose of testing the "Material Utilisation" scenario, the evaluator had to change his role to construction site manager. In this case, he had to be informed about how the material which had been delivered on the specific subcontractor on the construction site, would be used. From the menu of the graphical user interfaces, the evaluator selected the graphical user interface entitled "Material Handling GUI". The evaluator initiated a scanning of tags and the result is shown in Figure 7.17.

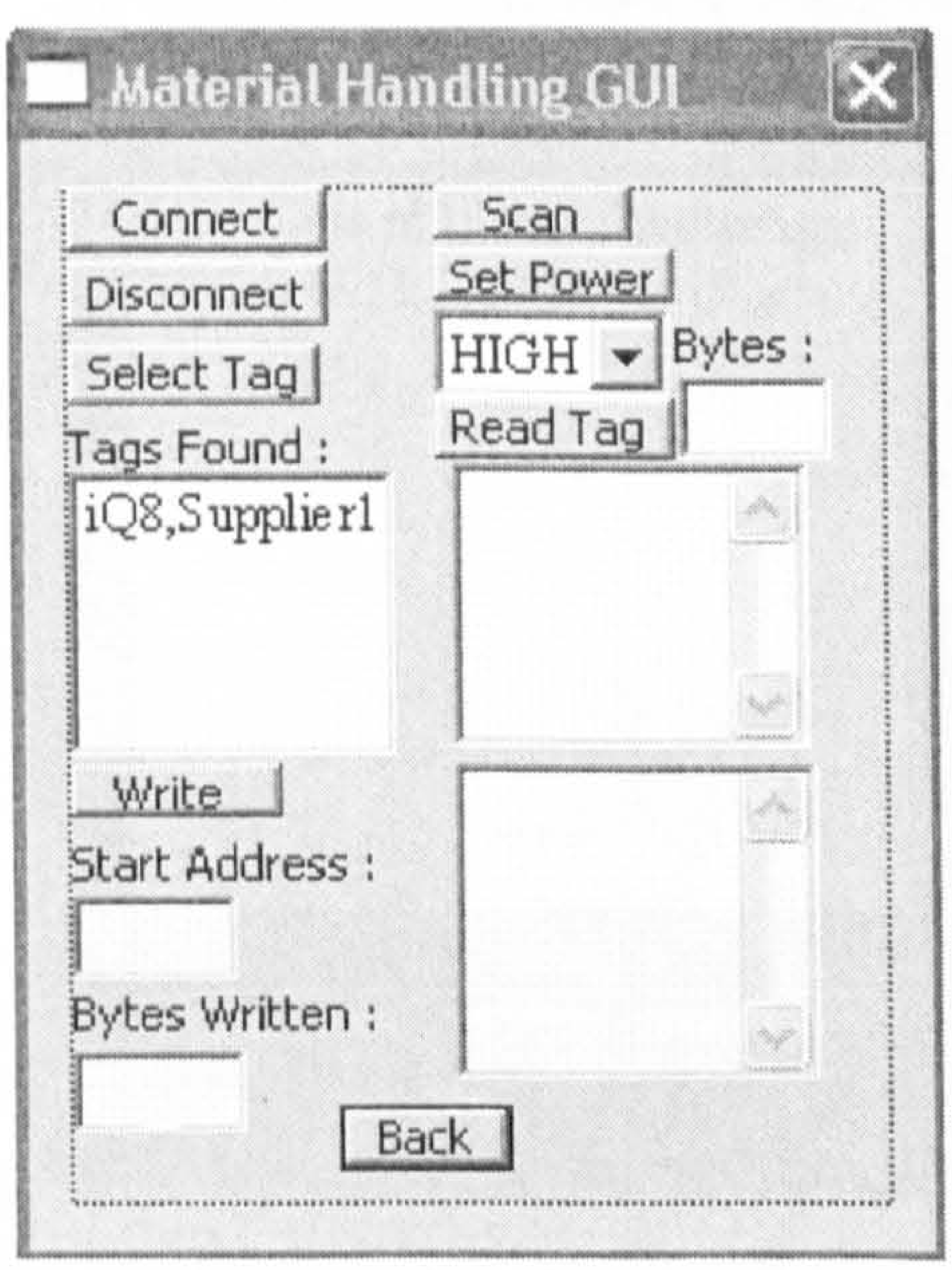


Fig. 7.17 Scanning of the tag of the newly arrived material by the construction site manager

The evaluator then highlighted the tag and read its contents by pressing the button "Read Tag". The result was the following:

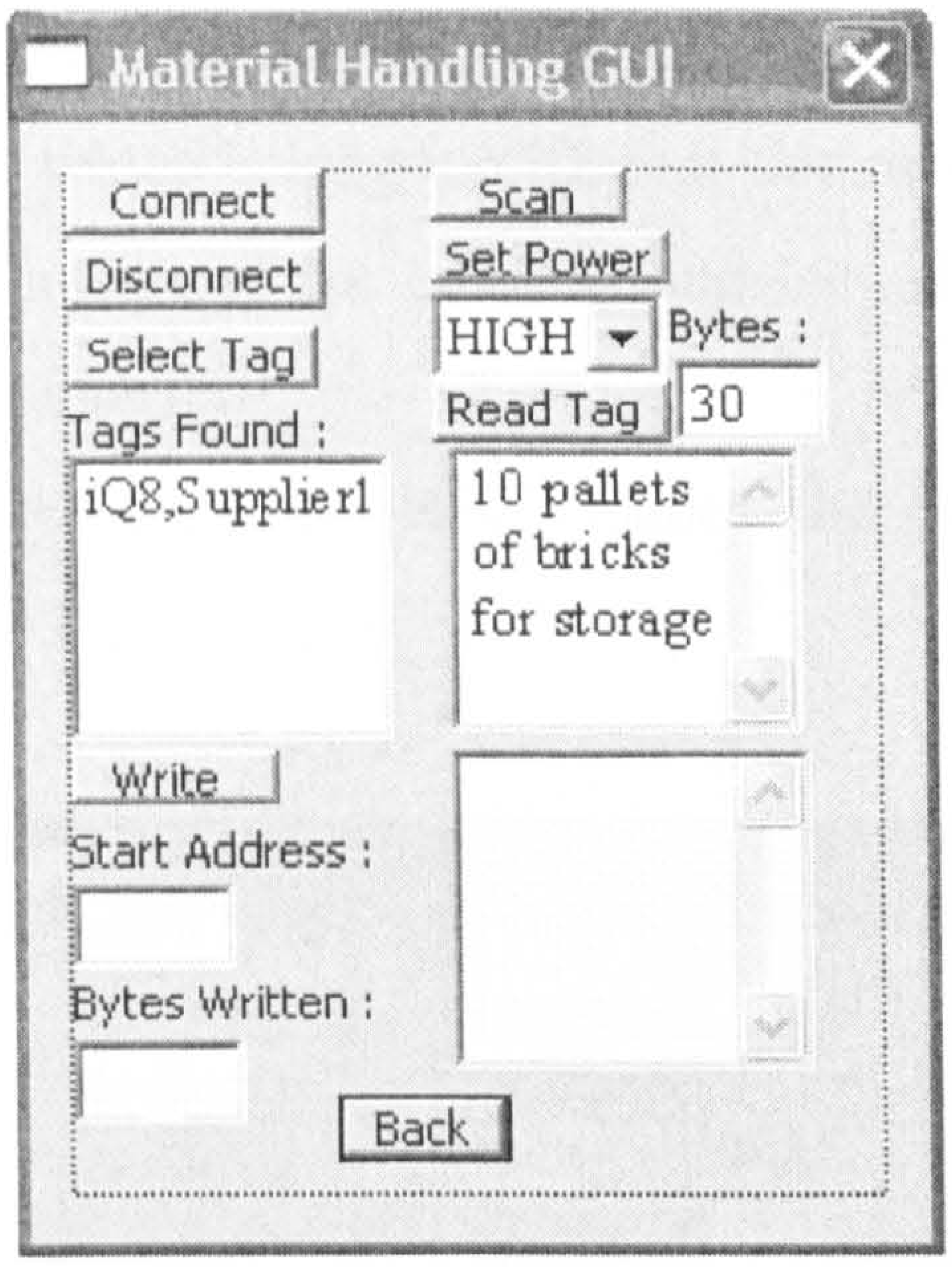


Fig. 7.18 Tag content related to the future use of the material

When the contents of the tag appear on the graphical user interface, they are automatically stored in a Notepad file entitled "Material Utilisation.txt". This file is shown in Figure 7.19.

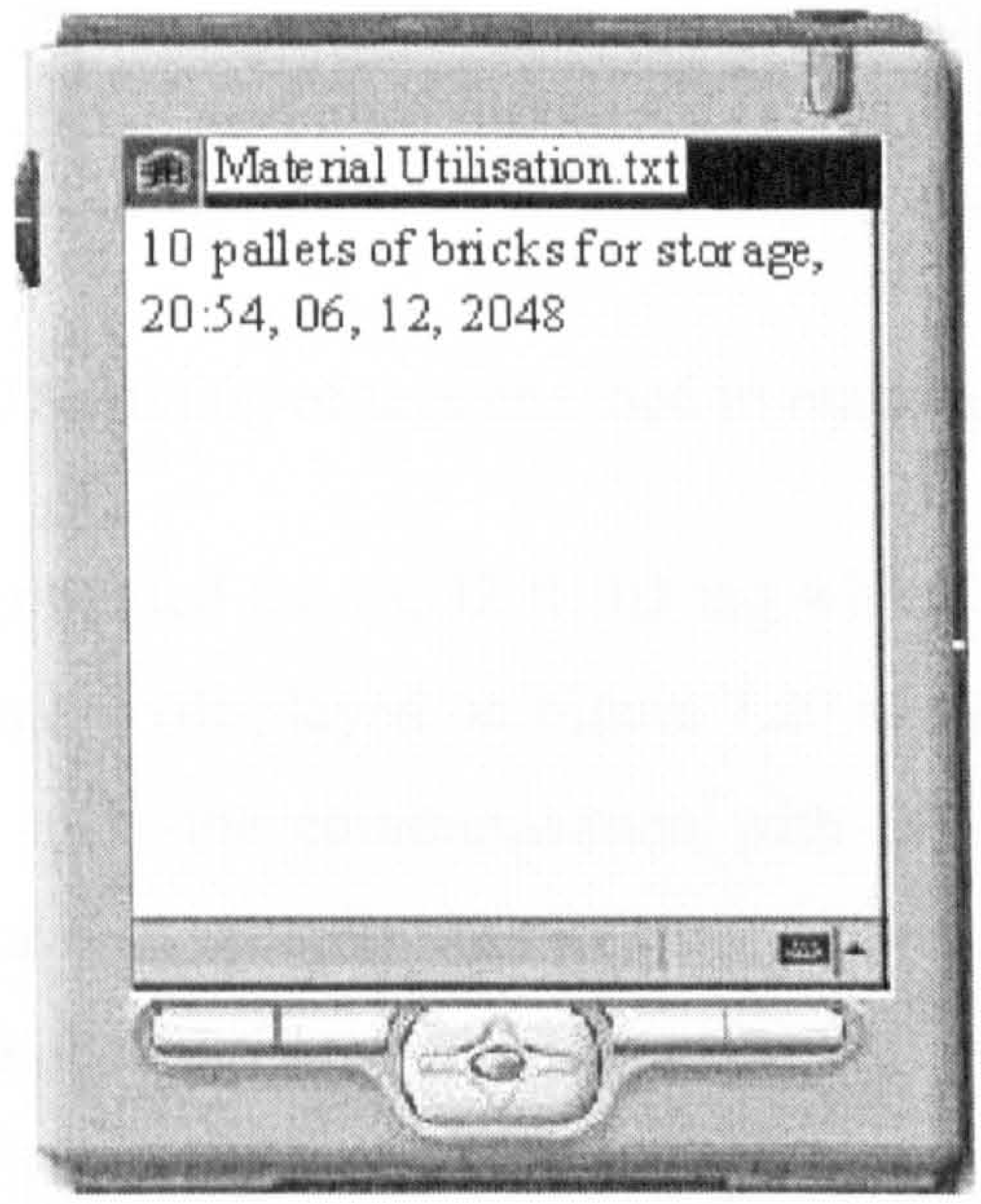


Fig. 7.19 Material Utilisation Notepad File

Again the time and date are displayed wrongly.

7.3.2.4 Monitoring of the Rate of Use of Materials

For this scenario, the evaluator acted as the construction site manager. i-Q8 RFID tags were placed at specific locations in the Sir Frank Gibbs building as if they were placed in warehouses which belong to different subcontractors on a construction site. The evaluator stood outside of the building and logged in to the 'Material Use Monitoring' graphical user interface.

After connecting to the i-Port3 RFID reader, the evaluator scanned for the specified i-Q8 RFID tags:

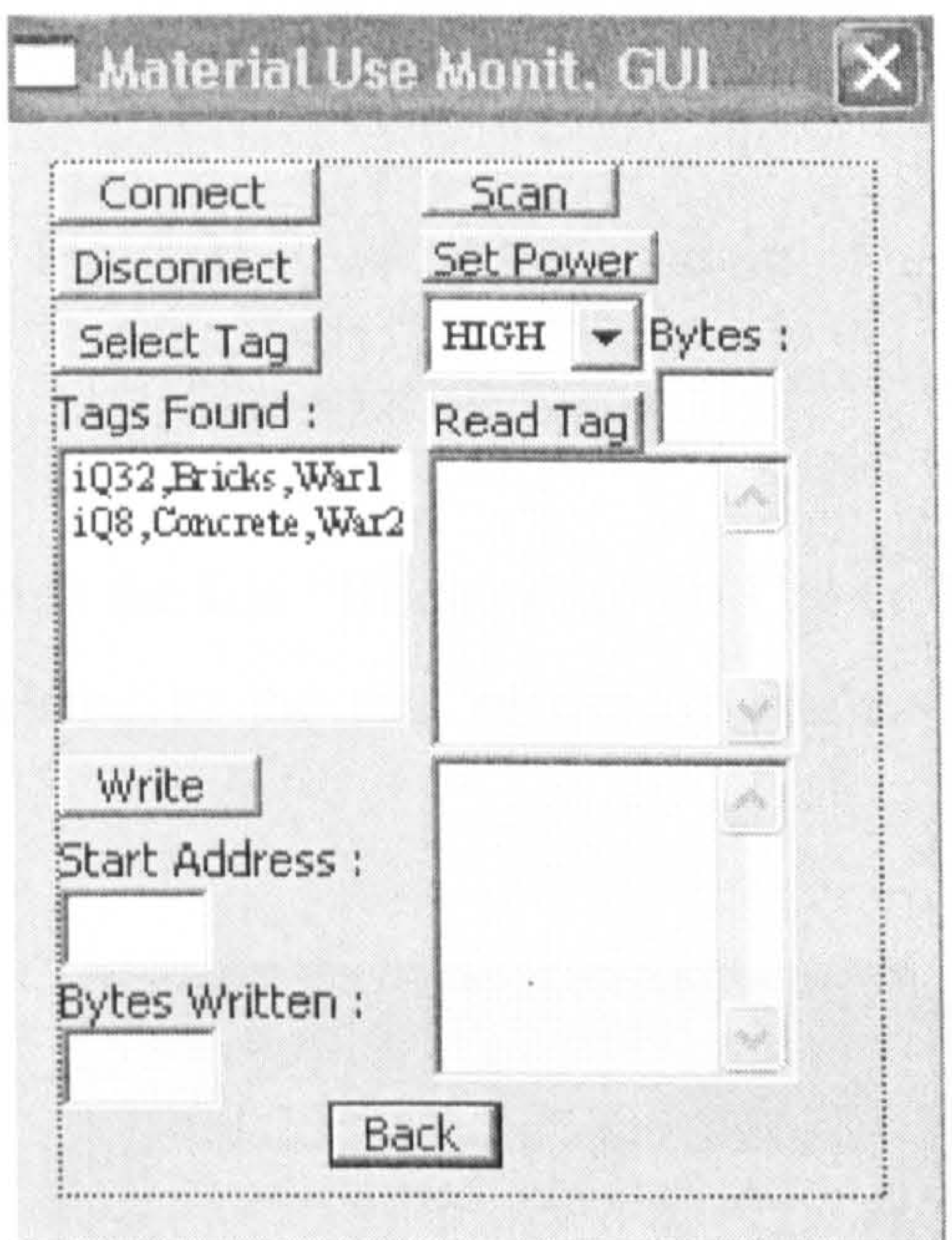


Fig. 7.20 Scanning of tags attached to materials on site

The evaluator highlighted the i-Q32 RFID tag which is attached to pallets of bricks located at warehouse 1 (displayed on Figure 7.20 as 'War1'). He then pressed the button "Select Tag" and the communication with the specific RFID tag was established. The evaluator then specified the number of bytes and pressed the button entitled "Read Tag". The content of the selected RFID tag appeared on the graphical user interface. This is shown in Figure 7.21.

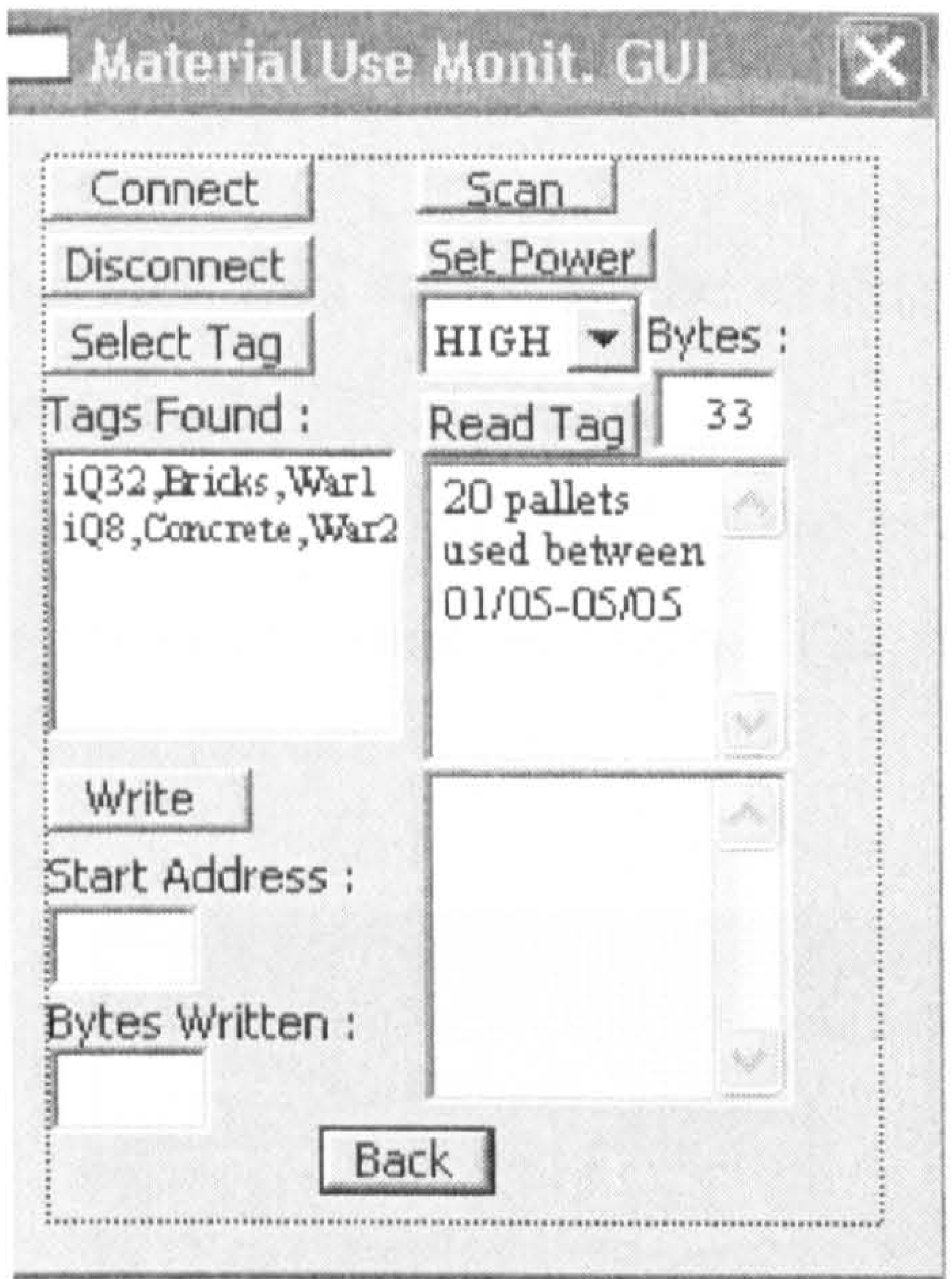


Fig. 7.21 Reading the contents of tags related to the use of a specific material

The evaluator opened the file "Bricks Rate Of Use.txt" which acts as the file for storing information related to the rate of use of bricks. This can be shown in Figure 7.22.

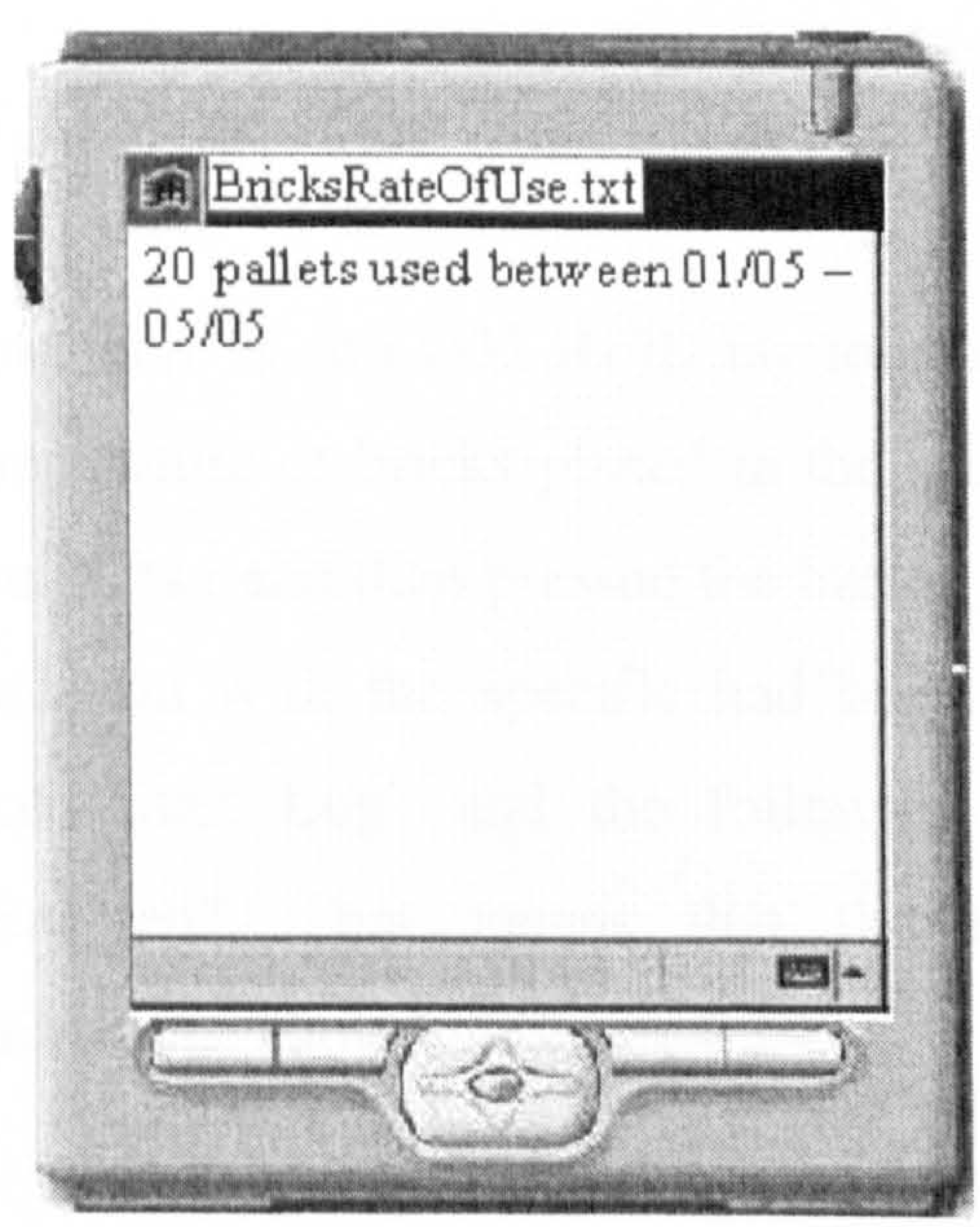


Fig. 7.22 "Material Rate Use Monitoring" Notepad file

7.3.2.5 Monitoring of the Temperature of Porous Materials

For the testing of the specified scenario, the evaluator selected the 'Porous Materials' graphical user interface.

After connecting to the i-Port3 RFID reader, the evaluator scanned for tags which are placed on porous materials, such as bricks. The result is shown in Figure 7.23.

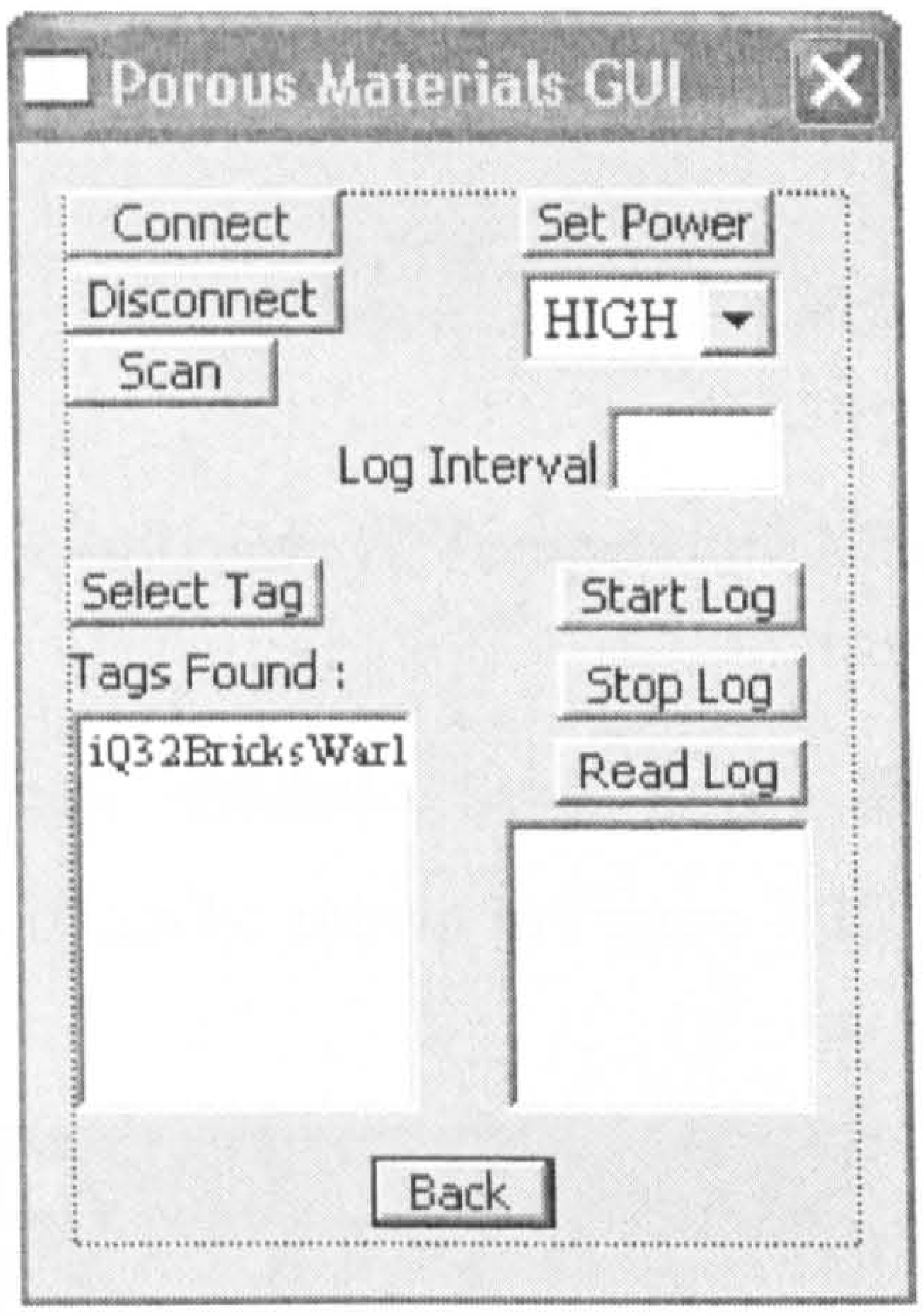


Fig. 7.23 Scanning for Tags of Porous Materials

The result shows that there is an i-Q32 RFID tag located at Warehouse 1 for the measurement of the temperature of bricks placed in the specific warehouse. The participant selected the specific tag and then pressed the button entitled "Select Tag". In this case, the communication with the specific had been established. He then pressed the button entitled "Start Log" and the following message appeared : "Temperature Logging Enabled". That means that the measurement of the temperature had started. This can be shown in Figure 7.24.

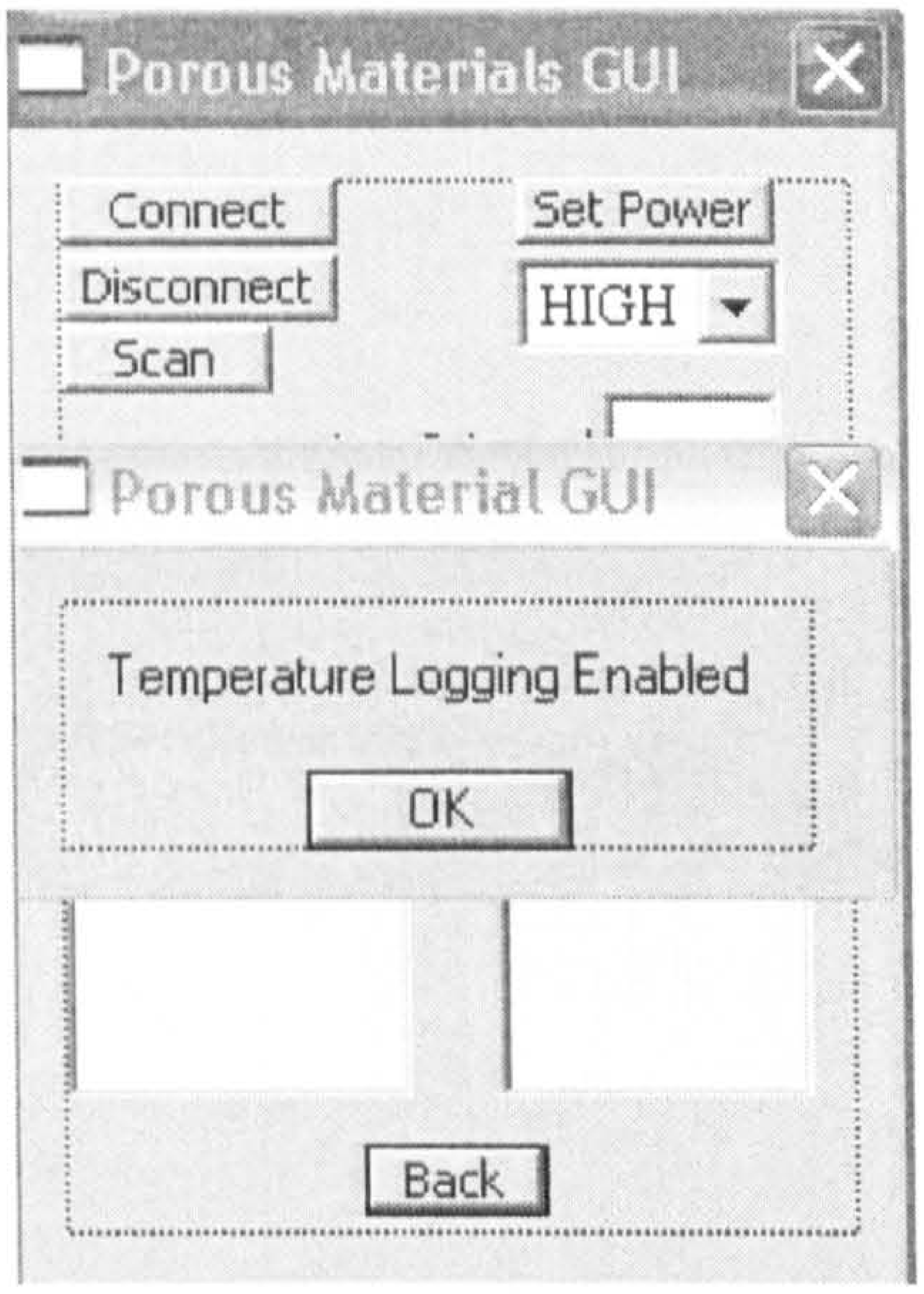


Fig. 7.24 Initiation of Temperature Monitoring

By pressing the button entitled "Stop Log", the measurement of the temperature can be stopped as it can be shown in Figure 7.25.

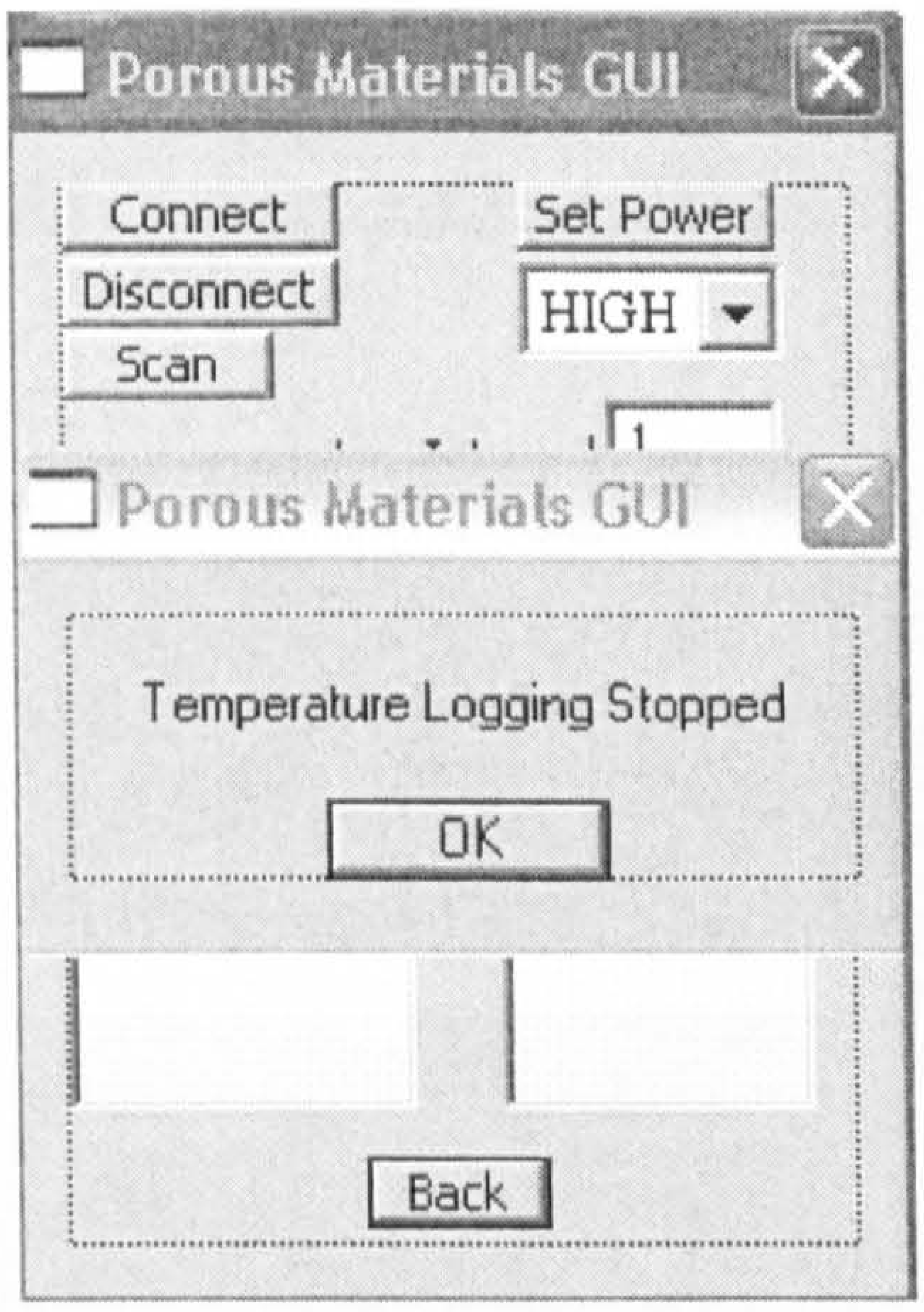


Fig. 7.25 Stopping Temperature Monitoring

The participant then pressed the button "Read Log". A list with the temperature measurements appears on the graphical user interface shown in Figure 7.26.

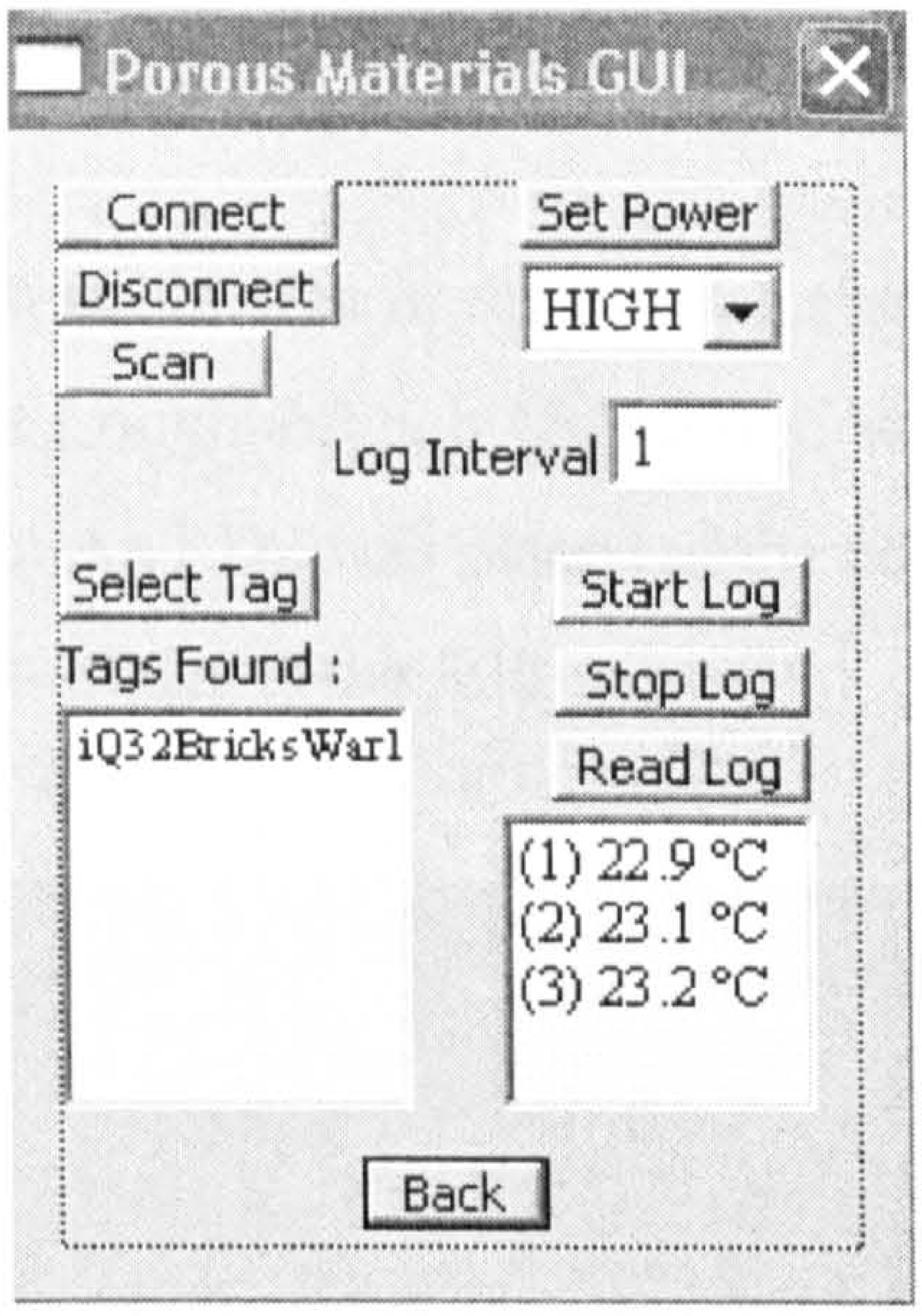


Fig. 7.26 Temperature Measurement Results

In addition, the participant opened the file "Temperature Monitoring.txt" which recorded the temperature measurements and the result was the following :

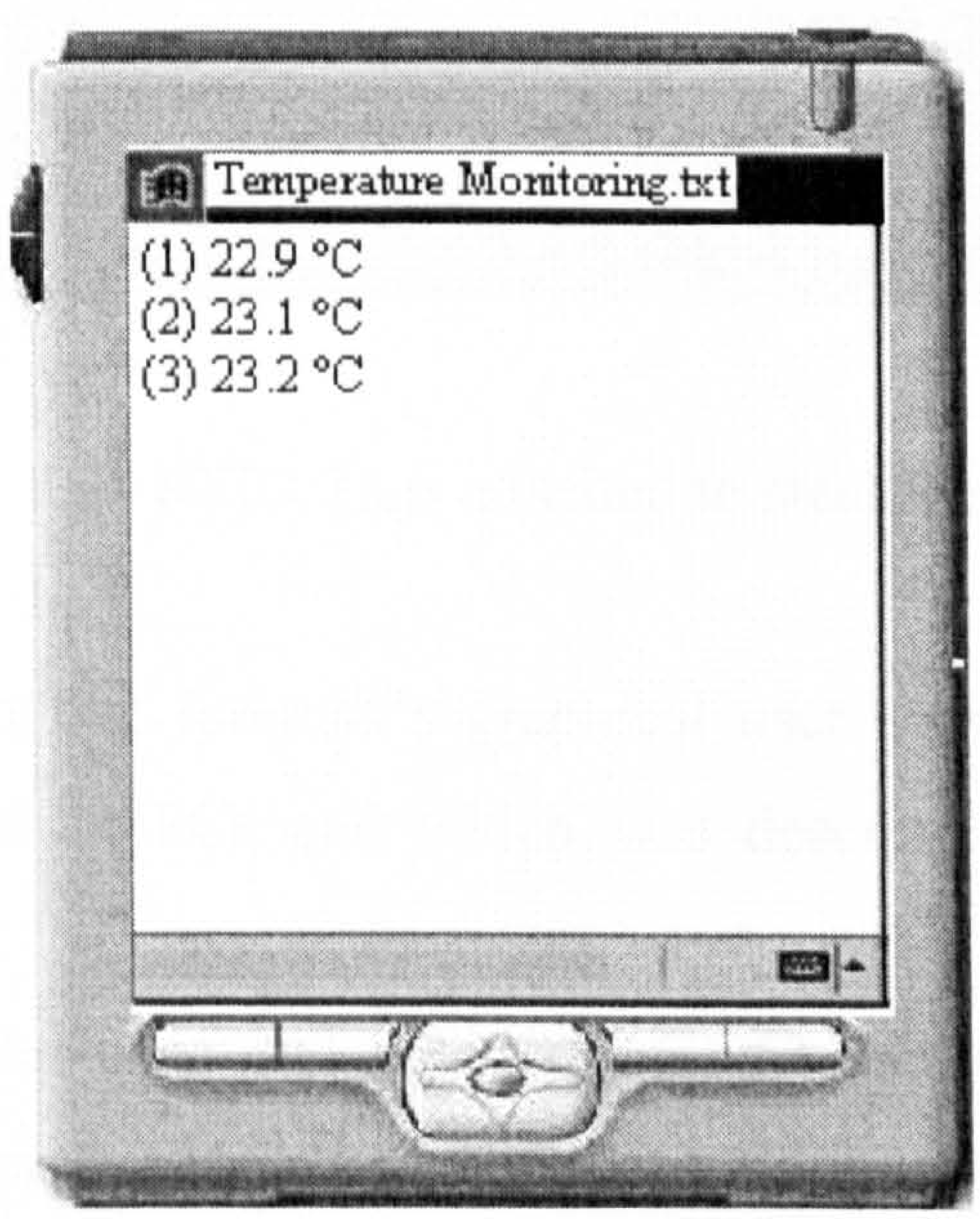


Fig. 7.27 Temperature Monitoring of Porous Materials Notepad File on PDA

7.3.2.6 Checking of the Sequence of Steel Members

For this scenario, a specific area in the laboratories of the department of Civil and Building Engineering at Loughborough University, was used. In this area, a pile of steel members was placed. An i-D2 was placed at the edge of each steel member. A picture of this pile of steel members is the following :

Fig. 7.28 RFID Tags attached to steel members

For this scenario, the foreman's graphical user interface which is designed only for laptops and tablet PCs and which was described on Section 6.4.1.2 of Chapter 6, was used.

A laptop computer was used with the i-Card3 RFID reader plugged into its PCMCIA slot. The system evaluator had to specify the type of scan but not the type of the tag to be scanned from the RFID reader as the system is programmed to scan for specific tags when the button "Steel Members Sequence" is pressed. After the connection to the i-Card3 RFID reader was established, the system evaluator attempted to scan for the first, second, third and so on steel member.

Depending on the evaluator's position, the orientation of the antenna of the reader and the power sensitivity of the reader, the scanning of a specific steel member may be successful or not. Even the order in which the scanned steel members appear on the graphical user interface depends on these specific factors.

The evaluator set the power level to 'LOW', and moved close to the left side of the pile of steel members while the antenna of the RFID reader was in a vertical position. The result of the scan is shown in Figure 7.29.

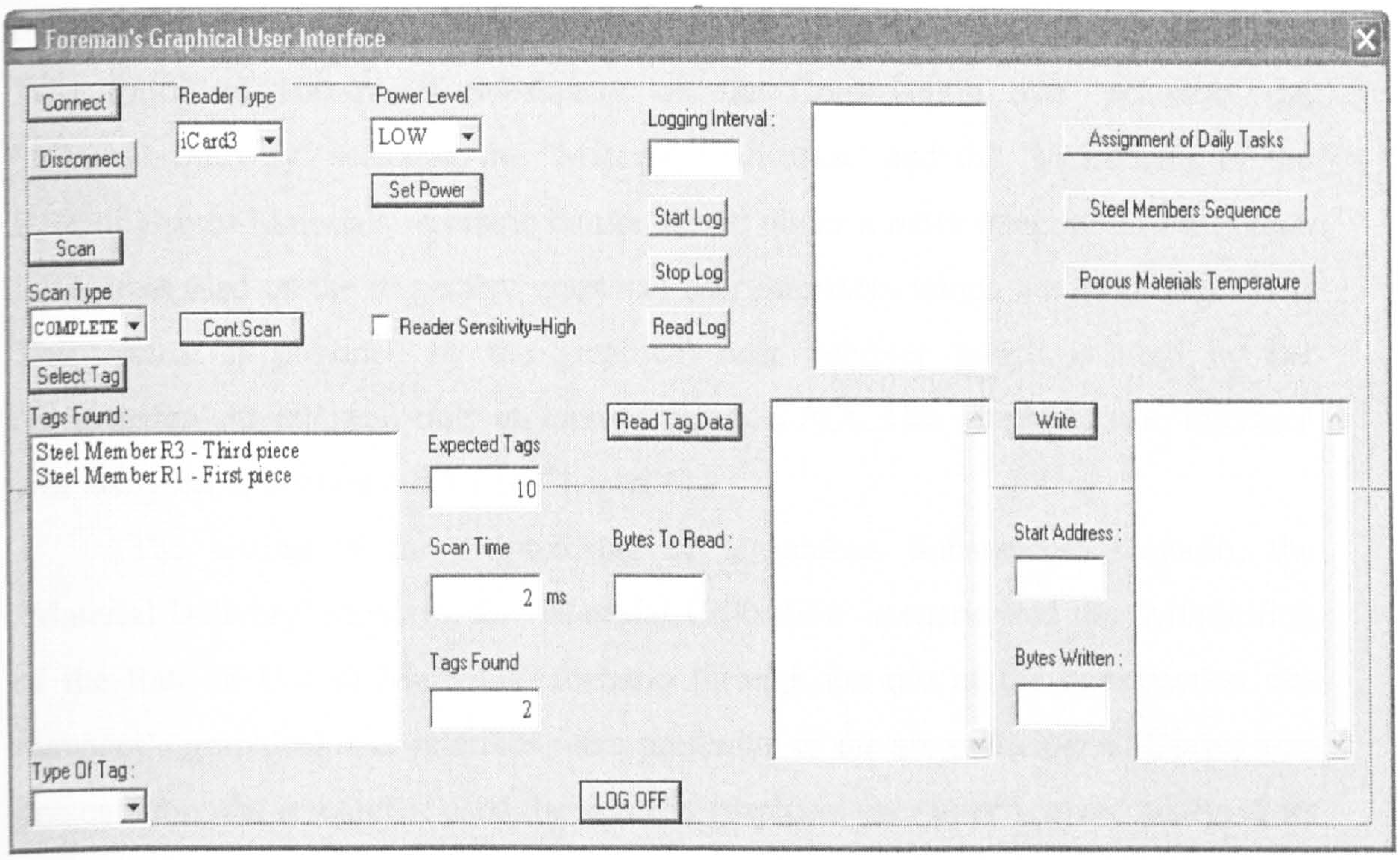


Fig. 7.29 Scanning of Tags attached to Steel Members

In order to identify the exact location of the steel member R1 which is considered to be the first piece to be erected in the steel structure, the system evaluator highlighted with the computer mouse the scanned tag which is considered to be placed on the specific steel member and which appeared on the graphical user interface as "Steel Member R1 – First Piece". He then pressed the button entitled "Select Tag". In this case, the light-emitting diode (LED) on the tag, lit up. As a result, the system evaluator was able to locate the specific steel member in the stack of steel members.

7.3.3 Presentation of Graphical User Interfaces not Used during Actual Testing

The six evaluators who participated in the field testing of the system which was developed for this thesis, were given a presentation of specific graphical user interfaces which are part of the system but were not used during the actual testing of the system. This is because these graphical user interfaces have exactly the same functionality as the used interfaces but they only differ in the format. For example, the 'Monitoring of Hazardous Substances on the Construction Site' scenario, the 'Material Delivery' scenario, the 'Material Utilisation' and the 'Monitoring of the Rate of Use of Materials' scenario can be tested under a more integrated format than the format used on the respective graphical user interfaces which are used on a PDA. This format is provided by the graphical user interface which is used by the construction site manager only on laptops or tablet PCs. This graphical user interface was analysed in Section 6.4.1.1 of Chapter 6.

The testing of the 'Monitoring of Hazardous Substances' scenario, the 'Material Delivery' scenario, the 'Material Utilisation' scenario and the 'Monitoring of the Rate of Use of Materials' scenario through the use of the construction site manager's graphical user interface were presented to the six participants. During this presentation, the researcher used the specific graphical user interface and analysed its different functions step-by-step. An example of the use of the above graphical user interface for the "Material Delivery" scenario is shown in Figure 7.30.

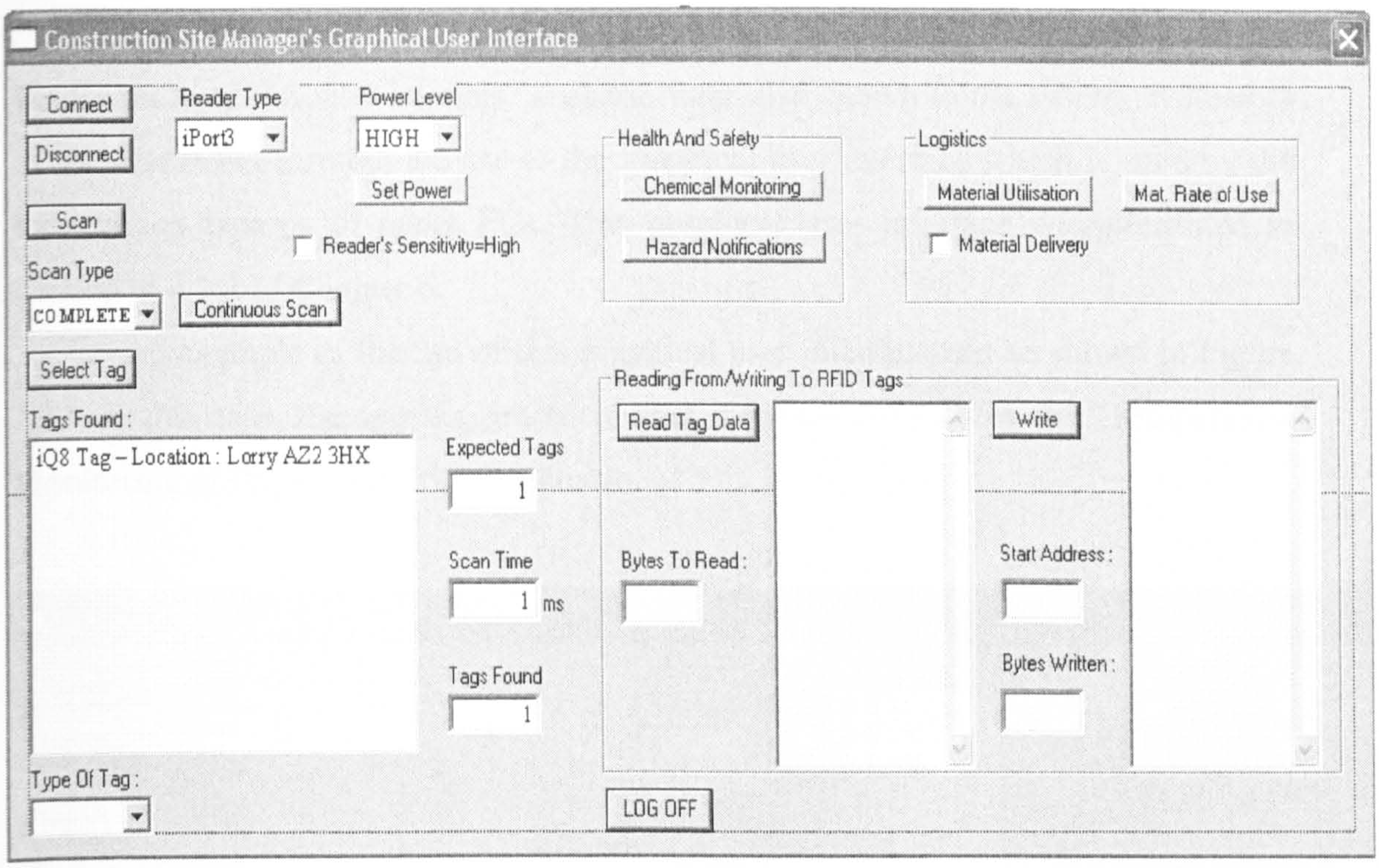


Fig. 7.30 Scanning in the Construction Site Manager's Graphical User Interface

The Notepad which was created in the C:\ directory of the laptop computer which was used by the researcher and which stores data related to the delivery of materials on the construction site, is called "Material Delivery.txt" and can be seen below :

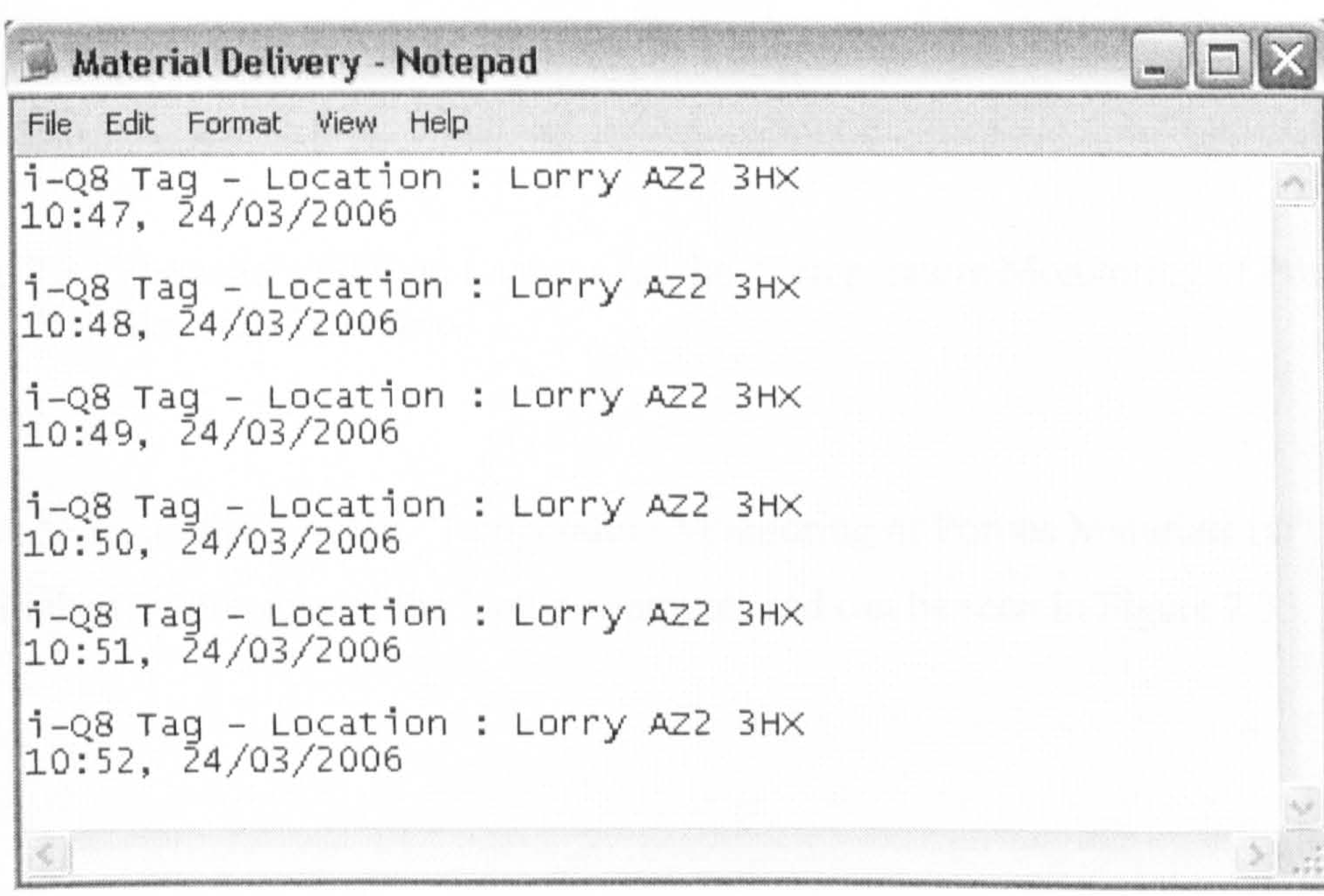


Fig. 7.31 Material Delivery File on Laptops

The "Assignment of Daily Tasks" scenario and the "Monitoring of the Temperature of Porous Materials" scenario were also shown to the system evaluators by the researcher through the use of the graphical user interface which is used by the foreman on laptops or tablet PCs. This graphical user interface was presented in Section 6.4.1.2 of Chapter 6.

An example of the use of this graphical user interface can be shown in Figure 7.32. In this case, the specific graphical user interface is used for the "Temperature Monitoring of Porous Materials" scenario.

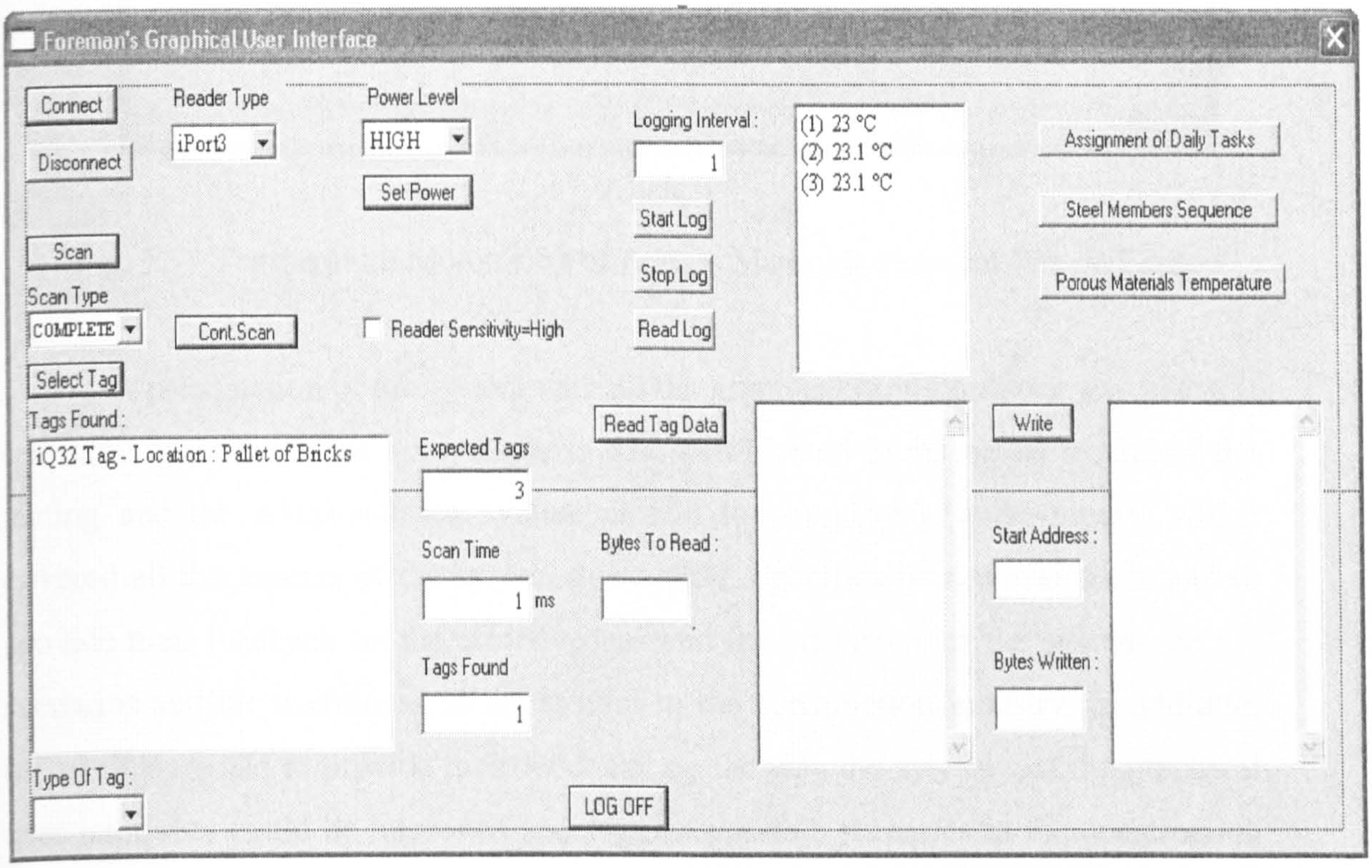


Fig. 7.32 Foreman's GUI on Laptops for the "Temperature Monitoring of Porous Materials" scenario

A Notepad file entitled "Temperature Monitoring of Porous Materials.txt" was created in the C:\ directory of the laptop computer and can be seen in Figure 7.33.

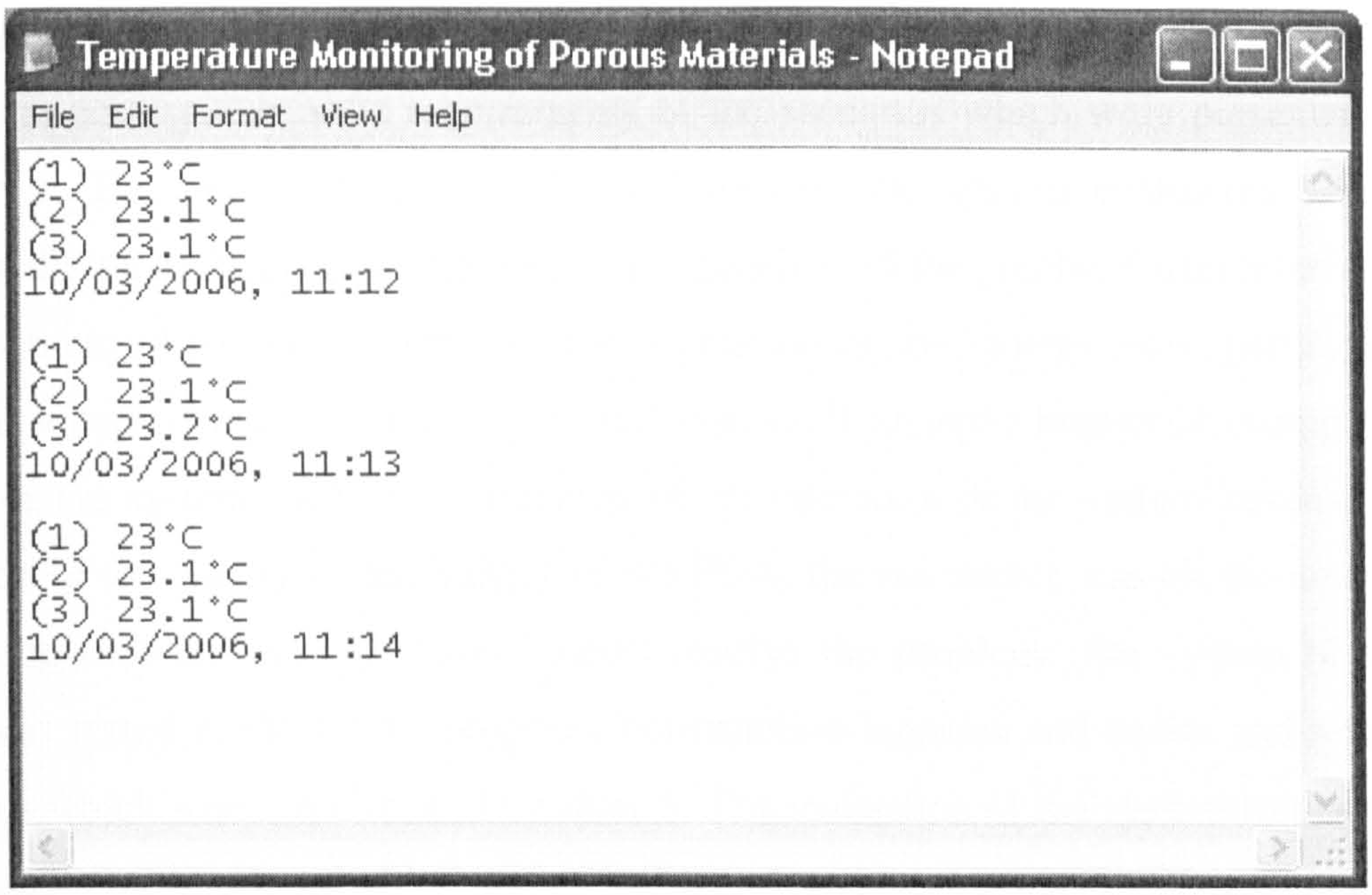


Fig. 7.33 Temperature Monitoring of Porous Materials Notepad File on Laptop

A presentation of the system with all the graphical user interfaces was given to ten more evaluators. The six evaluators who participated in the actual testing of the testing and the additional ten evaluators had to complete a questionnaire which covered all the aspects of the system thoroughly. Specifically, the evaluators had to provide their feedback on the effectiveness and the efficiency of the system, on the scenarios and the usefulness of the system to the construction industry. In addition, the evaluators had to provide their feedback on the way the system and the graphical user interfaces could be improved and suggest possible scenarios in the construction industry in which the system could be used. A copy of the questionnaire can be found in the Appendix of the thesis.

7.4 Summary

The testing of the system developed for the research occurred in order for specific parameters, such as the effectiveness and efficiency of the system, its graphical user interfaces and its usefulness to the construction industry to be examined. System testing was done in cooperation with a group of experts on an area of the campus of Loughborough University which was considered a simulated construction site. During the testing of the system, each evaluator had the opportunity to handle a number of different graphical user interfaces which belong to the system and which correspond to the requirements of the scenarios which were presented in Chapter 5. The mobile device which was used by the system evaluators was a personal digital assistant on which there were installed all the graphical user interfaces of the system of the thesis. Prior to the evaluation of the system, each participant received a presentation on how to use the system. If an error happened during the testing of the system, such as termination of the operation of the system because of reduction of the energy of the battery of the PDA, the researcher was on the area of the testing in order to help the evaluators resolve the problem. The system of the thesis was tested in the all the proposed construction logistics and health and safety scenarios which were presented in Chapter 5. The realisation of the system testing on a simulated construction site is characterised by advantages but also by disadvantages. The advantages are that the researcher can better cooperate with the participants since they are willing to use a system that may be proved useful for the development of innovative applications in the construction industry. In addition, the evaluators of the system of the thesis could provide accurate feedback since most of them had years of experience on real construction sites and they also had acquired in-depth knowledge of the research which is realised in the construction industry through their employment in academia. The disadvantages of the use of a simulated construction site for testing purposes are that specific characteristics of a real construction site, such as the existence of many metallic objects which could affect the detection range of the RFID readers of the system, do not exist in the same level on a simulated construction site.

Chapter 8 : System Evaluation

8.1 Introduction

This chapter is related to the analysis of the feedback of the evaluators of the system developed for this thesis. The chapter firstly presents the objectives of the evaluation of the system of the thesis and then progresses to a statistical analysis of the evaluators' feedback. Furthermore, there is presentation of the suggestions provided by the evaluators about possible improvements of the proposed system, the problems of the system, its best features and its possible applications in the construction industry.

8.2 Evaluators' Feedback

The evaluators of the system rated the system and expressed their opinions through a questionnaire. The design of this questionnaire was based on the objectives mentioned in Section 7.2 of Chapter 7. The questionnaire was divided into a number of sections which examine different aspects of the system. Specifically, these sections question the evaluators about the effectiveness and efficiency of the system, the quality of the graphical user interfaces, the proposed research scenarios and the usefulness of the proposed system for the construction industry. Each section contains a number of questions. Additionally, the evaluators can express their personal opinions about how the system could be improved, its advantages and disadvantages and possible applications in the construction industry. Each of these sections along with the relevant feedback from the evaluators is provided below.

A group of sixteen people participated in the evaluation of the system. Six of the evaluators participated in the actual simulation of the proposed scenarios while two presentations of the system were provided for the remaining evaluators. The six evaluators who participated in the actual simulation of the system were one postdoctoral researcher with extensive knowledge of mobile technologies used on the construction site, a research associate who had worked in a construction company for some years before undertaking research on European Union funded projects, a postdoctoral research associate with experience in a number of industrial and government-sponsored research projects and with a number of publications in international journal and conference papers as well as a completed book, a postdoctoral research associate with experience in the use of computing on construction sites, and two research students who are both involved in the use of mobile technologies on the construction site. One of the research students had also worked for some years in the construction industry. The ten people who were provided with a presentation of the system of the PhD thesis were one senior lecturer from a foreign university, a senior lecturer from Loughborough University, three senior engineers from large UK construction companies, postdoctoral researchers and research students involved in the use of mobile technologies in the construction industry.

8.2.1 Effectiveness/Efficiency of the Proposed System

This section examines how well the system achieved the goals of material tracking and improves the health and safety conditions. Also, the level of improvement of the communication between different experts on the construction site, such as the foreman and the workers, is examined. Diagram 8.1 represents the rating received by the system evaluators for the ability of the system to track materials and improve the health and safety conditions on the construction site. In addition, the improvement of the communication between construction experts through the use of the proposed system, is examined. The blue bars represent the ratings and the purple bars represent the numbers of evaluators who provided the ratings. For example, from the diagram it can be shown that eleven evaluators rated the system with '4'.

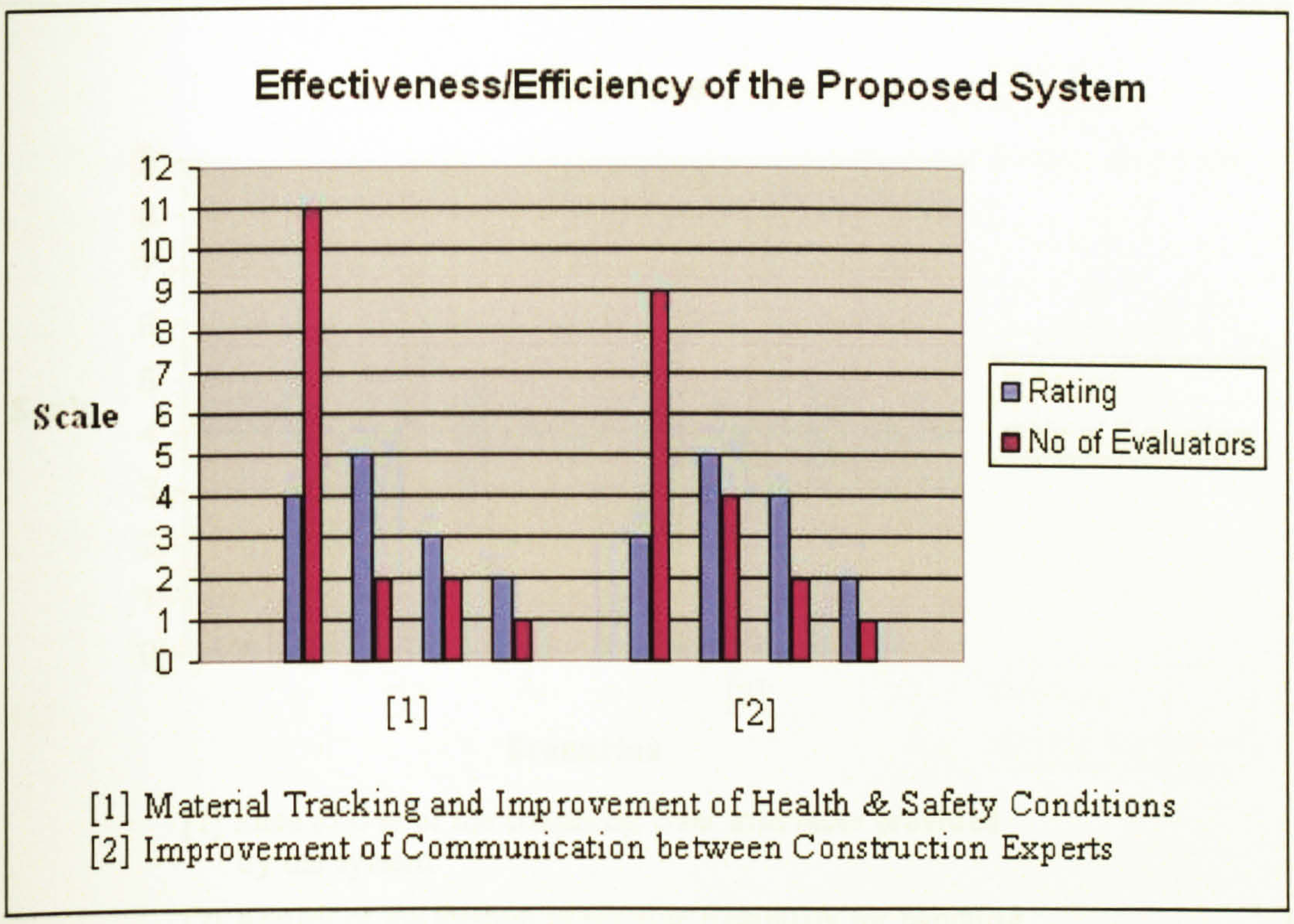


Figure 8.1

Diagram 8.1 shows that the majority of the evaluators of the system rated the system '4' and '3' respectively for the two scenarios. The average rating of the system for its effectiveness and efficiency can calculated by multiplying the percentage of evaluators who gave the system a specific rating, with the rating itself and then by adding the results and dividing them by two since the number of scenarios is two. Thus, the average rating of the system is :

[(11*4 + 2*5 + 2*3 + 1*2) + (9*3 + 4*5 + 2*4 + 1*2) /16] / 2 = [(62+57)/16]/2 =

= (119/16) / 2 = 3.71875

8.2.2 User – Interface

This section examines the ease of using the graphical user interfaces and the flexibility provided by the proposed system for the handling of different types of information, such as health and safety and logistics data.

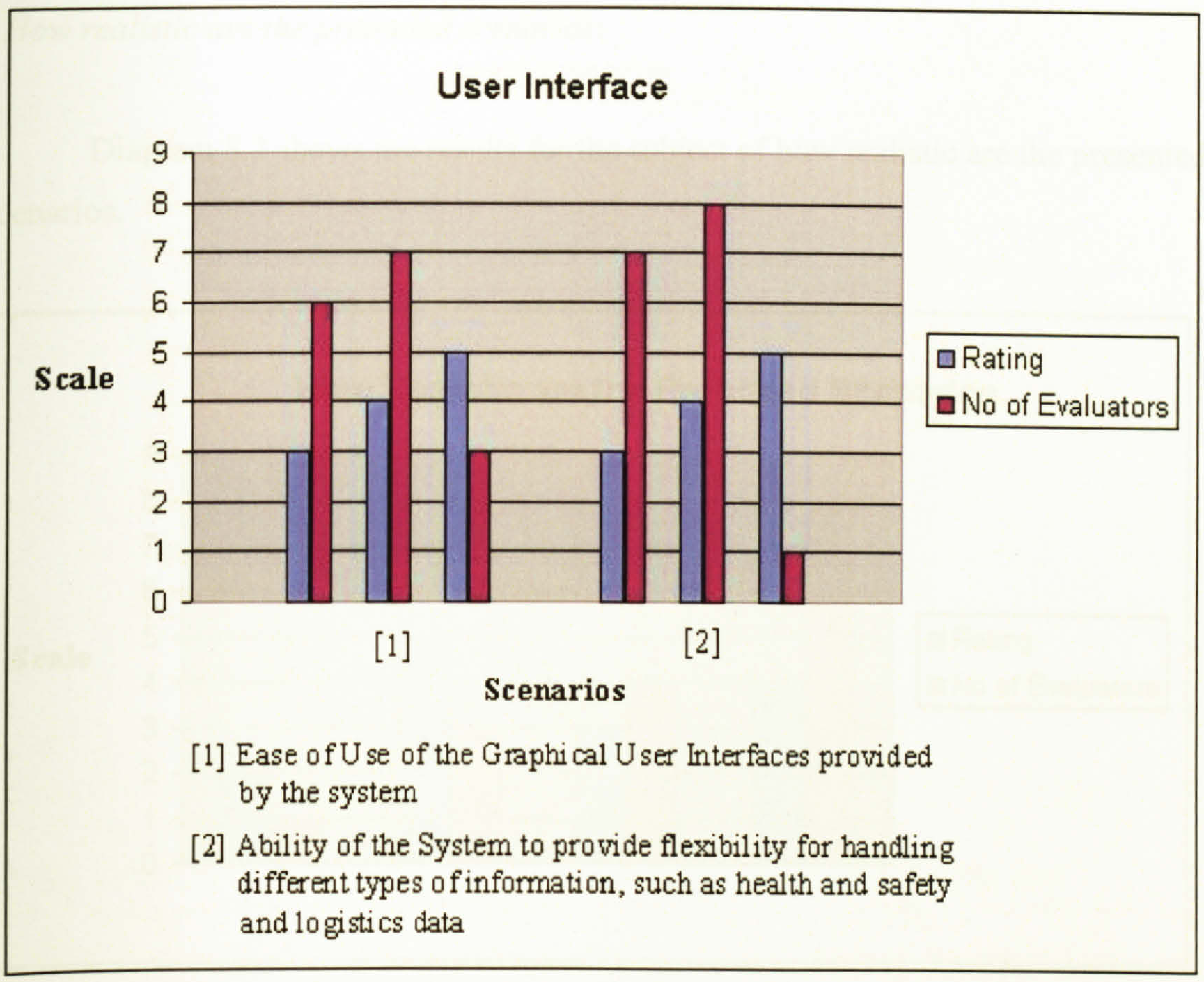


Figure 8.2

Diagram 8.2 shows the evaluators' results for this specific subject. The majority of the evaluators rated the system '4' for both the ease of using the graphical user interfaces of the system and the ability of the system to use different types of information. The average rating of the system for its graphical user interfaces is 3.71875.

8.2.3 Scenarios

This section examines a number of subjects related to the proposed research scenarios. These subjects are presented below:

• *How realistic are the presented scenarios*:

Diagram 8.2 shows the results for the subject of how realistic are the presented scenarios.

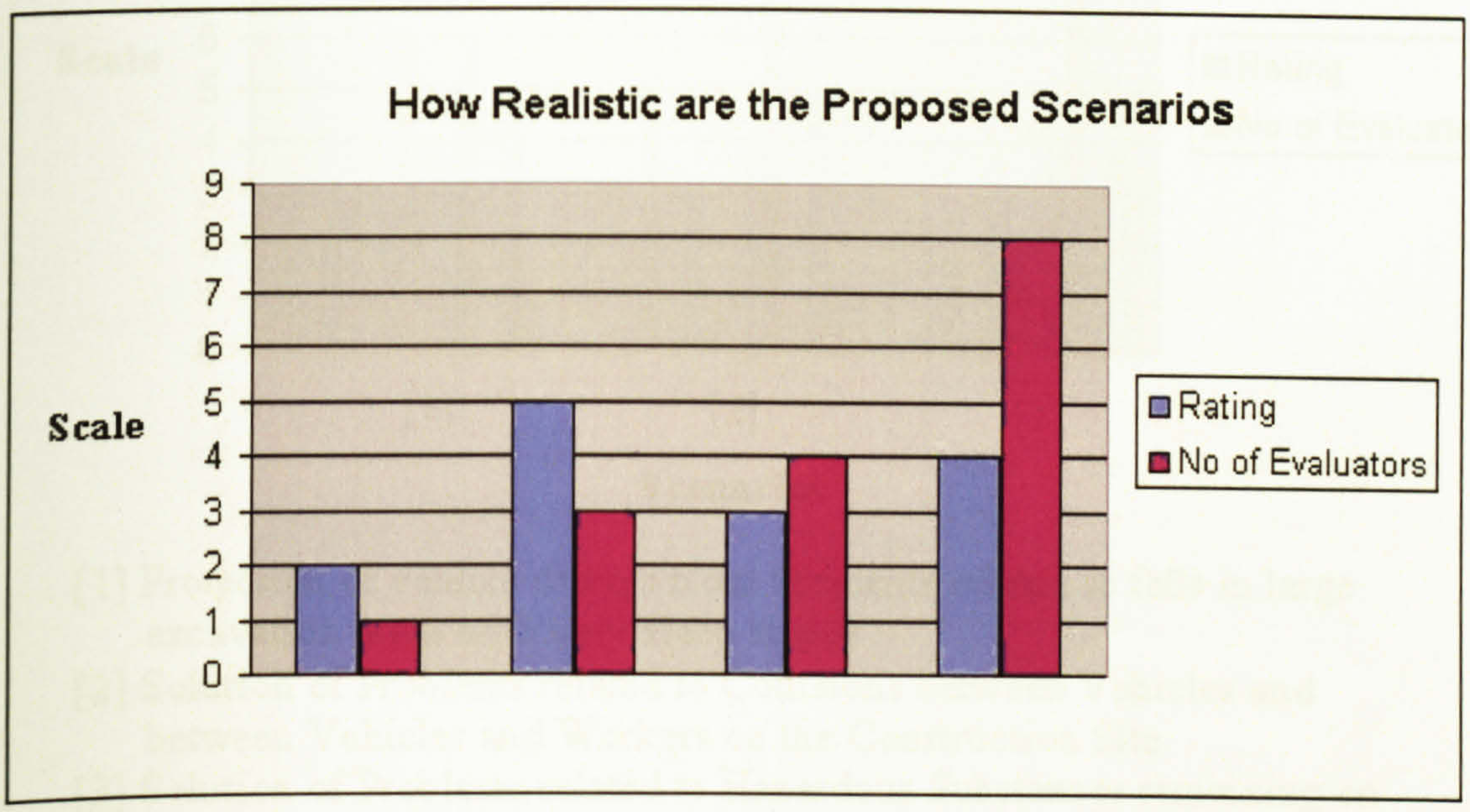


Figure 8.3

Diagram 8.2 shows that the largest portion of evaluators rated the system with '3' while the second largest rating is '5'. Specifically, 37.5% of the evaluators rated the system with '3', 31.25% rated it with '5', 25% rated it with '4' and 6.25% rated it with '2'. The average rating of the system is 3.8125.

• *Health and Safety Scenarios*:

The results of the evaluation of the system for its testing under the requirements of the health and safety scenarios presented in Chapter 5, are shown in Diagram 8.3. The blue bars represent the ratings given by the evaluators and the purple bars represent the number of evaluators.

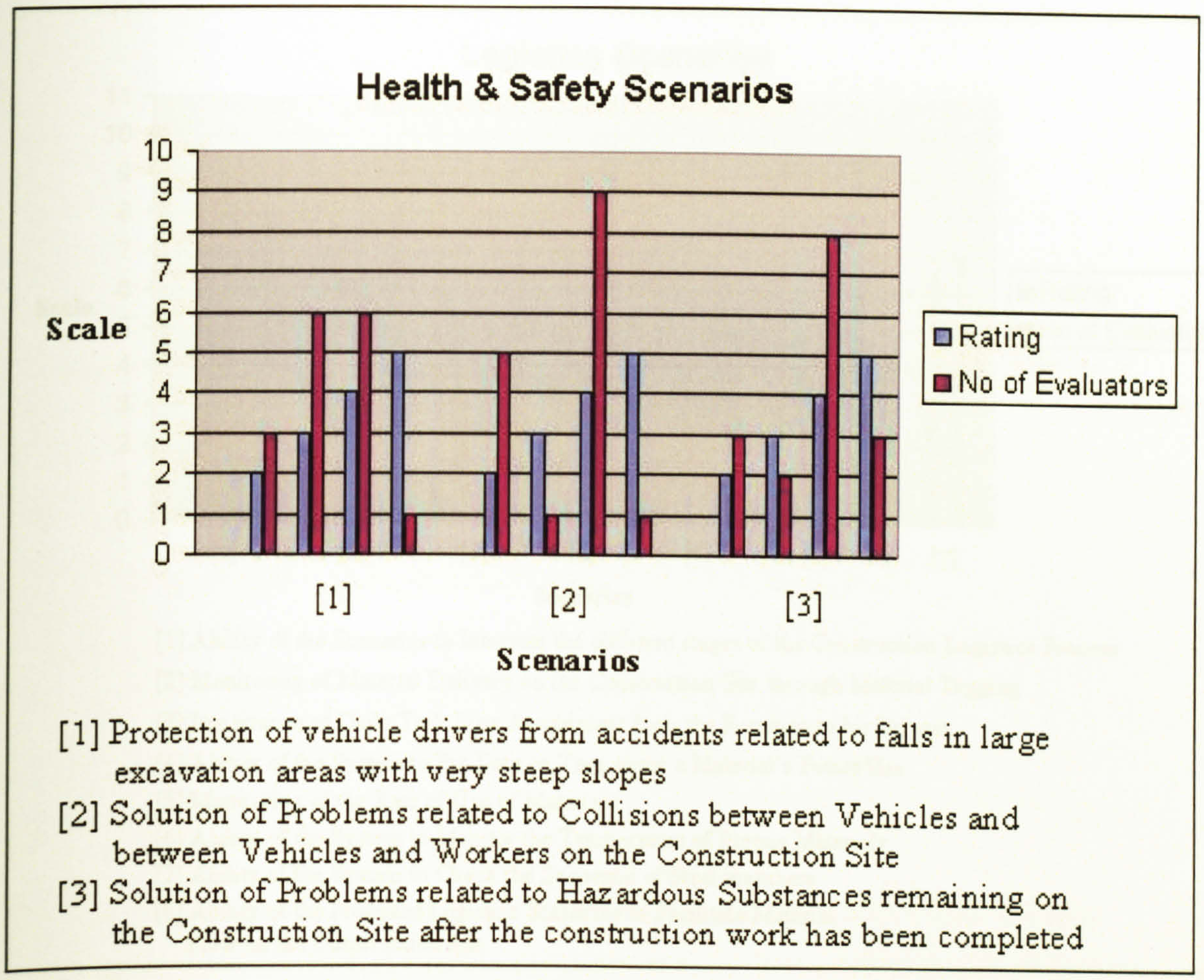
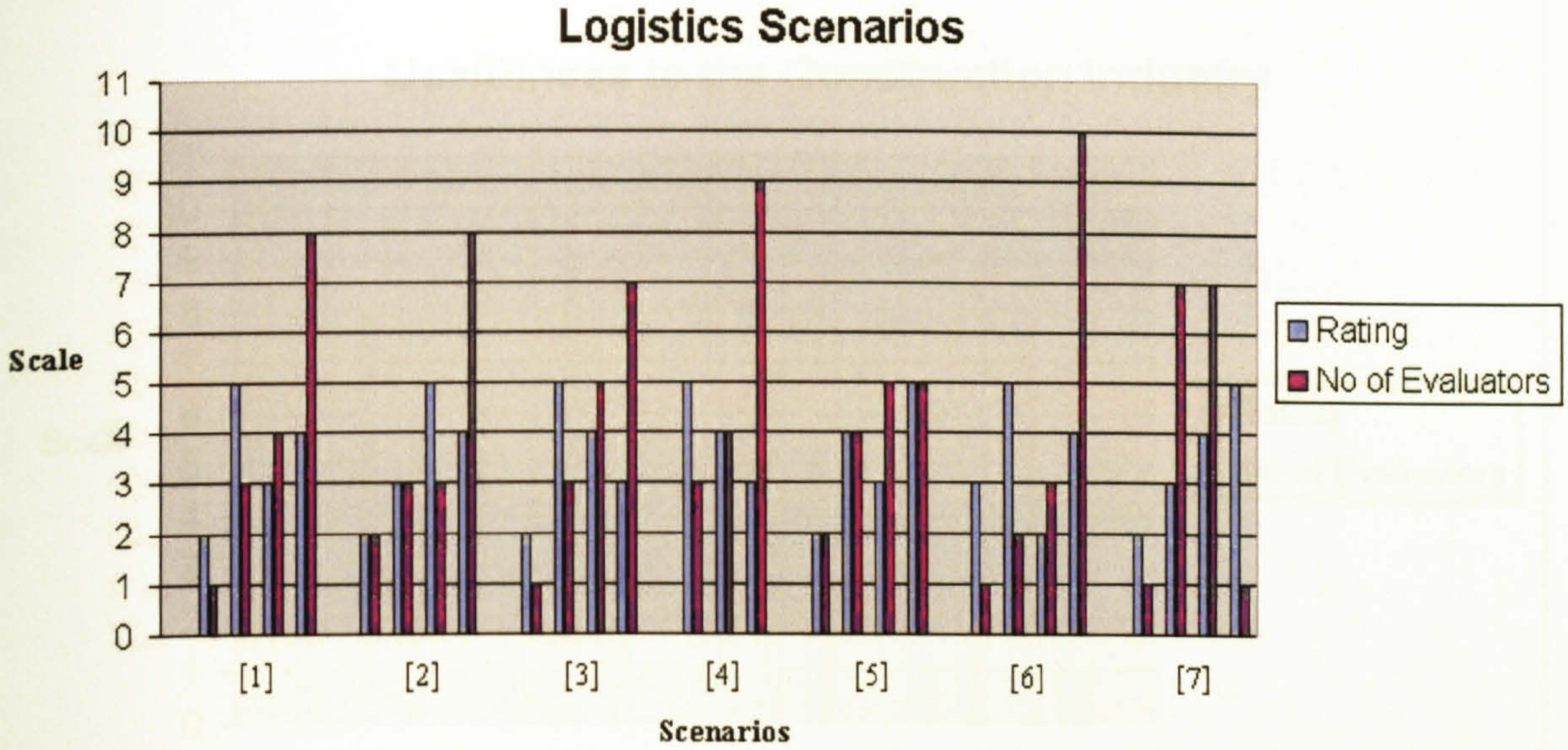


Figure 8.4

Diagram 8.3 shows that the majority of the evaluators rated the system with '3' and '4'. The average rating of the system for the health and safety scenarios is approximately 3.458333.

• *Logistics Scenarios*:

Diagram 8.4 shows the feedback received by the evaluators of the system for the capabilities of the proposed system under the requirements of the proposed logistics scenarios.



[1] Ability of the Scenarios to Integrate the different stages of the Construction Logistics Process

[2] Monitoring of Material Delivery on the Construction Site through Material Tagging

[3] Importance of Daily Task Lists Assignment from the Foreman to his Drivers

[4] Ability of the System to Put Data on Tags about a Material's Future Use

[5] Monitoring of the Rate of Use of Materials

[6] Ability of the System to Monitor the Temperature of Porous Materials

[7] Ability of the System to Check the Sequence of Steel members

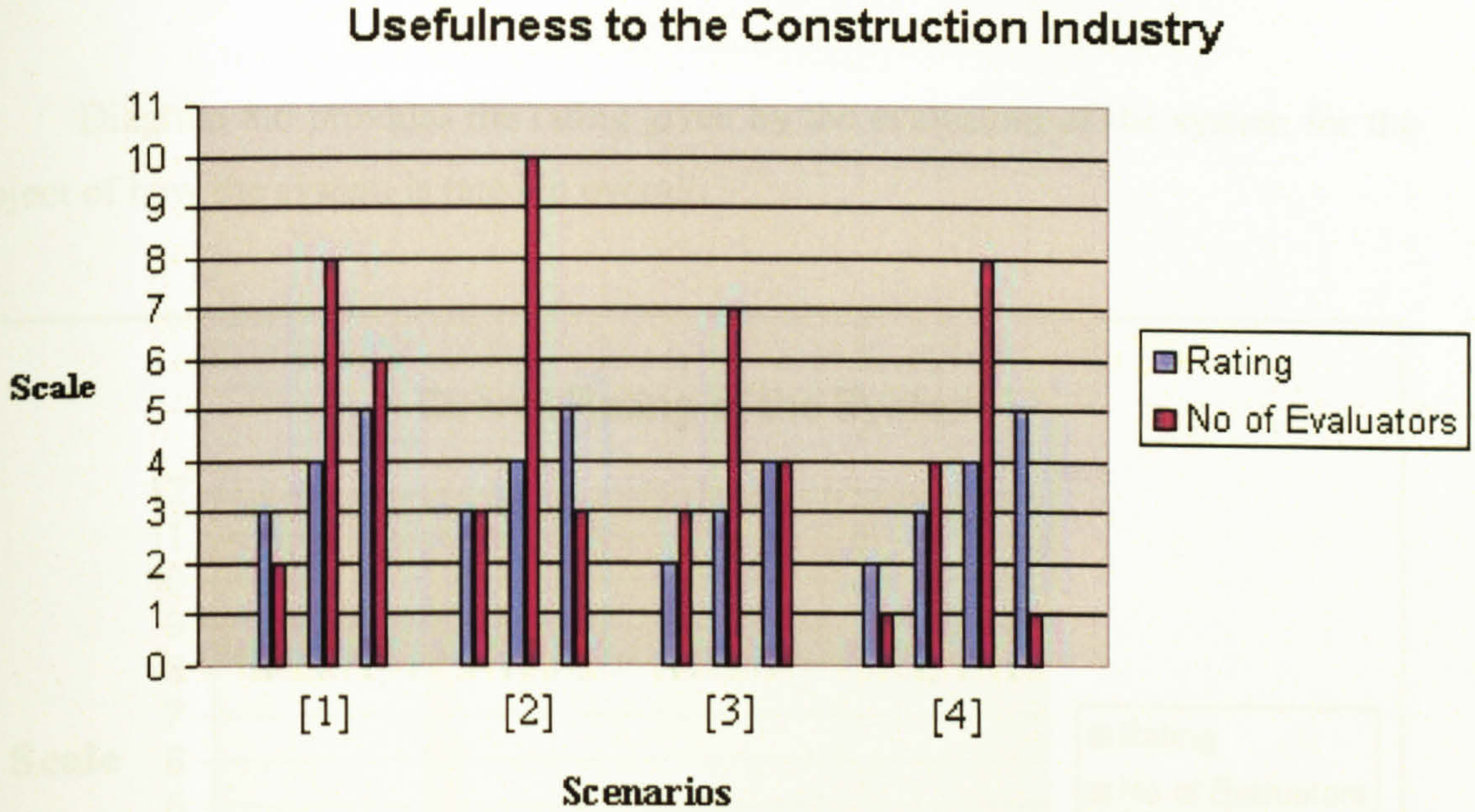
[8] Ability of the Proposed Logistics Scenarios to Facilitate Material Flow on the Construction Site

Figure 8.5

Diagram 8.4 shows that the most common rating of the system is '4' and the percentage of evaluators who provided this rating has reached even 75% of the total group of evaluators. The second most common rating of the system was '3'. The average rating of the system for the proposed logistics scenarios is 3.6484375.

8.2.4 Usefulness to the Construction Industry

This section examines how useful the proposed system is for the construction industry. It also examines how well the proposed system accelerates information flow during the construction process, to what extent the construction industry will accept the proposed system and to what extent the deployment of the proposed scenarios will enhance the use of RFID in the construction industry.



[1] Usefulness of the proposed system for the Construction Industry

[2] How well the proposed system accelerate information flow during the construction process

[3] Acceptance of the proposed system by the Construction Industry

[4] To what extent the deployment of the proposed scenarios enhances the use of RFID in the construction industry

Figure 8.6

As Diagram 8.5 shows, the system was mostly rated '4' and especially for the issue of how well the proposed system accelerates information flow during the construction process, the percentage of evaluators who rated the system with '4', was 62.5%. For the issues 3 and 4, two of the sixteen evaluators did not give a reply. The average rating of the system is 3.7410714.

8.2.5 General Section

This section is involved to the feedback received by the system evaluators related to the overall rating of the system and also its flexibility for implementation to other applications in the construction industry except those proposed in this thesis.

• *Overall Rating of the System*:

Diagram 8.6 provides the rating given by the evaluators of the system for the subject of how the system is rated in overall.

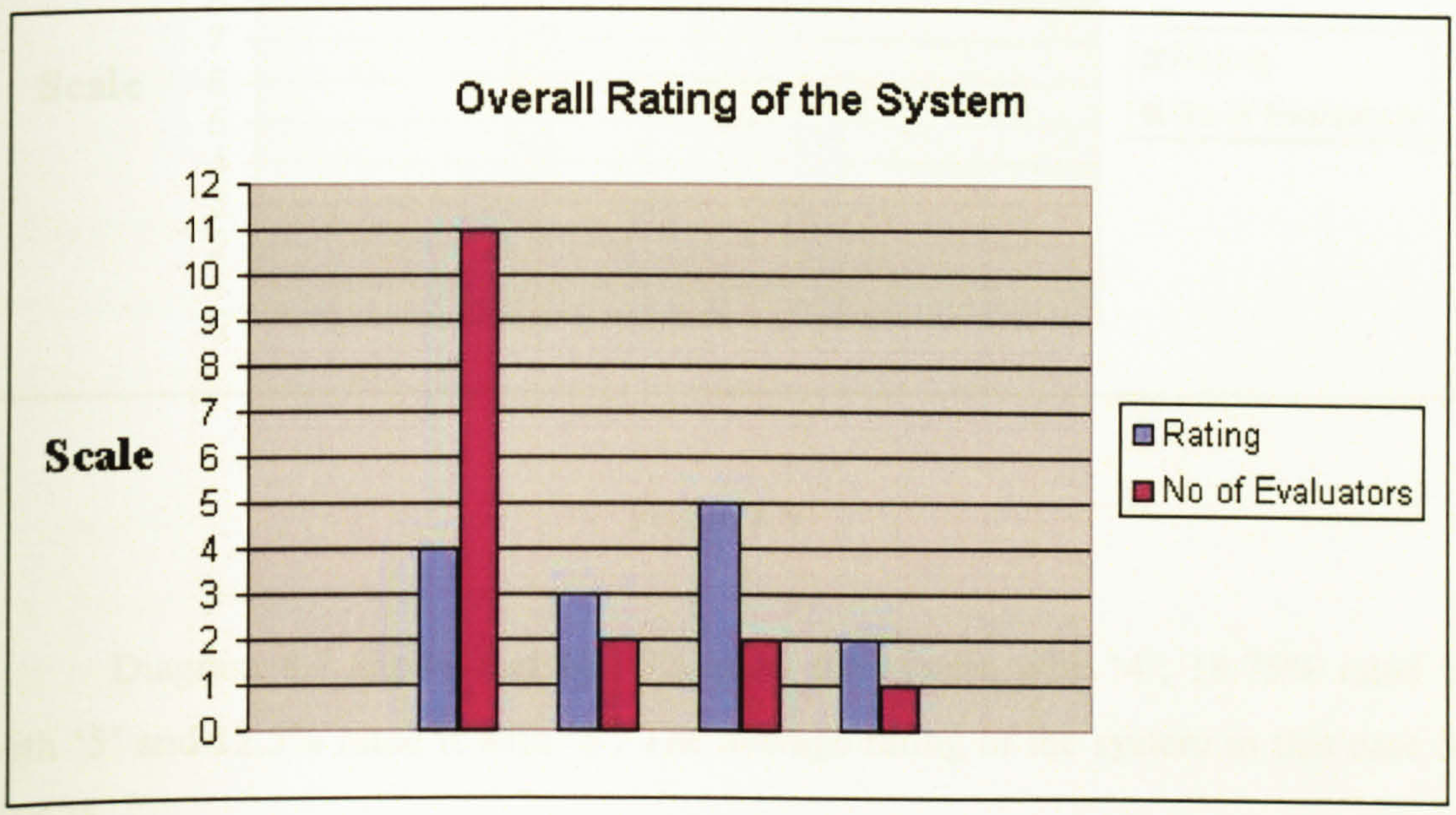


Figure 8.7

Diagram 8.17 shows that 68.75% of the evaluators rated the system with '4', 12.5% rated it with '5', 12.5% rated it with '3' and 6.25% rated it with '2'. The average overall rating of the system is 3.875.

• *Flexibility of the System for Implementation in other situations in the Construction Industry*:

Diagram 8.7 shows the feedback of the evaluators about how flexible the system is for implementation in other applications in the construction industry.

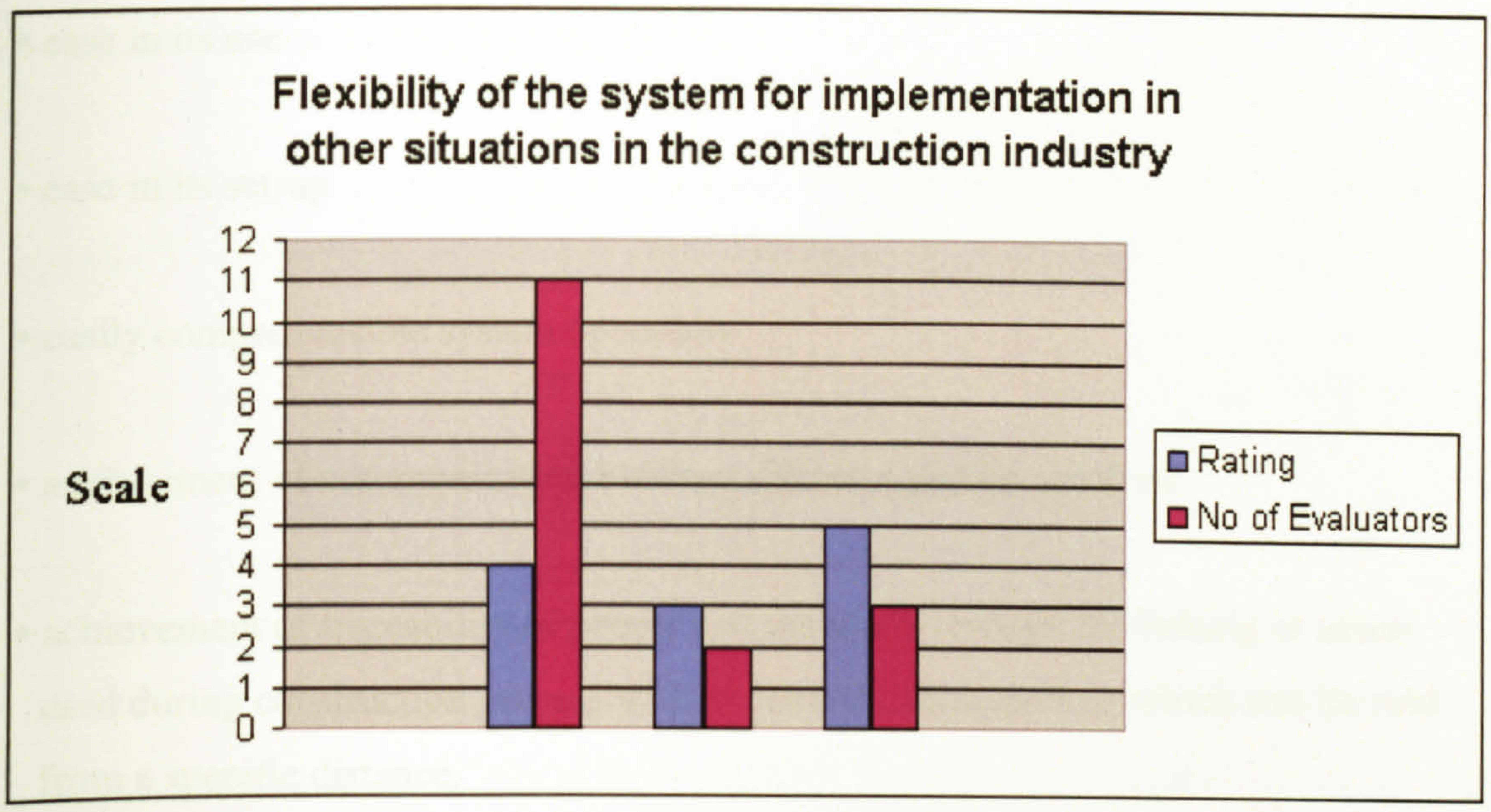


Figure 8.8

Diagram 8.7 shows that 68.75% rated the system with '4', 18.75% rated it with '5' and 12.5% rated it with '3'. The average rating of the system in this case is 4.0625.

8.3 Problems related to the System

Problems related to the system were noted only by five evaluators who comprise 31.25% of the total group of evaluators. The problems which were noted by these specific evaluators are mostly related to asset detection which may be affected by the existence of obstacles or the position of the tag which is attached to a tracked asset. One evaluator noted that in the monitoring of collisions between vehicles or between vehicles and workers, the connection of the PDA of the driver with the RFID reader may be lost and as a result, no warnings will be produced and this may cause problems to the safety of the driver.

8.4 Best Features of the System

The evaluators of the system which was developed for this PhD Thesis underlined its best features which are listed below:

- ease in its use
- ease in its set-up
- easily comprehensible system operation
- achievement of communication between different parties involved
- achievement of traceability of people and materials through the linking of assets used during construction process with an identification number which can be read from a specific distance.
- storage of the properties which characterise a material to the tag which is attached to that material and reading of them from a specific distance
- effective reading of tag data from a distance in cases in which it is difficult to reach the components to which there are tags attached
- enables storage of construction process-related data and detection of tags for different purposes
- provision of flexibility in the circulation of materials on the construction site and in the transfer of data related to the utilisation of the materials on the construction site
- use of different tags for different purposes which are able to provide a range of data
- integration of two important communication technologies, RFID and wireless local area networks (W-LANs)
- demonstrates the potential of the previously mentioned two communication technologies in realistic construction sites

8.5 Ways of Improving the System

According to the system evaluators, there are many ways of improving the system. The improvements which could be done on the proposed system are listed below :

- provision of location coordinates of tracked items
- integration of the proposed system with Internet-based technologies
- virtual mapping of every object on the construction site, thus resulting in better monitoring of the construction site activities
- deployment of the system on a real construction site
- linking of the system to Microsoft Project for the purpose of construction project planning
- improvement of the read range of the RFID reader
- provision of more data storage capacity to the RFID tags of the system with simultaneous reduction of their size

8.6 Ways of Improving the Graphical User Interfaces (GUIs)

The evaluators provided feedback also for the ways the graphical user interfaces used by the system could be improved. Their suggestions are listed below :

- Representation of the different functions of the system as icons. By clicking an icon, the appropriate graphical user interface will appear.
- Enhancement of the user-friendliness of the graphical user interfaces
- Replacement of the 'Connect/Disconnect' button used on the graphical user interfaces which are designed for use on personal digital assistants by a button

which when pressed, would change its name from 'Connect' to 'Disconnect'.

8.7 Evaluators' Proposed Scenarios for Use of the System in the Construction Industry

The system evaluators suggested a number of scenarios on how the proposed system could be used in the construction industry. These scenarios are the following :

- Placement of materials which have just been delivered to the construction site, close to the workers who will need them.

- Assignment of priorities in the deliveries of materials on the construction site depending on the progress of the construction project

- Measurement of the structural deformation of the different elements of a structure

- Installation of critical elements to each other. This is especially useful for huge infrastructure projects

- Protection of historical monuments.

8.8 Analysis of the Evaluators' Feedback

An analysis on the feedback provided by the evaluators must be done in order for useful conclusions to be formed. For the subject of how easy it is to use the graphical user interfaces of the system and how flexible the system is in the handling of different data types, the majority of the evaluators rated the system as almost excellent.

For the monitoring of the arrival of a specific material on the construction site at a specified time and date, the number of the evaluators who rated highly the system is larger than the numbers of the evaluators who rated the system highly for all the other issues related to the implementation of the system for specific health, safety and logistics scenarios. The system was rated at the highest level for its capability to monitor the temperature of porous materials and this was the highest rating of all the other ratings the system received. Furthermore, the system received as a maximum rate '4' for all the health and safety scenarios while for the logistics scenarios, the rating of the system presents variations which are close to '4'. Additionally, the rating which was given to the proposed system by the majority of the evaluators was more often '4' while in three occasions (realism of the proposed scenarios, ability of the system to allow workers to add information to an RFID tag about a material's future use, to what extent the construction site manager is able to monitor the rate of use of materials using the proposed system) the majority of the evaluators rated the system with '3'. For its ability to monitor the temperature of porous materials, the system received the maximum rating ('5') from the majority of the evaluators.

Also, the majority of the evaluators rated the proposed system with the highest grade for its capability to accelerate the information flow during the construction process. Exactly the same number of evaluators rated the system with '4' for the issues of how useful it is for the construction industry and to what extent the deployment of the system for the proposed scenarios will enhance the use of RFID technology in the construction industry. However, a slightly lower number of evaluators rated lower the system for the subject of what extent it will be accepted by the construction industry.

The majority of the evaluators provided an overall rating of '4' for the system while they also provided the same rating for the flexibility of the system to be applied in other situations in the construction industry except those proposed in this PhD thesis.

Two evaluators have not provided a rating for two specific subjects which are the extent to which the realisation of the scenarios which were proposed in Chapter 5 will enhance the use of RFID in the construction industry and also to what extent the construction industry accepts the proposed system. The evaluators could not provide a clear rating as they were unsure on how the construction industry would react in the introduction of a system like the system produced for this thesis.

The system evaluation approach is based on the use of a questionnaire. The use of a questionnaire enabled the evaluators of the system to provide a clear rating of the various aspects and capabilities of the proposed system. In addition, it provided to the researcher an accurate image of the different capabilities of the proposed system. The inclusion to the questionnaire of open-ended questions enabled also the evaluators to present their opinions in more detail. In general, the questionnaire which was used for the evaluation of the proposed system provided unambiguous feedback about all the operational aspects of the proposed system and also clarified the implications of the use of RFID technology from the construction industry.

8.9 Summary

The evaluation of the system is necessary in order for conclusions to be extracted about its capabilities. System evaluation involved the examination and use of the proposed system by a number of experts on a simulated construction site at the campus of Loughborough University. A presentation of the system by the researcher was also provided to some experts. A significant element of system evaluation included the completion by the system evaluators of a questionnaire which was covering all the aspects of the proposed system. The group of evaluators included university lecturers, postdoctoral researchers and research students who were involved in the examination of the use of mobile technologies on the construction site. The aspects of the system that were examined were its effectiveness and efficiency, its graphical user interfaces, the capabilities of the system in the resolution of the problems presented by the proposed construction logistics and health and safety scenarios and its usefulness for the construction industry. The evaluators of the system provided also an overall rating of the system. The system was usually rated above the average by the majority of the evaluators. Specifically, the most common rating provided by the majority of the evaluators for the system was usually '4'. Especially for the proposed logistics scenarios, the ratings of the system were close to '4'. The majority of the evaluators rated the system with '5' for its capability to accelerate data flow during the construction process while the ability of the proposed system to monitor the arrival of materials on the construction site was considered very efficient by most of the evaluators. For the proposed health and safety scenarios, the majority of the evaluators rated the system also '4'.

The questionnaire which was provided by the researcher to the system evaluators allowed them to provide feedback about the best features of the system and about any ways of improvement of the system and of the graphical user interfaces. In addition, the questionnaire allowed the evaluators of the system to suggest any new scenarios for use of the system in the construction industry. According to the evaluators, the system is characterised by ease in its use, integration of the RFID technology with other mobile technologies, such as wireless local area networks and flexibility in the handling of different data and the tracking of items during different stages in the construction process. However, according to the evaluators, the proposed system could be further improved through the provision of location coordinates for the tracked items, its integration with Internet-based systems, the connection of the system to software capable of providing construction project planning (eg., Microsoft Project) and the provision of more data storage capacity to the RFID tags. The graphical user interfaces of the proposed can also e improved further in order to become more user friendly and the proposed system can be used to more applications in the construction industry, such as the monitoring of the structural changes of the different elements of a building.

Chapter 9: Conclusions and Recommendations

9.1 Introduction

The review of the literature on the field of wireless sensors (especially of RFID technology) and the development of a system for the resolution of specific problems in the construction industry, have produced a number of conclusions about how wireless sensors and especially RFID technology can be used in the construction industry. These conclusions have been produced through the implementation of the system developed for this thesis and are related to the flexibility of using such a system for health and safety and logistics scenarios, the benefits offered to the construction industry by using the proposed system and the enablers and the barriers associated with the use of the system. This chapter also presents the limitations associated with the use of the proposed system. A number of recommendations on how else the proposed system and in general RFID technology could be used in the construction industry, are listed.

9.2 Realisation of Aim and Objectives

The aim and the objectives of the specific PhD research were presented in Section 1.6 of Chapter 1. Specifically, the main aim of this research project is the investigation of the potential for enhancing the integration of wireless sensor technologies with construction processes by focusing on their application to the resolution of crucial problems related to health, safety and logistics on construction sites. The specific objectives of the research project are:

a) To examine key features of wireless sensor technologies, such as the possible architectures of such technologies, the devices which comprise them, and the networking protocols and standards used for their deployment.

b) To identify barriers and enablers through the thorough examination of the applications of wireless sensors in other industries, such as medicine, computer-integrated manufacturing, chemical engineering and food industry.

c) To focus on a specific wireless sensor technology (namely RFID – Radio-Frequency Identification), identify its characteristics and show how these characteristics can benefit the construction industry.

d) To design, implement and evaluate an RFID-based system for a number of scenarios related to health and safety, and logistics on the construction site.

The first objective was realised through the development of Chapter 3 of the thesis. In order for this object to be realised, the research methods which were followed were the reading of papers published in journals, conference proceedings and also the realisation of telephone interviews with experts from industries which are involved to the use of wireless sensor technologies. Chapter 3 examined the different types of wireless sensors which exist and focused on a specific category of wireless sensor technologies which is the wireless sensor networking technology. Specifically, this chapter presented specific aspects of the wireless sensor networking technology such as the devices which consist of a wireless sensor network and the different topologies which characterise the placement of these devices.

The second objective was achieved through a number of telephone interviews with experts from different industries and also the examination of a number of applications of the wireless sensor networking technology in a variety of industries through the reading of books, journals and conference proceedings. Chapter 3 presents these interviews. In addition, it lists the barriers and enablers to the use of the wireless sensor networking technology.

The third objective was achieved through the development of Chapters 4 and 5. The research methods which were followed for this objective were the use of journals, books and conference proceedings. In addition, a visit to three construction sites occurred in order for data to be collected which would be used for the development of scenarios in which RFID technology would be used. Validation of these scenarios occurred by a group of experts. The validation process occurred in two stages. During the first stage, the experts had to study a report which presented in details the developed scenarios. During the second stage, each expert had a discussion with the researcher about the developed scenarios. Chapter 4 focused on a specific wireless sensor technology (RFID technology) and presented a number of key features related to the technology. Specifically, the chapter examined the devices which consist of a typical RFID system, the physics of RFID technology, the frequencies of use of the technology, the different standards which characterise RFID systems and its differences with other tracking technologies. Additionally, the chapter examined how RFID technology can be integrated with various software technologies. Additionally, Chapter 4 presented in detail the applications of RFID technology in a variety of fields including the construction industry. Chapter 5 presented how specific characteristics of RFID technology, such as the capability offered to the users of the technology to read/write information from/to the tags or the tracking of the identification number of a tag from a distance, can be useful in the resolution of specific health and safety and logistics problems.

The fourth objective was achieved through the development of an RFID-based system. This system was tested under the requirements of a number of proposed scenarios. Chapters 6 and 7 present in details the stages in the development of the system while Chapter 8 presents the results of the evaluation of the system from a group of experts. For the evaluation of the system, a questionnaire was provided to the group of experts.

9.3 Research Conclusions

A number of findings have been produced related to the use of wireless sensor technologies and especially of RFID technology. These findings are listed below :

- *Key Features of Wireless Sensor Technologies* [Objective (a)]: Wireless sensor technologies are characterised by the use of a variety of devices depending on the sensing operation which has to be performed. Specifically, there are different types of sensors while a number of devices, such as laptops or PDAs, can be used with the sensors in a number of topologies in order to facilitate the collection of sensor data. A variety of standards characterise also the use of wireless sensor technologies. RFID technology is based on the use of a reader and a number of tags for the collection of sensing data, however it presents flexibility in the integration with other devices and the use of various software technologies, such as databases. A number of standards also characterise the use of RFID technology.

• *Identification of the characteristics of RFID Technology* [Objective (c)]: There is a number of characteristics of wireless sensor technologies and especially of RFID technology which can benefit the construction industry. For example, the asset tracking ability of RFID technology is considered significant for a variety of construction processes, such as material distribution and utilisation. Additionally, the exchange of data through the reading/writing capability provided by RFID tags allows quick data exchange on the construction site.

• *Design of a Wireless Sensor-based system* [Objective (d)]: During the research, a wireless sensor-based system has been designed and tested for specific scenarios in the construction industry. This system shows the advantages of using RFID technology on the construction site, such as quick exchange of data between construction personnel but also its disadvantages, such as its weakness in detecting easily an item when there are many metal objects around the RFID reader.

• *Enablers to the use of Wireless Sensor Networks in the Construction Industry* [Objective (b)]: There are a number of enablers which facilitate the use of the wireless sensor networking technology in the construction industry. The Egan and Latham reports suggest that innovative technologies should be used more on construction sites while the economic progress has enhanced the research on such technologies. There is also an increased need for integration of the processes on the construction site as well as need for better monitoring of construction sites. Wireless sensor networks can execute many tasks simultaneously and also track items.

• *Barriers to the use of Wireless Sensor Networks in the Construction Industry* [Objective (b)]: There are issues related to wireless sensor networks which can prevent their use from the people of the construction industry. There are not exact facts on the cost of the deployment of wireless sensor networks on construction sites since the technology is new and the cost of deployment of a wireless sensor network on a construction site is affected by the needs of the construction project. Since wireless sensor networking is a new technology, there are many questions about their reliability. Furthermore, there is not much knowledge from the people who work on construction sites about wireless sensor networks and thus, contractors may be unwilling to use a technology which would require the training of construction workers as this could be costful.

• *Potential of RFID Technology for Health and Safety on the Construction Site* [Objective (d)]: The review of the literature reveals that RFID technology is not currently applied for the resolution of specific health and safety problems, such as those presented in Chapter 5. The testing of the system developed for this thesis showed that RFID technology can enhance health and safety on construction sites. For example, in the case of the monitoring of 'dangerous' areas on the construction site, such as large excavation areas, the driver of the vehicle which approaches the specific excavation area, can be warned on time by the RFID tag which is placed on the excavation area. The same tag can be used for the storage of information related to possible accidents which have occurred on the specific excavation area or information related to the possible existence of chemical substances in the specific excavation area. These information can be used by the construction site manager as feedback to the heath and safety conditions on the construction site. Additionally, the same tag can store information related to possible maintenance problems which occur in this area of the site. In this case, the construction site manager can be informed quickly about these maintenance problems and take the necessary actions before an accident occurs.

• *Improvement and Linkage of the Stages of Construction Logistics* [Objective (d)]: The system of the thesis showed also that RFID technology can improve and link the major phases of construction logistics (material delivery, distribution, utilisation). The use of RFID technology provides automation to the different stages of construction logistics and allows them to be executed in a more organised way. For example, from the moment the material arrives on the site, it is automatically tracked and the tracking continues constantly until the material has been used. Even when the material has been used, RFID technology enables the acquisition of knowledge related to the exact quantities of the specific material that have been used and how they have been used. In this case, the route of a material on the construction site can be always checked quickly and accurately and this is significant because it prevents confusion in the distribution of materials to different subcontractors and also it reveals possible delays of the construction project.

• *Quick and Safe Communication between Users* [Objective (d)]: RFID systems provide the capability to their users to exchange data quickly without the possibility of losing any data. This is achieved by writing information to the RFID tags. The system developed during this PhD research involved the exchange of data between the construction site manager, the foreman, the drivers who operate on the site and the workers. The implementation of the system showed that this data exchange can be achieved through the use of RFID technology in a more organised, quicker and less-error prone way. For example, the construction site manager can find information related to the rate of use of a material by simply reading the contents of the tag which is placed in the warehouse of a specific subcontractor. He/she can do this without having to telephone the specific subcontractor or send an email to him and wait for his reply. Also, the foreman can give instructions to his/her drivers by only placing these instructions to the tags of their vehicles and without for example having to leave a notice for them on a notice board which may be lost or not seen by the drivers. Thus, by using RFID technology, the information on the construction site can be conveyed in a safer and quicker way.

• *Combination of RFID Technology with other Technologies* [Objective (d)]: The system developed for this thesis showed also how RFID technology can be combined with other technologies, such as temperature sensors in order to monitor the temperature of porous materials. Thus, it can be considered that RFID technology can be combined with other types of sensors which could be useful on a construction site.

• *Integration of RFID Technology with Construction Processes* [Objective (d)]: The system developed for this thesis showed how RFID technology can be integrated to specific construction processes, such as construction logistics. Generally, RFID technology can be easily applied to a number of construction processes and this can be shown by the design of the graphical user interfaces which are used by the system of the research and allow the interaction of the user with a number of RFID tags. The graphical user interfaces are designed in such a way so that each of them are adjusted to the requirements of specific construction processes, thus enabling the use of RFID tags under different circumstances.

• *Enablers to the use of RFID Technology in the Construction Industry* [Objective (b)]: There are a number of factors which facilitate the use of RFID technology in the construction industry. The function of RFID technology is not characterised by complexity and this makes it easy for use even from users who are not familiar with information and communication technologies. Also, there are tags which are very small in size and cost a minimal amount of money. These tags could be used easily on a construction site and even if they were damaged, the cost of replacing them wouldn't be significant. The system which was developed for this research, used RFID tags which were expensive. However, these tags offered significant capabilities such as large memory capacity. Also, the i-Q32 RFID tags were characterised by temperature measurement capabilities. Thus, in comparison to tiny RFID tags which cost less, the tags of the proposed system offer other advantages.

• *Barriers to the use of RFID Technology in the Construction Industry* [Objective (b)]: There are still steps to be made in order for the technology to be fully adopted by the construction industry. The unwillingness of much of the construction personnel to quit traditional construction practices and adopt innovative technologies in order to perform the same tasks as well as the educational level of construction workers are some of the obstacles in the adoption of RFID technology by the construction industry.

9.4 Limitations

There are a number of limitations which characterise the realisation of the specific research, the use of the proposed system and in general the use of RFID technology on a construction site. These limitations are listed below:

• *Use of specific Research Methods*: The research was based on the use of a number of research methods, such as interview and questionnaires. There were limitations on the use of these research methods. Specifically, even though there was the aim of realising ten telephone interviews in order to acquire data related to wireless sensor technologies, only four were realised. The reason for this is that people from companies involved to wireless sensor technologies were most of the time busy. Telephone interviews were chosen as one of the selected method for data collection since the experts were at large distances from Loughborough University. The researcher realised visits to construction sites for the purpose of data collection. However, the number of these visits was limited since it was difficult to arrange a visit to a construction site which may be far away or because the construction personnel was busy to answer questions.

• *Existence of Metallic Objects*: The detection capability of RFID readers is significantly affected by the existence of metallic objects. The implementation of the system in this PhD research showed that the existence of metallic objects close to the RFID reader reduces the range of detection of RFID tags from the RFID reader.

• *Cost of RFID Equipment*: The cost of the RFID equipment which was used for the needs of this specific research was expensive and this makes the implementation of the system difficult especially for a large construction site where a large number of tags would have to be used. Even though there is RFID equipment in the market which is cheap, this equipment is usually characterised by lack of other capabilities, such as low memory capacity of the tags for data storage.

• *Acceptance from the People of the Construction Industry*: Another limitation is the acceptance of RFID technology from the people in the construction industry. There are cultural issues which must be considered before RFID technology is deployed on a construction site. The educational level of construction workers and the unwillingness of the construction personnel to quit traditional practices in favour of a new technology are examples of such issues. A suggestion which was made by an evaluator of the system developed for this PhD research was to make the graphical user interfaces of the system even simpler since some of its characteristics such as the word "Byte" which is displayed on the graphical user interfaces may not be comprehended by construction workers.

• *Simulation of Construction Site for Implementation Purposes*: The system which was developed for the research was tested on a simulated construction site at the campus of Loughborough University. It could not be tested on a real construction site because no construction site manager would agree to experimentation on a busy site, as this would mean loss of time which could affect the progress of the construction work. For this reason, possible difficulties which would be faced only in real-life conditions, such as the existence of many metallic objects which can be found on a construction site or the existence of erected structures which may be found between an RFID reader and the tags placed on specific items which would possibly create problems on the strength of the signal of the RFID reader, were not faced in such degree during the testing of the system. However, when the proposed system was tested on the checking of the sequence of steel members where there were many metallic objects, it was noticed that the existence of the metallic objects was reducing the strength of the signal of the RFID reader. Also, the evaluators of the system had some expertise in the use of information and communication technologies, therefore it was easy for them to comprehend quickly how to use the graphical user interfaces of the proposed system on a mobile device, such as a PDA. On a real construction site, there could be the possibility that the construction workers would not like the idea of using a mobile device in replacement of traditional methods, such as hand-writing.

• *Compatibility of RFID technology with Existing Technologies*: The i-Card3 RFID reader which was used for the PhD research could not be embedded to a PDA because an extension PCMCIA slot would have to be attached to the PDA. However, this slot is considered "old" technology and as a result, there is not going to be any more production of it. In this case, the development of applications on the construction site which are based on the use of PDAs and RFID tags becomes extremely difficult.

• *Lack of common standard for use of RFID technology*: The RFID equipment used in this thesis used elements bought from the same provider. Any other RFID element used by another provider could not be used with the specific equipment. The lack of a common standard which will allow the use of RFID components from different providers is an obstacle which prevents the use of RFID tags of different capabilities for different scenarios. It would be ideal if the software development kit which is provided by Identec Solutions and which was used for this PhD research, could be used with RFID tags of another companies, which would have smaller size than the tags provided by Identec Solutions and possibly the same capabilities with them.

9.5 Recommendations For Further Research

This thesis has not covered all the research which has to be done for the use of wireless sensors and especially RFID technology in the construction industry. For this reason, a number of recommendations for further research are provided in this section and these are listed as follows :

- *Adoption of RFID technology*: More efforts should be made in order to demonstrate the potential of RFID technology and in general wireless sensor technologies for the construction industry. Specifically, training in the form of oral presentations or the publication of booklets, should occur in order to inform the construction personnel about the potential benefits of the use of RFID technology in the construction industry. This would enhance the willingness of people to use the technology and would facilitate the development of more applications of the technology.

- *Provision of Coordinates of Tagged Items*: Further research could be undertaken on how an RFID system can provide coordinates of the location of a tagged item. Specifically, the system described in this thesis could be improved in such a way so that when a tagged item is detected, coordinates of its location and its orientation from the antennas of the RFID reader will be displayed along with the identification number of the tracked tag. Parameters which must be examined in this case are the direction of the electromagnetic waves transmitted by the antennas of the RFID reader in order for a tag to be detected and the time it takes for the detection of a tag to occur.

- *Development of Applications on Construction Site*: Wireless sensors and especially RFID technology could be used for the development of complex systems on the construction site. Specifically, different types of sensors, such as vibration and acoustic sensors and RFID tags can be used for the collection of maintenance data related to buildings. These data can be useful especially after earthquakes.

- *Reduction of the Interference of Metals*: Research should be undertaken on the enhancement of the signals produced by RFID readers and tags especially in environments in which many metallic objects exist. At the moment, the existence of many metallic objects reduces the strength of the signals produced by RFID readers and as a result, the detection of RFID tags becomes difficult. Especially for the construction industry, the enhancement of the signal of the RFID readers is very important since there are many metallic objects on a construction site.

• *Larger Memory offered by RFID tags*: RFID tags have some memory for data storage purposes. However, this memory is limited. RFID technology could be enhanced more if there is increment of the memory of the RFID tags. This is significant for large construction projects in which lot of information has to be exchanged between the members of the construction personnel.

• *Combination of RFID with Artificial Intelligence*: RFID tags could be combined with artificial intelligence techniques. The tracking ability of RFID technology in cooperation with the intelligence offered by AI systems, such as artificial neural networks and expert systems, would allow the development of more complex applications on the construction site. For example, an artificial neural network could decide if a specific vehicle should go to the main gate to take a material which has arrived on site, based on the availability of the driver and the load carrying capability of the vehicle. These facts could be provided to the network through the RFID tag attached to the vehicle.

9.6 Implications for the Construction Industry

The use of RFID technology on the construction site is an example of how information and communication technologies attempt to integrate with construction processes. These technologies attempt continuously to enter the construction site. This attempt started with the use of laptops and mobile devices, such as mobile telephones and personal digital assistants (PDAs) and in the future, it is possible that advanced technologies will be part of construction practices.

The introduction of advanced information and communication technologies on the construction site will intensify the training of the construction personnel. The feedback of the evaluators for the system developed for this research showed that even though the design of the system is simple, there may be difficulties in its use by construction workers. The construction site is characterised by the need for asset tracking however the required training must also exist.

This thesis underlines the significance of asset tracking for the construction industry. However, even though the people of the construction industry accept that there is a need for item tracking on construction sites, the review of the relevant literature reveals that not many significant efforts have been done in this direction. It is possible that in the future more efforts will be done in the introduction of innovative technologies to the construction site, which will provide asset tracking capabilities.

The use of information and communication technologies on the construction site will affect the way construction processes are executed. These technologies may become either part of the construction practices or even change them totally. In this case, a way must be devised on how all these technologies can be combined in order to ensure that any operations on the construction site are executed smoothly.

9.7 Closing Remarks

This thesis has shown how an innovative technology, such as RFID technology can be integrated to construction processes and help in the resolution of specific problems. The developed system is an example of how construction work could be modernised and also shows the benefits of advanced technologies for the construction industry.

The thesis provided a number of scenarios of how a specific sensor technology could be implemented in the construction industry. These scenarios attempt to show the strength of the technology in the resolution of specific problems which exist on a daily basis on the construction site. The thesis showed that RFID technology is characterised by advantages and disadvantages. The advantages are that it enables the tracking of items on the construction site, thus providing many benefits for the construction supply chain, such as organised and controlled routing of a material into the site and also it ensures security into the site since it can detect possible losses or thefts of items. The disadvantages are the reduction of the range capability of RFID readers when there are metallic objects around them and the cost of the RFID tags which may vary depending on their capabilities.

By underlining the benefits but also the problems of RFID technology, this PhD research tries to enhance the interest of the construction industry towards the technology and to encourage the realisation of further research on how the technology can be further integrated with current construction practices. RFID technology is not the only solution to the health, safety and logistics problems which characterise construction sites. It offers however many improvements in the current methods applied for solving these problems. Table 9.1 summarises what the specific research has achieved.

Table 9.1 Thesis' Contribution to Knowledge

Problems	*Current Knowledge*	*Contribution to Knowledge*
Monitoring of Large Excavation Areas	Use of protective barriers	Automatic warning generation when vehicle approaches large excavation areas
Hazard Notifications Collection	Use of reports for the recording of hazards	Quick and organised collection of hazard notifications
Collision Monitoring	Construction Site Drivers have to be aware continuously of any approaching vehicles	Detection of approaching vehicles in a close distance and automatic emission of sounds as warnings
Chemical Substances Monitoring	Searching of chemical substances by the construction site manager and members of the construction site personnel	Automatic discovery of any remaining chemicals on the construction site
Material Delivery	Materials arrive on the construction site and their delivery is recorded by paper or telephone communication	Automatic recording of the arrival of materials on the construction site and storage of data related to the time and date of arrival
Material Circulation	Drivers of boom-trucks are notified orally or through a note that ordered materials have arrived.	Electronic storage of data related to material deliveries
Material Utilisation	The construction site manager may be informed orally or through telephone communication about how materials will be used. It is also possible that there will not be any communication about the future use of materials.	Electronic storage of data related to material utilisation

Problems	*Current Knowledge*	*Contribution to Knowledge*
Communication between Users	Achieved through the use of mobile telephones, notes or orally	Communication between users is cost free and more secure
Connection between different construction processes	Construction processes are executed separately and sometimes	Organisation of construction processes in a connective manner

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APPENDIX

[A] QUESTIONNAIRE FOR THE RFID EXPERIMENTS

NAME :

PROFESSIONAL STATUS :

FAMILIARITY WITH I.T. :

Ranking : 1 is very poor & 5 is excellent

Section A: Effectiveness/Efficiency Of the System	1	2	3	4	5
1. How well does the proposed RFID system achieve the goals of material tracking and improvement of health and safety conditions?					
2. How well do you think the system improves the communication between different experts on the construction site (eg. communication between foreman and workers)?					
Section B: User-Interface					
3. How easy did you find the use of the Graphical User Interfaces (GUIs)?					
4. How well does the system provide flexibility for handling different types of information, such as health and safety and logistics data?					
Section C: Scenarios					
5. How realistic are the presented scenarios?					
6. How well does the proposed RFID system enhance the protection of vehicle drivers from accidents related to falls on large excavation areas with very steep slopes?					
7. To what extent can the proposed RFID system solve problems related to collisions between vehicles and collisions between vehicles and workers on the construction site?					
8. To what extent can the proposed RFID system solve problems related to hazardous substances remaining on construction sites after the construction work has been completed?					
9. How well do you think the presented scenarios integrate the different stages of the construction logistics process, such as material delivery, material transportation and material handling?					
10. To what extent does material tagging achieve the successful monitoring of the arrival of a specific material on the construction site at the specified time and date?					
11. How important is it that a foreman is able to assign a daily task list to his drivers using the proposed RFID system?					
12. How well does the system enable workers to add information to an RFID tag (about a material's future usage)?					
13. To what extent does the proposed Logistics scenario facilitate the flow of materials on the construction site?					
14. To what extent is the site manager able to monitor the rate of use of materials?					
15. To what extent can the proposed system check the sequence of steel members during the erection of a steel structure?					
16. To what extent can the proposed RFID system monitor the temperature?					

Section D: Usefulness to the Construction Industry					
17. How useful is the proposed RFID system for the Construction Industry?					
18. How well does the proposed RFID system accelerate information flow during the construction process ?					
19. To what extent will the construction industry accept the proposed RFID system ?					
20. To what extent will the deployment of the proposed scenarios enhance the use of RFID in the Construction Industry?					
Section E: General					
21. What is your overall rating of the system ?					
22. How flexible do you consider the proposed RFID system for impleme-ntation in other situations in the construction industry?					

23. Did you face any problems related to the communication range between the RFID readers and the tags? ☐ Yes ☐ No

If 'Yes', what are the problems?

24. What are the best features of the system?

25. Can you suggest ways of improving the system ?

26. In what way can the Graphical User Interfaces (GUIs) be improved?

27. Can you think of any other scenarios in the construction industry to which the proposed RFID system could be applied?

[B] QUESTIONNAIRE FOR THE VISIT TO THE EMIRATES STADIUM CONSTRUCTION SITE

(1) What type of equipment is used on the construction site?

(2) How the different processes on the construction site are linked to each other?

(3)What health and safety measures have been taken for the specific construction site?

(4) What is the process that is followed when there is problem with the equipment which is used on the construction site?

(5) What are the measures for the prevention of accidents from the fall of heavy items lifted by specially designed vehicles?

(6) How the transfer of materials to their destinations on the construction site is organised? Is there assignment of priorities to the vehicles which transport materials on the construction site?

(7) Protection against falls from scaffolds

(8) Use of logistics chain on the construction site

(9) Are there medical records kept for each worker on the construction site? Do you consider this as a violation of the privacy of each worker?

(10) What type of dangers are associated with excavations? What measures are taken in order for these dangers to be faced?

(11) Description of the demolition process. Safety measures which are taken during the process.

(12) Health and Safety issues associated with Construction Logistics.

(13)What is the most common causes of accidents on the construction site?

(14) What would you like to see on the construction site in terms of health, safety and logistics?

(15) Collaboration between the members of the construction site for issues concerning logistics.

(16) Gas Pipes/Water Pipes. Description of the work done by the construction personnel for these cases.

(17) Monitoring of the emission of Hazardous Substances.

(18) How the materials are distributed on the construction site?

(19) Is there use of any innovative technologies on the construction site which enhance the collaboration and the communication between the members of the construction personnel? Is there use of Personal Digital Assistants (PDAs), mobile telephones, mobile computers and tablet PCs?

(20) How the checking of the sequence of steel members is done?

(21) Protection against fire.

[C] DATA FLOW DIAGRAMS REPRESENTING PROPOSED SCENARIOS

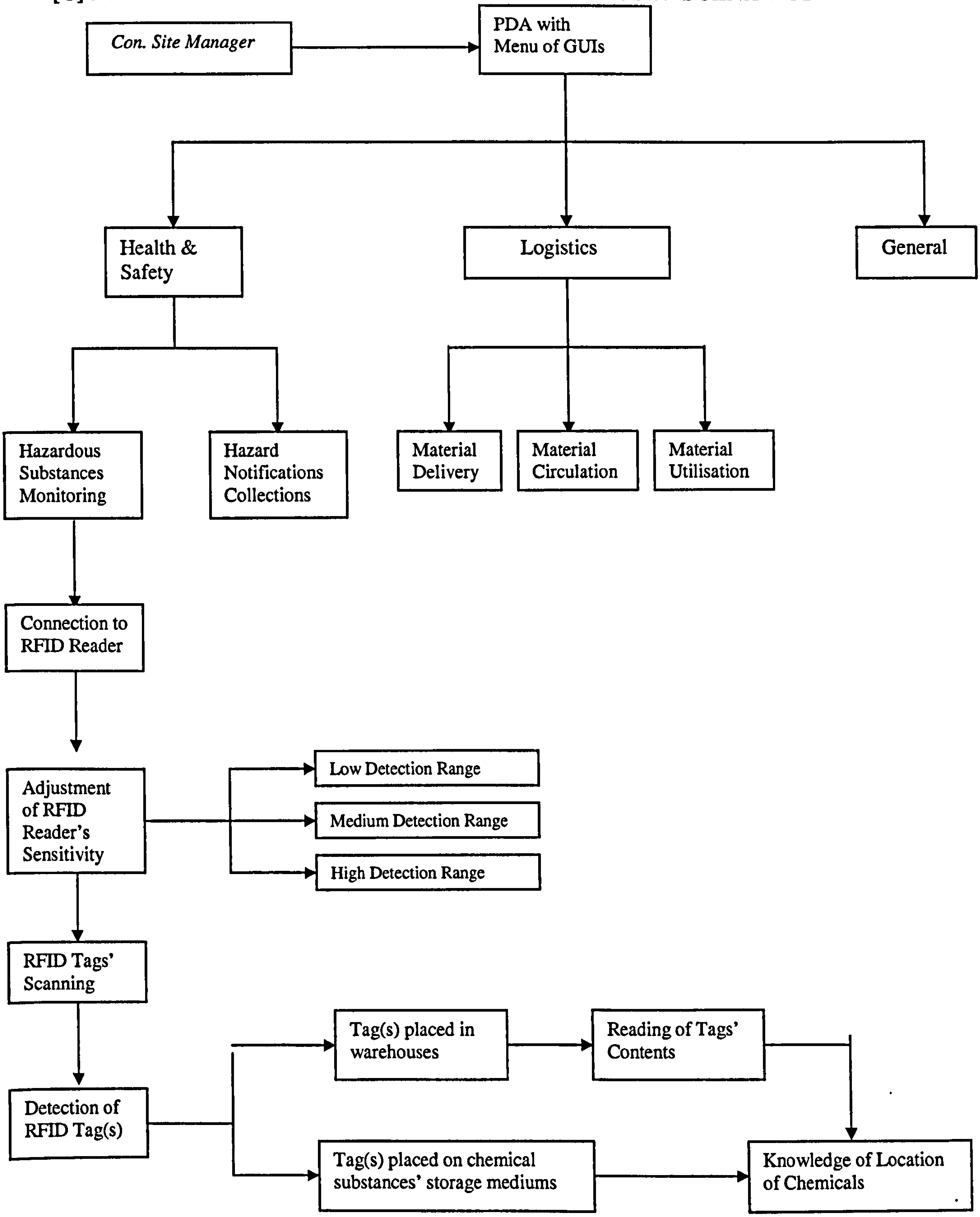

Fig. C1 Data Flow Diagram for the Detection of Chemical Substances Scenario

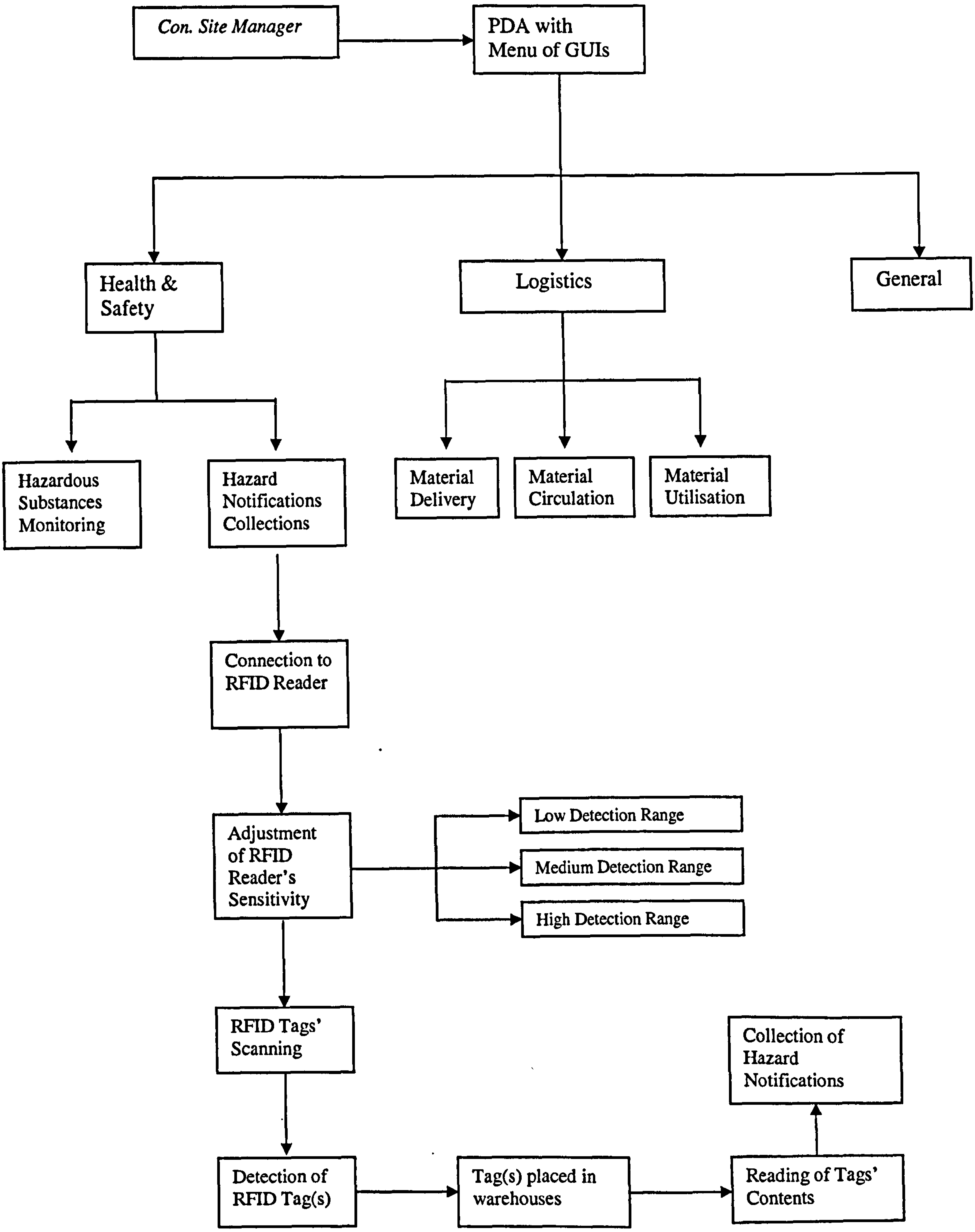

Fig. C2 Data Flow Diagram for the Collection of Hazard Notifications Scenario

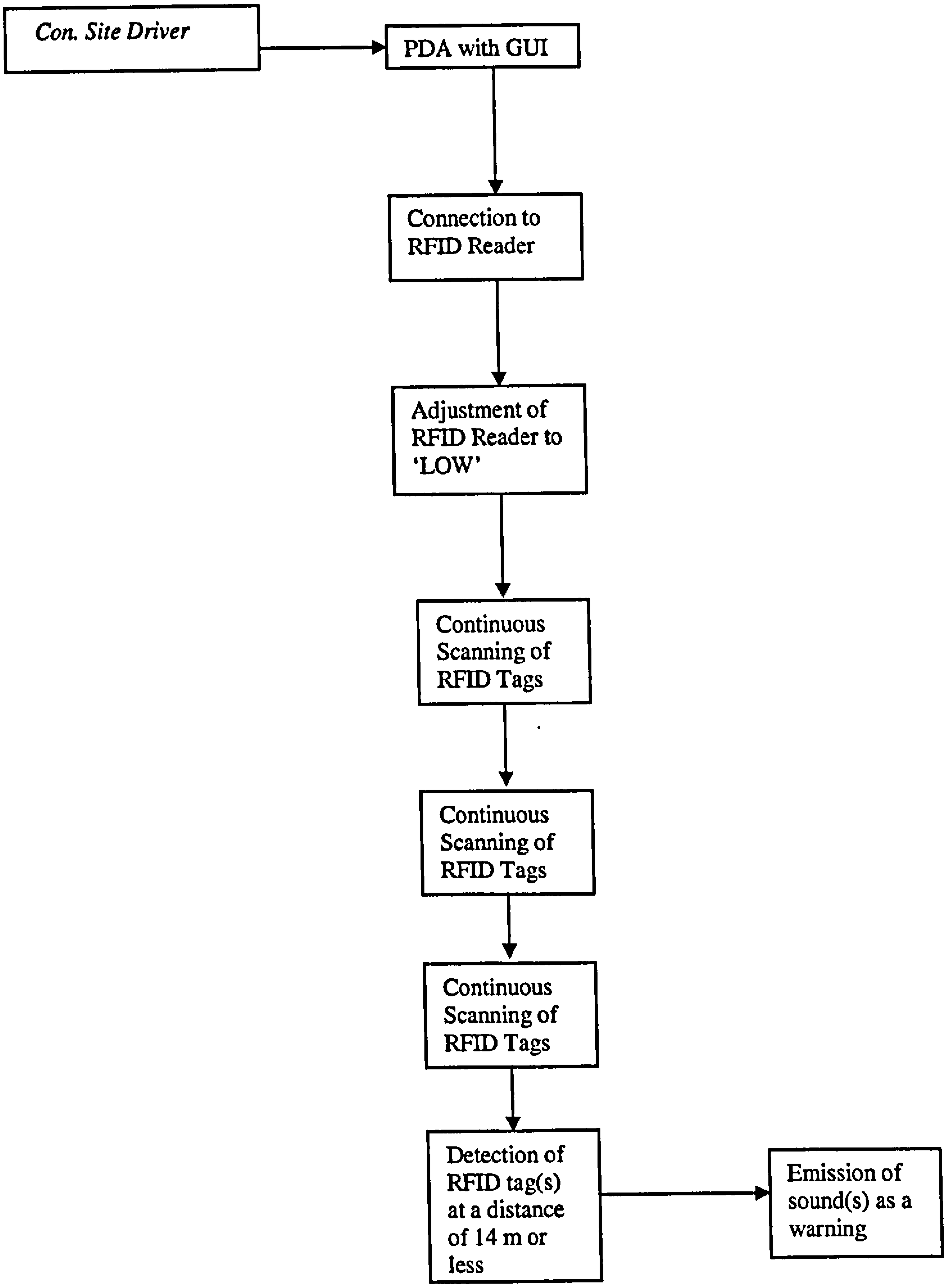

Fig. C3 Data Flow Diagram for the Protection against Dangerous Areas on the Construction Site

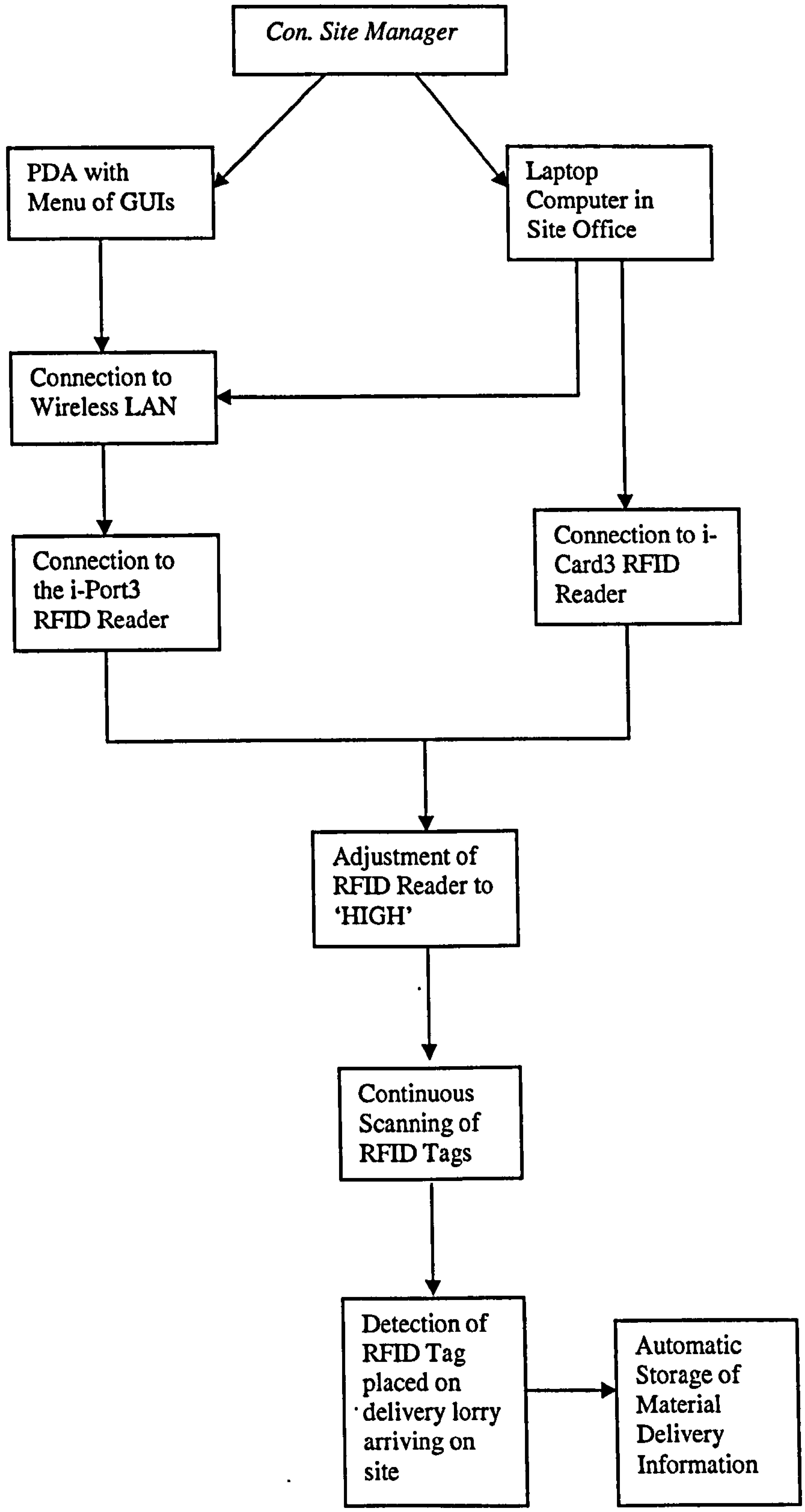

Fig. C4 Data Flow Diagram for the Material Delivery Scenario

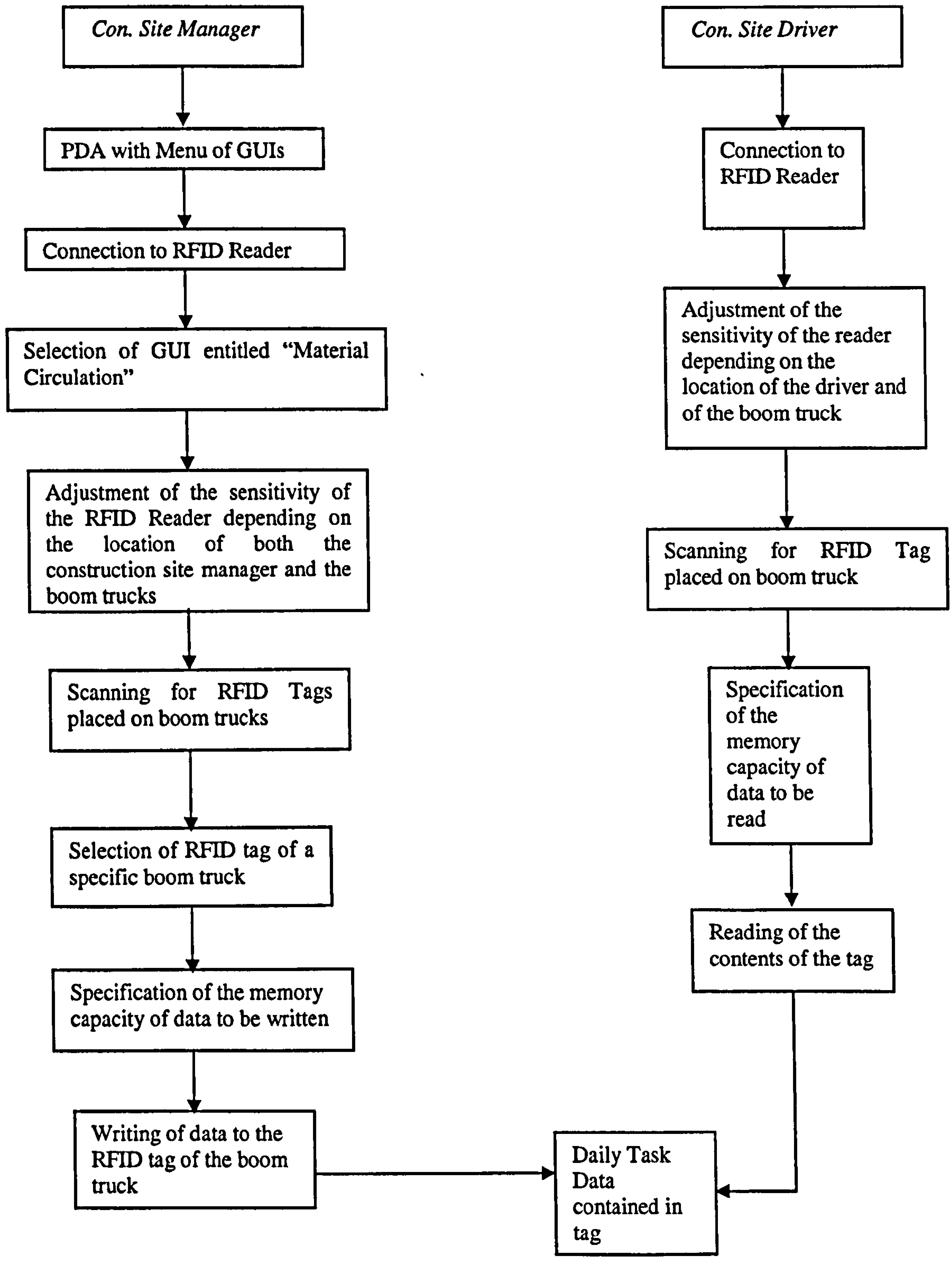

Fig. C5 Data Flow Diagram for the Material Circulation Scenario

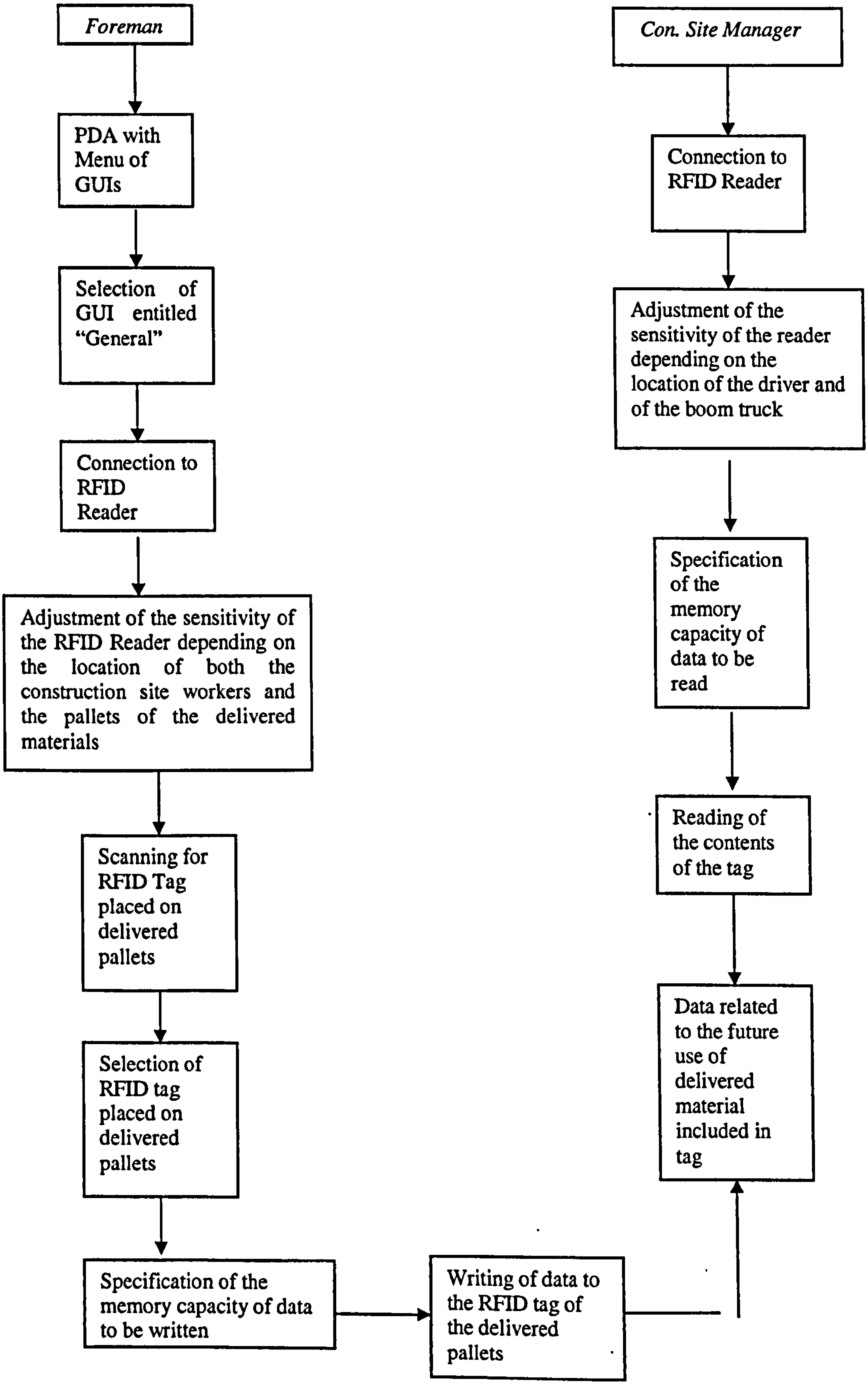

Fig. C6 Data Flow Diagram for the Material Utilisation Scenario

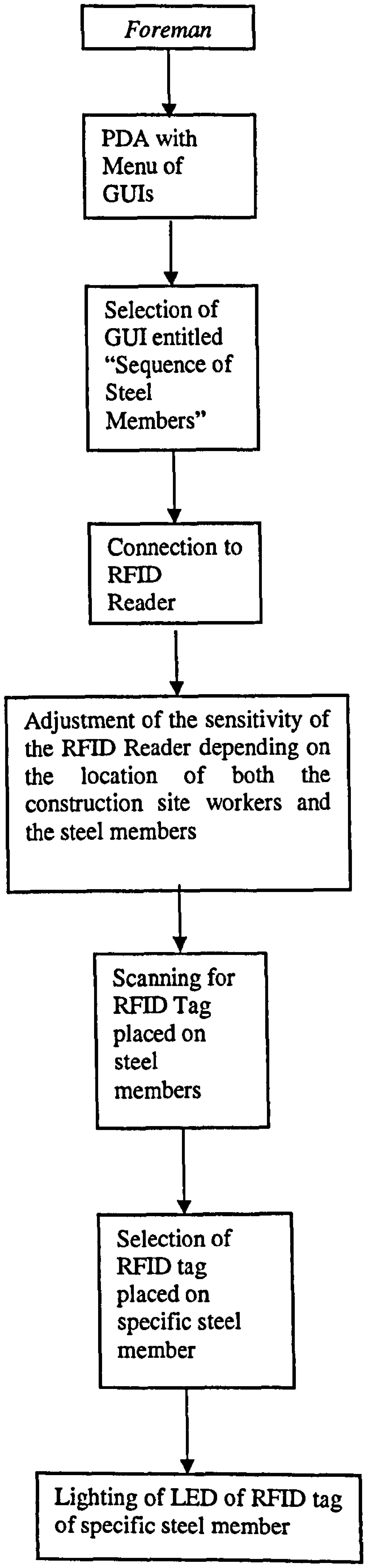

Fig. C7 Data Flow Diagram for the Checking of the Sequence of Steel Members Scenario

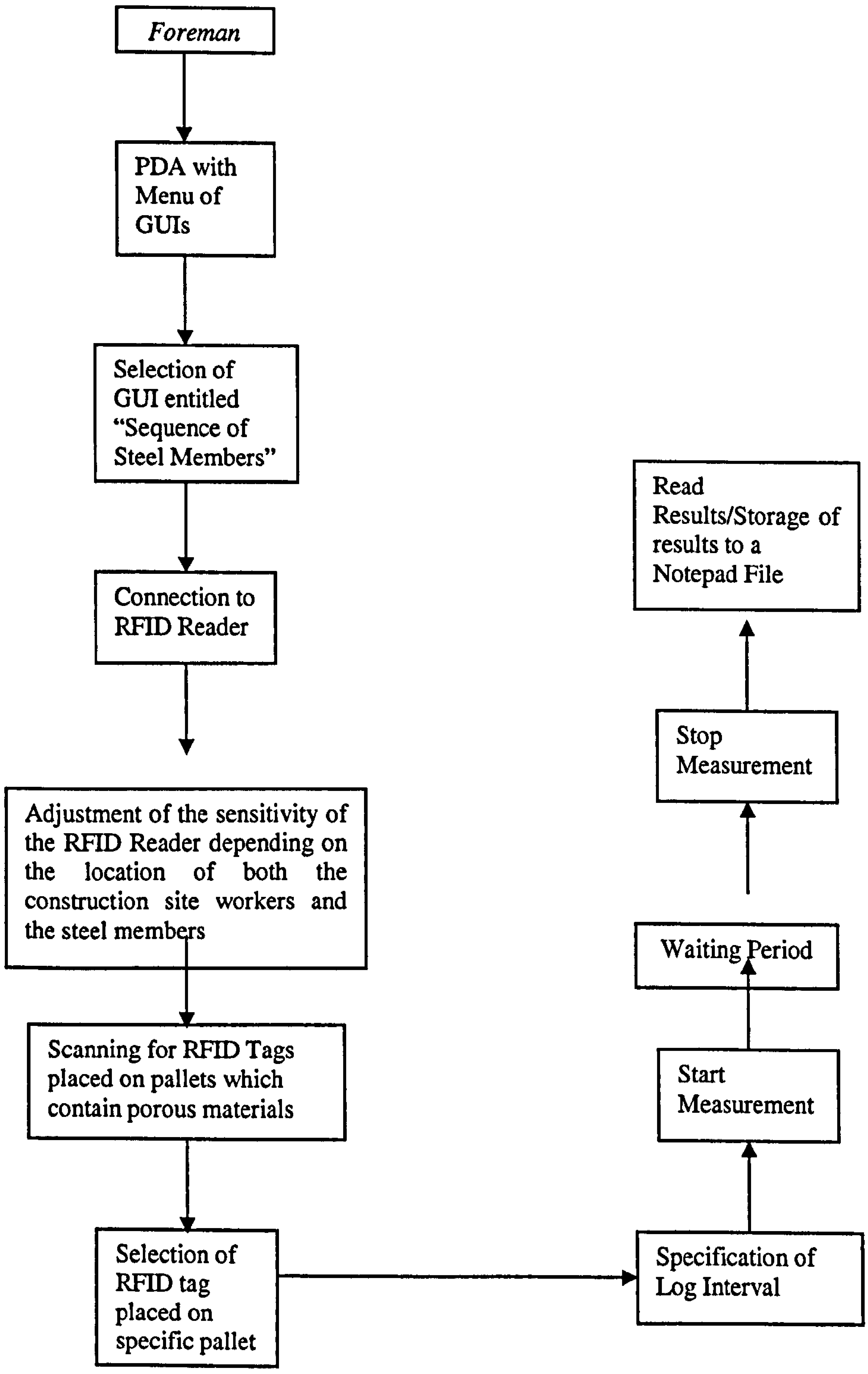

Fig. C8 Data Flow Diagram for the Monitoring of the Temperature of Porous Materials Scenario