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Multi Dimensional Analysis of Building Performance Data for Energy Efficient Building Operation

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Executive Summary

The global warming facts and figures have clearly established a link between a rise in global mean air temperature and atmospheric CO_2 levels. If emissions continue along their present trajectory it is estimated that by the end of this century average global temperatures are likely to have risen by 4-6^{o}C. Such increases may cause potentially catastrophic consequences.

Harmful consequences of the climate change can be eased without effecting the progress of economic development with a worldwide emphasis on energy efficiency and utilisation of renewable energy resources. For instance, leading industrialised countries USA and Germany have similar GDP (Gross Domestic Products) per capita figures but when it comes to GHG (Green House Gases) per capita figures, USA (23.5 Tonnes of CO_2e per capita) has nearly double emission levels in comparison to Germany (11.9 Tonnes of CO_2e per capita) which has been continuously focusing on energy efficiency and renewable energy resources. This policy resulted in lower GHG emissions without limiting the economic growth.

In terms of energy efficiency, buildings possess significant potential for energy and energy related CO_2 emissions savings since buildings account for 25-30% of total energy related CO_2 emissions. Future projections indicate that in 2030, buildings will be responsible 35.6% of primary energy use in the world and continue to maintain its importance. Therefore, efforts for saving energy in buildings are very crucial to cope with the consequences of the climate change.

In this thesis a process and a methodology leading to a system-*The Holistic Multi-Dimensional Information Management System*-appropriate to process and analyse building performance data is defined.

Initially, existing building performance assessment and monitoring systems are analysed to identify the deficits and weaknesses in current practices. This indicates that an internationally accepted standardised solution has not been agreed to quantify the energy performance of buildings. Also, current practices do not support Energy Performance of Building Directive and continuous commissioning which are a prerequisite for long term energy efficient building operation. Furthermore, building performance data is not evaluated from multiple stakeholder perspectives. Therefore, a monitoring and analysis process

is introduced to develop a basis for the Holistic Multi-Dimensional Information Management System.

Since the developed system requires information from multiple sources, the standardisation and integration efforts for the AEC/FM industry is analysed in order to develop a flexible standardised and extensible integration concept to maintain data exchange between the BIM tools and the Data Warehouse Core of the developed system. At present, a full integration and interoperability among various product models is not achieved in the AEC/FM industry due to the fact that a model trying to encapsulate the entire AEC/FM industry is a huge and very complex model which demonstrates difficulties with mapping between domains. Therefore, integration of specific tools for certain processes instead of a full BIM integration is likely to produce more accurate results for interoperability. The developed system addresses these problems by focusing on specific BIM tools and particular information within these tools which is required for building performance monitoring and analysis. Since the IFC is the only broad building level object schema and most of the BIM vendors offer IFC compatibility with building model repositories that support integration of the data generated by multiple applications. IFC data exchange methodology is used to extract required information from the BIM tools. This extracted information will then be used within the developed system in order to classify and categorize building performance data.

In the context of the initial research findings, *The Holistic Multi-Dimensional Information Management System* with a unique data aggregation layer backed by a data warehouse technology and web services specifically designed for building performance monitoring and analysis is introduced. The developed system is based on three integrated main components. These are; Data Warehouse Core, ETL (Extraction Transformation and Loading) Layer and Information Representation Layer.

Finally, the implementation of the developed system for validating its capabilities in an appropriately selected research building is specified. The demonstrator validated the developed system's capabilities for the described scenario; multi dimensional analysis of the building performance data. This proved that the system can be used as a nucleus for various end-product developments in the area of energy monitoring and optimisation. Therefore an affordable residential building specific wireless energy monitoring and optimisation system which is derived from the research findings presented in this work is introduced coupled with an initial business scenario.

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List of Abbreviations

AEC/FM	Architecture Engineering Construction/Facility Management
aecXML	Architecture Engineering Construction eXtensible Mark-up Language
agcXML	The Associated General Contractors of America XML
AmI-MoSES	Ambient Intelligent Interactive Monitoring System
AP	Application Protocols
ARIS	Architecture of Integrated Systems
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers Inc.
ASTM	American Society for Testing and Materials
ATLAS	A STEP Towards Computer Integrated Large Scale Engineering
BACnet	Data Communication Protocol for Building Automation and Control Networks
Be Aware	Boosting Energy Awareness with Adaptive Real-Time Environments
BEMS	Building Energy Management System
BER	Building Energy Rating
BeyWatch	Building Energy Watcher
BIM	Building Information Model
BLC	Building Life Cycle
BMS	Building Management System
BPM	Building Performance Metrics
BPMN	Business Process Modelling Notation
BPR	Business Process Re-Engineering

BREEAM	Building Research Establishment's Environmental Assessment Method
BSS	Business Support System
BuildWise	Building a Sustainable Future
CAD	Computer Aided Design
CC	Continuous Commissioning
CDM	Clean Development Mechanism
CER	Certified Emission Reduction
CIB	Conseil International du Batiment-International Council for Building
CIMsteel	Computer Integrated Manufacture of Constructional Steelwork
COM	Component Object Model
COMBINE	Computer Models for the Building Industry in Europe
CONCUR	Concurrent Design and Engineering in Building and Civil Engineering
COP-15	Conference on Parties
DEAP	Dwelling Energy Assessment Procedure
DEC	Display Energy Certificate
DEHEMS	Digital Environmental Home Energy Management System
DICE	Distributed and Integrated Environment for Computer-Aided Engineering
DIN	Deutsche Industry Norm
DT	Design Tool
DW	Data Warehouse
DXF	Data eXchange Format
EC	European Commission

EDE	Electronic Data Exchange
EDM	Engineering Data Model
EEB	Energy Efficiency in Buildings
EN	European Norm
EnEV	Energieeinsparverordnung-the German Energy Saving Regulation
EPA	Environmental Protection Agency
EPISTLE	European Process Industries STEP Technical Liaison Executive
ERI	Environmental Research Institute
ERU	Emission Reduction Units
ESD	Energy Services Directive
ETL	Extraction, Transformation and Loading
EU	European Union
EUETS	European Union Emission Trading System
EUI	Energy Use Intensity
FDD	Fault Detection and Diagnosis
FK	Foreign Key
GARM	General AEC Reference Model
gbXML	Green Building XML
GDP	Gross Domestic Product
GHG	Green House Gasses
Gt	Gigatonnes
GUI	Graphical User Interfaces
GW	Gateway

HPSB	High Performance and Sustainable Buildings Implementation Framework
HTML	Hyper Text Mark-up Language
HVAC	Heating Ventilating and Air Conditioning
IAI	International Alliance for Interoperability
IBDE	Integrated Building Design Environment
IBDS	Integrated Building Design System
ICC	International Code Council
IDM	Integrated Data Model
IEA	International Energy Agency
IESNA	Illuminating Engineering Society of North America
IFC	Industry Foundation Classes
IGES	Initial Graphics Exchange Specification
IPPC	International Panel on Climate Change
IRMA	Information Reference Model for Architecture, Engineering and Construction
ISO	International Organisation for Standardization
ITOBO	Information and Communication Technology for Sustainable and Optimised Building Operation
JI	Joint Implementation
KDD	Knowledge Discovery
kWh	Kilowatt hour
LDC	Least Developed Countries
LEED	Leadership in Energy and Environmental Design
LSE	Large Scale Engineering

LULUCF	Land Use, Land-Use Change and Forestry
MOLAP	Multidimensional Online Analytical Processing
MRV	Measured Reported Verified
NEAP	Non-Domestic Energy Assessment Procedure
NPV	Net Present Value
ODBC	Open Database Connectivity
ODS	Operational Data Store
OECD	Organisation for Economic Co-operation and Development
OGC	Open Geospatial Consortium
OOCAD	Object Oriented CAD
OPC	Open Connectivity
PDE	Product Data Exchange
PDM	Product Data Management
PDT	Product Data Technology
PDU	Product Definition Unit
PeBBu	Performance Based Building Program
PK	Primary Key
ppm	Parts Per Million
RF	Radio Frequency
RFI	Request for Information
RFP	Request for Proposal
ROI	Return on Investment
ROLAP	Relational Online Analytical Processing
SBEM	Simplified Building Energy Model

SIDS	Small Island Developing States
SOAP	Simple Object Access Protocol
SPF	Step Physical File
SQL	Structured Query Language
STEP	Standard for the Exchange of Product Model Data
TQM	Total Quality Management
UCC	University College Cork
UHF	Under Floor Heating Manifold
UK	United Kingdom
UML	Universal Modelling Language
UNCCC	United Nations Climate Change Conference
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
US DOE	United States Department of Energy
USA	United States of America
USGBC	U.S. Green Building Council
VDMA	Verband Deutscher Maschinen- und Anlagenbau - German Engineering Federation
VTT	Technical Research Centre of Finland
W3C	World Wide Web Consortium
WRI	World Resource Institute
WSN	Wireless Sensor Network
XML	eXtensible Mark-up Language

Declarations

This thesis or any part thereof, has not been, or is not currently being submitted for any degree at any other university.

Hasan Ufuk Gökçe

The work reported herein is as a result of my own investigations, except where acknowledged and referenced.

Hasan Ufuk Gökçe

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Ireland, September 2010

Hasan Ufuk Gökçe

Chapter 1

Introduction

Chapter 1 is the introductory section of the thesis entitled "Multi Dimensional Analysis of Building Performance Data for Energy Efficient Building Operation". In this chapter research motivation, hypotheses, research objectives and the thesis structure are introduced.

1.1 Motivation

The European Union (EU) outlined the objective to reduce energy consumption by 20 percent until 2020 in order to comply with the international legislations like the Kyoto Protocol and the Energy Performance Building Directive (EPBD). As buildings account for almost 40 percent of the total energy usage in Europe (EC 2005) (EC 2006), the European Commission undertakes much effort to reduce the energy consumption of buildings (EC 2002) emphasizing on energy rating to inform and stimulate subsequent building renovation activities.

Monitoring of buildings' energy performance through deploying wireless sensors and meters is of central importance for the renovation and energy-efficient operation of buildings since it allows the diagnosis of causes for inefficient energy usage. It is argued that improved control systems can contribute to the reduction of the energy-consumption of buildings by 5 to 30 percent (Salsbury 2000), (VDMA 2008). In order to achieve this, inexpensive, flexible and easy way to handle monitoring and control technologies are required (Itard 2008). Wireless embedded devices coupled with Data Warehouse technology can monitor and control building performance with higher precision and accuracy. Wireless embedded devices can be easily installed and require less installation cost since they run on batteries or harvest energy from their environment (Enocean 2007). Their cost and time efficient deployment capability makes these systems especially attractive for building performance monitoring and control implementations, as these systems allow variable scaling from small size monitoring and control implementation (e.g. residential buildings), up to high density installations used for detailed measurements (e.g. high precision production plants). This creates a significant competitive advantage for extension and replacement of existing technologies with wireless embedded devices coupled with tools supporting multi-dimensional performance data management and analysis.

Building Information Modelling is the process of generating and managing building data during its life cycle. The consistent data exchange is the biggest problem, as several tools are involved like geometry modelling, HVAC design, energy analysis, and facility management. Therefore, different Building Information Models (BIM) are developed. The most established BIM data exchange formats are IFC (Industry Foundation Classes) and aecXML (ISO 2010). While the IFC model focused on product data exchange, aecXML is designed for non-graphical data involved in the construction industries, and has a place alongside IFC. All major CAD tools support at least IFC (Holness 2008). Especially, several tools allow the rapid modelling of CAD models from paper drawings (Nemetschek 2009). Therefore, developing an IFC based data exchange methodology is of importance to use BIM information for classification and categorization of the building performance data.

The information generated by the wireless/wired device network and by the BIM needs to be stored, aggregated and analyzed. This requires a Data Warehouse (DW) system. This system is developed from existing software tools but requires adaptation for building performance monitoring applications.

Building Energy Management Systems (BEMS) are advanced Building Management Systems that are extended with Energy Monitoring & Management services (Capehart 2005). Building Management Systems (BMS) are usually computer systems that control and monitor the building's mechanical and electrical equipment such as HVAC (heating, ventilation and air-conditioning), and the lighting, power, fire, and security systems. These systems utilise a database system for data storage with limited analysis capabilities for more accurate building performance monitoring.

Modern Data Warehouse technologies address these deficits. These are commonly used to manage business data, and are designed to keep track of a changing environment (Inmon 2005). Data Warehouse technologies structure and aggregate the contained data to prepare queries and support decisions. The structure is pre-defined in so-called dimensions that span cubes. However, the specific content is imported from other data sources e.g. BIM. In addition, advanced data analysis techniques like Knowledge Discovery and Data Mining (KDD) (Han 2006) are often used on top of a DW. These offer a high potential for building performance monitoring and analysis as a powerful tool for data aggregation in building, but these are still not generally used.

About 85 percent of the European buildings are older than 20 years; 60 percent are older than 40 years and 30 percent are pre-war buildings (Itard 2008). Most of them are not equipped with advanced building management and control systems (Jagemar 2007). It is estimated that about 50 percent of these buildings will be renovated within the next 20 years opening the potential to improve their energy performance by deploying an affordable residential building specific wireless energy monitoring and management system.

1.2 Assumptions

Assumption 1: Increasing GHG emissions generated by the human use of fossil fuels cause a rise in the global mean air temperature.

It is possible to ease climate change without affecting the progress of economic development with a worldwide emphasis on energy efficiency and renewable energy sources.

Residential and office buildings account for one-third of total energy related CO_2 emissions. Therefore, energy efficiency in buildings plays a significant role in order to accomplish this objective.

Assumption 2: An internationally accepted standardised solution has not been agreed to quantify the performance of buildings.

Current practices do not support Energy Performance of Building Directive and continuous commissioning which are the prerequisite for long term energy efficient building operation. Also, building performance data is not evaluated from the multiple stakeholder perspectives.

Assumption 3: Monitoring of buildings' energy performance through deploying wireless sensors and meters is of central importance for the energy-efficient operation of buildings since it allows the diagnosis of causes for inefficient energy usage.

In order to achieve this, inexpensive, flexible and easy to handle monitoring and control technologies are required. Wireless embedded devices coupled with Data Warehouse technology can monitor and control building performance with higher precision and accuracy.

Assumption 4: Building Information Modelling (BIM) data can be used to classify and categorize building performance data.

Assumption 5: The information generated by the wired/wireless device network and by the BIM needs to be stored, aggregated and managed for in depth performance analysis. This requires a Data Warehouse (DW) system. Such a system could be developed from existing software tools but requires adaptation for building performance monitoring applications.

Assumption 6: Wireless Embedded Monitoring and Control Systems have the potential to play a key role in the reduction of the energy consumption of buildings since they may easily be added to old and new buildings. While the building automation and control domain focuses mostly on non-residential buildings, the proposed holistic design of wireless embedded monitoring and control systems enables the development of affordable wireless energy management solutions for residential buildings with a lower initial investment and shorter return on investment.

1.3 Objectives

The objective of this thesis is to research and develop a methodology leading to a system which is appropriate to process and analyse building performance data for energy efficient building operation. To reach this objective, new methods and tools are researched which increase system functionality covering the recent building energy regulations, wireless embedded devices, networks, BIM tools and integration of these to the information management backend system; the Data Warehouse (DW). As a new approach a DW coupled with On-Line Analysis Processing (OLAP) enables end-users to creatively approach, analyze and understand the building performance under different circumstances.

The research focuses on an innovative, holistic, interoperable, extensible and automated information management platform. This will be achieved through:

- Identifying the significance of building energy use and its environmental impact with a historical analysis and future projections. Specifying the requirements for energy efficient building operation through reviewing the international regulations.

- Analysing existing building performance assessment and monitoring systems to identify the deficits and weaknesses in current practices.

- Analysing the standardisation and integration efforts of the AEC/FM industry in order to develop a flexible, standardised and extensible integration concept to maintain data exchange between the BIM tools and the DW.

- Specifying the proposed Holistic Multi-Dimensional Information Management System with a unique data aggregation layer and web services specifically designed for building performance monitoring and analysis.

- Demonstrating the implementation of the specified system and validating its capabilities in an appropriately selected research building.

- Introducing an affordable residential building specific wireless energy monitoring and optimisation system which is derived from the research findings presented in this work.

1.4 Thesis Structure

The structure of the thesis is depicted in figure 1.1. In Chapter 2, the building energy use and its environmental impact are discussed. Also, international environmental drivers such as the Kyoto Protocol and the accord of the Copenhagen Summit are briefly defined from the building energy use aspect. Finally, European Union Directive on Energy Performance of Buildings is introduced.

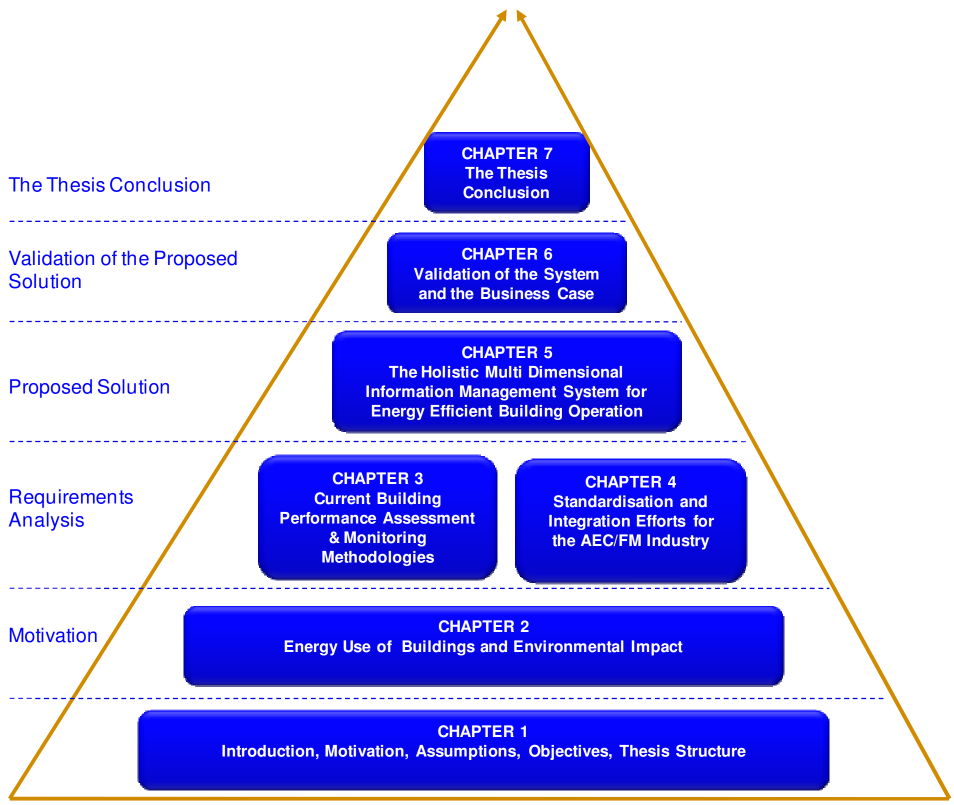

Figure 1. 1: Thesis Structure

In Chapter 3, current practices in building performance monitoring domain are reviewed. Also, building performance monitoring related research projects are introduced to create awareness for future projections and underline the requirements.

In Chapter 4, standardisation and integration efforts for AEC/FM industry is reviewed in order to define the requirements for developing a flexible, standardized and extensible integration concept for extracting “Dimensional Data” to build the multi-dimensional information model.

In Chapter 5, the holistic Multi-Dimensional Information Management System is introduced with its sub-components.

In Chapter 6, the validation of the proposed system is defined with a technical demonstration description. Also, an affordable residential building specific wireless energy monitoring and optimisation system which is derived from the research findings presented in this work is introduced including a possible business scenario.

In Chapter 7, the conclusions from this research and the future work are discussed.

Chapter 2

Energy Use of Buildings and Environmental Impact

Chapter 2 considers the energy consumption of buildings and its effects on environment. The chapter reviews international legislations aimed at minimizing green house gas (GHG) emissions.

2.1 Introduction

Atmospheric carbon dioxide levels are higher today than at any time in at least the past 650,000 years. They are about 35% higher than before the industrial revolution. It is highly probable that these increased emissions have been generated by the human use of fossil fuels (IPCC 2007). If emissions continue along their present trajectory it is estimated that by the end of this century average global temperatures are likely to have risen by 4 °C and possibly by 6 °C. Such increases bring with them potentially catastrophic consequences (Gaterell & McEvoy 2005).

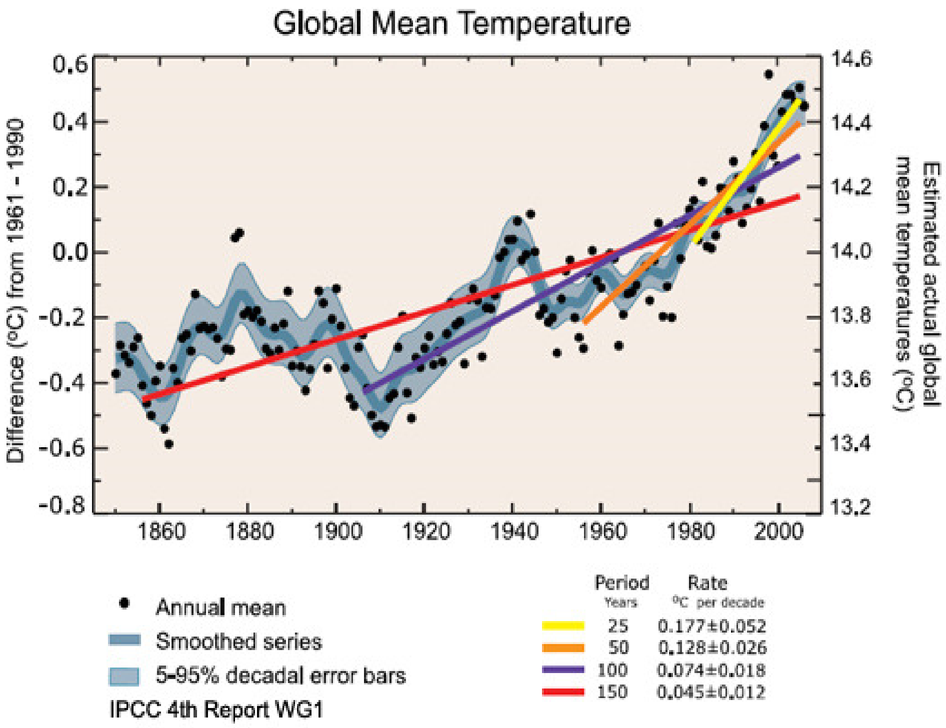

Figure 2. 1: Annual average global temperature (black dots) along with simple fits to the data (IPCC 2007).

As illustrated in Figure 2.1 the period from 1950s to the present demonstrates a dramatic increase in average global temperature. The concentrations of carbon dioxide and other greenhouse gases in atmospheric samples have been measured continuously since the late 1950s. Since then, carbon dioxide concentrations have increased steadily from about 315 parts per million (ppm, or molecules of carbon dioxide per million molecules of dry air) in the late 1950s to about 385 ppm now (Schneider 2008). In light of these information it is not surprising to mention that the hottest years on record have occurred over the last 14 years with the hottest being 2005 thus far (Gore 2006). As a consequence, human activities account for the increase in carbon dioxide levels which is directly impacting the earth's atmosphere and causing significant climate alterations.

2.2 Energy Consumption and Environmental Impact

The relationship between the emissions of greenhouse gasses and the negative impact on the environment has long been known. The latest report of the IPCC has clearly established a link between a rise in global mean air temperature and atmospheric CO_2 levels. Carbon dioxide is the most anthropogenic GHG. Its annual emissions have grown between 1970 and 2004 by about 80% from 21 to 38 gigatonnes (Gt) and represented 77% of total anthropogenic GHG emissions in 2004. The largest growth in GHG emissions between 1970 and 2004 has come from CO_2 caused by fossil fuel use with 56.6%.

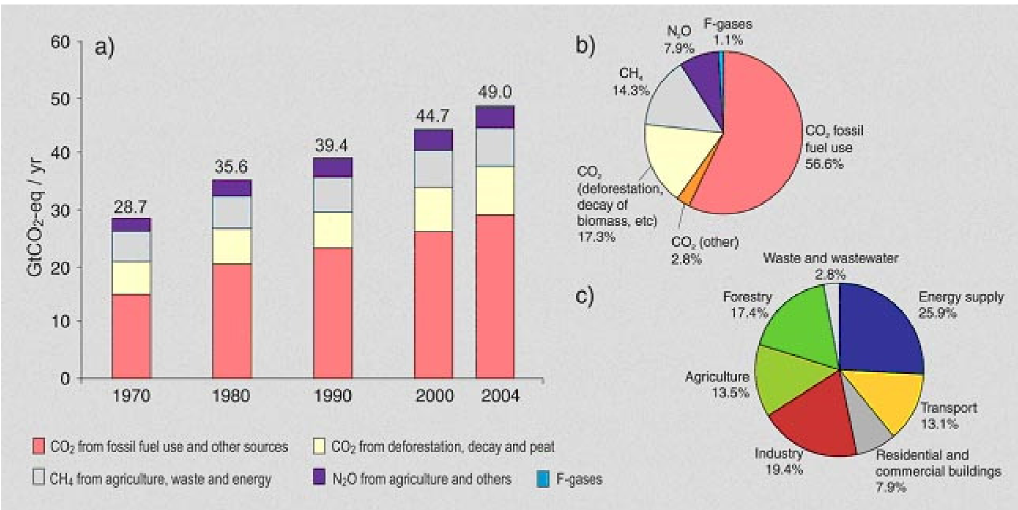

Figure 2. 2: Global Annual Emissions of Anthropogenic GHGs from 1970 to 2004 (IPCC 2007).

As illustrated in Figure 2.2, share of energy supply, transport and buildings accounts for 46.9% in total anthropogenic GHG emissions in 2004. It is obvious that with the growing necessities of developing countries for energy, transport and accommodation, anthropogenic GHG emissions will increase a lot more in near future than 1970-2004 period. According to 2006 United Nations Statistics Division List; China (21.5%), United States (20.2%) and the European Union (13.8%) are contributing more than half of the World's total GHG emissions (United Nations 2009). As of 2006 China's rapidly developing economy and corresponding coal production has resulted in it becoming the world's leading contributor of recorded greenhouse gasses (NEAA 2007). Recent studies using province level information for evaluating China's CO_2 emissions determined that actual emissions are far higher than previously calculated (Auffhammer & Carson 2008). On the other hand, India as a developing nation with high population figures, currently contributes only 5.3% of the World's total GHG emissions but it is estimated in recent studies that India may in time surpass China in terms of population and CO_2 emissions (Hubacek et al. 2007).

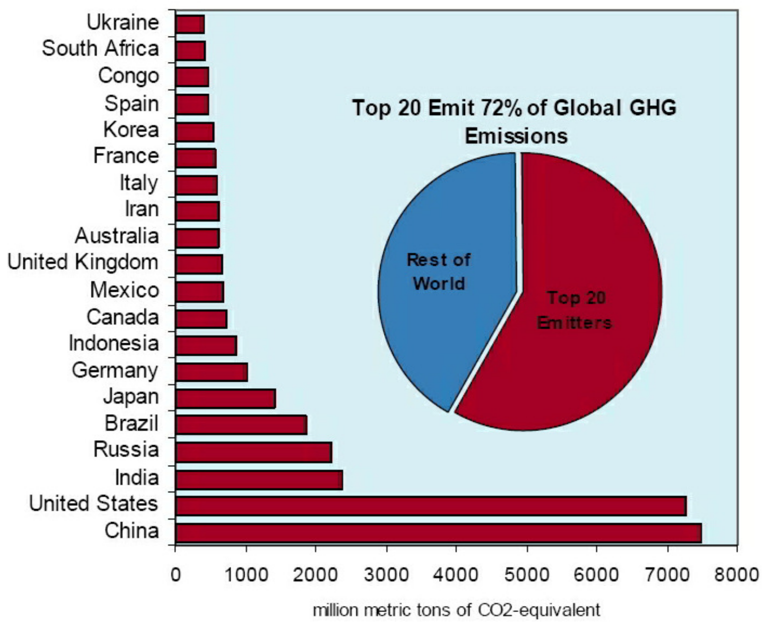

Figure 2. 3: Top 20 Emitters of Greenhouse Gasses in 2005(IEA 2008).

In order to analyse the GHG emissions by countries, Greenhouse Gas Emissions per Capita list is prepared by World Resources Institute (WRI 2009). This list manifests huge discrepancies between developed and developing countries. For example with the 2005 figures USA demonstrates 23.5 Tonnes of CO_2e per capita and India demonstrates only 1.7 Tonnes of CO_2e per capita. This discrepancy is huge but relatively expectable. On the other hand, there are discrepancies among developed nations that require attention. For instance, Australia has 26.9 Tonnes of CO_2e per capita and Germany has only 11.9 Tonnes of CO_2e per capita. Ireland has a moderate position in this picture with 16.7 Tonnes of CO_2e per capita but still highest within European Union. China with its huge population and developing economy has 5.5 Tonnes of CO_2e per capita GHG emission and this figure is rapidly growing.

Ranking (2005)	Country	Year 2000 Tonnes of CO_2e	Year 2005 Tonnes of CO_2e
5	Australia	25.6	26.9
7	USA	24.3	23.5
12	Ireland	17.3	16.7
25	Germany	12.3	11.9
57	Switzerland	7.2	7.3
72	China	3.9	5.5
120	India	1.9	1.7

Table 2. 1: List of Countries by Greenhouse Gas Emissions per Capita (WRI 2009).

These figures indicate that there is a correlation between countries' economic development and GHG emission levels. When the developing economies with high population reach the same level as the developed countries like USA and the EU in terms of economic development, the effect of increasing GHG to the climate change will be extremely more significant than today. On the other hand, discrepancies within developed and industrialized countries in terms of GHG per capita figures support the applicability of reducing GHG emissions without affecting the progress of industry and economic development. Both

USA and Germany have similar Gross Domestic Product (GDP) per capita figures but when it comes to GHG per capita figures, USA has nearly double emission levels in comparison to Germany. As the world's third biggest economy, Germany have been continuously focusing on energy efficiency and renewable energy resources. This policy resulted as lower GHG emissions without limiting the economic growth of the country.

In conclusion, recent GHG emission figures and correlation of these figures with the countries' economic development and population indicate the seriousness of climate change issue in short term. On the other hand, these figures points out the solution to overcome this issue. With a worldwide emphasis on energy efficiency and renewable energy sources, it is possible to ease climate change without affecting the progress of economic development.

2.3 Energy Use of Buildings and Environmental Impact

Current residential and office buildings provide a significant contribution to total energy consumption and CO_2 emissions. Reports by the Intergovernmental Panel on Climate Change (IPCC) and the U.S. Department of Energy note that buildings account for 25-30% of total energy related CO_2 emissions (Price et al. 2006). The overall building stock in the U.S. accounts for 40% of the total energy consumption of the country (Filippn 2000). It has been estimated that the operation of buildings (space lighting, heating and cooling) is responsible for about 50% of primary energy use and a slightly lower share of CO_2 and green house gas emissions in the EU (Cohen et al. 2004). In the case of Ireland energy consumption of buildings accounts for approximately 30% of green house gas emissions and approximately 40% of total energy consumed (Howley et al. 2006).

Sector	Historical		Avg. (A1, A2 Scenario)			Change (%)	
	1971	2000	2010	2020	2030	1971-2000	2000-30
Industrial	91	140	203	244.5	291.5	53.8%	108.2%
Buildings	89	149	183.5	224.5	274	67.4%	83.9%
Transport	42	87	106.5	142	185	107.1%	112.6%
Agriculture	6	11	11	16	18.5	83.3%	68.2%
Total	228	387	504	627	769	69.7%	98.7%

Table 2. 2: World Primary Energy Consumption (EJ) (Data extracted from Sectoral Trends in Global Energy Use and Greenhouse Gas Emissions Report, Berkley National Laboratory).

Table 2.2 indicates the sectoral breakdown of the global energy consumption. Energy consumption of the buildings has the highest portion among other sectors in year 2000. Also, its growth rate is expected to increase within 2000-2030 period. Future projections indicate that in 2030, buildings will be responsible for 35.6% of primary energy use in the World and continue to maintain its importance.

Region	Historical		Avg. (A1, A2 Scenario)			Change (%)	
	1971	2000	2010	2020	2030	1971-2000	2000-30
Pacific OECD	57	188	188.5	197.5	201	229.8%	6.9%
North America	457	643	700	757	890.5	40.7%	38.5%
Western Europe	310	339	372.5	388.5	399	9.4%	17.7%
Central/E. Europe	73	82	59.5	63	74	12.3%	-9.8%
Former Soviet Union	243	247	166.5	199.5	220.5	1.6%	-10.7%
Centrally Planned Asia	59	212	411.5	603.5	814.5	259.3%	284.2%
Other Asia	20	154	216	342.5	476.5	670.0%	209.4%
Latin America	24	69	132.5	191.5	243.5	187.5%	252.9%
Sub Saharan Africa	12	30	73	127	234.5	150.0%	681.7%
Middle East/N. Africa	12	128	168	230.5	294.5	966.7%	130.1%
Total	897	1252	1320.5	1406	1564.5	39.6%	25.0%

Table 2. 3: Historical and Projected Buildings Sector CO_2 Emissions (MtC) (Data extracted from Sectoral Trends in Global Energy Use and Greenhouse Gas Emissions Report, Berkley National Laboratory).

Table 2.3 depicts regional breakdown of historical and projected CO_2 emission of the buildings sector. As it is clearly observed from the table, buildings sector will continue to contribute CO_2 emissions in the long run. A significant increase in buildings related CO_2 emissions is expected in Africa and Centrally Planned Asia (China, Chinese Taipei, Hong Kong, DPR of Korea and Vietnam). Also, Western Europe building sector will continue to contribute CO_2 emissions with an increasing trend. Although Western Europe CO_2 emissions increase is not as high as Asia and Africa, there is nearly twice as much increase in comparison to previous period 1970-2000. These figures indicate the importance of buildings and their continuous impact to global climate change in the long run.

In the case of Ireland energy consumption in buildings accounts for approximately 30% of GHG emissions and approximately 40% of total energy consumed (Howley et al. 2006). The projected rise in GHG emissions in Ireland from 1990-2010 is 25% of 1990 levels compared to the proposed limit of 13% under the EU burden sharing agreement (O'Donnell 2009). Figure 2.4 illustrates the causes of this growth by sectors; Ireland's energy related CO_2 emissions are expected to rise 62% in total. The increases in energy demand in transport that are projected in the coming years are reflected here by the 157% increase in transport related CO_2 emissions in 2010 compared to 1990. The second largest growth sector in CO_2 with an increase of 76% is the tertiary sector, with industry being the third largest increase. Residential buildings' CO_2 emissions are expected to rise about 19.2%. Also, with both the tertiary sector and industrial sector being building dependent to a large extent, the need for energy consumption to be reduced in these areas again highlights the need for more efficient building energy management. Moreover, Ireland has a relative increase in the number of new buildings compared with the European Union. Therefore Ireland has a relatively greater responsibility to give more emphasis on efficient building operation.

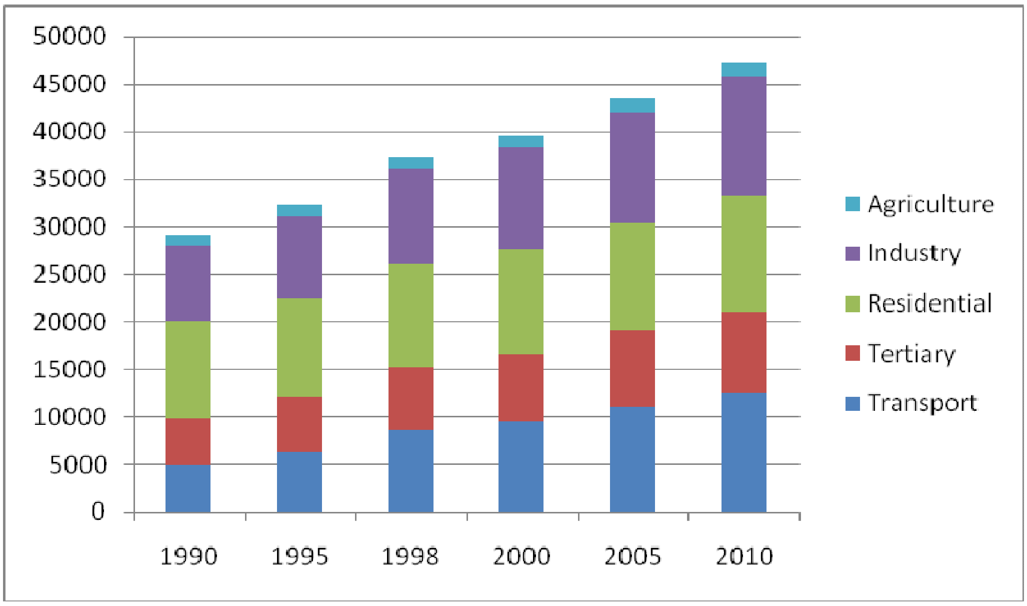

Figure 2. 4: Ireland's Energy Related CO2 Emissions (Million Tons)

Energy consumption in buildings is metered and measured in kWh (Kilowatt hours). Each kWh of energy delivered to a building causes atmospheric emission of CO_2 from the extraction, processing and delivery of the fuel to its eventual consumption on site (DETR 2002). In order to convert kWh into CO_2 SEI (Sustainable Energy Ireland) provides a conversion table from the fuel type used on site to kg of CO_2 emitted and is shown in Table 2.4. Hence by calculating the amount of CO_2 emitted by a facility, it is possible to estimate its environmental impact and performance efficiency.

Fuel	t CO2/TJ	kg CO2/kWh
Motor Spirit (Gasoline)	70.0	0.252
Gas/Diesel Oil	73.3	0.264
Residual Oil	76.0	0.273
LPG	63.7	0.229
Coal	94.6	0.341
Gas		
Natural Gas	57.1	0.206
Electricity (2007)	150.8	0.543

Table 2. 4: Conversion to CO2 Emissions from Different Fuel Types.

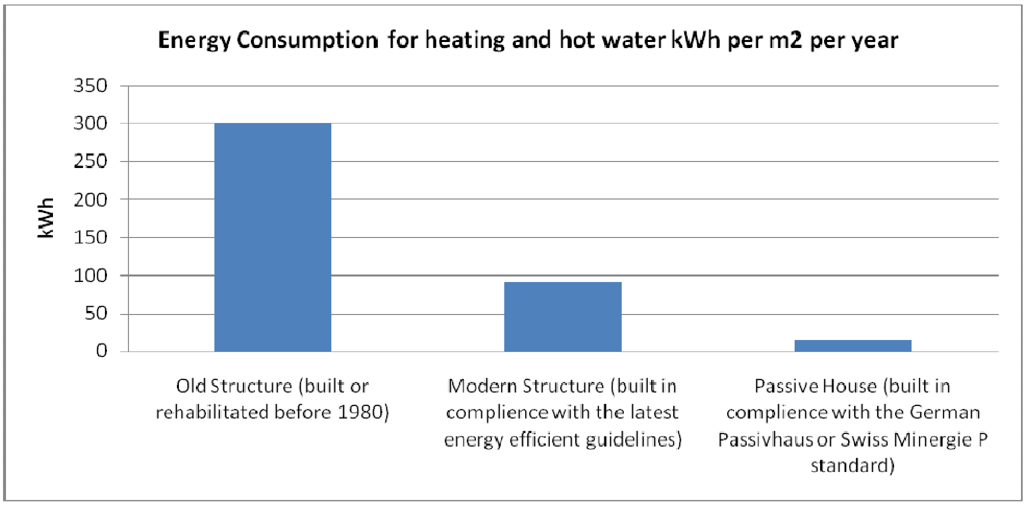

Figure 2. 5: Energy Consumption and CO_2 Emissions from Buildings.

Inefficient buildings should be the major focus area in order to reduce energy consumption and CO_2 emissions. Buildings are responsible for more than 40 % of energy use in OECD (Organisation of Economic Co-operation and Development) countries and at a global level they account for about 30% of GHG emissions according to UNEP's (United Nations Environmental Programme) Sustainable Building and Construction Initiative. In absolute terms the amount is rising fast as construction continues a pace, especially in rapidly developing countries. Heating, cooling and lighting our homes and using household appliances absorbs 11 % of global energy. As illustrated in Figure 2.5, there is significant energy consumption and CO_2 emissions discrepancies among modern structure buildings and old structure buildings which are rehabilitated before 1980. Currently 85 percent of European buildings are older than 20 years; 60 percent are older than 40 years and 30 percent are pre-war buildings (Itard 2008). It is estimated that the average UK household could save around two tonnes of CO_2 annually by making its home energy-efficient; in essence, improve insulation, heating systems and lighting (UNEP 2008). The World Business Council for Sustainable Development's Energy Efficiency in Buildings (EEB) project concludes that by cutting energy use in buildings by about 30 per cent, Europe's energy consumption would fall by 11 per cent, more than half of the 20-20-20 target (20 % less carbon dioxide by 2020, with 20 % renewables in the energy mix). What is more, it saves money (UNEP 2008).

International Energy Agency (IEA) set Eco-Design Strategies in order to increase the energy efficiency of buildings Table 2.5. Among these strategies home automation systems are the most cost effective solution without going under heavy refurbishments. Several case studies suggest that energy savings between 15%-40% can be made in buildings by closer monitoring and supervision of energy-usage and monitoring of related data (Salsbury & Diamond 2000).

Super insulation	High efficiency insulation materials, often including gases with extremely low heat transfer values
High-performance windows	Windows combining high level of light penetration with low level of heat transfer, for example double-glazed windows.
Ventilation heat recovery systems	Ventilation system that uses outgoing heated indoor air to pre-heat incoming cold air
Ground couple heat exchangers	Uses the more stable ground temperature (cooler on hot days and warmer of cold days) to adjust the temperature of incoming air.
Sunspaces	Spaces heated by direct sun light.
Materials with high termal storage capacities	Materials that keep their temperature for extended periods of time, even if the surrounding air temperature changes, hence storing heat gained during a hot day to heat the building during a cold night, and vice versa.
Active solar water systems	Water heating through direct sunlight, for example by leading water through pipes located in the centre of concave steel mirrors focussing sun light on the pipes.
Photovoltaic systems	Panels with semi-conductor cells convert sun light to electricity
Integrated mechanical system	Automated features of a building, e.g. sunshades, responding to incoming sun light or indoor temperature so as to maintain comfortable conditions.
Home automation systems	Computer controlled heating, cooling and ventilation adjusting the indoor temperature and ventilation according to pre-set parameters, often designed to minimize energy use.
Energy-efficient lights and appliances	Appliances and lights meeting minimum criteria for energy use per output. For example, low-energy lamps often use about 30-40% less energy to provide the same levels of light as ordinary lamps do.

Table 2. 5: Eco-design Strategies.

2.4 The Kyoto Protocol

The Kyoto Protocol which was initially adopted for use on 11 December 1997 in Kyoto, Japan and which entered into force on 16 February 2005, is a protocol to the United Nations Framework Convention on Climate Change (UNFCCC or FCCC), an international environmental treaty with the goal of achieving stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system (UNFCCC 2009b). The Kyoto Protocol establishes legally binding commitment for the reduction of four greenhouse gases (carbon dioxide, methane, nitrous oxide, sulphur hexafluoride), and two groups of gases (hydrofluorocarbons and perfluorocarbons) produced by "annex I" (industrialized) nations, as well as general commitments for all member countries. As of January 2009, 183 parties have ratified the protocol (UNFCCC 2009c). Under the Kyoto Protocol, industrialized countries agreed to reduce their collective green house gas (GHG) emissions by 5.2% from the level in 1990. National limitations range from the reduction of 8% for the European Union and others to 7% for the United States, 6% for Japan, and 0% for Russia.

Under the Treaty, countries must meet their targets primarily through national measures. However, the Kyoto Protocol offers them an additional means of meeting their targets by way of three market-based mechanisms. The mechanisms help stimulate green investment and help Parties meet their emission targets in a cost-effective way.

The Kyoto mechanisms are:

- *Emissions trading (the carbon market):* This as set out in Article 17 of the Kyoto Protocol, allows countries that have emission units to spare - emissions permitted them but not "used" - to sell this excess capacity to countries that are over their targets.

- *Clean development mechanism (CDM):* This, as defined in Article 12 of the Protocol, allows a country with an emission-reduction or emission-limitation commitment under the Kyoto Protocol (Annex B Party) to implement an emission-reduction project in developing countries. Such projects can earn tradable certified emission reduction (CER) credits, each equivalent to one tonne of CO_2, which can be counted towards meeting Kyoto targets. A CDM project activity might involve, for example, a rural electrification project using solar panels or the installation of more energy-efficient boilers. This mechanism aims to stimulate sustainable development and emission reductions, while giving industrialized countries some flexibility in how they meet their emission reduction or limitation targets.

- *Joint implementation (JI):* This as defined in Article 6 of the Kyoto Protocol, allows a country with an emission reduction or limitation commitment under the Kyoto Protocol (Annex B Party) to earn emission reduction units (ERUs) from an emission-reduction or emission removal project in another Annex B Party, each equivalent to one tonne of CO_2, which can be counted towards meeting its Kyoto target. This offers Parties a flexible and cost-efficient means of fulfilling a part of their Kyoto commitments, while the host Party benefits from foreign investment and technology transfer.

2.5 The Copenhagen Summit

The 2009 United Nations Climate Change Conference, also known as the Copenhagen Summit, was held in Copenhagen, Denmark. The conference included the 15^{th} Conference of the Parties (COP 15) to the United Nations Framework Convention on Climate Change and the 5^{th} Meeting of the Parties (COP/MOP 5) to the Kyoto Protocol. According to the Bali Road Map, a framework for climate change mitigation beyond 2012 was to be agreed there.

During the conference some countries stated what actions they were proposing to take if a binding agreement was achieved. In the end, no such agreement was reached and the actions will instead be debated in 2010. Table indicates some of the selected countries and their proposed actions.

Country	1990 to 2020	Reference Base
Brazil	+5% to -1.8%	
EU	-20% to -30%	CO_2e w/o LULUCF @ 20%
		CO_2e w/- LULUCF @ 30%
Germany	-40%	CO_2e w/- LULUCF
Japan	-25%	
Russia	-20% to -25%	
Switzerland	-20% to -30%	
Country	**2005 to 2020**	**Reference Base**
China	-40% to -45%	CO_2 Emissions Intensity
India	-20% to -25%	CO_2 Emissions Intensity
USA	(-17% by 2020) (-42% by 2030) (-83% by 2050)	CO_2e w/o LULUCF

Table 2. 6: Proposed Actions of the Countries

In the table LULUCF stands for land use, land-use change and forestry is defined by the UN Climate Change Secretariat as "A greenhouse gas inventory sector that covers emissions and removals of greenhouse gases resulting from direct human-induced land use, land-use change and forestry activities."

CO_2 Emissions Intensity is the average emission rate of a given pollutant from a given source relative to the intensity of a specific activity; for example grams of carbon dioxide released per mega joule of energy produced, or the ratio of greenhouse gas emissions produced to GDP. Emission intensities are used to derive estimates of air pollutant or greenhouse gas emissions based on the amount of fuel combusted, the number of animals in animal husbandry, on industrial production levels, distances travelled or similar activity data. Emission intensities may also be used to compare the environmental impact of different fuels or activities. The related terms emission factor and carbon intensity are often used interchangeably, but "factors" exclude aggregate activities such as GDP, and "carbon" excludes other pollutants.

In the final session of the conference, Brazil, China, India, South Africa and the United States drafted the Copenhagen Accord which is the document that delegates at the United Nations Climate Change Conference (UNCCC) agreed to "take note of" at the final plenary session of the Conference on 18 December 2009 (COP-15). It is a draft COP decision and, when approved, is operational immediately.

The Accord (UNFCCC 2009a);

- Endorses the continuation of the Kyoto Protocol
- Underlines that climate change is one of the greatest challenges of our time and emphasises a "strong political will to urgently combat climate change in accordance with the principle of common but differentiated responsibilities and respective capabilities"
- To prevent dangerous anthropogenic interference with the climate system, recognises "the scientific view that the increase in global temperature should be below 2 degrees Celsius", in a context of sustainable development, to combat climate change.
- Recognises "the critical impacts of climate change and the potential impacts of response measures on countries particularly vulnerable to its adverse effects" and stresses "the need to establish a comprehensive adaptation programme including international support"
- Recognises that "deep cuts in global emissions are required according to science" (IPCC AR4) and agrees cooperation in peaking (stopping from rising) global and national greenhouse gas emissions "as soon as possible" and that "a low-emission development strategy is indispensable to sustainable development"

- States that "enhanced action and international cooperation on adaptation is urgently required to... reduc[e] vulnerability and build.. resilience in developing countries, especially in those that are particularly vulnerable, especially least developed countries (LDCs), small island developing states (SIDS) and Africa" and agrees that "developed countries shall provide adequate, predictable and sustainable financial resources, technology and capacity-building to support the implementation of adaptation action in developing countries"
- About mitigation agrees that developed countries (Annex I Parties) would "commit to economy-wide emissions targets for 2020" to be submitted by 31 January 2010 and agrees that these Parties to the Kyoto Protocol would strengthen their existing targets. Delivery of reductions and finance by developed countries will be measured, reported and verified (MRV) in acordance with COP guidelines.
- Agrees that developing nations (non-Annex I Parties) would "implement mitigation actions" to slow growth in their carbon emissions, submitting these by 31 January 2010. LDC and SIDS may undertake actions voluntarily and on the basis of (international) support.
- Agrees that developing countries would report those actions once every two years via the U.N. climate change secretariat, subjected to their domestic MRV. Nationally appropriate mitigation actions (NAMAs) seeking international support will be subject to international MRV.
- Recognises "the crucial role of reducing emission from deforestation and forest degradation and the need to enhance removals of greenhouse gas emission by forests", and the need to establish a mechanism (including REDD-plus) to enable the mobilization of financial resources from developed countries to help achieve this.
- Decides to pursue opportunities to use markets to enhance the cost-effectiveness of, and to promote mitigation actions.

- Developing countries, specially those with low-emitting economies should be provided incentives to continue to develop on a low-emission pathway
- States that "scaled up, new and additional, predictable and adequate funding as well as improved access shall be provided to developing countries... to enable and support enhanced action"
- Agrees that developed countries would raise funds of $30 billion from 2010-2012 of new and additional resources
- Agrees a "goal" for the world to raise $100 billion per year by 2020, from "a wide variety of sources", to help developing countries cut carbon emissions (mitigation). New multilateral funding for adaptation will be delivered, with a governance structure.
- Establishes a Copenhagen Green Climate Fund, as an operating entity of the financial mechanism, "to support projects, programme, policies and other activities in developing countries related to mitigation". To this end, creates a High Level Panel
- Establishes a Technology Mechanism "to accelerate technology development and transfer...guided by a country-driven approach"
- Calls for "an assessment of the implementation of this Accord to be completed by 2015... This would include consideration of strengthening the long-term goal", for example to limit temperature rises to 1.5 degrees.

2.6 The EU Perspective

Europe's objective under the Kyoto and Copenhagen Protocols is a reduction in the level of GHG emissions while also decreasing the current dependence on imported energy due to the fact that the EU currently imports 82% of its oil and 57% of its gas, making it the world's leading importer of these fuels (EC 2006). European Parliament approved a road map at a meeting of the European Council on March 9, 2007 which was prepared in the light of the report prepared by European Commission (EC 2007). Underlying many of the proposals are designed to limit global temperature changes to no more than 2°C above pre-industrial levels (EC 2007).

This road map includes;

- A cut of at least 20% in greenhouse gas emissions from all primary energy sources by 2020 (compared to 1990 levels), while pushing for an international agreement to succeed the Kyoto Protocol aimed at achieving a 30% cut by all developed nations by 2020.
- A cut of up to 50% in carbon emissions from primary energy sources by 2050, compared to 1990 levels.
- A minimum target of 10% for the use of biofuels by 2020.
- That the energy supply and generation activities of energy companies should be 'unbundled' from their distribution networks to further increase market competition.
- Improving energy relations with the EU's neighbours, including Russia.
- The development of a European Strategic Energy Technology Plan to develop technologies in areas including renewable energy, energy conservation, low-energy buildings, 4th generation nuclear power, clean coal and carbon capture.
- Developing an Africa-Europe Energy partnership, to help Africa 'leap-frog' to low-carbon technologies and to help develop the continent as a sustainable energy supplier.

In order to address these issues three EU Directives, Energy End-Use Efficiency and Energy Services Directive [Directive 2006/32/EC], Emissions Trading Directive [Directive 2003/87/EC] and Energy Performance of Building Directive [Directive 2002/91/EC] were commissioned.

Energy End-Use Efficiency and Energy Services Directive also referred as the Energy Services Directive (ESD) (EU 2006), requires the establishment of an indicative target of 9% improvement in energy efficiency by 2016. The objective of the Directive is to improve energy end-use efficiency in a cost effective manner for the member states by (O'Donnell 2009):

- Providing the necessary indicative targets, mechanisms, incentives and institutional, financial and legal frameworks to remove existing market barriers and address imperfections that impede the efficient end-use of energy;
- Creating the conditions for the development and promotion of a market for energy services and for the delivery of other energy efficiency improvement measures to final consumers;
- Placing an emphasis on measurement and verification of energy savings;
- Stipulating the public sector must play an exemplary role.

In January 2005 the European Union Greenhouse Gas Emission Trading System (EU ETS) commenced operation as the largest multi-country, multi-sector Greenhouse Gas Emission Trading System world-wide. The scheme is based on Emissions Trading Directive [Directive 2003/87/EC], which entered into force on 25 October 2003 (EC 2009). Emissions Trading Directive requires that the EU Member States will set limits of CO_2 emissions from energy-intensive companies by issuing allowances as to how much CO_2 these companies are allowed to emit. Reduction below the limits will be tradable (O'Sullivan 2005). Companies that achieve reductions can sell certified emission reduction (CER) credits to the companies that excess the allowed limits. For the first time Financial Controllers must now take account of the financial penalties associated with exceeding the predefined energy consumption threshold. Carbon credits are purchased or sold on a per ton basis. 100 Euro per ton purchased and 40 Euro per ton sold (B.P. O'Gallachoir et al. 2007). A legally binding requirement has now been established for maintaining energy efficient buildings or pay financial penalties. Emissions trading have been implemented in two phases 2005-2007 and 2008-2012 to coincide with the time frame for the Kyoto protocol (Georgopoulou et al. 2006). University College Cork (UCC) campus is a participant, requires that sites with a thermal input capacity in excess of 20 MW thermal input possess a GHG permit as of 2005 (O'Donnell 2009).

Energy Performance of Buildings Directive [Directive 2002/91/EC] was approved by the European Council on 16 December 2002. The directive requires that the Member States must apply minimum requirements as regards the energy performance of new and existing buildings, ensure the certification of their energy performance and require the regular inspection of boilers and air conditioning systems in buildings. This directive will be explained in detail in the following section.

2.7 The EU Directive on the Energy Performance of Buildings

The Directive forms part of the EU initiatives on climate change prior to responsibilities under the Kyoto Protocol and security of supply because of the ever increasing energy dependency as stated in the Commission's report "Green Paper" (EU 2000). The EU can have little influence on external energy markets and energy supply but can influence domestic energy demand. One possible solution to both the above problems is to reduce energy consumption by improving energy efficiency. Energy consumption for buildings-related services accounts for approximately one third of total EU energy consumption. It is obvious that, with initiatives in this area, significant energy savings can be achieved, thus helping to attain objectives on climate change and security of supply.

2.7.1 Background

This Directive is a follow-up to the directives under the SAVE programme provisions on buildings. Earlier directives that created a basis for the Energy Performance of Buildings Directive listed as;

- Directive [92/42/EEC] on efficiency requirements for new hot-water boilers fired with liquid or gaseous fuels: This concerns the promotion of energy efficiency in the Community, determines the efficiency requirements applicable to new hot-water boilers fired by liquid or gaseous fuels with a rated output of no less than 4 kW and no more than 400 kW, hereinafter called 'boilers'.
- Directive [2006/32/EC] on energy end-use efficiency and energy services (repealing Council Directive 93/76/EEC): The purpose of this Directive is to enhance the cost-effective improvement of energy end-use efficiency in the Member States by: (a) providing the necessary indicative targets as well as mechanisms, incentives and institutional, financial and legal frameworks to remove existing market barriers and imperfections that impede the efficient end use of energy; (b) creating the conditions for the development and promotion of a market for energy services and for the delivery of other energy efficiency improvement measures to final consumers.
- Decision [1600/2002/EC] 6th Environmental Action Programme: This calls for full implementation of the Kyoto Protocol as a first step towards reaching a long-term target of 70% in emission cuts, final version of the Directive 2002/91/EC was initiated.

2.7.2 Objectives

The major objectives of the Directive can be summarised as: (a) Developing a common methodology for calculating the integrated energy performance of buildings; (b)Setting minimum standards on the energy performance of new buildings and existing buildings that are subject to major renovation; (c) Developing systems for the energy certification of new and existing buildings and, for public buildings. (d) Enforcing prominent display of this certification and other relevant information. (Certificates must be less than five years old); (e) Enabling regular inspection of boilers and central air-conditioning systems in buildings and in addition an assessment of heating installations in which the boilers are more than 15 years old.

The common calculation methodology should include all the aspects which determine energy efficiency and not just the quality of the building's insulation. This integrated approach should take account of aspects such as heating and cooling installations, lighting installations, the position and orientation of the building, heat recovery, etc. This legislation will lead to benchmarking of buildings both in terms of energy usage and associated CO_2 emissions and places demands on building owners to identify/quantify the energy usage of their buildings against benchmarks set by government energy/environmental agencies throughout the building life cycle (design, construction and operation). This will place the onus on building stakeholders (e.g. owners, designers, operators, etc.) to document/label: (a) the potential (during design) and actual (during operation) energy consumption of buildings; (b) the climatic conditions of the proposed (design) and constructed (operation) environments (O'Sullivan 2005).

2.7.3 Scope and Impact

The Directive concerns the residential sector and the tertiary sector (offices, public buildings, etc.). The scope of the provisions on certification does not, however, include some buildings, such as historic buildings, industrial sites, etc. It covers all aspects of energy efficiency in buildings in an attempt to establish a truly integrated approach. The Directive does not lay down measures on moveable equipment such as household appliances.

In Ireland starting from 1 January 2009 a Building Energy Rating (BER) and advisory report is to be supplied by the owner to a prospective buyer or tenant when a non-residential (non domestic) and a residential (domestic) building is constructed, sold or rented. The intention of the advisory report is to encourage implementation of energy efficiency measures.

In order to generate the BER and advisory report for new and existing non domestic buildings, The Non Domestic Energy Assessment Procedure (NEAP) methodology is used. This calculates the energy consumption and CO_2 emissions associated with a standardised use of a building. The energy consumption is expressed in terms of kilowatt hours per square metre floor area per year ($kWh/m^2/yr$) and the CO_2 emissions expressed in terms of kilograms of CO_2 per square metre floor area per year ($kg\ CO_2/m^2/yr$). Also, the calculation can be carried out by approved software packages or by the default calculation tool, Simplified Building Energy Model (SBEM), which is based on CEN standards and has been developed by BRE on behalf of the UK Department of Communities and Local Government and was adjusted for Ireland. SBEM, accompanied by a basic user interface, iSBEM, calculates monthly energy use and CO_2 emissions based on building geometry, construction, use and HVAC and lighting equipment (SEAI 2010).

For the domestic buildings a BER is generated according to the Dwelling Energy Assessment Procedure (DEAP), which is the Irish official procedure for calculating and assessing the energy performance of dwellings. DEAP version 3.1.0 calculates the energy performance of new and existing dwellings. The procedure takes account of the energy required for space heating, ventilation, water heating and lighting, less savings from energy generation technologies. For standardised occupancy, it calculates annual values of delivered energy consumption, primary energy consumption, carbon dioxide emissions and costs, both totals and per square metre of total floor area of the dwelling (SEAI 2010).

Also, all public buildings with a gross internal floor area greater than 1000m^2 are required to display a Display Energy Certificate (DEC) in a prominent place clearly visible to the public. While the BER is calculated as an asset rating, the DEC is calculated as an operational rating, where the actual energy consumed in the building is compared to a benchmark for buildings of the same type, and shown on the certificate A-G scale in terms of primary energy. There is also a CO_2 indicator which shows the CO_2 emissions associated with the building's energy consumption (SEAI 2010).

As of September 2010, 144156 buildings were certified in Ireland. The distribution of those buildings is depicted in Table 2.7.

Rating	New Dwellings	Existing Dwellings	Non Domestic	DEC
A1	5	0	0	1
A2	67	12	8	19
A3	841	54	51	71
B1	2,758	604	158	144
B2	5,736	2,982	384	223
B3	6,857	7,464	606	240
C1	3,271	11,032	687	245
C2	1,393	12,785	640	252
C3	650	14,383	493	212
D1	505	15,220	508	225
D2	282	15,065	377	180
E1	159	9,278	204	128
E2	66	7,765	177	83
F	18	7,660	238	84
G	50	10,141	266	149
Total	**22658**	**114445**	**4797**	**2256**

Table 2. 7: Distribution of BER and DEC certified buildings in Ireland (SEAI 2010).

2.8 The Chapter Conclusion

In this chapter, building energy use and its environmental impact were introduced with the global warming aspect. The global warming facts and figures have clearly established a link between a rise in global mean air temperature and atmospheric CO_2 levels. If emissions continue along their present trajectory it is estimated that by the end of this century average global temperatures are likely to have risen by 4 °C and possibly by 6 °C. Such increases bring with them potentially catastrophic consequences.

Currently buildings account for 25-30% of total energy related CO_2 emissions. Future projections indicate that in 2030, buildings will be responsible for 35.6% of primary energy use in the World and continue to maintain its importance. Therefore, efforts for saving energy in buildings are very crucial to cope with climate change.

Also, international environmental drivers such as the Kyoto Protocol and the Copenhagen Summit were briefly discussed from the building energy use perspective.

Finally, the European Union Directive on Energy Performance of Buildings which is one of the most important measures of the EU to reach its 20-20-20 target was introduced.

In the following chapter, current practices in building performance assessment domain will be reviewed. Also, ongoing building performance monitoring related research projects will be introduced.

Chapter 3

Current Building Performance Assessment & Monitoring Methodologies

Chapter 3 reviews current building performance assessment and monitoring methodologies and building performance metric sets, both intended to improve the process of building performance monitoring. Also, building performance monitoring research projects are introduced to create awareness for future projections. Finally, a monitoring and analysis process is introduced.

3.1 Introduction

As mentioned in the previous chapter, current residential and office buildings provide a significant contribution to total energy consumption and CO_2 emissions. However, an internationally accepted standardised solution has not been agreed to quantify the performance of buildings. In order to overcome this problem numerous building performance assessment frameworks are being developed in the US and Europe for monitoring Building Lifecycle (BLC) stages; design, construction, commissioning, and operation & maintenance.

In this chapter, building performance assessment frameworks will be reviewed with an emphasis on specifying Building Performance Metrics (BPM) which finally informs the process of compiling and modelling data from sensors and meters. Also, current building performance monitoring and evaluation efforts will be introduced briefly to demonstrate current performance monitoring tools and products. In the final section of the chapter, a monitoring and analysis process will be introduced which creates a basis for the developed system.

3.2 Building Performance Assessment Frameworks

Building performance assessment framework examples such as the Building Research Establishment's Environmental Assessment Method (BREEAM), American Society for Testing and Materials (ASTM), U.S. Department of Energy (DOE) High Performance and Sustainable Buildings Implementation Framework (HPSB), US Green Building Council's LEED Green Building Rating System, International Council for Building (CIB) Performance Based Building Program (PeBBu 2005), the German Energy Saving Regulation *"Energieeinsparverordnung"* (EnEV), the International Code Council (ICC) Performance Code for Buildings and Facilities (ICC 2000), and the US Department of Energy (DOE) High Performance Metrics Project provide platforms to describe facilities. Initial building performance assessment is carried out at the design stage utilising various simulation tools. Further assessments are carried out in the form of commissioning tests, but there was little or no monitoring or feedback once the building was occupied (US-DOE 2002). As a result, Directive 2002/91/EC by the European Parliament for energy performance of buildings was accepted in 2003. The directive requires owners to quantify the energy usage of their buildings against benchmarks set by government agencies throughout the building life cycle.

3.2.1 BREEAM

Building Research Establishment's Environmental Assessment Method (BREEAM) is a voluntary measurement rating for green buildings that was established in the UK by the Building Research Establishment (BRE). BREEAM was established in 1990 as a tool to measure the sustainability of new non-domestic buildings in the UK. It has been updated regularly in line with UK building regulations and underwent a significant facelift on 1 August 2008, called BREEAM 2008. Since its inception it has since grown in scope and geographically, being exported in various formats across the globe. In June 2009, it was announced that the BRE had signed a Memorandum of Understanding to work together with the French CSTB *(Centre scientifique et technique du bâtiment)* and its subsidiary CertiVéA to develop a pan-European building environmental assessment method. The CSTB are one of the organisations behind the French *Haute Qualité Environnementale* (High Environmental Quality) standard, which has similarities to BREEAM. Its equivalents in other regions include LEED North America and Green Star in Australia, HQE in France and Enegiepass in Germany.

BREEAM provides clients, developers, designers and others with: (a) market recognition for low environmental impact buildings, (b) assurance that best environmental practice is incorporated into a building, (c) inspiration to find innovative solutions that minimise the environmental impact, (d) a benchmark that is higher than regulation, (e) a tool to help reduce running costs, improve working and living environments, (f) a standard that demonstrates progress towards corporate and organisational environmental objectives (BREEAM 2009).

Buildings are rated with credits in each area according to performance. A set of environmental weightings then enables the credits to be added together to produce a single overall score. The building is then classified on a scale of pass, good, very good or excellent, and a certificate awarded that can be used for promotional purposes.

3.2.2 ASTM E1334 & E1480

American Society for Testing and Materials (ASTM) is an international standards organization that develops and publishes voluntary consensus technical standards for a wide range of materials, products, systems, and services (ASTM 2009).

There are two standards developed by ASTM which compromise the building performance related practices and terminology. These standards are:

ASTM E1334 - 95(2005) Standard Practice for Rating the Serviceability of a Building or Building-Related Facility: This standard covers a definitive procedure for rating the serviceability of a building or building-related facility, that is, for ascertaining its capability to perform the functions for which it is designed, used, or required to be used. A separate scale is used for each topic of serviceability. For each topic, a serviceability level is ascertained. Overall serviceability is expressed as a profile of levels (that is, not as a single number), and may be presented as a bar chart.

ASTM E1480 - 92(2004) Standard Terminology of Facility Management (Building-Related): This terminology consists of terms and definitions pertaining to the description, measurement, prediction, improvement, and management of buildings and building-related facilities, and, in particular, terms related to the standards generated by ASTM Committee E06 on

Performance of Buildings. The purpose of this terminology is to provide meanings and explanations of technical terms, written for both the technical expert and the non-expert user.

The standards do not specify an appropriate level for each of the functional requirements. Rather, they provide a framework and process for elaborating the desired levels for a given building use, and assessing the capability of alternative facilities to meet these levels (Davis & Szegeti 1999).

3.2.3 U.S. DOE HPSB

The U.S. Department of Energy (DOE) is committed to designing, building, operating, and maintaining High Performance and Sustainable Buildings (HPSB). In order to accomplish this objective, a framework for organising parameters, metrics and data that quantitatively characterise the performance of buildings has been developed. The principles for the HPSB Framework (US-DOE 2008) can be summarised as;

Employ integrated design principles: (a) Use a collaborative, integrated planning and design process. (b) Incorporate life-cycle cost-effective energy, water, materials, and indoor environmental quality principles throughout the design, construction, and life of the building. (c) Employ total building commissioning practices.

Optimize energy performance**:** (a) For new construction, reduce the energy cost budget by at least 30% compared to the baseline building performance rating per ASHRAE Standard 90.1-2004. (b) For major renovations, reduce the energy cost budget by at least 20% compared to a pre-renovations 2003 baseline. (c) Install building-level utility meters to track and continuously optimize performance.

Protect and conserve water: (a) Use at least 20% less potable water than the indoor water use baseline calculated for the building. (b) Reduce outdoor potable water consumption by at least 50%; reduce storm water and polluted water runoff.

Enhance indoor environmental quality: (a) Meet ASHRAE Standards 55-2004, Thermal Environmental Conditions for Human Occupancy, and 62.1-2004, Ventilation for Acceptable Indoor Air Quality. (b) Establish and implement a moisture control strategy to prevent mold contamination. (c) Achieve a minimum daylight factor of 2% in 75% of all space. (d) Specify materials and products with low or no pollutant emissions. (e) Protect indoor air quality during construction and prior to and after occupancy.

Reduce environmental impact of construction materials: (a) Use designated recycled-content and bio based-content materials and supplies. (b) Recycle or salvage at least 50% of the construction, demolition, and land clearing waste. (c) Eliminate the use of ozone-depleting compounds during and after construction.

The frameworks utilises the general standards such as American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., (ASHRAE) and the Illuminating Engineering Society of North American (IESNA) Standard 90.1-2004, Energy Standard for Buildings with benchmark values from Energy Star Benchmarking Tool to assess the building energy performance.

3.2.4 LEED

The Leadership in Energy and Environmental Design (LEED) Green Building Rating System, developed by the U.S. Green Building Council (USGBC) is an internationally recognized green building certification system, providing third-party verification that a building was designed and built using strategies aimed at improving performance across all the metrics that matter most: energy savings, water efficiency, CO_2 emissions reduction, improved indoor environmental quality, and stewardship of resources and sensitivity to their impacts. LEED provides building owners and operators a concise framework for identifying and implementing practical and measurable green building design, construction, operations and maintenance solutions. Since its inception in 1998, LEED has grown to encompass more than 14,000 projects in the United States and 30 countries covering 1.062 billion square feet (99 km^2) of development area (USGBC 2009). Since April 2009, LEED v3 which includes updates for the rating systems is in use.

LEED is applicable to all building types – commercial as well as residential. It works throughout the building lifecycle – design and construction, operations and maintenance, tenant fit out, and significant retrofit.

LEED points are awarded on a 100-point scale, and credits are weighted to reflect their potential environmental impacts. Additionally, 10 bonus credits are available, four of which address regionally specific environmental issues. A project must satisfy all prerequisites and earn a minimum number of points to be certified (40+ points is the minimum requirement for certification, 50+ points is Silver, 60+ points is Gold and 80+ points is Platinum). Each prerequisite or credit is elaborated with descriptive statements related to its intent and requirements, and advice on technologies/strategies that can be employed to earn the prerequisite or credit. Table 3.1, depicts key areas with brief description and credits/points awarded by key areas for certification. Similar to other performance assessment frameworks such as ICC Performance code and DOE/HPSB, the elaboration of prerequisites and credits within LEED is given in descriptive text.

A list of LEED Rating Systems is given below:

- ***LEED for New Construction and Major Renovations*** is designed to guide and distinguish high-performance commercial and institutional projects.

- ***LEED for Existing Buildings (Operations & Maintenance)*** provides a benchmark for building owners and operators to measure operations, improvements and maintenance.
- ***LEED for Commercial Interiors*** is a benchmark for the tenant improvement market that gives the power to make sustainable choices to tenants and designers.
- ***LEED for Core & Shell*** aids designers, builders, developers and new building owners in implementing sustainable design for new core and shell construction.
- ***LEED for Schools*** recognizes the unique nature of the design and construction of K-12 schools and addresses the specific needs of school spaces.
- ***LEED for Retail*** recognizes the unique nature of retail design and construction projects and addresses the specific needs of retail spaces.
- ***LEED for Healthcare*** promotes sustainable planning, design and construction for high-performance healthcare facilities.
- ***LEED for Homes*** promotes the design and construction of high-performance green homes.
- ***LEED for Neighbourhood Development*** integrates the principles of smart growth, urbanism and green building into the first national program for neighbourhood design.

Key Areas	Explanation	Points Awarded				
		New Construction	Core & Shell	Schools	Commercial Interiors	Existing Buildings
Sustainable Sites	discourages development on previously undeveloped land; minimizes a building's impact on ecosystems and waterways; encourages regionally appropriate landscaping; rewards smart transportation choices; controls stormwater runoff; and reduces erosion, light pollution, heat island effect and construction-related pollution.	26	28	24	21	26
Water Efficiency	encourages smarter use of water, inside and out. Water reduction is typically achieved through more efficient appliances, fixtures and fittings inside and water-wise landscaping outside.	10	10	11	11	14
Energy & Atmosphere	encourages a wide variety of energy strategies: commissioning; energy use monitoring; efficient design and construction; efficient appliances, systems and lighting; the use of renewable and clean sources of energy, generated on-site or off-site; and other innovative strategies.	35	37	33	37	35
Materials & Resources	encourages the selection of sustainably grown, harvested, produced and transported products and materials. It promotes the reduction of waste as well as reuse and recycling, and it takes into account the reduction of waste at a product's source.	14	19	13	14	10
Indoor Environment Quality	promotes strategies that can improve indoor air as well as providing access to natural daylight and views and improving acoustics.	15	6	19	17	15
Innovation in Design	provides bonus points for projects that use new and innovative technologies and strategies to improve a building's performance well beyond what is required by other LEED credits or in green building considerations that are not specifically addressed elsewhere in LEED.	6	6	6	6	6
Regional Priority	USGBC's regional councils, chapters and affiliates have identified the environmental concerns that are locally most important for every region of the country, and four LEED credits that address those local priorities were selected for each region.	4	4	4	4	4
Total		110				

Table 3. 1: Example for LEED Rating System.

3.2.5 CIB PeBBu

The *Conseil International du Bâtiment*-International Council for Building (CIB) Performance Based Building (PeBBu) is a building market environment in which all the stakeholders involved in the various phases of the building process address the need to ensure performance-in-use of buildings as an explicit target. PeBBu is expected to facilitate the development and introduction of innovative technologies and building systems into the market, to reduce the technical barriers on free trade, and enhance the overall quality of buildings.

Its implementation can be achieved by using innovative, strictly performance-based, procedures and documents in design, construction tendering and procurement, but may also include the more conventional tools and procedures that are based on well documented and approved prescriptive provisions, which are known to supply given levels of performance. It is believed that the implementation of a PeBBu environment may actually improve the general performance-in-use of buildings, and supply new opportunities for organisational and technological innovation within the building and construction process (PeBBu 2005).

PeBBu consists of nine domains. These are under the area of building technique (1) Life Performance Construction Materials and Components, (2) Indoor Environments. Under the area of buildings and the build environment (3) Design of Buildings, (4) Built Environment. Under the area of building process (5) Organisation and Management, (6) Legal and Procurement Practices. Under the area of building industry (7) Regulation, (8) Innovation, (9) Information and Documentation.

The end product of this program is intended to be the first edition of a publication entitled "CIB Compendium of Building Performance Models." This compendium will provide a framework that can be populated with new or revised models as they become available. The compendium will be structured to parallel an envisaged performance-based building code or regulatory document, organized according to building attributes or user needs, with a hierarchy of building parts, from whole building to individual elements or materials, under each attribute (Foliente & Becker 2001).

On the other hand, PeBBu implementation has barriers and difficulties such as relating building performance requirements to material and component requirements because the sum of component performances gives no sufficient indication of system performance. Also, matching required performance and provided performance is difficult to accomplish. Moreover, there is a potential for misunderstanding of service life and performance information as if being warranties.

3.2.6 EnEV 2009-The German Energy Saving Regulation

In order to cope with climate change, the German Federal Ministry for the Environment set up a "National Energy Efficiency Plan" in 2008. The end product of this plan is the amended Energy Saving Regulation (*Energieeinsparverordnung* - EnEV), which entered into force on 1 October 2009 (EnEV 2010). The EnEV 2009 provides new energy saving regulations to be observed by real estate developers and owners.

The EnEV 2009 applies to all heated or cooled buildings and parts of buildings provided that the building permit is applied for on or after 1 October 2009. From1 January 2009 on, purchasers and tenants of real property can ask for an "Energy Performance Certificate" (*Energieausweis*). This certificate provides information on the building's energy demand and suggests modernisations that would enhance its energy efficiency. The obligation to present the certificate to purchasers or tenants, if requested, is subject to public law and the failure to comply can be punished by means of an administrative fine.
In comparison to the previous regulation EnEV 2007 which came into force on October 1st, 2007 as reflection to EU directive on the Energy Performance of buildings, the regulation provides for a reduction of the energy consumption

based on heating and hot water use by an average of 30%. The permitted energy demand of residential buildings is assessed on the basis of a reference building. Substantial modernisations of existing buildings, such as the renewal of exterior walls, the windows or the roof, lead to similar obligations also for older buildings. The standard used for the calculation of the energy efficiency of heating and ventilation systems in buildings is the DIN V 18599.

Default of the EU Guideline	Conversation to Germany
Requirements of the total energy efficiency	EnEV: evaluation of the energy efficiency of buildings by inclusion of energetic quality of the building cover. Efficiency of the heating system and the system for water heating. Evaluation of the ventilation system icl. Air tightness, inclusion of active and passive inclusion of renewable energies.
Calculation method	EnEV (DIN 4108-6/4701-10), DIN-V 18599
Minimum requirements on refurbishment	EnEV
Energy documents on identification	New Buildings: EnEV energy requirement document of identification
Inspection of the heating systems	BlmSch-Vo(*Bundes Immissionsschutzgesetzes Verordnung*) Federal Pollution Control Regulation

Table 3. 2: Overview of the EnEV

Scope

The regulation is applicable for:

- Buildings with normal indoor temperatures (>19^{o}C) used wholly or mainly for living.
- Buildings with low internal temperatures (12^{o}C>x>19^{o}C) including its heating, ventilation and air conditioning and water heating systems.

The regulation is not applicable for:

- Farm Buildings which serve for livestock
- Large farm buildings, which must be kept open

- Underground structures
- Spaces that serve the cultivation and sale of plants
- Air domes, tents and similar buildings that need to be repeatedly built and dismantled.

The amendments to the EnEV 2009

- The upper limit of the allowable annual primary energy is reduced for both new and existing buildings (when upgrading) an average of 30 %
- The energy requirements for thermal insulation of new buildings are increased by an average of 15%.
- In the refurbishment of older buildings with major structural changes (façade, windows and roof) the energy saving requirement is increased by 30 %. Lofts must have a thermal insulation until the end of 2011.
- Air conditioning systems which change the humidity of the air will be retrofitted with an automatic system for the humidification and dehumidification.
- Night storage heaters, which are 30 years or older, have until January 2020 to be replaced by more efficient heating systems. This applies particularly to residential buildings with at least six residential units and non-residential buildings with more than 500 m^2 of floor space. Excluded are buildings that are built to the standard of Thermal Insulation Regulations 1995 or the exchange would be uneconomical. Also in buildings, subject to public service rules must eliminate the use of electric storage heating systems.
- The strict enforcement of the Ordinance will be reviewed. In addition, uniform penalty provisions for breaches of key provisions of EnEV are introduced.

Table 3.3 depicts the comparison of the EnEV with the two widely used building rating systems BREEAM and LEED.

	BREEAM	LEED	EnEV
Date Introduced	1990	1998	2002
Schemas Available	Offices Retail Industrial Education Ecohomes Healtcare Bespoke Multi Residential International Courts Prisons	New Construction Existing Buildings Commercial Interiors Shell & Core Schools Retail Healthcare Homes Neighbourhood Development	New Construction Existing buildings Buildings facing major retrofits Buildings facing minor retrofits
Categories	Management Health and well-being Energy Transport Water Materials Land use and Ecology Pollution	Sustainable sites Water Efficiency Energy and Atmosphere Materials and resources Indoor environmental quality Innovation in design	Reduction in energy consumption (30%) Consideration of primary energy Integration of solar energy Air tightness Thermal insulation
Ratings	Pass Good Very Good Excellent Outstanding	Certified Silver Gold Platinum	Building Energy Evaluation Certificate-Energieausweis
Assessment	Trained Assessors	US-GBC	EnEV Trained Assessors
QA/Certification	BRE	US-GBC	Building Energy Evaluation Certificate-Energieausweis
Number of Units Certified	110808 (109450 Domestic)	1823 (540 Domestic)	
Strenghts	Allows comparison and benchmarking of different buildings Independently audited Adjusted to UK legislation and UK Culture Can assess any building with the bespoke version	Strong marketing gets the message through Lots of information available No need for assessor and training	Complies with EU EPBD Sets higher saving standards Integrates renewable energy
Weaknesses	Very exact requirements Complex weighting system Cost of complience	Based on US systems Intense documentation required No independent audit of the assesment Mixing builidng function and form is difficult to assess	Relatively low implementation cases Based on German building regulations

Table 3. 3: BREEAM, LEED and EnEV Comparison

3.3 Building Performance Objectives and Metrics

Another approach to building performance assessment is the use of energy-related performance metrics (D. O'Sullivan 2004). The scenario modelling technique for holistic environmental and energy management provides a flexible framework to incorporate overall building operation in the context of the building energy manager (O'Donnell 2009). This performance framework provides a suitable platform to translate building performance data in respect to operation levels through the application of standard engineering formulae. Examples include the US DOE High Performance Metrics Project (US-DOE 2002), the ANSI/ASHRAE Standard 105-1984 (ANSI/ASHRAE 1999). Entitled "Standard Methods of Measuring and Expressing Building Energy Performance", Laboratories for the 21st Century Program and CIBSE Guide F (CIBSE 2004) which highlights Energy Use Intensity (EUI) values, measured in kWh/m2/per year, for different building types.

Standardised Performance Objectives and Metrics are a methodology for explicit representation of qualitative (Objective) and quantitative (Metric) criteria in a dynamic and structured format (Robert J Hitchcock 2003). For example, a high-level performance objective can be specified as a qualitative statement such as "optimise energy performance" in a building. In order to accomplish this objective, multiple related objectives and metrics are utilised.

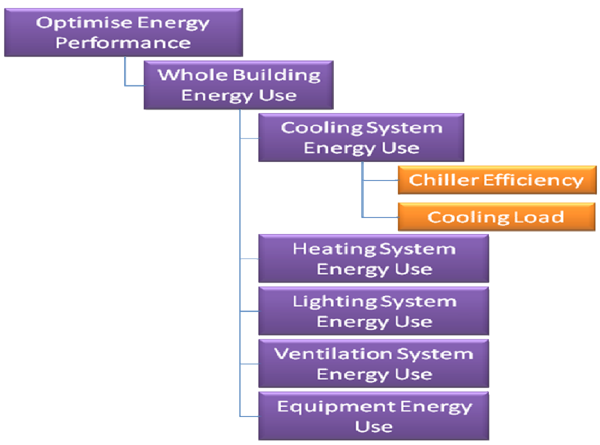

Figure 3.1: Performance Metric Breakdown for Energy Performance (O'Donnell 2009)

Figure 3.1 depicts a hierarchical structure that could be used to specify, monitor and maintain energy efficiency in a building. Whole Building Energy Use is the sum of intake from "primary sources" plus gains from local "renewable sources". Cooling System Energy Use is influenced by a variety of factors including Chiller Efficiency and Cooling Load, among other possible factors.

Figure 3.2 depicts a generic structure of performance metrics and objectives with a sample implementation for heating coil1 installed in the ERI Building. Each performance metric must be capable of being predicted or measured at each stage of the building life cycle so its objectives can be evaluated. Performance Metrics simplify the complexity of building performance for different end user. Quantitative Performance Metrics transform raw data such as sensor measurements and simulation output into meaningful user specific information in a logical structured format. This Performance Metric Information supports effective decision making in relation to energy consumption, efficiency values etc (O'Donnell 2009).

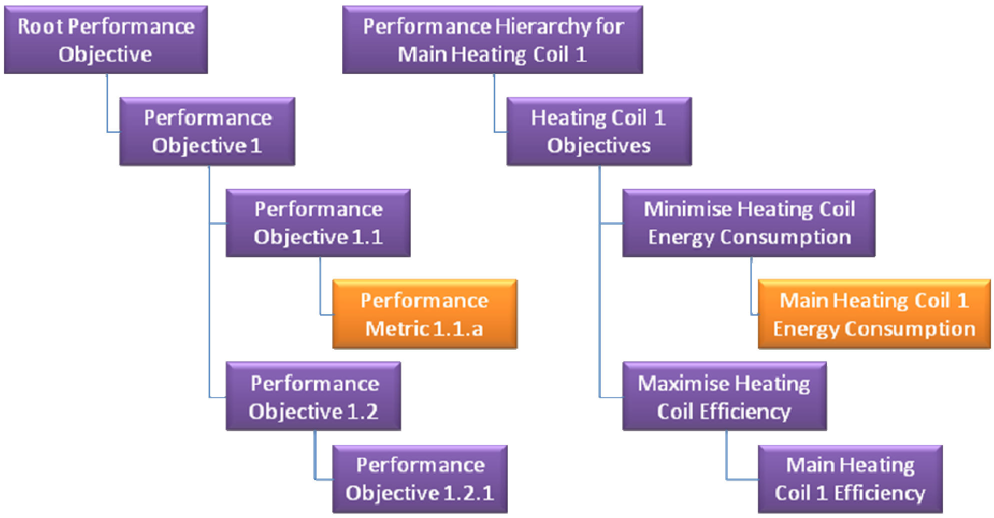

Figure 3. 2: Suggested Generic Structure of Performance Objectives and Associated Metrics (O'Donnell 2009).

The following sections briefly describe several projects and efforts about performance objectives and metrics.

3.3.1 US DOE High-Performance Buildings Metrics Project

The US DOE supported project focused on the issue of measuring energy use in buildings, and the overall impacts due to this energy use.

An example of the metrics developed is shown in Figure 3.3. These metrics are intended to support assessment of resource consumption and environmental loading at both the site of the energy use and at the source where the energy was generated. It is anticipated that each metric will therefore have separate site and source values, and that both quantity and cost values will be determined for each of these where appropriate. Also, separate values should be calculated for each metric by energy type. This provides flexibility in the ways in which these individual metric values can be aggregated (Hitchcock 2002).

Figure 3. 3: Example of US-DOE High-Performance Buildings Metrics.

3.3.2 ANSI/ASHRAE Standard 105-2007

This standard is intended to foster a commonality in reporting the energy performance of existing or proposed buildings to facilitate comparison, design and operation improvements, and development of building energy performance standards. It provides a consistent method of measuring, expressing, and comparing the energy performance of buildings (ANSI/ASHRAE 2007). This revision of ANSI/ASHRAE Standard 105-1984 provides a method of energy performance comparison that can be used for any building, proposed or existing, and that allows different methods of energy analysis to be compared. Historically Standard 105 has provided a basis for reporting energy use, with only limited ability to express or compare building energy performance. This version of Standard 105 extends the reach considerably and is intended to provide a common basis for reporting building energy use, expressions of energy performance, and comparisons of energy performance.

Standard 105 includes considerable detailed information including procedures and minimum requirements for measuring energy performance in existing buildings, estimating performance in new buildings, and expressing (i.e. documenting) this energy performance. This information includes methods for measuring energy consumption, frequency and duration of these measurements, units of measurement for various forms of energy, and a minimum set of associated building characteristics. The standard also includes the minimum requirements for a database containing these measurements that could then be used to generate a building energy performance standard. Several appendices that are not officially part of the standard identify methods of classifying building occupancy/use and its associated industry that would lead to the type of database filtering variables described previously (Hitchcock 2002).

3.3.3 CIBSE Guide F: Energy efficiency in buildings

CIBSE Guide F highlights Energy Use Intensity (EUI) values for different building types.

The importance and relevance of Guide F has been given added emphasis because of the EU Energy Performance of Buildings Directive which came into force on 4 January 2003. This directive gives public profile to the energy efficiency performance of buildings across the Europe. It raises awareness of how energy efficient different buildings really are. Prospective owners and occupiers will, for the first time, be able to compare one building with another and see what could be done to bring energy efficiency performance up to the standards of the best. The directive should help stimulate substantial increases in investments in energy efficiency measures in all buildings both commercial and domestic.

The guide has three major headings; Part A: Designing the building: Energy design checklist. Part B: Operating and upgrading the building: Why buildings fail on energy? Part C: Energy Benchmarks.

3.3.4 Laboratories for the 21st Century Program

Co-sponsored by the U.S. Environmental Protection Agency (EPA) and U.S. Department of Energy (DOE), the Labs21 program aims improving the energy efficiency and environmental performance of these facilities requires examining the entire facility from a "whole building" perspective (Labs21 2010). Adopting this perspective allows owners to improve the efficiency of the entire facility, rather than focusing on specific building components. As Labs21 participants understand, improving the efficiency of individual components without examining their relation to the entire system can eliminate opportunities to make other more significant efficiency improvements. Labs21 is dedicated to the pursuit of sustainable, high performance, and low-energy laboratories that will:

- Minimize overall environmental impacts.
- Protect occupant safety.
- Optimize whole building efficiency on a life-cycle basis.
- Establish goals, track performance, and share results for continuous improvement.

As part of the Laboratories for the 21st Century Program, an effort has been undertaken to "develop a standard set of energy performance metrics that will become commonly used in the design, commissioning, and operation of laboratories." These metrics are intended to support both benchmarking and performance tracking over time, leading to continuous improvement of laboratory performance. It was envisioned that the resulting set of performance metrics will be used consistently within the various related activities of the Laboratories for the 21st Century Program. Similarly to the US DOE High Performance Building Metrics Project discussed above, this effort went on to identify additional data elements required for both calculating the metrics and filtering data records in the envisioned performance database (Hitchcock 2002).

3.4 Building Performance Monitoring Systems

In this section, current research projects and efforts related to building performance and energy monitoring systems are briefly reviewed.

3.4.1 Metracker Software Implementation

Metracker is a prototype software implementation designed to demonstrate the specification, tracking, and visualization of building performance objectives and their associated metrics across the complete life cycle of a building (LBNL 2009). The underlying concept is that, to better assure the intended performance of a building, it is necessary to establish a baseline for expected performance and periodically compare actual performance to this baseline.

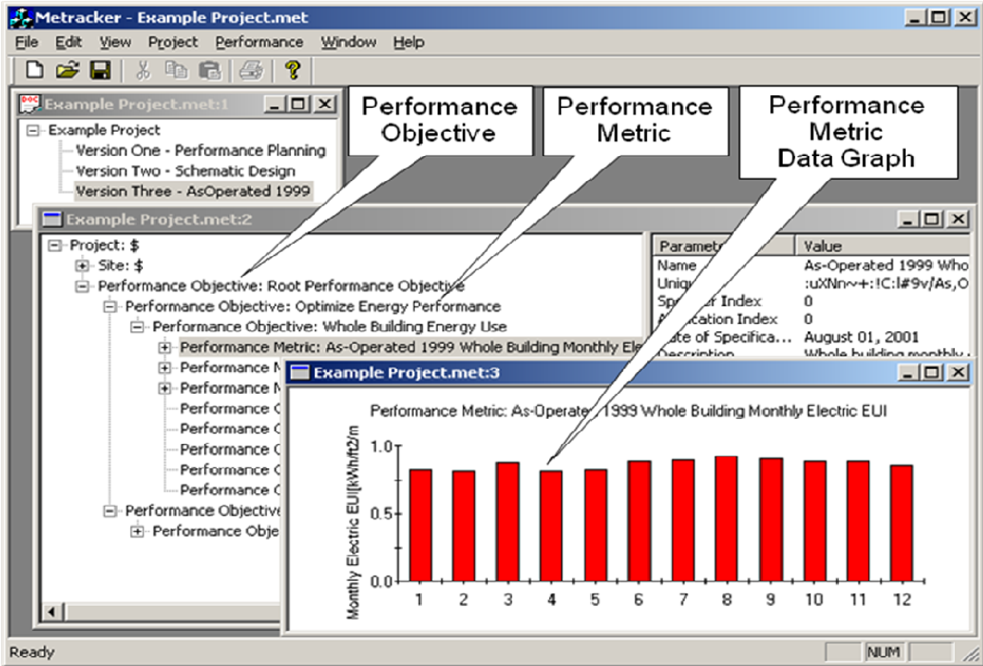

Figure 3. 4: Metracker Graphical User Interface (LBNL 2009).

This process requires a standardized yet flexible format for archiving performance data, and sharing these data between various software tools and their users across the building life cycle. Ideally, this performance data is archived with, and related to, other information about the building. To these ends, Metracker is based on the Industry Foundation Classes (IFC) data standard developed by the International Alliance for Interoperability.

Figure 3.4 depicts a graphical user interface screen shot from Metracker software, the Performance Metric As-Operated 1999 has been selected in the tree-view.

The metric data for this single Performance Metric have been displayed in the graph. The Data Type that was defined for this Metric is Vector (bar chart), and so the graph has automatically been displayed as a bar chart. If the defined data type had been Time Series then the graph would have automatically been displayed in that format.

3.4.2 Building EQ

The aim of the project Building EQ (Building EQ 2010) is to support the introduction of both: the Energy Performance of Buildings Directive (Directive 2002/91/EC) and of continuous commissioning, which is seen as a prerequisite for an energy efficient long term operation of buildings. This can be summarised as developing “Tools and Methods for Linking EPBD and Continuous Commissioning (CC)” by;

- Identifying the possible links between EPBD and CC.
- Defining a general methodology for a cost effective ongoing commissioning that is based upon the general regulations of the EPBD.
- Providing tools that can support this methodology.
- Evaluating the methodology in at least 12 demonstration buildings.
- Disseminating the results.

In the framework of Building EQ, “Guidelines for the Evaluation of Building Performance” have been developed. The guidelines describe a 4-step procedure for the cost effective performance analysis following a general top-down approach that tries to combine the outcomes of the certification process according to EPBD with CC. The idea of this top-down approach is to put effort in form of measurements and analysis only where and when necessary. The transition from one step to the next should only be performed if certain criteria are fulfilled. Figure 3.5 depicts the Building EQ approach

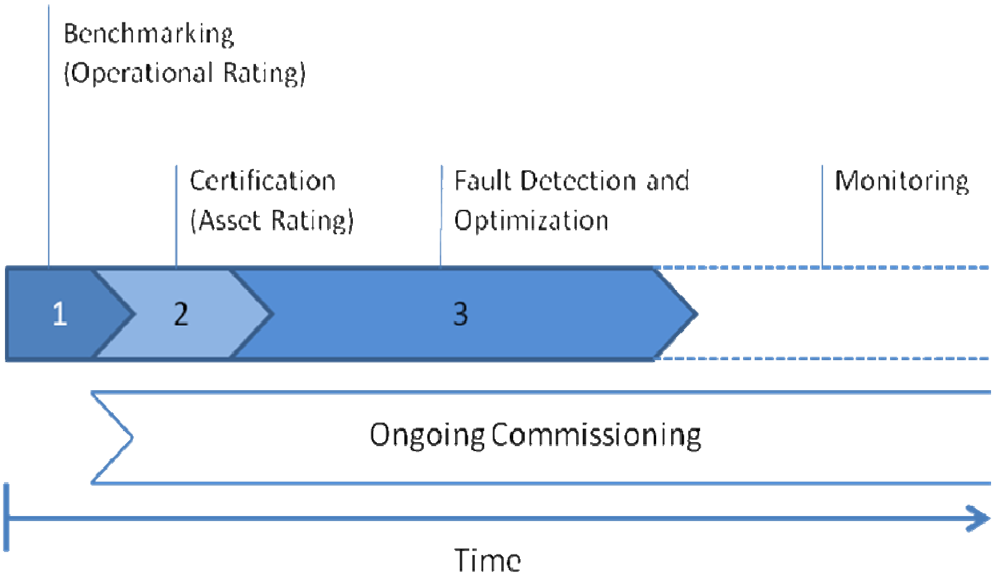

Figure 3. 5: Building EQ Approach

On the basis of the Building EQ project results, it is envisaged to develop a tool which should comprise the following features:

- *Data handling:* General features for storing time series data.
- *Data visualization:* "Intelligent" data visualization on the basis of the minimal data set that reveals, "operation patterns".
- *Building specific benchmark (Model based analysis):* A simplified model of the building (zones + HVAC) is used for identification of faults and optimization potentials. Models in this context are based on the regulations of the CEN standard as much as reasonable.
- *Statistical analysis / simple rule based analysis:* Find correlations between the variables of the minimal data set in order to identify unusual behaviour or faults in operation, respectively.

The tool itself has a modular structure. The kernel is a data storage library which stores measured data. The analysis functions and the importer are modules which can be connected to the data storage.

3.4.3 BEYWATCH

Building Energy Watcher (BeyWatch) is European Commission (DG Information Society and Media) funded research project aiming at *ICT tools for environmental management and energy efficiency*. The project will develop an energy-aware and user-centric solution, able to provide intelligent energy monitoring/control and power demand balancing at home/building & neighbourhood level (BEYWATCH 2009).

To reach its objectives, BeyWatch has undertaken the following:

- Design ultra-low energy-consumption white-goods
- Implement methods, techniques and services to reduce the power consumption in smart/green homes/blocks/neighbours by intelligent control of electrical devices
- Generate hot water and electricity from renewable energy sources at building level,
- Elaborate business plans and business support system (BSS) applications that will help the users and providers to reach beneficiary contracts
- Motivate user's awareness, towards less CO_2 emissions on the whole energy value chain (production, transportation, distribution, supply) and cleaner environment.

For the electricity providers the project elaborates business plans and business support system (BSS) applications based on cooperation between the users and the utility by relying on the use of smart meters in order to benefit to the users (better rates) and meeting the utility needs (load balancing, energy peaks).

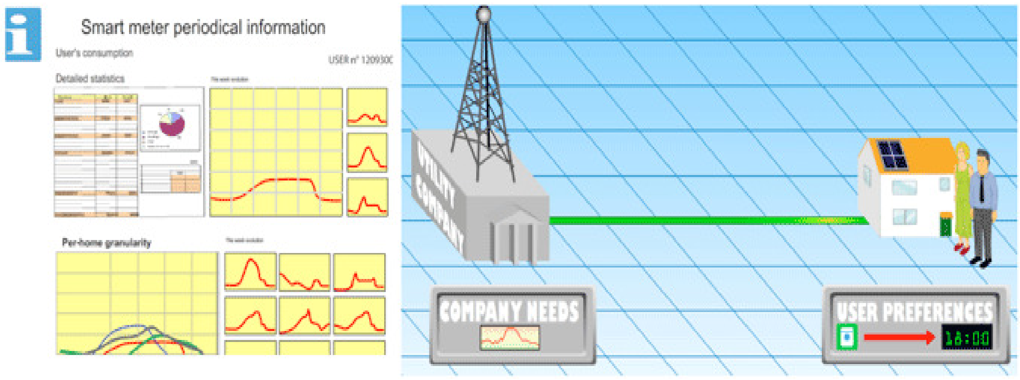

Figure 3. 6: BEYWATCH Business Scenario

For the end-users the project expects to enable green energy generation and energy savings, better contracts with the utility and easy monitoring and control of home appliances through GUI.

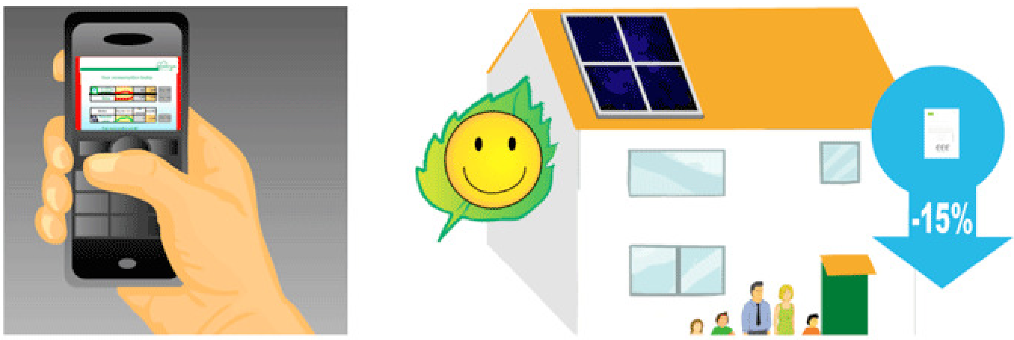

Figure 3. 7: BEYWATCH End-user Scenario

3.4.4 DEHEMS

The Digital Environmental Home Energy Management System (DEHEMS) is an European Union funded project aims to improve the current monitoring approach to levels of energy being used by households, with an overall aim of reducing CO_2 emissions across Europe. The project aims to extend the current state of the art in intelligent meters, moving beyond energy 'input' models that monitor the levels of energy being used to an 'energy performance model' that also looks at the way in which the energy is used. It will bring together sensor data in areas such as household heat loss and appliance performance as well as energy usage monitoring to give real time information on emissions and the energy performance of appliances and services. It will enable changes to be made to those appliances/services remotely from the mobile phone or PC and provide specific energy efficiency recommendations, for the household. The impact will be to personalise action on climate change, and so help enable new policies such as Personal Carbon Allowances as well as supporting the move towards increased localized generation and distribution of energy (DEHEMS 2009).

Figure 3.8 depicts the GUI that implements the end user requirements for showing power, energy and comparatives in real time.

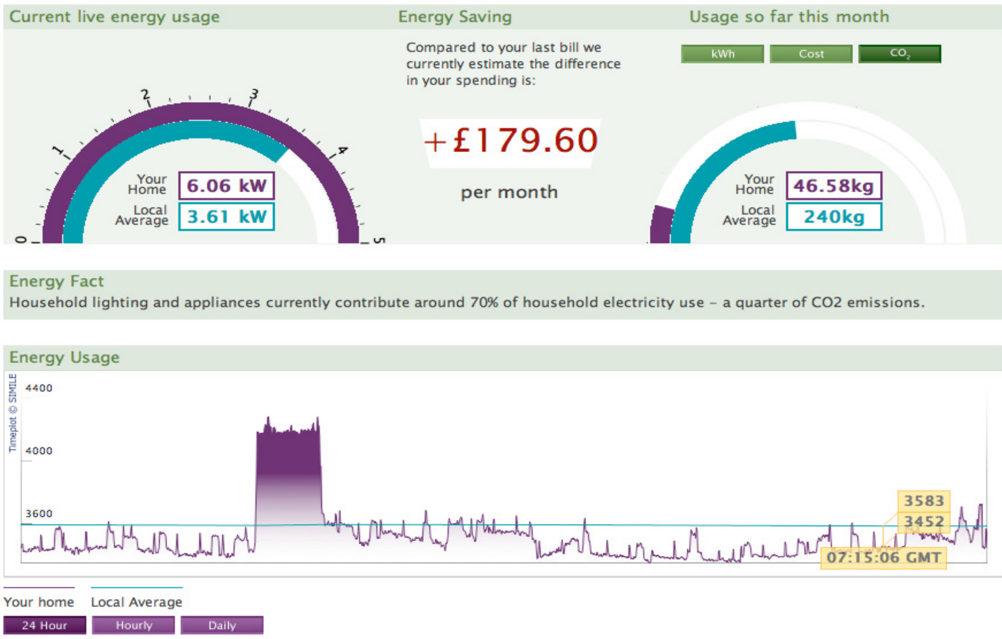

Figure 3. 8: DEHEMS Project’s individual household dashboard showing power and energy consumption.

3.4.5 AMI-MOSES

The Ambient-intelligent interactive monitoring system for energy use optimisation in manufacturing SMEs (AmI-MoSES) project's main aim is to produce a leap forward in energy efficiency by introducing Ambient

Intelligence (AmI) aspects into the classical energy consumption monitoring in manufacturing SMEs.

In order to achieve this aim, the project will develop an (ambient) intelligent monitoring system for energy consumption, dedicated to manufacturing SMEs, to provide comprehensive information about the energy use and knowledge-based support for improvements in energy efficiency. Existing energy consumption data will be complemented by different information from ambient intelligence systems such as AmI systems for monitoring interactions between human operators and machines/processes, and process related measurements and processed within a service-oriented-architecture-based platform. The platform will allow for building of different software services, using the measured and processed data, such as On-line diagnostics of energy related problems, continuous improvement of energy consumption, etc. The services will, among other functionalities, interactively provide suggestions for the appropriate actions for problem elimination and energy efficiency increase (AMI-MOSES 2009).

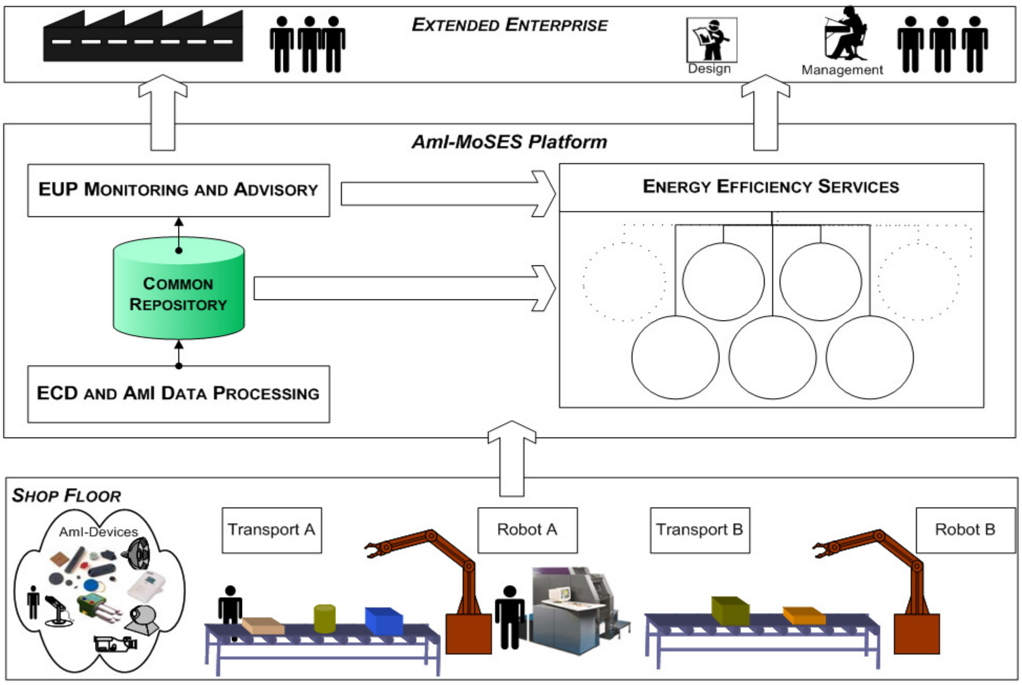

Figure 3. 9: AMI-MOSES System Architecture

3.4.6 SmartHouse-SmartGrid

The SmartHouse-SmartGrid project introduces a holistic concept for smart houses situated and intelligently managed within their broader environment. The project develops intelligent networked ICT technology for collaborative technical-commercial aggregations of Smart Houses able to communicate, interact and negotiate with both customers and energy devices in the local energy grid so as to achieve maximum overall energy efficiency as a whole (SmartHouse/SmartGrid2009).

The technology is built on:

- using available open industry standards in both the ICT and energy sectors;
- employing communication and computing capabilities that are already in widespread use in mainstream home and working environments.

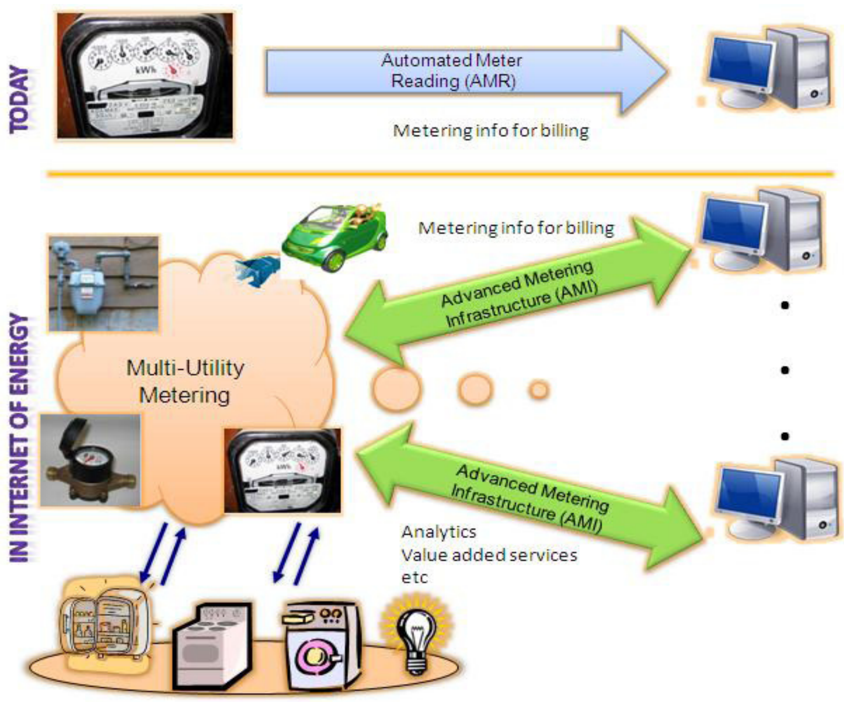

Figure 3. 10: Smart meter and device collaboration beyond billing.

3.4.7 BE AWARE

Boosting energy awareness with adaptive real-time environments (BeAware) project aims to study how ubiquitous information can turn users into active players by developing: (1) an open and capillary infrastructure sensing wirelessly energy consumption at appliance level; (2) ambient and mobile interaction to integrate energy use profiles into users' everyday life; (3) value added service platforms and models where consumers can act on ubiquitous energy information while energy producers and other stakeholders gain new businesses/opportunities.

BeAware combines research excellence with relevant industrial involvement. In order to ensure wide applicability, a Nordic and a Southern evaluation site are planned. A liaison with the CITRIS programme in the USA facilitates dissemination. The expected impact focuses on: (1) grounding the conservation potential to users' cognitive constraints and practices, (2) ubiquitous computing applications for sensing wirelessly energy use and enabling users to act, and (3) value added service models to innovate a new energy and multi-utility market.

3.5 Monitoring and Analysis Process

In the previous sections building performance assessment frameworks, building performance objectives & metrics and building performance monitoring related efforts have been reviewed. In this section, a building performance monitoring and analysis process is introduced which creates a basis for the developed holistic multi dimensional information management system (Chapter 5).

A basic monitoring system should aim to: (a) state current consumption (b) compare current consumption with historical data and benchmarks (c) identify trends and patterns.

The monitoring and analysis process establish a standard for energy performance and CO_2 emissions through conversion factors for each energy consuming object e.g. zone, individual, organisation and building system. In order to achieve energy savings, the standard performance of the each energy consuming object needs to be improved. The level of improvement in performance is determined through comparison of the standard performance with the benchmark performance values underlined by several regulations (e.g. CIBSE Guide F Benchmarks). The proposed monitoring and analysis methodology is depicted in Figure 3.11.

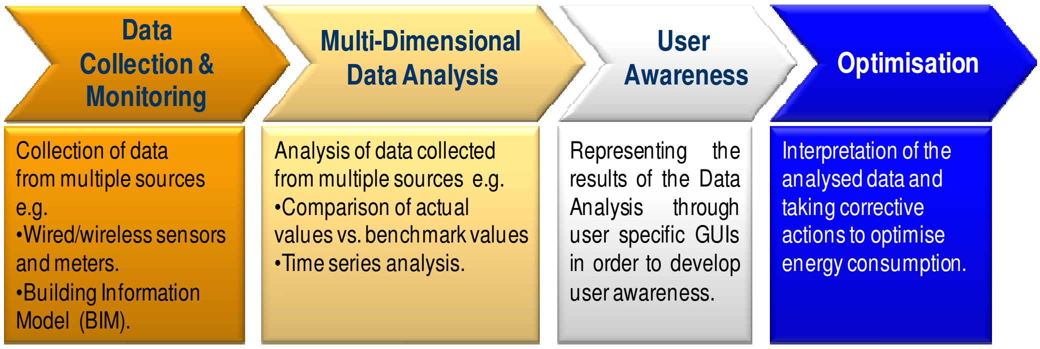

Figure 3. 11: Proposed Monitoring and Analysis Process.

The process is broken down into the following four steps:

Data Collection: Energy consumption data is usually obtained from meter readings and energy consumption bills. This conventional process slows down the data collection process. Recent improvements in the sensor and meter technology offer cost effective and quick solutions to collect building related data. Therefore, it is recommended to use wireless/wired sensors and meters to collect both consumption and comfort related data.

In order to define, categorise and classify the data collected from sensing devices, building related information such as architectural layout, material information, HVAC systems, sensing device placement, occupant related information etc. is required. BIM technology (Chapter 4) offers the opportunity to get all building related information.

Multi-Dimensional Data Analysis: Exponentially increasing data sources and data points make it impossible to analyse data manually. Modern Data Warehouse technologies (Chapter 5) provide multi-dimensional data analysis and decision support functionalities by using the huge amounts of data sets.

The main objectives of data analysis are to: (a) measure progress towards benchmarks. (b) indicate when performance has been good and should be replicated. (c) evaluate the significance of changes in performance (d) determine where/when corrective action is required.

A range of analysis methods are used for assessing building performance and the three main methods are shown below. With these methods, actual energy consumption is compared with the following (CIBSE 2004):

- *League tables:* based on a range of factors e.g. highest CO_2/m^2, highest electricity $kW.h/m^2$ etc. league tables can be used to identify the worst performing buildings in a large estate.
- *Benchmarks:* a comparison is made with a standard consumption benchmark to establish how the building compares with typical and best practice buildings. These are specified as performance indicators usually in kg CO_2/m^2 per year for fossil fuel and electricity in $kW.h/m^2$.
- *Performance lines:* these lines (e.g. variation of heating consumption with degree-days) make it possible to check whether the services continue to function in relation to key variables.
- *Historical data:* a comparison with a previous measurement to ascertain whether previously adopted energy efficiency measures have been effective, and to identify the need for further improvement.

User Awareness: Analysed data is represented to the different stakeholders e.g. building owner, facilities manager, occupant/tenant and technical staff through specific Graphical User Interfaces (GUI) in order to develop user awareness.

Optimisation: Data represented through GUIs, interpreted and necessary corrective actions should be completed to optimise building energy consumption.

3.6 The Chapter Conclusion

In this chapter, building performance framework examples such as BREEAM, ASTM, U.S. DOE HPSB, LEED, CIB-PeBBu, and German Energy Saving Regulation EnEV were reviewed to understand the different aspects of building performance assessment implementations and derive the requirements for building performance monitoring.

Also, building performance metrics and objectives which is an another approach to building performance assessment is reviewed by introducing relevant efforts such as US DOE High Performance Buildings Metrics project, ANSI/ASHRAE Standard 105-2007, CIBSE Guide F and Laboratories of the 21^{st} Century Program.

These have pointed out that an internationally accepted standardised solution has not been agreed to quantify the performance of buildings.

Furthermore, previous and current projects such as Metracker software implementation, Building EQ, BeyWatch, DEHEMS, Ami-Moses, Smarthouse-Smartgrid and BeAware which are aiming to develop a building monitoring and assessment system were examined.

In the scope of the current practices mentioned, Energy Performance of Buildings Directive and continuous commissioning which are the prerequisite for long term energy efficient operation are not supported. Also, building performance data is not evaluated from the multiple stakeholder perspectives.

A process and a methodology leading to a system appropriate to process and analyse building performance data is required to address these deficits.

Therefore in the final part of this chapter, a monitoring and analysis process was introduced to develop a basis for the proposed system which will be introduced in the Chapter 5.

The following chapter reviews the standardisation and integration efforts for the AEC/FM industry in order to define the requirements for maintaining data exchange between BIM tools and the DW core.

Chapter 4

Standardisation and Integration Efforts for the AEC/FM Industry

Chapter 4 reviews the standardisation and integration efforts for the AEC/FM industry in order to define the requirements for developing a flexible, standardised and extensible integration of BIM tools to extract and use required information in the data warehouse core for performance monitoring and analysis.

4.1 Introduction

In this chapter the building information modelling concept is discussed together with building product modelling approach. A building product model is a digital information model of the objects making up a building, capturing the form, behaviour and relations of the parts and assemblies within the building.

Building performance monitoring and analysis process requires multiple building information from different BIM tools. Integration of these tools in order to extract and use required information in the data warehouse core for performance monitoring and analysis is of importance. Therefore, integration and standardisation efforts for the AEC/FM industry will be introduced together with the IFC (Industry Foundation Classes).

4.2 Building Information Modelling Technology

Building Information Modelling (BIM) promises to revolutionize the way Architecture, Engineering, and Construction (AEC) professionals design and execute projects. Many anticipate a future where they will collaboratively use computer based methods to improve the multidisciplinary performance of their designs rapidly and execute these designs effectively. Currently, AEC professionals are benefiting from discipline-specific BIMs and methods that improve single discipline performance (Haymaker, 2005).

BIM (Building Information Modelling) has its roots in computer aided research from decades ago through the works of Eastman on conceptual modelling (Eastman 1988), Fischer on 4D CAD (Computer Aided Design) Approach (Fischer 1995) and others, yet it still has no single, widely accepted definition.
According to G. Lee et al., BIM is the process of generating and managing building data during its life cycle (Lee et al. 2006). Typically it uses three-

dimensional, real-time, dynamic building modelling software to increase productivity in building design and construction (Holness 2008).
Another BIM definition has been mentioned as intelligent simulation of architecture (Campbell 2006). In order to achieve integrated delivery, this simulation must exhibit six characteristics. It must be: digital, spatial (3D), measurable (quantifiable, dimension-able, and query-able), comprehensive (encapsulating and communicating design intent, building performance, constructability, and financial aspects of means and methods), accessible (to the entire AEC/owner team through an interoperable and intuitive interface), and durable (usable through all phases of a facility's life).

There are many definitions of BIM. In its infancy, it was associated with a 3D model of an architectural design, but at present it is much more than a 3D model. A BIM model is an information source of a building or a facility. BIM includes models of electrical/mechanical installations, safety and security measures, occupancy specifications, energy consumption, CO_2 emissions or whatever information one needs to collect regarding a site or a building. In fact many BIM building projects do not start with a model made by a CAD system, but from information about clients' requirements for project brief; long before anything about the geometry, the shape, the number of stories, floor plans etc. have been created. This information could be considered the "nucleus" for a BIM and can later be feed into Architectural CAD/BIM system to enrich the model with geometry and further design specifications. In the following section a brief history and the development trends of the CAD will be explained.

4.2.1 History of CAD

The world's first interactive computer-aided design belongs to Ivan Sutherland, who in 1963 developed special graphics hardware and a program called "Sketchpad" (Sutherland 1963).

The ability to represent a fixed set of polyhedral forms-shapes defined by a volume enclosing a set of surfaces-for viewing purposes was developed in the late 1960s.

In 1973, the easy creation and editing of arbitrary 3D solid shapes were developed independently. Bruce Baumgart (Baumgart 1972) from Stanford University designed and implemented a shape modelling program which defined an object by the set of surfaces that bounded it. The program also had operators that, given two shapes, could generate the union, intersection or difference of these shapes. Ian Braid from Cambridge University developed a system, in which a solid was represented by the surfaces that bounded it. Therefore, this solid modelling approach was called boundary representation or BRep. This work with the commercial system Romulus led to Parasolid, and ACIS which are the basis for many of today's commercial CAD systems.

Building modelling based on 3D solid modelling was first developed in the late 1970s and early 1980s. This was an incremental step, adding 3D vertices, new editing operations 3D coordinates and a multiple view display allowed both users and developers to begin working in 3D (Eastman 1999).

After solid modelling a new generation of geometric modeller was introduced based on parametric modelling in which a shape is defined through similar set of construction operations. Each operation is defined with its parameters.

The current generation of BIM architectural design tools all emerged from the object based parametric modelling. In traditional 3D CAD every aspect of an element's geometry must be edited manually by users, the shape and assembly geometry in a parametric modeller automatically adjusts to changes in context and to high level user controls.

As depicted in the Figure 4.1, it is envisaged within few years to achieve CAD format standardisation. In the following section standardisation and integration efforts in the AEC/FM industry will be explained.

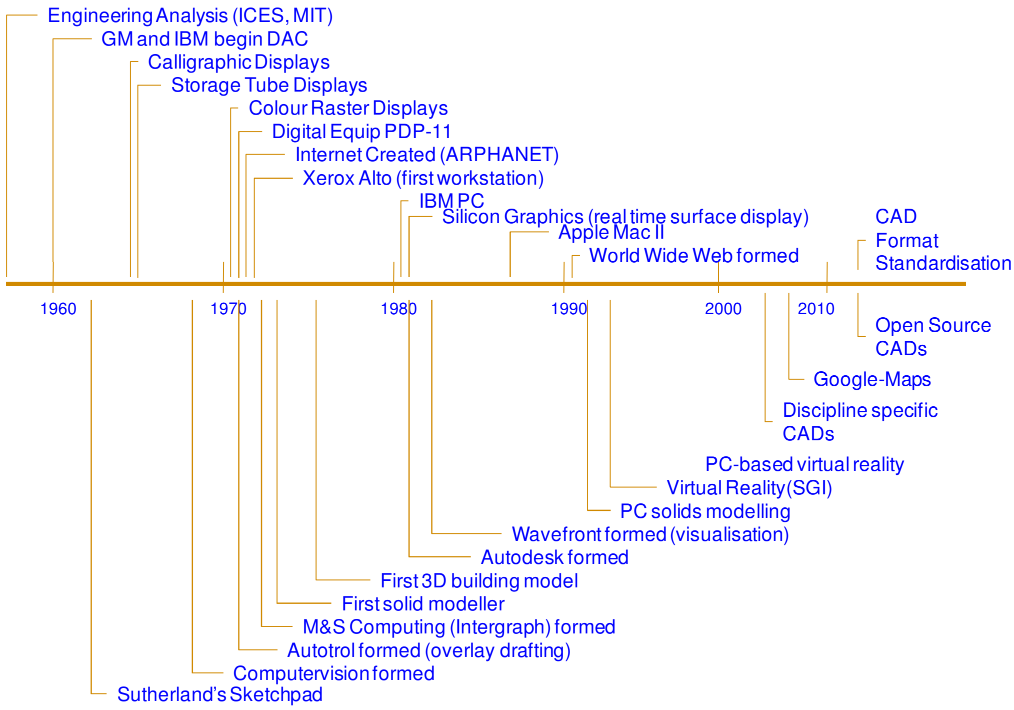

Figure 4. 1: A Timeline for Major Technological Developments Affecting CAD (Data extracted from (Eastman 1999)).

4.3 Standardisation and Integration Efforts for the AEC/FM Industry

Architecture, Engineering, and Construction (AEC) projects require multi-disciplinary solutions. In order to develop these solutions, AEC professionals need to construct their discipline specific information, but they also need to integrate this information to the information of other disciplines. Today, AEC professionals have formal methods to construct much of their single discipline information; however, they lack formal methodologies to plan, communicate control and manage their multidisciplinary solutions over the building life cycle.

In this context, several methods and implementation techniques have been provided to define the basic attributes of processes and products to support efficient management of construction applications.

Business Process Re-engineering (BPR), Total Quality Management (TQM), several International Organization for Standardization (ISO) Standards, Electronic Data Exchange (EDI), Product Data Exchange (PDE) and Product Data Management (PDM) are well known methods and implementation techniques that are used worldwide (Gokce 2008).

Because of differences such as: complex structures, variable disciplines, overlapped processes, customized products and different organizational approaches are examined in construction, the integration and harmonization of BIM requires an advanced interoperability and an essential ontology solution. From this standpoint the research studies such as; General AEC Reference Model (GARM) (Gielingh 1988b), Integrated Building Design Environment (IBDE) (Fenves et al. 1989), AEC Building Systems Model (Turner, 1990), Distributed and Integrated Environment for Computer-Aided Engineering (DICE) (Sriram 1991), Engineering Data Model (EDM) (Eastman 1992), Object Oriented CAD (OOCAD) (Seren et al. 1993), A STEP Towards Computer Integrated Large Scale Engineering (ATLAS) (Böhms & Storer 1994), Computer Models for the Building Industry in Europe (COMBINE) (ed. Augenbroe 1995), Computer Integrated Manufacture of Constructional Steelwork (CIMsteel) (Watson & Crowley 1995), COMBI (Scherer & Sparacell 1996), EPISTLE Core Model (Angus 1996), ISO 10303 AP225: Building Elements Using Explicit Shape Representation (ISO/TC184/SC4 1996b), AP230: Building Structural Frame: Steelwork (ISO/TC184/SC4 1996c), and Part 106: Building Construction Core Model (ISO/TC184/SC4 1996a), Concurrent Design and Engineering in Building and Civil Engineering (CONCUR) (Storer & Los 1997), and Industry Foundation Classes (IFC) Core Model (IAI 2005) are accepted as significant initiatives for interoperability in the AEC/FM industry.

The standardization and interoperability initiatives undertaken in the frame of ISO, as STEP and by the IAI's IFC are the most common standards for product and process definitions in construction environment. The international Standard for the Exchange of Product Model Data (STEP) standardization work, an ISO activity for defining a standard for the representation and exchange of product model data, was initiated in 1985 and is still continuing. The Industry Foundation Classes (IFC) is an IAI (International Alliance for Interoperability) activity aiming specifically for the construction industry.

4.3.1 Interoperability

The design and construction of a construction project involves team work and increasingly each task is supported by specific computer applications such as geometry layout, structural and energy analysis, cost estimation and scheduling the construction, fabrication issues for each subsystem and facility management activities. A single computer application cannot support all of the tasks associated with building design and production. Interoperability is the ability of two or more systems or components to exchange information and to use the information that has been exchanged (IEEE 1990). With respect to software, the term interoperability is used to describe the capability of different programs to exchange data via a common set of exchange formats, to read and write the same file formats, and to use the same protocols. Interoperability eliminates data redundancy and facilitates integration and automation.

The need to exchange data between two different applications was present even in the 2D CAD era. A set of businesses arose to write software to translate project files to other systems which was a costly and time consuming process. In order to avoid this, two NASA funded companies Boeing and General Electric offered to work on a public domain exchange format. The resulting exchange standard was IGES (Initial Graphics Exchange Specification). Using IGES, each software company need only develop two translators for exporting and importing, instead of developing a translator for every pair-wise exchange. IGES was an early success that is still widely used throughout all design and engineering communities (Eastman et al. 2008).

There are various analysis applications for structures, energy use, lighting, acoustics, air flow, etc. that have the potential to inform design. Because the BIM design tools have been developed in an industry where these diverse applications already exist, the need to interface or more intimately interoperate with these tools is a basic requirement (Eastman et al. 2008).

Interoperability among different computer tools is central to concurrent engineering in construction and vital for facilitating effective communications between project team members and between stages in the project lifecycle issues. In this context, Product Modelling approach plays a central role by maintaining the data exchange and sharing among a wide range of heterogeneous software tools, taking into consideration the multidiscipline nature of construction projects.

4.3.1.1 Interoperability of Building Product Models

In the late 1980s, the product modelling approach was introduced in construction and suggested as a key technology for successful information exchange and sharing among different tools. On the basis of the emerging international standard STEP several international projects have developed prototype integration environments which have proven the validity and effectiveness of the approach and have stimulated further research, standardisation and implementation activities. These projects will be reviewed briefly in this section.

EPISTLE: EPISTLE (European Process Industries STEP Technical Liaison Executive) was lunched in 1993. The aim was to identify collaboration potential, between parties involved in developing standards for the exchange of technical information in the process industries (Angus 1996). It has gone on to establish the basis of ISO10303 (STEP) Parts (Application Protocols). The main idea is the definition of a data modeling framework for conceptual data models. EPISTLE models comprise three principles: (1) Definition of the objects related to a basic underlying technology, (2) Enabling the description and identification of things in multiple ways (3) Maintaining fine grains versions of data related to time. The Core Model does not include fully elaborated entity types, but provides a set of entity types from which a set of application-specific generic entity type is derived from the EPISTLE Core Model by sub-typing it from precisely one sub type from each of the four orthogonal sets-subject, instantiation, life cycle reality (Angus 1996). Moreover EPISTLE models are data driven, not process dependent and they effectively only provide a framework for data storage which is specialized for a particular purpose by a class library (Bailey 1997).

GARM: GARM (General AEC Reference Model) is an initiative of TNO (Dutch research institute) and was developed by Gielingh (Gielingh 1988a). GARM focused on all AEC applications but it doesn't comprise of specific product extensions. The aim is to provide a general high level abstraction/reference model. Complex products are implemented by specifying their functionality as a whole. Then solutions are realized which also contains design problems. Moreover it includes general decomposition model where a part can be part of a system and a system can be a part of another system etc. Product Definition Unit (PDU) is the basic class and can be formed as a whole product, a sub-system, an element, a component, a part or a feature of a product. The related information to a PDU is composed of collection of characteristics, which are related to an aspect like strength, cost etc. (Tarandi 1998).

EDM: EDM (Engineering Data Model) can be identified as a generic product data modeling language and developed by Eastman (Eastman 1992). The aim is to manage the design information, related with the conventional building information, in spite of the restrictions within the CAD systems for structural and architectural design. Thereby relations are identified operationally in a structure which also provides a control mechanism. The EDM is realized based on low level primitives such as: domain, aggregation, constraints, design knowledge etc. thereby the data sets and the relations are represented as design data according to these primitives. Also with using of these primitives three form types are established: (1) defining of data objects and relations between them, (2) conceptual data information (3) low level production information.

OOCAD-Object Oriented CAD: The OOCAD project was lunched by VTT, the Technical Research Center of Finland, and was formed according to RATAS-II project (Enkovaara et al. 1988). The results are identified as neutral exchange format 'OXF' and OOCAD data model. The OOCAD model is developed according to composition of objects with part-of relationships. Moreover it is composed of three generic relationships as hierarchy, links and grouping. The basic concepts related with this approach are: (1) Type object which defines common properties of several occurrence objects, (2) Occurrence object which defines an occurrence of a type object, (3) Group-occurrence object which belong to multiple groups, (4) Attribute set which defines properties of object and (5) Relationship which links between occurrence objects (Tarandi 1998).

CIMsteel: The overall aim of the CIMsteel Project (Watson & Crowley 1995) was to improve the efficiency and effectiveness of the European construction steelwork industry. The focus was the application of Computer Integrated Manufacturing Techniques to steel fabrication. The goal is the establishment of an "open standard" for structural steelwork in order to provide global use. The CIS (CIMsteel Integration Standards) resulting data exchange standard, have already been widely implemented. The work on CIMsteel based on IDEF1X as a conceptual modeling language and on the use of STEP technology. The idea was to realize and test a series of prototypes which would evolve into a STEP-compliant model. The first release of the CIS (CIS/1) specifications was first made available to software developers in late 1995. CIS/1 is relied on Version 4 of the Logical Product Model (LPM), a model which was developed and tested by CIMsteel project. The LPM comprises the engineering information that arises in the design, fabrication and erection of steel framing in construction.

COMBINE: In the scope of the European JOULE program, COMBINE project was started in 1990 (ed. Augenbroe 1995). The main aim is to use Product Data Technology (PDT) in the building industry and to represents the benefits of it to AEC actors. The framework has comprised of STEP and usage of existing design applications in an integrated framework. In the first phase, the research has focused on data integration using a central common repository. The Integrated Data Model (IDM) has been established in this phase to formulate Aspect Models for different applications. Aspect models represent Design Tool specific (DT) information. Each aspect model is addressed by an IDM sub-schema which is also a subset of IDM. In this sub-schema all information which is derived from IDM that is used or influenced by the DT, is identified. The IDM realize exchange of information between DT. In the second phase the combination of first phase results has been adopted to an operational structure and Integrated Building Design System (IBDS) has been formed.

IRMA: IRMA (Information Reference Model for Architecture, Engineering and Construction) is a project comprising participating researchers' models. The conceptual schemata is realized based on the 'Unified Approach Model' (Björk 1992), the 'General Construction Object Model' (Froese 1992), the Building Product Model' (Luiten & Bakkeren 1992) and the 'ICON Method-Modeling Perspectives' (Cooper et al. 1992). The aim is to form a common reference model for the future work. The conceptual schema basically defines generic relationships between products (results), activities, resources and participants in the building processes. It is identified as a reference model for specific applications.

ATLAS: The ATLAS Project provides development, demonstration, evaluation, and dissemination of architectures, methodologies and tools for Computer Integrated Large Scale Engineering (LSE) (Tolman et al. 1994). It is specialized for different engineering sectors with using of STEP resource models and supports information exchange between them. The structure is composed of three layers. In the top layer the large-scale engineering (LSE) model provides an integration mechanism between different sectors of the construction industry. One layer below, the building model and process model provide an integration mechanism between disciplines of their own sectors. Again one layer lower a number of discipline models (Architecture, structural engineering, HVAC engineering in the building case) provide an integration mechanism between different applications of the discipline (Tolman 1999).

PISA: PISA, ESPRIT III project is lunched to provide integration of various information models for product and process modeling. This is achieved in part, through the PISA product and process model which contains general principles for product and process modeling and which shows how these principles are interrelated (Williems 1993). The objects, which might be products, resources, planning objects, control the processes. Processes carry out activities according to tasks which can cause the occurrence of events.

At present, a full integration and interoperability among various product models is not achieved in the AEC/FM industry. However, there are some exchange formats available to provide relatively limited data exchange among different BIM tools. These formats will be reviewed briefly in the following section.

4.3.2 BIM Data Exchange Formats

There are four main ways that widely utilised for exchanging data among different BIM tools (Eastman et al. 2008). These are: (1) Direct, proprietary links between specific BIM tools (2) Geometry specific proprietary file exchange formats. (3) XML based exchange formats. (4) Public product data model exchange formats.

Direct, proprietary links provide an integrated connection between two applications, usually called from one or both application user interfaces which make portions of application's building model accessible for creation, export, modification or deletion. Direct links rely on middleware software interfacing capabilities such as ODBC (Open Database Connectivity) or COM (Component Object Model) or proprietary interfaces, such as ArchiCAD GDL or Bentley MDL. These are all programming level interfaces, relying on C, C++ or C# languages.

Geometry specific proprietary file exchange formats are developed by BIM software vendors for interfacing with their software. DXF (Data eXchange Format) developed by Autodesk is a well known proprietary exchange format in AEC environment.

Extensible Mark-up Language (XML), an extension to HTML, is a widely supported open technology (i.e, non-proprietary technology) for data exchange developed by the World Wide Web Consortium (W3C) (Deitel 2002). XML allows definition of the structure and meaning of some data of interest; that structure is called a schema. XML schemas support exchange of many types of data between applications.

Public level product data model exchange formats that carry object and material properties and also relations between objects in addition to geometry, are essential for interfacing to analysis and construction management applications. The IFC (Industry Foundation Classes)-for building planning, design, construction and management and CIMsteel Integration Standard Version 2 (CIS/2)-for structural steel engineering and fabrication are the prior options. The IFC data model is likely to become an industry standard for data exchange and integration within the building construction industries (Eastman et al. 2008).

A summary of most common exchange formats in the AEC area is listed in Table 4.1.

Image (raster) Formats	
JPG, GIF, TIF, BMP, PIC, PNG, RAW, TGA, RLE	Raster formats vary in terms of compactness, number of possible colours per pixel, some compress with some data loss.
2D Vector Formats	
DXF, DWG, AI, CGM, EMF, IGS, WMF, DGN	Vector formats vary regarding compactness, line widths and pattern control, colour, layering and types of curves supported.
3D Surface and Shape Formats	
3DS, WRL, STL, IGS, SAT, DXF, DWG, OBJ, DGN, PDF(3D), XGL, DWF, U3D, IPT, PTS	3D surface and shape formats vary according to the types of surfaces and edges represented, whether they represented surfaces and/or solids, any material properties of the shape (colour, image bitmap, texture map) or viewpoint information.
3D Object Exchange Formats	
STP, EXP, CIS/2	Product data model formats represented geometry according to the 2D or 3D types represented. They also carry object properties and relations between objects.
Game Formats	
RWQ, X, GOF, FACT	Game file formats vary according to the types of surfaces, whether they carry hierarchical structure, types of material properties, texture and bump map parameters, animation and skinning.
GIS Formats	
SHP, SHX, DBF, DEM, NED	Geographical information system formats
XML Formats	
AecXML, Obix, AEX, bcXML, AGCxml	XML schemas developed for the exchange of building data. They vary according to the information exchanged and the workflows supported.

Table 4. 1: Common Exchange Formats in AEC Applications (Data extracted from Eastman et al. 2008).

4.3.3 ISO-STEP

Information exchange among complex object models of piping, mechanical, electrical and other systems with their geometry, attributes and relations makes any file exchange format quickly became so large and complex as to be useless. In order to overcome these issues, the International Standards Organisation (ISO) in Geneva, Switzerland initiated a technical committee, TC184, which deals with Industrial Automation Systems and Integration, to provide a neutral format for product data exchange. Further, within this technical committee a sub-committee known as SC4 was established to develop a standard called ISO1303-Industrial Automation Systems-Product Data Representation and Exchange in well known name STEP (Standard for Exchange of Product Model Data).

STEP is the first data exchange standard that includes product data in the exchange, e.g., assembly instructions, design criteria thresholds used/evaluated, color, weight etc. to address the required to real time data exchange and maintenance. The main aim is to produce finished standards that can be used in industrial applications.

The ISO-STEP organisation developed a new set of technologies, such as:

- Use of a machine readable modelling language instead of a file format.
- The language emphasizes data declarations but includes procedural capabilities for rules and constraints.
- The language has mappings to different implementations, including a text file format, database schema definitions, and recently, XML schemas.
- Reference sub-models that are shared and re-used subsets of larger standard models for geometry, measurements, representation classification and other generic needs.

One of the main products of ISO-STEP was the EXPRESS language. This is a textual data specification language. It is based on the Entity–Attribute–Relationship of data and also it is both computer-interpretable and human-readable. EXPRESS defines the product data and it is used as a conceptual data model in the context of STEP. As a machine-readable language, it is excellent for computational use, but difficult for human users. Thus, a graphical display version of the language was developed and commonly used, called EXPRESS-G.

EXPRESS can have multiple implementations. These include a compact text file format called Part 21 or P-21 file, SQL and object-based database implementations, and XML implementations called Part 28 format.

4.3.4 Industry Foundation Classes

In 1994, an international organization called International Alliance for Interoperability (IAI) was formed in order to develop a shared project model which would cover all necessary information for buildings' whole lifecycle: requirements management, different design activities and construction and maintenance processes (see Figure 4.2).

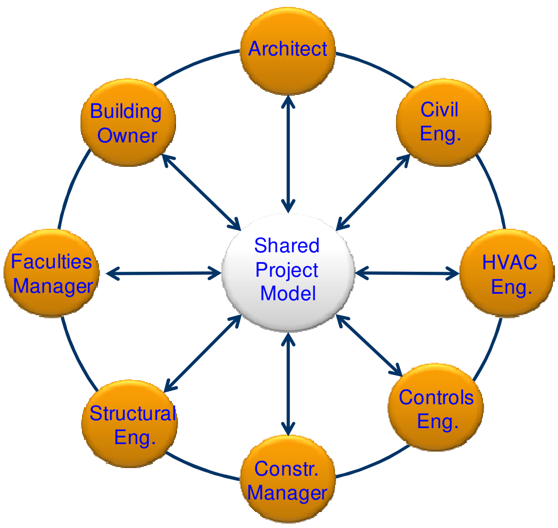

Figure 4. 2: IFC Shared Project Model.

The main objective was to identify the specifications and enabling interoperability between AEC/FM applications from different software vendors and publish them as Industry Foundation Classes (IFC).

IAI possessed the first full release of its Industry Foundation Classes (IFC) Information Model; IFC Release 1.0 in January 1997. Several further Releases as: IFC 1.5, IFC 1.5.1, IFC 2.0, IFC 2x2, IFC 2x3 and IFC 2x4 have been issued since.

Methodology

An early technical decision of the IAI was to base development work on the EXPRESS data definition language that had been developed as an ISO standard within the STEP project. A key benefit of this decision was the immediate availability of a large body of development work in basic technologies such as geometry as well as providing access to substantial research and development effort from many leading industry centers throughout the world that was EXPRESS based (IAI 2010).

IFC Model Architecture

IAI defined the model requirements as: (1) disciplines within the AEC/FM processes (2) Life-cycle stages of the projects (3) Level of details (4) Software application and provide model architecture, the ‘model schemata’ (IAI 2000) as given in Figure 4.3. A strict referencing principle is used within four conceptual layers to define a set of model schemata.

Resource layer form the lowest layer in IFC Model Architecture and can be used or referenced by classes in the other layers (IAI 2000). Resources can be defined as general purpose, low level concepts or objects that are independent of application. All resources represent business concepts. Resources can be identified under general resources (measure, actor etc.), geometry resources (explicit and implict), and business concepts (material, cost etc.).

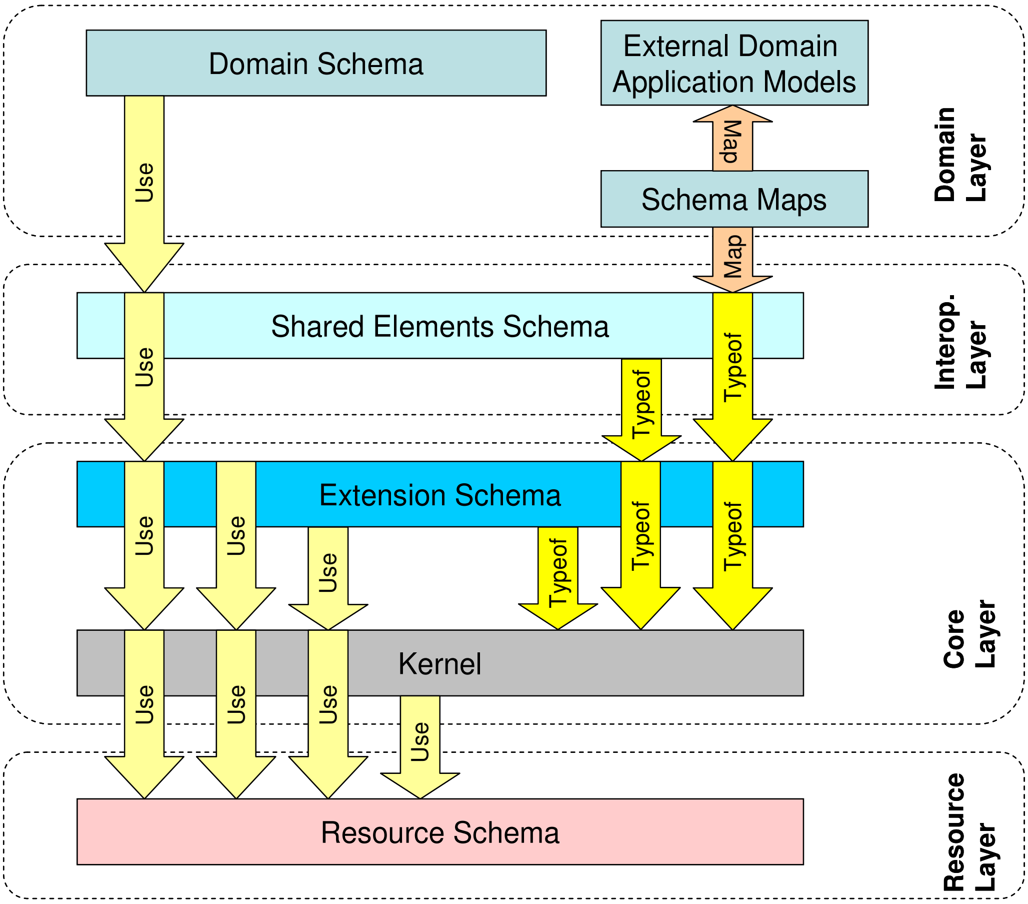

Figure 4. 3: Layering Concept of IFC Structure (IAI 2000).

Core Layer classes can be referenced and specialized by all classes in the interoperability and domain layers (IAI 2000). The Core Layer includes two levels of generalization namely: Kernel and Extensions Schema. Kernel provides basic concepts like objects, relationships, type definitions, attributes, roles and it also determines the model structure and decomposition. Kernel can be identified as the foundation of the core model. Extensions Schema, provide extension or specialization of concepts defined in Kernel (product, process etc.). Each Extension Schema is a specialization of classes defined in Kernel and develops further specialization of classes rooted in the IfcKernel. Additionally, primary relationships and roles are also defined within Extensions Schema (IAI 2000).

Interoperability Layer determines of schemata that define concepts (or classes) common two or more domain models. These allow interoperability between different domain models. The plug-in model approach is used in this layer. The multiple domain models can be plugged into IFC Core in the schemata defined in this layer (IAI 2000).

Domain Layer provides further model detail within the scope requirements for an AEC/FM domain processes or a type of application (IAI 2000). They reference the classes defined in the Core and Independent Resource layers. The aims of these models are to provide 'leaf node' classes that enable information from external property sets to be attached appropriately (IAI 2000).

IFC is delivered in different releases, the following diagram Figure 4.4 shows the complete set of IFC 2x4 Beta 2 Model schema. The IFC 2x edition 4 release (IFC2x4), combines a number of feature increases with some major rework and improvements of the existing IFC specification. It has been developed as the next basis for IFC enabled interoperability of Building Information Models.

It is also intended that the IFC2x4 release will be submitted to the International Standardization Organization (ISO) for approval as a full International Standard ISO16739 (IAI 2010).

This latest version offers new entities required for the research. IfcSensor, IfcActuator, IfcFlowInstrument and IfcUnitaryControlElement are the new entities which are required to extract and use wired/wireless sensor, meter and actuator information such as device specifications and placement coordinates, for the developed system. These methods will be introduced in Chapter 5.

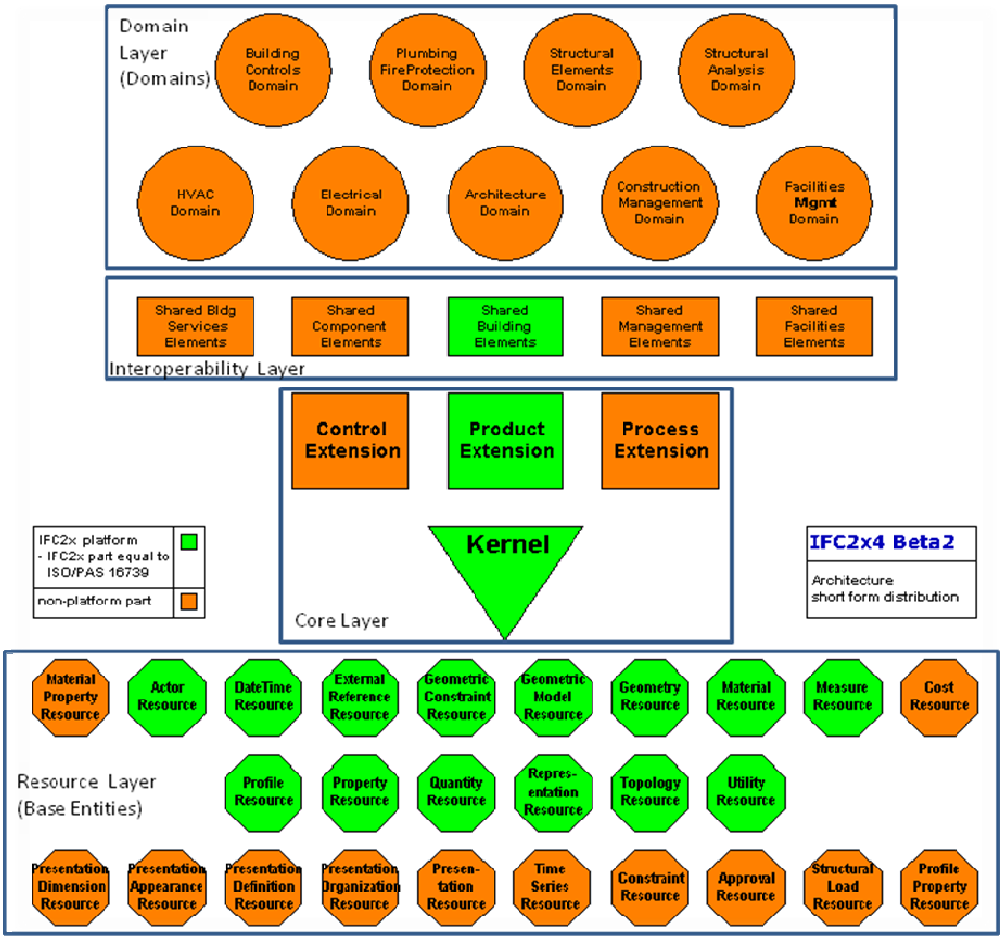

Figure 4. 4: IFC 2x4 Overall Architecture (IAI 2010)

The all schema are named in a manner that enables identification of their architecture (IAI 2000):

- Schema at the resource layer are suffixed with term ‘Resource’
- Schema at the core extension layer are suffixed with the term ‘Extension’
- Schema at the interoperability layer are suffixed with the term ‘Elements’ (other than the Kernel schema which is considered to be a special case)
- Schema at the domain layer are suffixed with the term ‘Domain’

All application-defined objects, when translated to an IFC model, are composed of the relevant object type and associated geometry, relations and properties. These are briefly explained as:

Geometry: The IFC means to represent a fairly wide range of geometry, including extrusions, solids defined by a closed connected set of faces and shapes defined by a tree of shapes and union-intersection operations.

Relations: Care has been taken in the IFC data model to represent a rich set of relations between objects in some BIM design tool for translation into IFC.

- *Assigns* deals with relations between heterogeneous objects and a group, or selection of parts of assemblies for particular uses; for example, all entity instances installed by a particular trade may be referenced by assigns relation.
- *Decomposes* is the general relation dealing with composition and decomposition, of assemblies and their parts.
- *Associates* relates shared project information, such as external equipment specifications, with model instances; an example may be a modeled piece of mechanical equipment which associates with its specification in the supplier's catalog.
- *Defines* deals with the relation between a shared description of an object and various instances of that object, for example a description of a window type and the various instances of the window.
- *Connects* defines a general topological relationship between two objects, which is defined functionally by subclasses. For example walls have "connects" with their bounding walls, floors or ceilings.

Properties: IFC places emphasis on property sets, or P-sets. These are sets of properties that are used together to define material, performance, and contextual properties, e.g., wind, geological or weather data.

Meta-properties: IFC designers have thought about the use of information over time and the meta-data needed to deal with information management, IFC is strong in addressing information ownership, identification, change management and tracking of changes, controls and approvals.

Use of IFC

A typical IFC data exchange scenario is depicted in Figure 4.5. Information instances in the source application are extracted by a translator. Then, extracted data is assigned to appropriate IFC entity classes. The entity instance data are then mapped from the IFC objects into a text file format defined by the ISO-STEP Part 21. This file is then received by the other application and interpreted by the receiving application's translator in terms of the IFC object instances it represents. The translator in the receiving application writes the relevant IFC objects into its native data structure for use.

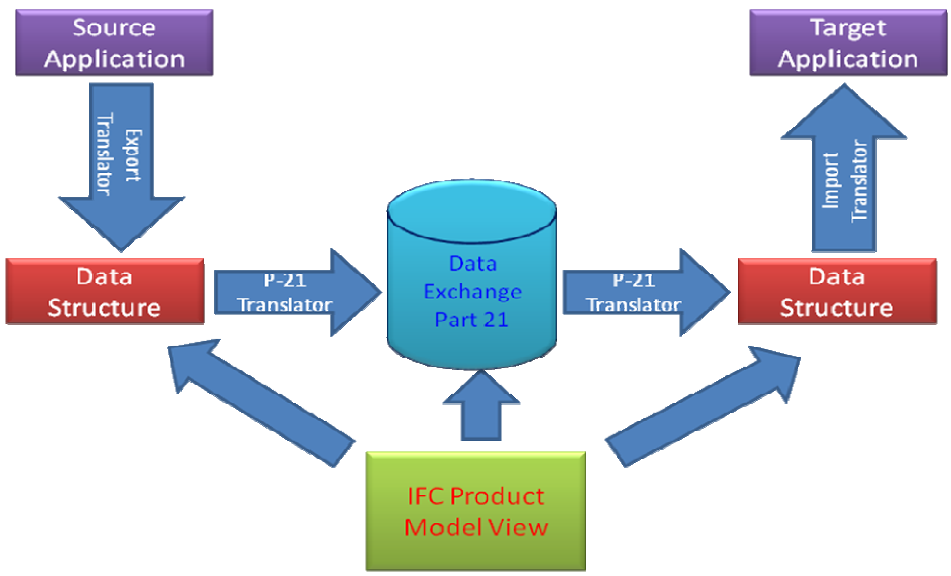

Figure 4. 5: IFC Data Exchange Scenario (Eastman et al. 2008).

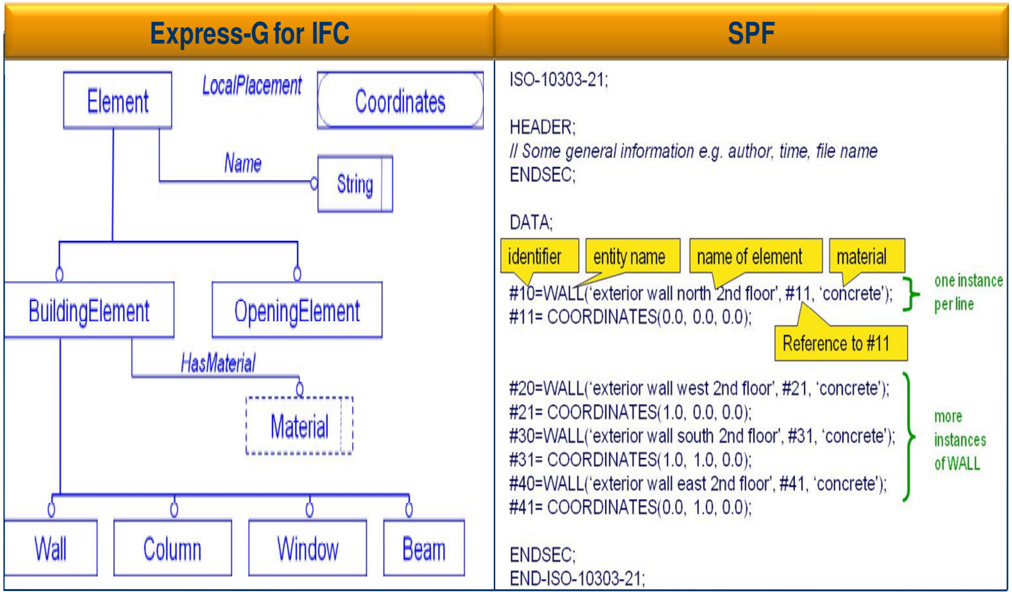

Figure 4. 6: An example of an Express-G model and SPF notation for IfcWall

Figure 4.6 depicts a basic example of an Express G imodel and Step Physical File (SPF) notation for IfcWall. STEP-File is the most widely used data exchange form of STEP. Due to its ASCII structure it is easy to read with typically one instance per line. The format of a STEP-File is defined in ISO 10303-21 *Clear Text Encoding of the Exchange Structure*.

ISO 10303-21 defines the encoding mechanism on how to represent data according to a given EXPRESS schema, but not the EXPRESS schema itself. STEP-File are also called *p21-File* and *STEP Physical File*. The file extensions *.stp* and *.step* indicate that the file contain data conforming to STEP Application Protocols while the extension *.p21* should be used for all other purposes.

4.3.5 XML Schemas

XML is an alternative way to exchange data. XML is an extension to HTML, the language used to send information over the web. HTML has a fixed set of tags that depicts what kind of data follows. In addition to HTML, XML provides user defined tags to specify an intended meaning for data transmitted, allowing user defined schemas.

Using the current available schema definition languages, some effective XML schemas and processing methods has been developed in AEC areas. These AEC specific schemas are described briefly as;

OGC (Open Geospatial Consortium) has developed the OpenGIS Geographic Objects (GO) Implementation Specification. It defines an open set of common, language-independent abstractions for describing, managing, rendering and manipulating geometric and geographic objects within an application programming environment (OGC 2009).

gbXML (Green Building XML) is a schema developed to transfer information needed for preliminary energy analysis of building envelopes, zones and mechanical equipment simulation (gbXML 2009).

aecXML is administered by FIATECH, a major construction industry consortium supporting AEC research, and the IAI. It can represent resources such as contract and project documents (Request for Proposal (RFP), Request for Quotation (RFQ), Request for Information (RFI), specifications, agenda, change orders, contracts, purchase orders), attributes, materials and parts, products, equipment; meta data such as organisations, professionals, participants; or activities such as proposals, projects, design, estimating, scheduling and construction. It carries descriptions and specifications of buildings and their components, but does not geometrically or analytically model them (FIATECH 2009).

IFC XML is a subset of the IFC schema mapped to XML, supported by IAI. It also relies on XML Schema for its mapping. It currently supports the following use cases: Material Catalogs, Bill of Quantities and adding User Design Quantities. Support for additional use cases are planned (IAI 2009).

BLIS-XML is a subset of the IFC Release 2.0, developed to support a small number of use cases. It was developed in 2001-2002 in an effort to get into use a practical and productive version of the IFC. BLIS-XML uses the BLIS schema with a schema converter developed by Secom Co. Ltd (BLIS 2009).

agcXML Project, inaugurated and funded by The Associated General Contractors of America (AGC), resulted in a set of XML schemas for the transactional data that is now commonly exchanged in paper documents such as owner/contractor agreements, schedules of values, requests for information (RFIs), requests for proposals (RFPs), architect/engineer supplemental instructions, change orders, change directives, submittals, applications for payment, and addenda, to name a few. To ensure compatibility with related efforts, the agcXML Project is being executed as part of the aecXML Domain framework under the auspices of buildingSMART alliance, the North American chapter of buildingSMART International. (AGC 2009).

4.3.6 Building Model Repositories

A building model repository is a technology for exchanging data between combinations of applications. It is a database system whose schema is based on a published object based format. Building model repositories are object based, allowing query, transfer, updating, and management of individual project objects from a potentially heterogeneous set of applications. Production use of IFC-based data exchange and XML-based e-business exchanges have begun with file exchanges. Overtime, management of the versions, updating, and change management of the data associated with an increasingly complex number of heteregenous applications, leads to major data management challenges. These issues are best resolved by repositories (Eastman et al. 2008):

- Supporting exchanges between multiple concurrent applications that both read and write project data; that is, workflows are not linear.

- Propagating and managing changes that impact multiple application datasets.
- When there are multiple authoring applications that must be merged for later use.
- Supporting very frequent or real-time coordination between multiple application users.

The only broad building level object schema is the IFC. A number of companies have developed building model repositories using the IFCs. An IFC repository can support integration of the data generated by multiple applications for use in other applications support iterations on parts of the design and track changes at the object level. They provide access control, version management, and various levels of design history relating the various geometric, material and performance data that represent a building (Jotne 2009, Eurostep 2009).

A number of companies have developed building model repositories such as;

Jotne EDMServer™: A Product Model Server capable of storing all your data for complex systems, including native support for any standard data model, like IFC, STEP, PLM/PLCS or Reference Data Libraries. The unified database system to manage the life cycle for products and systems, using a model driven architecture (Jotne 2009).

LKSoft IDA v4 STEP Database: This is a new generation of standards-based tools from LKSoft. Based on international standard ISO 10303 (STEP), IDA-STEP v4 supports viewing and management of various STEP data: 3D/2D models, PCB/PCA, PDM and other data. The component-based IDA-STEP v4 structure provides full customization capabilities and is easily extendable (LKSoft 2009).

EuroSTEP Share-A-Space Model Server: This enables product data integration in heterogeneous organisations, processes and IT-system environments using state of the art technologies and standards, such as Web Services and ISO 10303-239, PLCS.

Oracle Collaborative Building Information Management: This platform offers a unique way to collect, share and collaborate upon BIMs across the many participants of a construction process. Oracle uses IFC as a consistent way of structuring and communicating the information (Dunwell 2007).

4.4 The Chapter Conclusion

In this chapter, building information modelling concept was discussed with building product modelling approach. Also, standardisation and integration efforts for the AEC/FM industry were explained and various relevant initiatives were introduced. Moreover, the methodology and use of IFC standard was explained. Furthermore, AEC/FM industry specific XML schemas and building model repositories were briefly discussed.

At present, a full integration and interoperability among various product models is not achieved in the AEC/FM industry due to the fact that a model trying to encapsulate the entire AEC/FM industry is a huge and very complex model which demonstrates difficulties with mapping between domains and far from implementation. Therefore, integration of specific tools for certain processes instead of a full BIM integration is likely to produce more accurate interoperability.

In this context, the Holistic Multi-Dimensional Information Management System addresses these problems by focusing on specific BIM tools and particular information within these tools which is required for building performance monitoring and analysis.

Since the IFC is the only broad building level object schema and most of the BIM vendors offers IFC compatibility with building model repositories that support integration of the data generated by multiple applications for use in other applications support iterations on parts of the design and track changes at the object level. IFC data exchange methodology is used to extract required information from the BIM tools. This extracted information is then used within the developed system in order to classify and categorize building performance data.

In the following chapter, the Holistic Multi-Dimensional Information Management System and its subcomponents will be introduced coupled with a methodology and a tool in order to use specific BIM information for multi-dimensional analysis of building performance data.

Chapter 5

The Holistic Multi Dimensional Information Management System for Energy Efficient Building Operation

Chapter 5 introduces the "Holistic Multi Dimensional Information Management System" with a unique data aggregation layer and web services specifically designed for building performance monitoring and analysis.

5.1 Introduction

As stated in the Chapter 2, a worldwide intention was developed with the Kyoto Protocol and the Copenhagen Summit on achieving a marked reduction in CO_2 emissions by means of energy savings, to limit the harmful effects of climate change. Buildings account for almost 40% of the total energy usage in Europe (EC 2006) (Itard 2008). This underlines the great importance that has to be attached to the energy efficiency of buildings. The EU has introduced a whole series of directives aiming to reduce energy consumption: the Directive on Energy Efficiency of Buildings, the Energy Services Directive, and the Directive on Energy Using Products.

Apart from meaningful building insulation measures, the only means of achieving marked improvements in the energy efficiency of buildings is to make use of efficient building automation technologies which comprises automatic control, monitoring and optimisation (VDMA 2008). According to European standard *"EN 15232 Energy Performance of Buildings-Impact of Building Automation"* building operation systems can, depending on building type and equipment standard, produce the following potential savings of energy: restaurants 31%, hotels 25%, offices 39%, shopping centres 49%, hospitals 18%, schools/universities 34% and residential 27% (DIN EN 2007).

Building Management Systems (BMS) are usually computer systems that control and monitor the building's mechanical and electrical equipment such as HVAC (heating, ventilation and air-conditioning), and the lighting, power, and security systems. Therefore, it collects the most relevant data from the network, implements high layer control function (like a night temperature setback), Fault Detection and Diagnosis (FDD) (Dexter 2001) (Katipamula 2005) and provides Graphical User Interfaces (GUIs) to the building operator, the facility manager and other stakeholders. The functionality of BMS is continuously extended and nowadays the BMS may link to Facility Management Systems (Schach 2004) and Enterprise Management Software (Malatas 2008), (Wong 2005) which offer web services (Wang 2002) (Wang 2007) (Jang 2008) (Malatas 2008).

Building Energy Management Systems (BEMS) are advanced Building Management Systems that are extended with Energy Monitoring & Management services (Capehart 2005) (Smith 2005) (Menzel 2008).

BMS and BEMS consist of an interface layer to the usually Ethernet-based network backbone using management layer protocols like BACnet, OPC, SOAP, etc. (Wang 2002) (Kaster 2005) (Wang 2007) to communicate with gateways connected to the field level network protocols (BACnet, LON, EIB, EnOcean, ZigBee). On top of this a data storage level is placed that is usually a database. Based on this data storage, several software modules realize the dedicated analysis and control functions like high layer control, FDD, and the GUI. This software system needs to be set up for each specific project, each datapoint in the network that should be monitored or controlled needs to be specified, the analysis functions need to be parameterized, etc. This laborious task is one of the main disadvantages of BMS (Wang 2007) (Malatas 2008).

Modern Data Warehouse technologies allow reducing this parameterization effort. They are commonly used to manage business data, and are designed to keep track of a changing environment (Inmon 2005) (Mensah 2005). Data Warehouses structure and aggregate the contained data to prepare queries and support decisions. The structure is pre-defined in so-called dimensions that span cubes (e.g. location dimension: building, floor, room, zone). The specific content (e.g. which rooms) is imported from other data sources. In addition, advanced data analysis techniques like Knowledge Discovery and Data Mining (KDD) (Han 2006) are often used on top of a DW. They have a high potential for energy performance analysis (Tso 2007) (Augenbroe 2005). This makes them a powerful tool for data aggregation in building, but they are still not generally used.

If an existing building should be refitted or extended by an energy monitoring system then the first step is to analyze existing systems within the building. The system needs to be inventoried, its capability analyzed and compared to the requirements. Also, during the life cycle, buildings evolve with regards to various end-user requirements. These kinds of adjustments directly affect buildings performance and FM procedures. In this context, BIM (Chapter 4) plays a central role. A novel exchange method facilitates the data exchange between BIM and DW.

Aggregated data need to be visualised through stakeholder specific Graphical User Interfaces (GUI) for analysis. Service Oriented Architecture (SOA) approach is taken into consideration for GUI and interface development. SOA is an approach to organize IT resources and data collectively in order to enable integration between different technologies and allow for standardized data interaction (Mensah 2005). SOA focuses on interoperable, robust, reusable, and modular services that abstract the application functionality and data of each technology. Two important aspects of implementing a successful SOA are Web Services and Ontologies. While Web Services (Wang 2002) (Wang 2007) are partially integrated in Building Management Systems a consistent Service Oriented Architecture is still missing (Malatras 2008).

In this context a holistic information management system based on a data warehouse technology in order to support multi-dimensional analysis of building performance data will be introduced in this chapter.

5.2 The Holistic Multi-Dimensional Information Management System

Recent advancements in building technologies and building control strategies coupled with the introduction of new building codes have contributed to the improvement of poor energy performance in commercial and residential buildings.

In order to address these issues a methodology leading to a system appropriate to process and analyse building performance data named as "Holistic Multi-Dimensional Information Management System" (Figure 5.1) is developed to store, integrate, analyse complex data sets from multiple data and information sources such as wired/wireless sensing devices (sensors and meters) and BIM tools. Data collected from the sensing devices is classified and categorised by the information collected from BIM tools and used for performing multi-dimensional analysis of building performance data to support decision making process of the end users.

A holistic approach for building performance monitoring requires consistent and simultaneous access to the data and information extracted from different sources. Energy efficiency reports and trend analysis should be accessible to energy managers also other stakeholders but this is often not the case (Piette et al. 2005).

The system developed as part of this thesis enables continuous monitoring to tune building systems for optimal comfort and peak efficiency based on current operational requirements. These methods have saved an average of over 20% of the total energy cost and over 30% of the heating and cooling cost in more than eighty American buildings. It is also possible to achieve savings of $18 billion or more annually if a systematic commissioning was applied to the entire U.S. commercial building stock (Mills et al. 2004). As a result the holistic multi-dimensional information management system supported with data a warehouse technology which provides required tools and methods to perform building performance monitoring, enables more efficient performance analysis and further energy savings.

The system developed in this thesis extracts sensor data from building management systems and from a wireless sensor network (Tyndall 2010). Collected sensor/meter data is stored in the operational data store (ODS) for data cleansing and redundancy check processes. This pre-processed data is loaded to the fact data section of the data warehouse system via an Extraction, Transformation and Loading (ETL) tool. Simultaneously, data gathered from the building information model e.g. CAD tool and the performance framework specification tool (O'Donnell 2009) is loaded to the dimensional data section of the data warehouse. Loaded fact data and dimensional data is aggregated with regards to different stakeholder requirements in the data warehouse system and presented through specific Graphical User Interfaces.

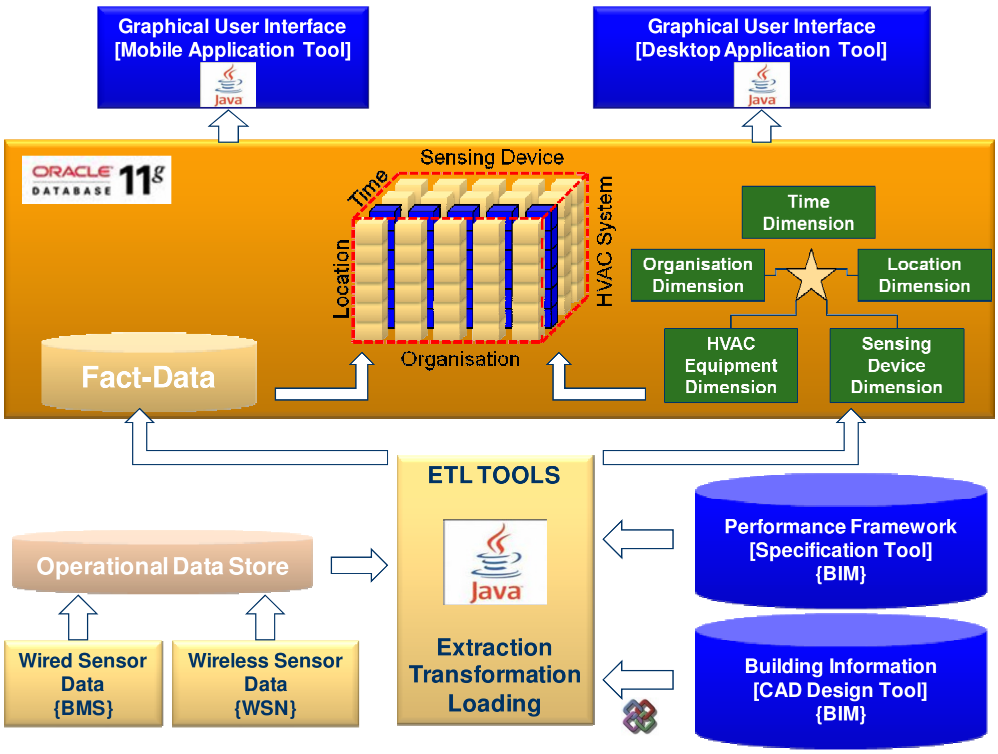

Figure 5. 1: Architecture for Holistic Multi-Dimensional Information Management for Building Performance Data.

The system architecture to support multi-dimensional analysis of building performance data is depicted in Figure 5.1. The system consists of three integrated main components which will be explained in the following sections. These components are:

1. Data Warehouse Core (ODS, Fact Data, Dimensional Data, Data Cube)
2. Extraction, Transformation, Loading (ETL) Layer (ETL Tool)
3. Information Representation Layer (Graphical User Interfaces)

5.3 Data Warehouse Technology

The topic of data warehousing encompasses architectures, algorithms, and tools for bringing together selected data from multiple databases or other information sources into a single repository called a data warehouse, suitable for direct querying and analysis (Widom, 1995).

A data warehouse is a subject oriented, integrated, time varying, non-volatile collection of data that is used primarily in organisational decision making (Inmon, 1992). Data warehouses exist to facilitate complex, data intensive, and frequent ad hoc querying that is accessing data with any meaningful combination of values for the attributes in the dimension (Section 5.3.2) or fact tables (Section 5.3.3) (Elmasri & Navathe 2004).

Data warehouses offer pre-programmed functionalities such as:

- *Roll-up:* Data is summarised with increasing generalisation (e.g. weekly to monthly to annually).
- *Drill-down:* Increasing levels of detail are revealed (the complement of roll-up).
- *Pivot (Rotation):* Cross tabulation is performed.
- *Slice and Dice:* Performing projection operations on the dimensions.
- *Sorting:* Data is sorted by original value.
- *Selection:* Data is available by value or range.
- *Derived (computed) attributes:* Attributes are computed by operations on stored and derived values.

Data warehouses do not have the restrictions of the transactional environment. Therefore, there is an increased efficiency in query processing. Among the tools and techniques used are query transformation, index intersection and union, special ROLAP (Relational Online Analytical Processing) and MOLAP (Multidimensional OLAP) functions, SQL extensions, advanced join methods, and intelligent scanning.

Statistical Analysis techniques (e.g. lagging, moving averages, and regression analysis) and Artificial Intelligence techniques, (e.g. genetic algorithms and neural networks) are used for classification and are employed to discover knowledge from the data warehouse.

Recent developments in wired building automation systems and the current emerging of easy-to-integrate wireless solutions have increased the amount of available building performance data (Menzel 2008). To evaluate these indicators nowadays, traditional database management systems (DBMS) are used to store building monitoring data. These DBMS lack the ability to create consolidated and aggregated building performance data and do not support the analysis of this data to deliver reports and actionable information (Lane 2007).

Data warehousing systems allow a number of alternative ways to integrate and query information stored in it. Thus, as a new approach data warehouse coupled with On-Line Analysis Processing (OLAP) enables end-users to creatively approach, analyze and understand the building performance under different circumstances. The data warehouse technology is used to provide solutions for building performance monitoring and analysis, since it transforms operational data into strategic decision-making information. In order to enhance the decision making capability of the Data Warehouse core, "Dimensional Modelling" technique is used.

5.3.1 Dimensional Modelling

In order to achieve a decision support platform "Dimensional Modelling Technique" is used for developing the data warehouse core. Dimensional Modelling (DM) is the name of a logical design technique often used for data warehouses.

Stackowiak et. al. (Stackowiak 2007) defines DM as de-normalisation technique used in providing an intuitive view of historically correct information that corresponds to the needs of users.

Multi-dimensional models take advantage of inherent relationships in data to populate data in multidimensional matrices called a data cube (Section 5.5.1). For the multidimensional data modelling, query performance in multidimensional matrices can be much better than in the relational data model. For example, a standard spreadsheet is a two dimensional matrix contains the measurements by time/date. Adding a location dimension would produce a three dimensional matrix which could be represented using a data cube. By including additional dimensions a data hypercube could be produced. The data can be queried directly in any combination of dimensions, bypassing complex database queries. Tools exist for viewing data according to the user's choice of dimensions.

The Multidimensional model enables hierarchical views in what is known as roll-up display and drill down display.

The multidimensional storage model involves two types of tables: fact tables and dimension tables. A dimension table consists of tuples of attributes of the dimension. A fact table can be thought of as having tuples (e.g. measurements, meter readings), one per a recorded fact. This fact contains raw measurements and identifies them with pointers to dimension tables. The fact table contains the data, and the dimensions categorise and classify each tuple in that data.

Facts are typically (but not always) numeric values that can be aggregated, and dimensions are groups of hierarchies and descriptors that define the facts. For example, temperature measurement is a fact; timestamp, location, organisation etc. are elements of dimensions.

Two common multi-dimensional schemas are the star schema and the snowflake schema. The star schema consists of a fact table for each dimension. The snowflake schema is a variation on the star schema in which the dimensional tables from a star schema are organised into a hierarchy by normalising them.

Dimensional models are built by business process requirements, e.g. energy consumption, user comfort, etc. Because the different business process areas share some but not all dimensions, efficiency in design, operation, and consistency, is achieved using conformed dimensions.

The dimensional model could be constructed as a star-like schema, with dimensions surrounding the fact table. To build the schema, the following design model is used (Kimball 2002);

1. **Choose the Business Process:** The process of dimensional modelling builds on a 4-step design method that helps to ensure the usability of the dimensional model and the use of the data warehouse. The basics in the design build on the actual business process which the data warehouse should cover. Therefore the first step in the model is to describe the business process on which the model builds. This could for instance be a energy consumption analysis of a particular building. To describe the business process, one can use different methodologies such as Business Process Modelling Notation (BPMN) or Universal Modelling Language (UML).
2. **Declaring the Grain:** After describing the Business Process, the next step in the design is to declare the grain of the model. The grain of the model is the exact description of what the dimensional model should be focusing on. This could for instance be "the metering and sensing interval in which the data is collected from the sensors and meters" and "a measurement is taken at the intersection of all the dimensions (Time, Sensing Device, Location, Organisation and HVAC Equipment)" This list of dimensions defines the grain of the fact table and points out the scope of the measurement. To clarify what the grain means, one should pick the central process and describe it with one sentence.
3. **Identify the Dimension:** The third step in the design process is to define the dimensions of the model. The dimensions must be defined within the grain from the second step of the 4-step process. Dimensions

are the categorisers and descriptors of the fact table, and are where the data for the fact table is collected. Typically (but not always) dimensions are nouns like time, organisation, inventory etc. For instance, in the time dimension, tables like year, month, weekday is located.

4. **Identify the Fact:** After defining the dimensions, the next step in the process is to make keys for the fact table. This step is to identify the numeric facts that will populate each fact table row. In the case of this research wired/wireless sensor and meter measurements (values) are the facts. Each row contains one measurement from an individual sensing device.

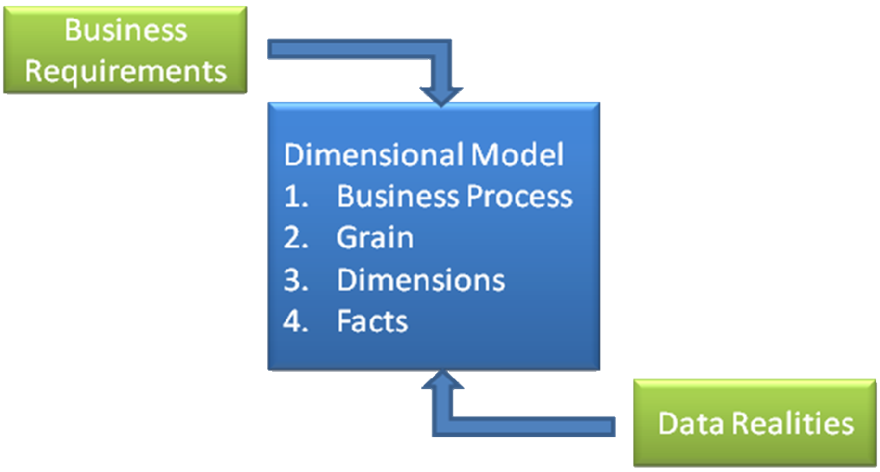

Figure 5. 2: Key Inputs to the Four-Step Dimensional Design Process

The data warehouse stores summarized information instead of operational data. This summarized information is time-variant and provides effective answers to queries such as ‘‘Energy consumption of a particular room in a particular building when the outside temperature is 21^{o}C.”

The aim of the data warehouse component of the system is to:

1. Collect dynamic data (streaming data) which is data that is asynchronously changed as further updates to the data become

available, from different sources such as wired/wireless sensors and meters.

2. Map the dynamic data with the persistent data which is data that is infrequently accessed and not likely to be modified, extracted from BIM tools to define and categorize dynamic data.
3. Perform multi-dimensional data aggregation to support decision making process.

Data Warehouse components are the following:

1. Operational Data Store
2. Fact Data and Dimensional Data
3. Aggregated Data

5.3.2 Operational Data Store

The Operational Data Store (ODS) is a database designed to integrate current valued subject oriented, volatile and real time data from multiple sources such as building management system and wireless sensor/meter network. An ODS is usually designed to contain low level or atomic (indivisible) data (e.g. measurements) with limited history that is captured "real time" or "near real time" as opposed to the much greater volumes of data stored in the data warehouse generally on a less frequent basis. According to Inmon, the originator of the concept, an ODS is "a subject-oriented, integrated, volatile, current-valued, detailed-only collection of data in support of an organization's need for up-to-the-second, operational, integrated, collective information (Inmon 1999)." In our case this temporarily stores the data collected by the sensor/meter network. Also, ODS provides input to the data warehouse by storing regularly changing electricity and gas prices that are necessary for energy cost calculation. ODS processes include data cleansing, redundancy corrections and integrity checks. Figure 5.3 below depicts the operational data store and its data sources.

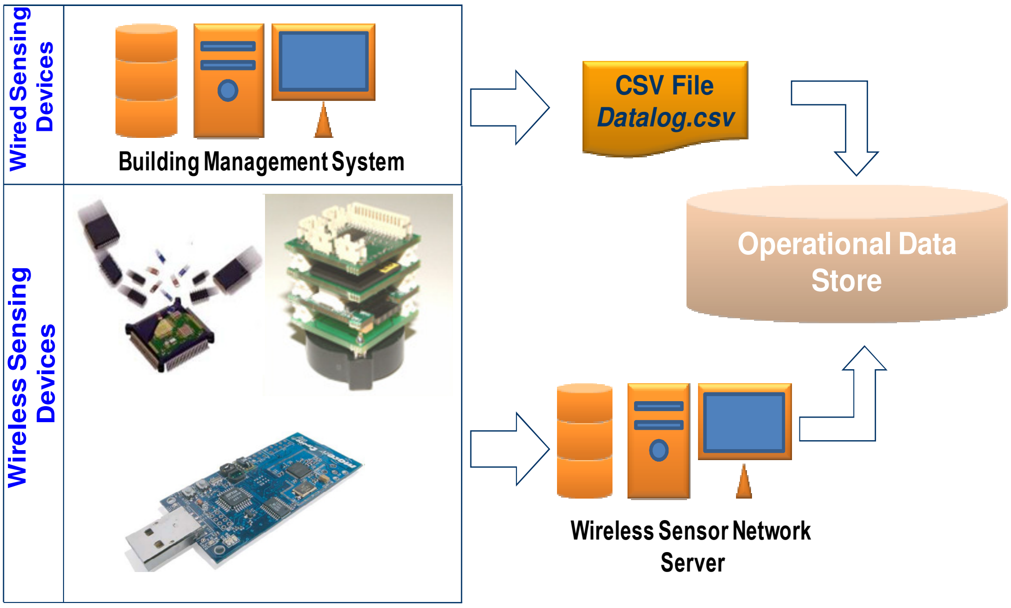

Figure 5. 3: Operational Data Store

5.3.3 Fact Data

Fact data is the main repository for long term storage of dynamic data. A fact table is the primary table in a dimensional model where the numerical performance measurements of the business are stored (Kimball 2002). A measurement is taken at the intersection of all the dimensions (e.g. Time, Location, Organisation). This list of dimensions defines the grain of the fact table and depicts the scope of the measurement. A row in a fact table corresponds to a measurement. All the measurements in a fact table must be at the same grain.

Measures or metric columns provide information about the event that is classified as additive, semi-additive, or non additive values (Stackowiak et al. 2007). Additive measures support discrete arithmetic operations along all of the dimensions, semi-additive measures support arithmetic operations along only some of the dimensions, and non-additive measures are typically descriptive and provide no arithmetic value. The most useful facts in a fact table are numeric and additive (Kimball 2002) because data warehouse applications almost never retrieve a single fact table row. Rather, they bring back thousands, or even millions of fact rows at a time and most useful solutions are to perform operations such as addition and averaging.

Fact tables express many to many (M:N) relationships between dimensions in the dimensional model. M:N cardinality ratio for a binary relationship specifies the maximum number of relationship instances that an entity can participate in. For example multiple sensors may have multiple measurements in the Fact Data table. A fact data table is comprised of two types of columns, foreign key references to dimension tables and measurements. Foreign key columns are provided to join the fact table to dimension tables that enable the filtering and constraining of data. When all the keys in the fact table match their respective primary keys correctly in the corresponding tables, referential integrity of the tables is satisfied.

For the developed system, fact data subcomponent stores and updates the dynamic data collected by wired/wireless sensors and meters. Also, it stores and updates the energy unit prices which are necessary for energy cost calculations. Data collected and temporally stored in the operational data store, is received at certain intervals.

Fact data contains measured variables and identifies them with pointers to dimensional data such as Time, Sensing Device, Location, Organisation and HVAC Equipment Dimension. Dimensional data will be explained in the following section.

5.3.4 Dimensional Data

As explained in the previous section the Fact Data table contains the data, and the Dimensional Data identifies each tuple (row) in that data. A dimension table consists of tuples of attributes of the dimension. According to Kimball (Kimball 2002), “dimension tables are the integral companions to a fact table and contain the description of the business." It provides the means to "slice and dice" data.

The number of rows in dimensional tables is relatively fewer but in terms of columns (attributes). Dimension tables contain attributes and hierarchies that enable a logical grouping and constraining of data. Dimension attributes are normally descriptive and represent details about the dimension. Hierarchies within a dimension provide a natural summarization of information ranging from the lowest level of detail to the highest summary level (Stackowiak et al. 2007).

Each dimension is defined by its single primary key, depicted by "PK" notation (see Figure 5.4), which serves as the basis for referential integrity with any given fact table to which it's joined.

Dimension attributes are very crucial in the data warehouse. These serve as the primary source of query constraints, groupings, and report labels. For example, a user request stating "Minimum temperature of the offices which are occupied by Civil Engineering Department staff in the ERI Building for the last 3 months", is only achieved with time, location, sensing device and organisation dimension attributes.

"HVAC Equipment", "Sensing Device" "Location", "Time", and "Organization" are all dimensions that could be applied meaningfully to the fact data. Each dimension in a data warehouse may have one or more hierarchies applied to it. The hierarchy is a series of parent-child relationships, typically where a parent member represents the consolidation of the members which are its children. Parent members can be further aggregated as the children of another parent. For example for the "HVAC Equipment" dimension the possible hierarchy is structured as HVAC System>HVAC Equipment Category>HVAC Equipment.

Figure 5.4 depicts the data warehouse star schema also called as star join schema which is the simplest style of data warehouse schema. The fact table consisting of measurements is joined to a set of dimension tables filled with descriptive attributes. The most important thing about the resulting dimensional schema is its simplicity and symmetry. Obviously, end users benefit from the simplicity because the data is easier to understand and navigate. Related studies (Kimball 2002) have demonstrated literally hundreds of instances where users agree immediately that the dimensional model is their business. Furthermore the reduced number of tables and use of meaningful business descriptors make it less likely that mistakes will occur. Also, simplicity of a dimensional model has performance benefits. DW optimisers will process these simple schemas more efficiently with fewer joins. A database engine can make very strong assumptions about first constraining the heavily indexed dimension tables, and then attacking the fact table all at once with the cartesian product of the dimension table keys satisfying the user's constraints. This approach enables to evaluate arbitrary n-way joins to a fact table in a single pass through the fact table's index (Kimball 2002). Finally, star schemas are extensible to maintain future extensions and/or possible changes in user behaviour. Every dimension is equivalent; all dimensions are symmetrically equal entry points into the fact table. Different from the logical models, dimensional models consider flexible business requirements at the initial phase.

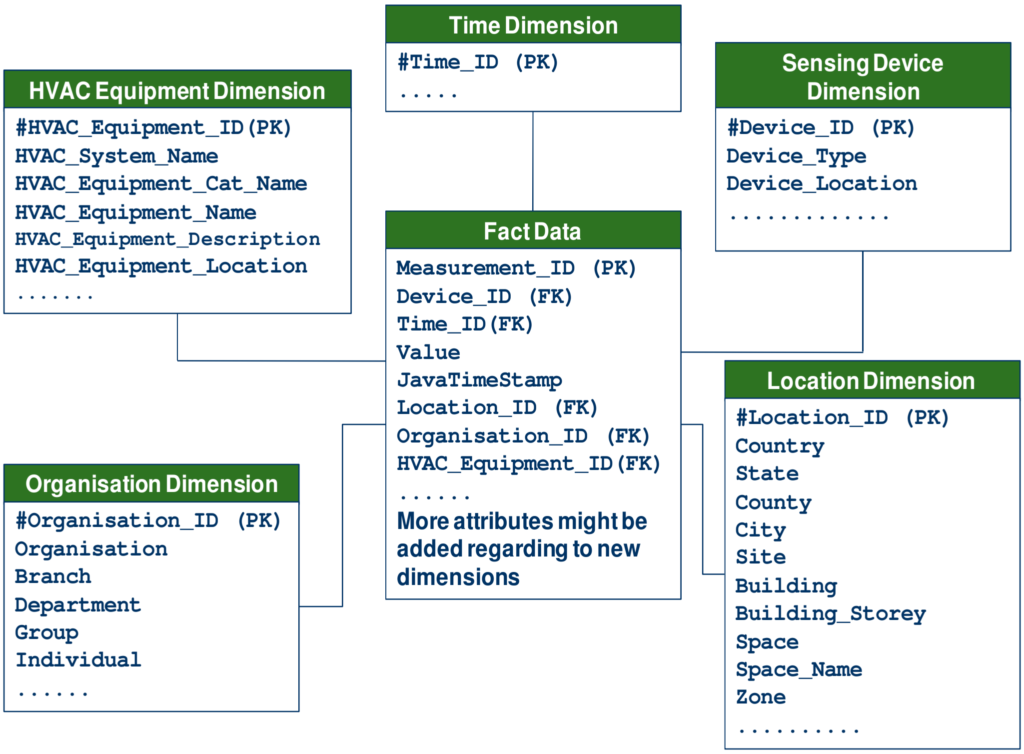

Figure 5. 4: Data Warehouse Star Schema

Considering the developed system's data warehouse star schema, `Fact_Data` is the fact table and there are five dimension tables, `Sensing_Device_Dimension`, `Location_Dimension`, `Organisation Dimension` `HVAC_Equipment_Dimension` and `Time_Dimension`. Each dimension table has a primary key on its `Id` column, relating to one of the columns of the `Fact_Data` table's five-column primary key (`Time_ID`, `Device_ID`, `Location_ID`, `Organisation_ID`, `HVAC_Equipment_ID`). The non-primary key `Value` column of the fact table in this star schema represents a measure or metric that can be used in calculations and analysis. The non-primary key columns of the dimension tables represent additional attributes of the dimensions (such as the `Device_Type` of the `Sensing_Device_Dimension`).

A brief description of the dimensions illustrated is given below. Detailed table and attribute definitions for each dimensional table is provided in the Appendix A.

`Time_Dimension`: This consists of time and date information. Automatically generated Oracle standard time dimension deals only with “date level”. In order to solve this problem a java time stamp is also provided within the fact data table which deals with “time level”. This enables end-users to analyze the historical data with regards to time and date basis, e.g., “energy consumption of a particular building in August 2009.”

`Location_Dimension`: This consists of all location information of a particular building including all the individual zones. It enables end users to analyse information according to different locations, e.g., “humidity level of the offices located at the second floor in a particular building.”

`HVAC_Equipment_Dimension`: This consists of the HVAC system information of a particular building. It enables end users to analyse information according to specific HVAC equipment installed in the building, e.g., “return water temperature of the vacuum tube solar collectors.”

`Organisation_Dimension`: This consists of organizations and individuals that are occupied in the building. It enables end users to analyse information according to different organizations and individuals, e.g., “Monthly energy consumption of the Civil and Environmental Engineering Group.”

`Sensing_Device_Dimension`: This consists of sensing device information such as wired/wireless sensors and meters. It classifies the devices with regards to their types. It enables end-users to analyse information according to different sensing device type, e.g., “Humidity level of the second floor for August 2009”

5.4 Extraction, Transformation and Loading Tool

Data need to be loaded to the data warehouse regularly. To do this, data from one or more operational systems needs to be extracted and loaded into the warehouse. The processes of extracting data from source systems and bringing it into the data warehouse is commonly called ETL, which stands for Extraction, Transformation, and Loading (Loney 2004).

In the data warehouse, raw operational data is transformed into a warehouse deliverable fit for user query and consumption (Kimball, 2002). This is executed by a set of processes called ETL processes which involves:

- Extracting data from multiple sources such as wired/wireless sensor/meter readings and BIM tools.
- Transforming it to fit data warehouse requirements which might be inconsistent with the outside data sources, e.g., data type inconsistencies.
- Loading it to the data warehouse core.

The advantages of efficient and consistent data warehouses make ETL very important as the way data actually gets loaded. For the developed system the ETL tool is used to populate the fact data table which stores long term dynamic data such as measurement streams. Also, the ETL tool is used to populate Dimensional Tables which store persistent data extracted from BIM tools.

5.4.1 Populating the Fact Data Table

One of the objectives of the developed system is to collect readings from both wired and wireless sensors and meters. Current building management systems mainly rely on wired sensor networks. Completely focusing on wireless sensor and meter readings causes inefficient use of resources and the already installed and proven wired system becomes obsolete. In order to avoid this situation, the developed system has the capability to integrate both wired and wireless sensor readings. In most of the building management systems, the data collected from the wired sensors are logged to a Comma Separated Values (CSV) file. The Environmental Research Institute Building (ERI) which is a “Living Laboratory” used for demonstration and test purposes, has a wired BMS installed by Cylon Controls (Cylon 2010) with 100 sensors and 180 actuators. Data collected by this BMS is logged to a CSV files achieve. In order to extract, transform and load this data into the DW for analysis purposes an ETL tool is developed.

During the development phase, current CSV file archive is used as Operational Data Store. Every CSV file belongs to one specific sensor installed in the ERI building. Table 5.1 shows a sample BMS CSV file.

001_ERI	001_01_MCC01	01_Outside Temperature	900		
39030.29	1024	6.47	6.45	6.13	6.11
39031.29	1024	13.17	13.23	13.28	13.39
39032.29	1024	8.91	8.77	8.96	9.54

Table 5. 1: A CSV file sample

Cell A1 depicts the building ID, cell B1&C2 shows the Sensor_ID and cell D1 shows the measurement interval (e.g. every 900 Seconds=15 Minutes)

Cell A2 depicts the date and time. Timestamp conversion: days since 1/1/1900|0=00:00

Cell B2 shows the number of measurements in that particular row. (e.g. 1024 measurements took place in that time period)

Cell C2 is the measurement value. (e.g. 6.47 Celsius)

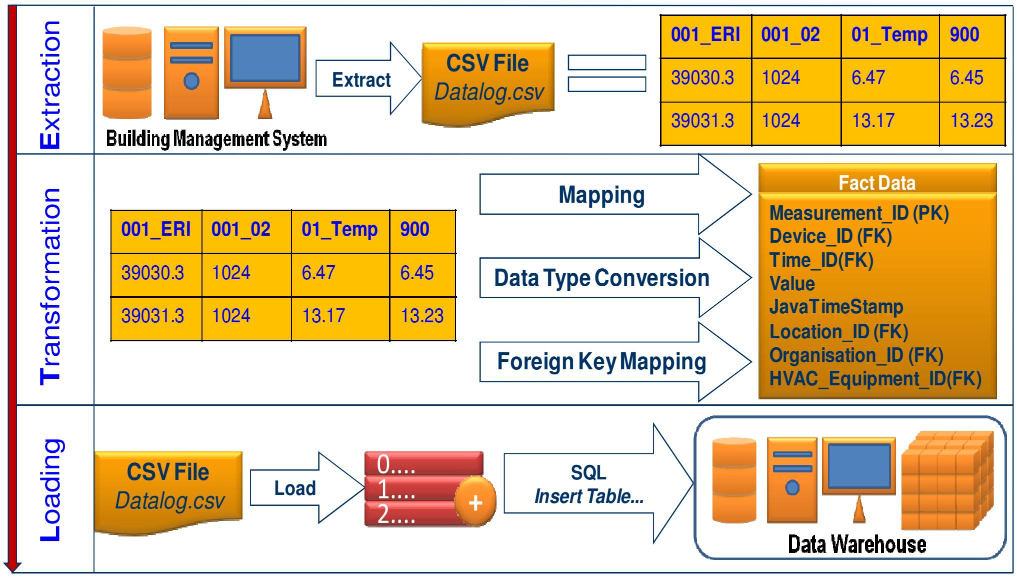

Figure 5. 5: Extraction, Transformation and Loading.

Figure 5.5 depicts an ETL process developed for the BMS of ERI Building in order to populate the fact data table which:

- Extracts data from the current building management system (BMS) comma separated values (CSV) file archive,
- Eliminates inconsistencies such as duplicate rows,
- Transforms the CSV file structure to the data warehouse fact data table structure,
- Loads the CSV files to the data warehouse fact data table.

Mapping and Data Type Conversion

In this section mapping and data type conversion processes of the ETL tool is explained. Arrows and dashed arrows are used to illustrate these processes.

Mapped to: ———►

Converted to: - - - -►

CSV File to Fact Data Mappings

CSV File Cell A2: MS Timestamp 39634.01042 ----→ Java Timestamp: 04-JUL-08 04.45.00.187000 ——→ `Fact_Data.JavaTimeStamp`

CSV File Cell C2: 22.91 ——→ `Fact_Data.Value`

Foreign Key Mappings

Device_ID Foreign Key Mapping:

CSV File Name ——→ `Sensing_Device_Dimension.Datalog` ——→ `Sensing_Device_Dimension.Device_ID` ——→ `Fact_Data.Device_ID`

Location_ID Mapping:

`Sensing_Device_Dimension.Device_Location` ——→ `Location_Dimension.Location_ID` ——→ `Fact_Data.Location_ID`

HVAC_Equipment_Dimension Mapping:

`Location_Dimension.Location_ID` ——→ `HVAC_Equipment_Dimension.Location_ID` ——→ `HVAC_Equipment_Dimension. HVAC_ID` ——→ `Fact_Data.HVAC_ID`

Organisation_Dimension Foreign Key Mapping:

`Fact_Data.Location_ID` ——→ `Organisation_Dimension.Location` ——→

`Organisation_Dimension.Organisation_ID` ——→ `Fact_Data.Organisation_ID`

5.4.2 Populating the Dimensional Tables

The ETL tool is also used to populate the dimensional tables. HVAC equipment dimension, location dimension and sensing device dimension tables can be populated by extracting the data from the BIM tools. In the following sections an ETL methodology will be introduced to populate each separate dimension. In this methodology, an interface consisting of an IFC based data extraction tool and an ETL tool, will be introduced.

Populating the Location Dimension Table

The Location Dimension consists of all location information of a particular building including all the individual zones. In order to extract this data a CAD Tool is used as a source application. Architectural building information contains required location information. Therefore, main emphasis is given to the architectural domain of the IFC.

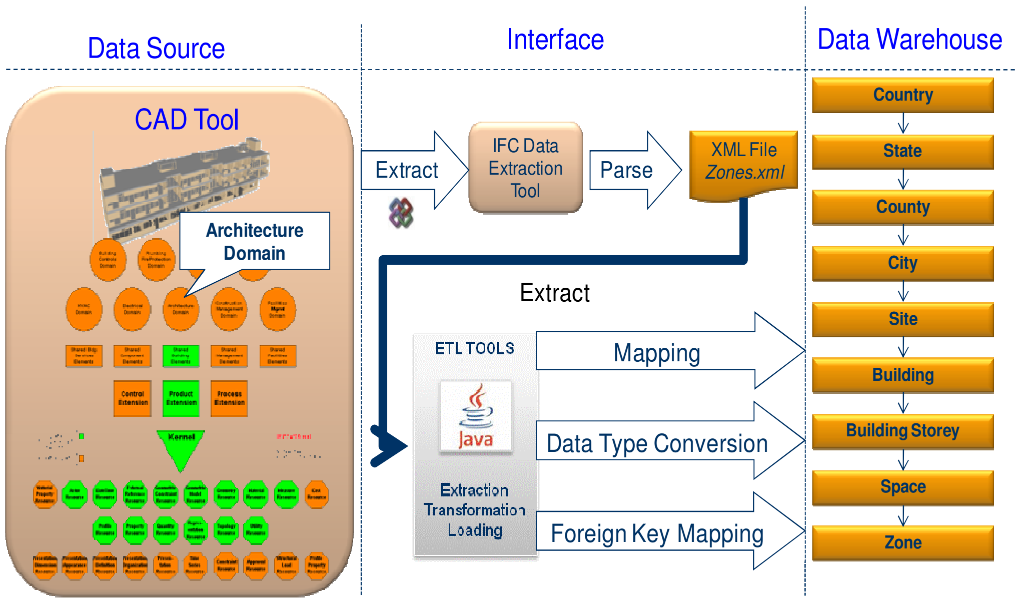

Figure 5. 6: The ETL Process for Populating Location Dimension Table

Figure 5.6 depicts the developed system's ETL process to populate the Location_Dimension table of the data warehouse.

This process involves:

- Extracting architectural building information by using IFC (Industry Foundation Classes) data extraction tool which will be explained in the following section.
- Parsing the extracted data to a file in XML format, e.g., Zones.xml.
- Extracting the data from the XML file.
- Transforming the extracted data by proving necessary mappings, data type conversions and foreign key associations.
- Loading the pre-processed data to the data warehouse's location dimension table.

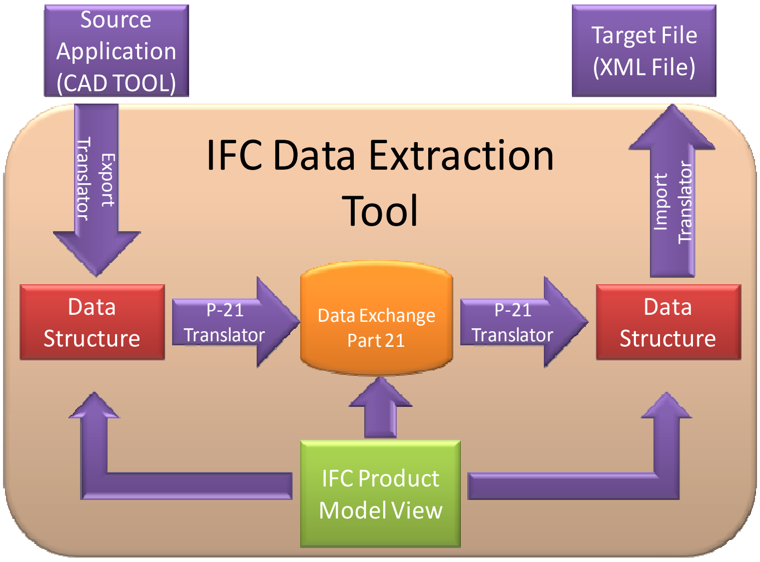

Figure 5. 7: IFC Data Extraction Tool

Figure 5.7 depicts the IFC Data Extraction Tool which extracts the data from a source application (CAD Tool) and loads the extracted data to the Target Application (XML file). The processes of the tool involve:

- Information instances in the source application (e.g. CAD Tool) are extracted by the translator and assigned to appropriate IFC entity classes

- The entity instance data are then mapped from the IFC objects into a text file format defined by the ISO-STEP Part 21.
- This file is then received by the other application and interpreted by the receiving application's translator in terms of the IFC object instances it represents.
- The translator in the target application (e.g. XML File) writes the relevant IFC objects into its native data structure for use.

Development of the IFC Parser, which extracts architectural building information and parses this to a target application is ongoing within the BuildWise project by the IRUSE Galway group (IRUSE 2010).

Populating the HVAC Equipment Dimension Table

HVAC Equipment Dimension consists of the HVAC system information of a particular building. A CAD tool containing HVAC system information is used as a source application. Main emphasis is given to the HVAC domain of the IFC.

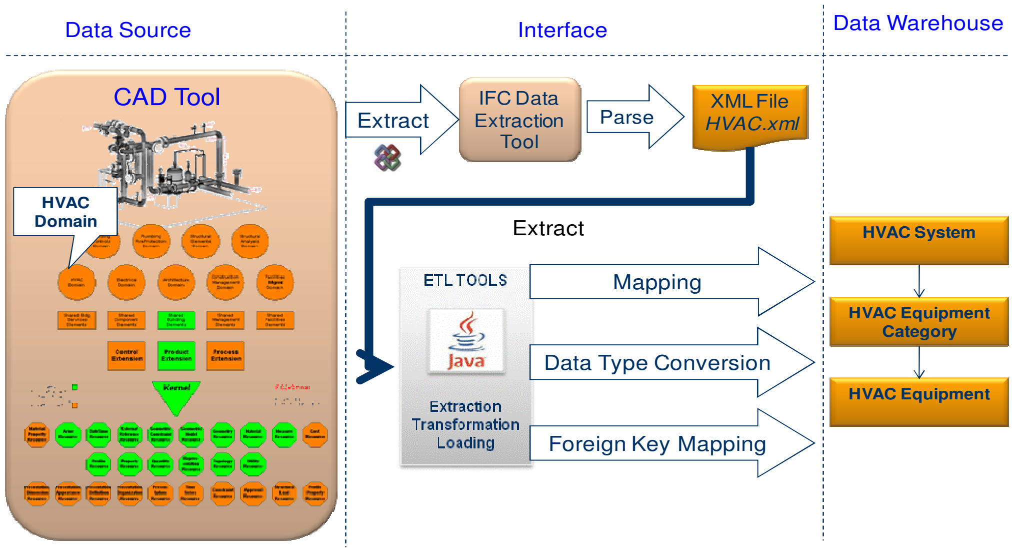

Figure 5. 8: The ETL Process for the HVAC Equipment Dimension Table

Figure 5.8 depicts the developed system's ETL process to populate the HVAC dimension. This process involves:

- Extracting HVAC systems information by using IFC (Industry Foundation Classes) data extraction tool.
- Parsing the extracted data to a file in XML format, e.g., HVAC.xml.
- Extracting the data from the XML file.
- Transforming the extracted data by proving necessary mappings, data type conversions and foreign key associations.
- Loading the pre-processed data to the data warehouse's HVAC_ Equipment _Dimension table.

Populating the Sensing Device Dimension Table

Sensing device dimension consists of sensing device information such as wired/wireless sensors and meters. Virtual deployment and placing of these sensors is done automatically by a tool called "WSN Design Optimisation Tool" developed by CIT AWS group. This tool contains sensing device information required by the DW.

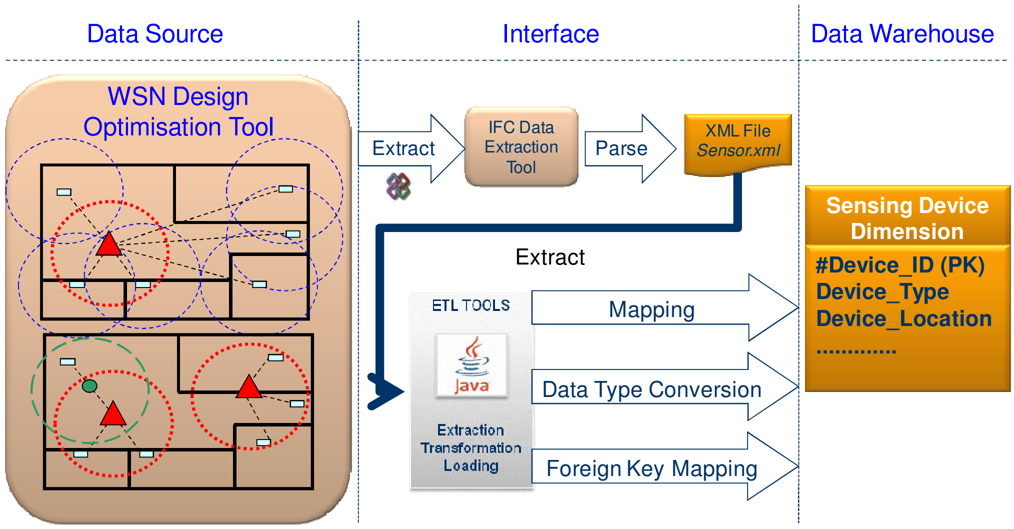

Figure 5. 9: The ETL Process for the Sensing_Device_Dimension Table

Figure 5.9 depicts the developed system's ETL process to populate the Sensing_Device_Dimension table. This process involves:

- Extracting the sensor placement information from the WSN Design Optimization Tool which is developed by CIT AWS Group (Mc Gibney et al. 2008) by using IFC (Industry Foundation Classes) data extraction tool.
- Parsing the extracted data to a file in XML format, e.g., Sensor.xml.
- Extracting the data from the XML file.
- Transforming the extracted data by proving necessary mappings, data type conversions and foreign key associations.
- Loading the pre-processed data to the data warehouse's Sensing_ Device _Dimension table.

The sensor is the most basic component of the developed system and the accuracy and the signal quality needs to be specified at design. The deployment of wireless sensors is usually undertaken following an ad hoc procedure. Connectivity between nodes is obtained through a "try it and see" approach. Although such an ad hoc approach may work in a small environment it relies heavily on the designer's experience, is time consuming and is unlikely to provide an optimal solution in large scenarios. In order to assist the deployment of the developed system based on wireless sensors and actuators a scalable WSN design optimization algorithm and methodology integrated in a software tool to support designers and system integrators when undertaking the difficult task of WSN deployment for wireless building energy management(Guinard et al. 2009).

Figure 5.10 depicts the basic illustration of the WSN Design Optimisation Tool. The details of the WSN Design Optimization Tool can be obtained from the Cork Institute of Technology AWS Group (Guinard et al. 2009), (Mc Gibney et al. 2008).

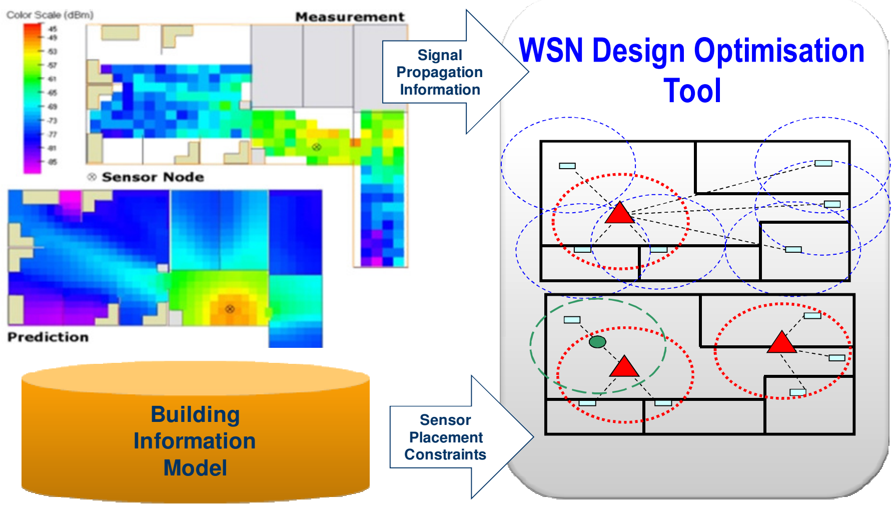

Figure 5. 10: Wireless Sensor Networks Design Optimisation Tool

After populating the fact and the dimensional tables, data in the DW becomes available for aggregation in order to perform multi-dimensional analysis of building performance data. Aggregated data will be explained in the following section.

5.5 Aggregated Data

Data aggregation is any process in which information is expressed in a summary form for purposes such as reporting, analysis and decision support.

Seven criteria are defined for an effective aggregation solution (Ghiossi 2005). These are; (1) *Flexible Architecture* for exponential growth and flexibility. (2) *Performance* which refers to the speed, responsiveness and quality of the application. (3) *Scalability* to support the huge amount of data caused by rapid data generation technologies such as wired/wireless sensors. (4) *Fast Implementation* with a proven methodology and approach. (5) *Efficient use of hardware and software resources* to avoid unnecessary costs (6) *Price/Performance* ratio for selecting the technology requirements must coincide with the value of the solution to make it worth implementing. (7)

Enterprise-Class Solution to support dynamic business environments ensuring high availability and easy maintenance.

Aggregated data is the decision support level of the multi-dimensional data warehouse. Every data warehouse contains pre-calculated and pre-stored aggregated data. In the context of the work sensed raw data collected from wired/wireless sensors and meters populates the Fact Data table of the data warehouse. Fact data becomes meaningful when it is associated with the dimensional data and provides the end user the means to create data cubes.

5.5.1 Data Cube

The results are stored in the data cube also called OLAP cube. OLAP is a term used to describe the analysis of complex data from the DW. It can also be defined as the capability of manipulating and analyzing data from multiple perspectives. The cube is used to represent data along some measure of interest. Although called a "cube", it can be 2-dimensional, 3-dimensional, or higher-dimensional. These may be called hypercube if they have more than three dimensions (Elmasri & Navathe 2004). Each dimension represents some attribute in the database and the cells in the data cube represent the measure of interest. For example, they could contain a count for the number of times that attribute combination occurs in the database, or the minimum, maximum, sum or average value of some attribute. Queries are performed on the cube to retrieve decision support information. In essence cube is a data structure that allows fast analysis of data. It can also be defined as the capability of manipulating and analyzing data from multiple perspectives. A cube can be interpreted as a data view in a multi-dimensional model.

Common operations associated with the data cubes are the following:

- *Slice*: A slice is a subset of a multi-dimensional array corresponding to a single value for one or more members of the dimensions not in the subset.

- *Dice*: The dice operation is a slice on more than two dimensions of a data cube (or more than two consecutive slices).
- *Drill Down/Up*: Drilling down or up is a specific analytical technique whereby the user navigates among levels of data ranging from the most summarized (up) to the most detailed (down).
- *Roll-up*: Also known as "Summarisation" A roll-up involves computing all of the data relationships for one or more dimensions.
- *Pivot*: To change the dimensional hierarchy (orientation) of a report or page display.

The definition of cubes requires a frequency analysis of the queries required by the end user. The main objective of the developed system is to retrieve the decision support information from the data cube in the most efficient way possible. There are two possible solutions applicable for the developed system:

Pre-compute all cells in the cube: The advantage of pre-computation is the faster query response. The disadvantage is that the pre-computed cube has limited end user contribution to flexible analysis and requires a lot of memory space.

Pre-compute most frequently used cells in the cube: As a compromise, it is suggested to pre-compute only those cells in the cube which will most likely be used for decision support queries. The trade-off between memory space and computing time is called the *space-time trade-off* in computer science and it often exists in data warehousing and data mining. For the developed system it is suggested to pre-compute data cubes with regards to time and location dimension which are the inputs for the most frequently requested queries by the end users to analyse building performance data for energy efficient building operation.

Multidimensional models take advantage of inherit relationships in data to populate data in multidimensional matrices called data cubes. Regarding the business requirements the data cube emphasises on one or more dimensions:

e.g., computing and ranking the monthly energy consumption of each floor. Time is a dimension that is of particular significance to decision support (e.g., trend analysis). Other possible operations include comparing two measures: e.g., current building performance compared with the performance objectives defined by the building performance assessment regulations. The scale of the data cube can be adapted to different requirements; hence the Performance Metrics provided by the building information model (BIM) can be calculated in multiple dimensions and granularities. Figure 5.11 depicts an example of data cube and aggregated data with regard to sensing device and organisation dimensions.

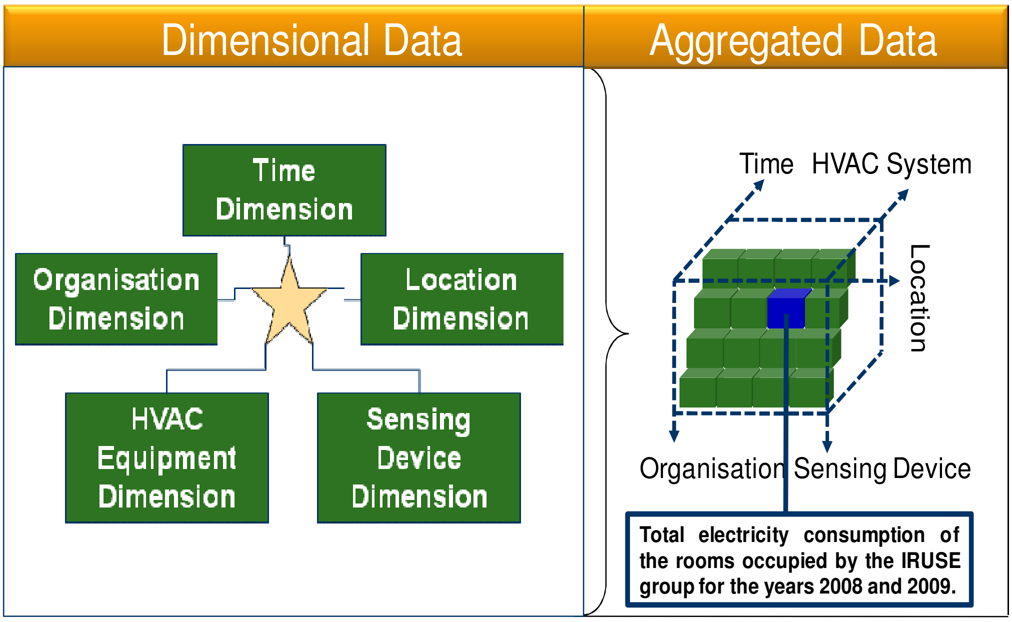

Figure 5. 11: Aggregated Data and Data Cube

The SQL statement for the cube illustrated in Figure 5.11 is given below. In order to create this cube, Time, Sensing_Device and Organisation dimensions are required.

```
SELECT O.GROUP, T.CAL_YEAR_NUMBER, L.SPACE, SUM(F.VALUE)
FROM ORGANISATION_DIMENSION O, TIME_DIMENSION
T,LOCATION_DIMENSION L, SENSING_DEVICE_DIMENSION S,
FACT_DATA F
WHERE T.TIME_ID=F.TIME_ID
AND S.DEVICE_ID=F.DEVICE_ID
AND O.ORGANISATION_ID=F.ORGANISATION_ID
AND O.ORGANISATION LIKE 'IRUSE%'
AND T.YEAR BETWEEN 2008 AND 2009
AND S.DEVICE_TYPE='ELECTRICITY METER'
GROUP BY CUBE (L.SPACE, T.CAL_YEAR_NUMBER);
```

The output of this SQL statement creates a 2D cube (see Table 5.2). The semantics of the CUBE operator are that it first aggregates over all the <select list> attributes in the GROUP BY clause as in a standard GROUP BY. Then it UNIONs in each super-aggregate of the global cube—substituting ALL for the aggregation columns.

Space	Cal_Year_Number	Value
LG04	2007	2482
LG04	2008	2628
LG04	All	5110
G07	2007	4428.5
G07	2008	4689
G07	All	9117.5
All	2007	6910.5
All	2008	7317
All	All	14228

Table 5. 2: Example of a 2-Dimensional Cube Output.

If there are N attributes in the <select list>, there will be 2^N -1 super-aggregate values. The size of a cube for N attributes $A_1,...,A_N$ with cardinalities $|A_1|,...,|A_N|$ is $\pi(|A_i|+1)$. The extra value in each domain is ALL. This size increases exponentially with the number of attributes and linearly with the cardinalities of those attributes. For example the 2D data cube shown has two attributes Space and Year. Each attribute has cardinalities of two Space={LG04, G07} Year={2007,2008}. The size of the cube is π(2+1)=> 3x3 9 rows. If the application wants only a roll-up or drill-down report the full cube is meaningless. The solution is to offer `ROLLUP` instead of `CUBE`. `ROLLUP` enables a `SELECT` statement to calculate multiple levels of subtotals across a specified group of dimensions. It also calculates a grand total:

(v1 ,v2 ,...,vn, f()),

(v1 ,v2 ,...,ALL, f()),

...

(v1 ,ALL,...,ALL, f()),

(ALL,ALL,...,ALL, f()).

Cumulative aggregates, like running sum or running average, work especially well with `ROLLUP` because the answer set is naturally sequential (linear) while the full data cube is naturally non-linear (multi-dimensional). Below a `GROUP BY ROLLUP` SQL statement is shown.

```
SELECT O.GROUP, T.CAL_YEAR_NUMBER, T.CAL_MONTH_NUMBER,
T.DAY_OF_CAL_MONTH, T.DAY,  L.SPACE, SUM(F.VALUE) FROM
ORGANISATION_DIMENSION O, TIME_DIMENSION T,
LOCATION_DIMENSION L, SENSING_DEVICE_DIMENSION S,
FACT_DATA F
WHERE T.TIME_ID=F.TIME_ID
AND S.DEVICE_ID=F.DEVICE_ID
AND O.ORGANISATION_ID=F.ORGANISATION_ID
AND O.ORGANISATION LIKE 'IRUSE%'
AND T.CAL_YEAR_NUMBER BETWEEN 2008 AND 2009
AND S.DEVICE_TYPE='ELECTRICITY METER'
GROUP BY ROLLUP (T.CAL_YEAR_NUMBER, T.CAL_MONTH_NUMBER,
T.DAY_OF_CAL_MONTH, T.DAY);
```

The output of the given SQL statement creates a huge table containing data for every aggregation level declared within the `GROUP BY ROLLUP` statement. It also calculates a grand total in the final row.

Space	Year	Month	Day	Value
LG04	2007	January	1	75
LG04	2007	January	2	68
LG04	2007	January	3	79
LG04	2007	January	4	80
LG04	2007	January	5	92
LG04	2007	January	6	68
.....	.....	.....	.....	.....
All	All	All	All	14228

Table 5. 3: An Example Output of a Cube with Roll-Up Function

Aggregated data within the DW core is represented through specifically developed Graphical User Interfaces (GUI) to the different stakeholders for monitoring and analysis purposes. Information representation scenarios and developed GUIs will be introduced in the following section.

5.6 Information Representation

The objective of the information representation component of the system is to visualise the results of the multi-dimensional analysis of building performance data to the different stakeholders with regards to their roles for developing user awareness and supporting decision making.

In order to develop user awareness and support decision making process of the stakeholders, two types of software tool- a visualisation tool or a data mining tool offer the potential to assist decision maker (Shneiderman 2002). According to O'Donnell (O'Donnell 2009), a hybrid information delivery tool that allows an Energy Manager access to holistic building information has not yet been developed for the AEC/FM industry.

Developments in Information Technology (IT) have brought a new dimension to the methodology of building monitoring. Current sensing technology combined with computer networking communication systems provides remote monitoring capability of plant facilities to building managers and operators. The information from these sensors is displayed to the system users in a context that can easily be interpreted and facilitates stakeholder decision making (Menzel 2008).

One of the mechanism through which users access a software application is referred to as the user interface (Far 2004). Inputs from users trigger an action and an application should respond in a controlled and predictive manner. This promotes the concept user friendly applications. An International Standards Organisation (ISO) standard, ISO 13407:1999, was created to standardise human centered design activities (ISO 1999).

Information representation is achieved by developing and implementing user friendly Graphical User Interfaces (GUI) which enable stakeholders to visualise information both in graphical and in tabular format through the use of build-in data mining tools.

In order to achieve this, web based GUI mock-ups are developed which enable end users easy querying of building performance related data without dealing with complex SQL statements and allows multiple users to visualise information.

5.6.1 Stakeholder Analysis

In the scope of the Buildwise research project, several interviews supported by structured questionnaires were carried-out with the industry partners Cylon Controls, The Vector FM (Vector FM 2010), The Wirelite Sensor Company (Wirelite 2010) and the Spokesoft Company (Spokesoft 2010) in order to accomplish stakeholder analysis (Yue Wang 2009).

Stakeholders analysis refers a range of tools for the identification and description of stakeholders on the basis of their attributes, interrelationships, and interests related to a given issue or resource.

Grimble and Wellard (Grimble 1996) underline the usefulness of stakeholder analysis in understanding complexity and compatibility problems between objectives and stakeholders. Likewise, Freeman and Gilbert (Freeman and Gilbert 1987) propose the concept of stakeholder management as a framework to help managers understand the turbulent and complex business environment. Stakeholder analysis seeks to differentiate and study stakeholders on the basis of their attributes. For example, in Graphical User Interface design, the stakeholder analysis reflects an increasing recognition of how the characteristics of stakeholders – individuals, groups and organizations – influence decision-making processes. Stakeholder analysis can be used to generate knowledge about the relevant actors so as to understand their requirement to bear on decision making processes.

To carry out stakeholder analysis, the most important step is to do a user and task analysis

User and task analysis is the process of learning about ordinary user by observing them in action. It focuses on understanding deeply how users perform their tasks.

This information can then be used to develop strategies for managing these stakeholders, to facilitate the implementation of graphical user interface development. Table 5.4 depicts the summary of results for the stakeholders Building Owner, Facility Manager, Occupant/Tenant and Building Technician.

	Roles
Building Owner	Review the overall energy consumption of building.
	Review the overall energy consumption of particular organisation, individual person or plant.
	Generate bills and control cost.
Facility Manager	View and analyse building performance data for a given zone/zones.
	Evaluate cumulative data to support operation and maintenance activities.
	Review the history of performance objects.
Occupant/Tenant	Able to submit a thermal comfort evaluation within his zone.
	View a relevant zone/room performance data.
Building Technician	Monitor individual HVAC equipment performance

Table 5. 4: Summary of the Stakeholder Analysis (Data extracted from (Yue Wang 2009))

5.6.2 Information Representation Scenarios

There are two main use case scenarios considered for the system such as analysis of building performance data and on-site diagnostics.

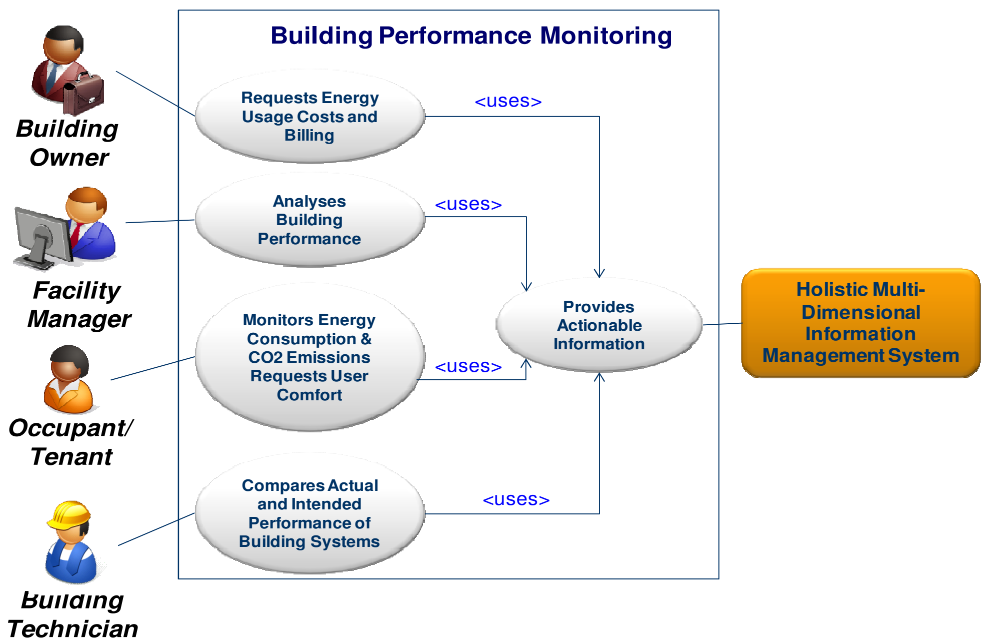

Figure 5. 12: Information Representation Scenarios

Figure 5.12, depicts the information representation scenario and the roles of the stakeholders that interact with the system. This is developed with the use of Unified Modelling Language (UML) use case diagram which shows use cases, actors, and their interrelationships (Scott 2004)

Stakeholders include any person or organisation that may be affected by the success or failure of the software (Marinilli 2006). The principle stakeholders, their data requirements and roles are described below:

Building Owner: (a) Reviews the overall energy consumption and CO_2 emissions of facilities. (b) Reviews the energy consumption and CO_2 emissions of a particular organisation, occupant or zone (c) Generates consumption bills and audits the costs of facilities.

Facilities Manager: (a) Monitors and analyses the building performance data with regards to particular zone (Location_Dimension), organisation/occupant (Organisation_Dimension), building system (HVAC_Equipment_Dimension) and/or time interval (Time_Dimension). (b) Maintains optimum occupant comfort level.

Occupant/Tenant: (a) Monitors relevant energy consumption and CO_2 emissions. (b) Views real time energy consumption costs. (c) Requests user comfort.

Building Technician: (a) Compares actual and intended performance of building systems (HVAC Systems) in order to perform preventive maintenance activities.

Holistic Multi-Dimensional Information Management System: (a) Stores the raw data collected from the sensing devices. (b) Stores the dimensional data extracted from the BIM. (c) Performs data aggregation and multi-dimensional analysis (d) Provides actionable information to develop user awareness and to support decision making process of the stakeholders.

In order to satisfy the requirements of the different stakeholder roles described, two different types of user interface need to be applied:

- Desktop Application for performance evaluation
- Mobile Application for onsite facility management and building diagnostics

5.6.3 User Interface Mock-ups for Stakeholders

Graphical User Interface mock-ups have been developed based on the roles and the requirements of the stakeholders in a multi-dimensional analysis of building performance application. Data compiled from the ERI Building for the Buildwise research project through wired BMS and wireless sensor/meter network has been used for the mock-up development and implementation.

The most important element of a user interface is the representation of data. Data must be presented clearly and unambiguously to leave the user in a state of mind that they can precisely interpret and trust what they see (O'Donnell 2009). Early attempts at displaying energy consumption data involved the use of graphs to inform the user of trends within their building systems (Haberl 2009) (Prazeres 2003).

Current applications facilitate increased interactivity with the availability of WIMP (window, icon, menu, and pointing device) paradigm on screen based systems. This enables the organised layout of information elements. Multiple data streams can be viewed on a single screen to lessen user navigation issues.

The proposed application is a Java-based Applet which provides users the ability to access the system via the Web. The system starts with user log-in; this log-in is setup for the occupants of the ERI building and enables authorised and authenticated access to the data. Based on the log in user name, the system can load role-based and location-based information from the Organisation_Dimension of the Data Warehouse.

In the following sections, a more detailed description of the GUI mock-ups for the four essential stakeholders will be presented.

Occupant/Tenant GUI

The primary objective of this GUI is to represent the real time energy consumption and CO_2 emissions to the relevant building occupant in order to develop end-user energy consumption and CO_2 emission awareness which might lead to an incentive for further energy savings. Secondary objective is to visualise all available zone measurements such as current temperature, humidity and lux levels in order to deliver the comfort related information to the end users.

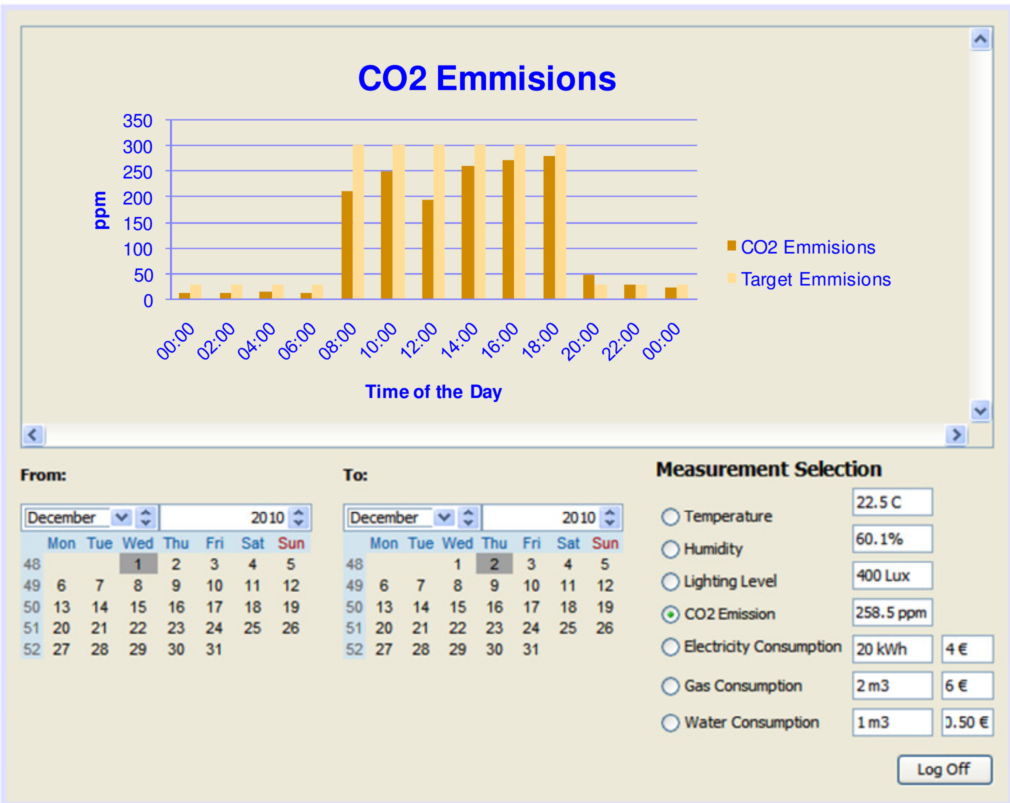

Figure 5. 13: Occupant/Tenant Graphical User Interface

Figure 5.13 depicts the GUI developed for the occupants/tenants. The developed GUI consists of three sections.

1. "Time Selection" section to analyse data with regards to user specified time interval.

2. "Measurement Selection" section visualises the current measurement data through text windows located next to selection buttons. The end user can also visualise the detailed information in graphical format by selecting one of the measurement buttons.

3. "Information Representation" window shows the selected measurement and time aggregation in a bar chart graphical format with a comparison of the actual and target levels. Figure 5.13 shows one day's CO_2 emission level with the target emission levels.

Facility Manager GUI

The facility manager has the most comprehensive role in the overall scenario definition. Therefore, the facility manager has access to all defined dimensions within the system. The facility manager has the capability to analyse the performance of all zones, organisations, occupants/tenants, building systems and consumption information with CO_2 emissions.

Figure 5.14 depicts the GUI developed for the facility manager. The developed GUI consists of six sections.

1. "Location Selection" section to select particular zones within the building.

2. "Organisation Selection" section to select the particular organisations and/or occupants/tenants occupied in the building.

3. "Building Systems" section to select specific building equipments such as gas boiler flow temperature and heat pump return temperature.

4. "Measurement Selection" section buttons to visualise sensed or metered data for the relevant locations and/or organisations within the given time interval.

5. "Time Selection" section to analyse data with regards to user specified time interval.

6. "Information Representation" window to visualise data both in graphical and in tabular format. Figure 5.14 visualises one day's temperature readings with the temperature set point for a particular zone.

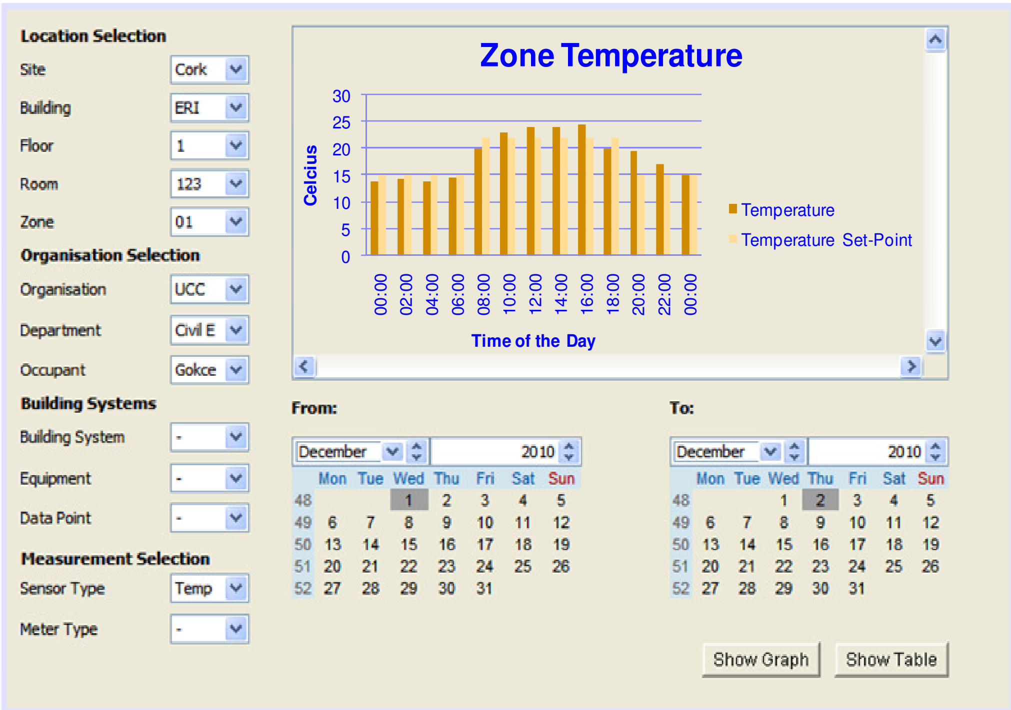

Figure 5. 14: Facility Manager Graphical User Interface

Building Owner GUI

The interest of the building owner is to monitor the general energy consumption of the building zones, organisations and occupants/tenants. Also, review costs and create bills for the individual tenants. Moreover, with the new trend carbon trading, CO_2 emission levels of the organisation can be used as a financial instrument. For trading purposes, one allowance or CER (Certified Emission Reduction) is considered equivalent to one metric tonne of CO_2 emissions. These allowances can be sold privately or in the international market at the prevailing market price. Therefore, a CO_2 meter is embedded into the GUI which calculates the monetary value of the emissions by using CO_2 spot prices.

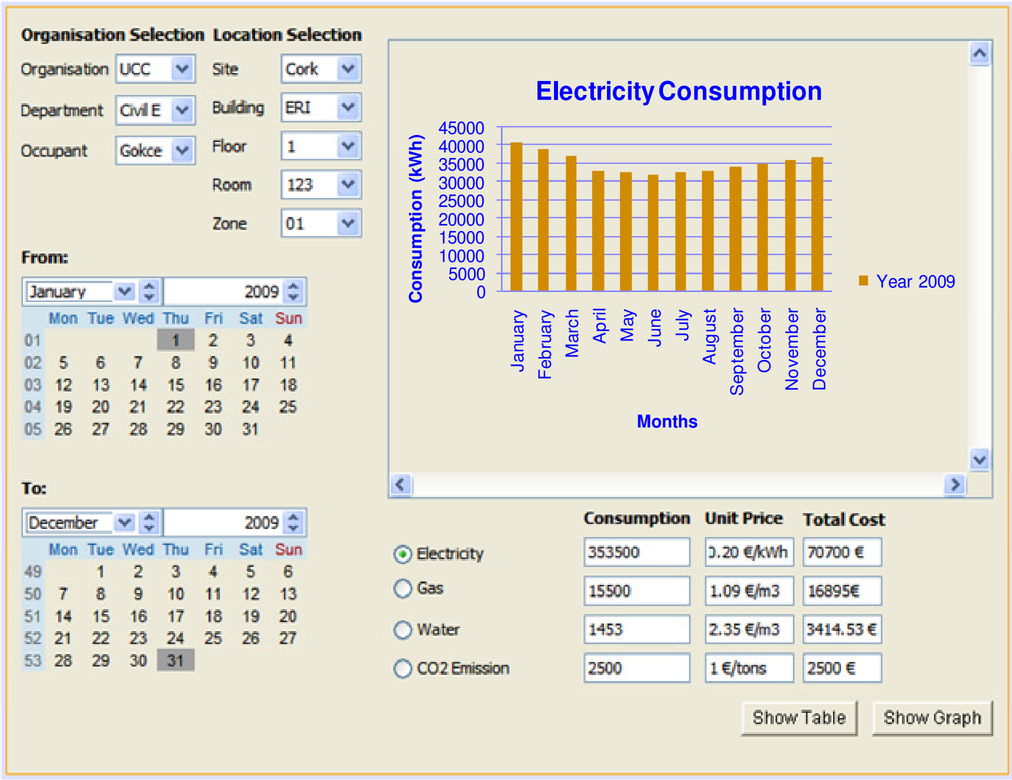

Figure 5. 15: Building Owner Graphical User Interface

Figure 5.15 depicts the GUI developed for the building owner. The GUI consists of four sections.

1. "Time Selection" section to analyse data with regards to user specified time interval.

2. "Organisation Selection" section to select the particular organisations and/or occupants/tenants occupied in the building.

3. “Location Selection” section to select particular zones within the building.

4. “Measurement Selection” section shows the metered data through text windows located next to selection buttons as well as unit prices and total consumption costs.

5. “Information Representation” window to visualise data both in graphical and in tabular format. Figure 5.15 visualises monthly electricity consumption of a specific occupant for the year 2009.

Building Technician GUI

Onsite building technicians require support to perform maintenance activities in an effective manner as identified during the preventive maintenance planning phase. Preventive maintenance is a series of scheduled inspection routines on building plants. In this case failures can be seen before a failure may occur. In order to achieve critical support for members of the FM team, a mobile device application is developed. Figure 5.16a depicts the GUI developed for the performance based preventive maintenance system. This GUI retrieves compares and presents actual and intended performance of the selected building systems. This enables building technicians to monitor performance losses of the particular system which causes more energy consumption and may lead to more costly maintenance activities. The GUI consists of Location Selection, Building Systems Selection and Time Selection sections.

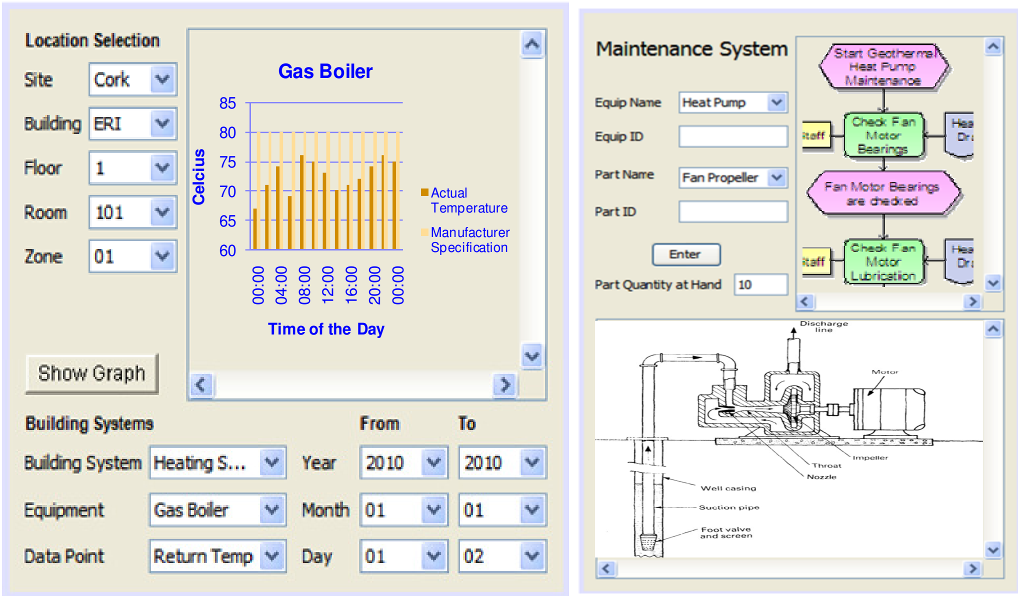

Figure 5. 16: Building Technician GUIs (left a, right b)

In addition to the performance monitoring GUI described earlier, a more comprehensive GUI to complement the maintenance activities is also developed.

The scenario for this GUI implementation starts with performance monitoring which enables end-user to detect performance problems prior to specific building equipment. In our case a decline in the heat output and an increase in electricity consumption of the geothermal heat pump is detected. Secondly, the responsible maintenance technician who is specified with ARIS Model[1] is informed to diagnose the problem. Finally, maintenance staff performs the required maintenance activities that are specified with ARIS EPC.

Figure 5.16 b depicts the maintenance prototype user interface. This GUI retrieves and presents inventory data, the ARIS process model for specified maintenance tasks and equipment schematics. Onsite maintenance staff is

[1] ARIS Architecture of Integrated Systems is developed by IDS Prof. Scheer GmbH as a business process engineering tool. ARIS as a modelling method provides semi-conceptual methods of describing process-organisational issues.

better equipped to track spare part inventory and to see availability of required spare parts, perform exact maintenance activities as defined with ARIS EPC model and visualise technical drawings for the specific equipments.

5.7 The Chapter Conclusion

In this chapter, the Holistic Multi-Dimensional Information Management System was described with its components: Data Warehouse core, Extraction, Transformation and Loading (ETL) tool and Information Representation tools.

The purpose of the developed system is to store, integrate, analyse complex data sets from multiple data and information sources such as wired/wireless sensing devices (sensors and meters) and BIM tools. Data collected from the sensing devices is classified and categorised by the information extracted from the BIM tools and aggregated for performing multi-dimensional analysis of building performance data to support decision making processes of the different stakeholders through specifically developed GUIs.

The developed system is open to further expansions. Since the system stores all building related information, it offers a high potential for building performance monitoring and multi-dimensional analysis as a powerful tool for data aggregation. This aggregated data can be used and be further developed for more advanced data analysis techniques like Knowledge Discovery (KDD) and Data Mining.

The following chapter will introduce the validation of the developed system. Also, an affordable wireless energy management solution which is derived from the proposed system will be introduced including a possible business scenario.

Chapter 6

Validation of the System and the Business Case

Chapter 6 introduces the implementation and validation of the Holistic Multi Dimensional Information Management System in order to demonstrate and test its capabilities in an appropriately selected research building. Also, in the final section of the chapter a possible business case is discussed to demonstrate the commercial potential of the developed system.

6.1 Introduction

In this chapter, the implementation and validation of the Holistic Multi-Dimensional Information Management System (Chapter 5) will be introduced with a technical demonstration description. The Environmental Research Institute (ERI) Building which is denoted as “the living laboratory” is used as a test bed for the system validation and implementation purposes within the scope of Buildwise and ITOBO projects.

In the second part of this chapter, an affordable wireless energy management solution which is derived from the proposed system, focusing on installation in residential buildings, will be introduced. A possible business scenario will also be discussed in the final part of the chapter in order to demonstrate the commercial potential of the system.

6.2 The ERI Building

The building of the Environmental Research Institute (ERI) is used as a test bed for our research in order to implement and validate the system described in this thesis. The ERI building is a 4500 m^2 office and laboratory facility located on the campus of University College Cork, Ireland. The building is equipped with geothermal heat pumps, under floor heating systems and different types of solar panels. It has a Building Management System with 180 wired sensors and meters. Additionally, a wireless sensor network along with wireless sensors and meters has been operational since April 2008. Sensors include temperature, humidity, CO_2 and lighting sensors. Meters include devices to measure electricity, mains water, cold water, gas, lighting, energy consumption, boiler heat, solar heat and under floor heat.

A technical overview of the ERI Building is provided in Table 6.1.

<table>
<tr><td>Location:</td><td>Lee Road, Cork, Ireland</td><td rowspan="3"></td></tr>
<tr><td>Climate:</td><td>(08°30´48´´W,
51°53´44´´N)

North-South facing</td></tr>
<tr><td>Inauguration:</td><td>2006</td></tr>
<tr><td>Type:</td><td colspan="2">The low energy facility usually consists of a mixture of lab and office facilities. The building structure is based on low energy features such as passive solar architecture, improved thermal bridging details, reduced infiltration levels and quality natural lighting and ventilation.
• Superstructure: exposed concrete
• Façade: wood-framed windows, high-performance glazing</td></tr>
<tr><td>Size and Occupation</td><td colspan="2">1. 4500 m^2 of laboratory, office and meeting space over three floors.
2. The building is currently capable of housing approximately ninety researchers.</td></tr>
<tr><td>Heating, Ventilation, Cooling</td><td colspan="2">The following services items will directly relate to the low energy performance of the building:
1. Solar Collectors
• evacuated tube & flat plate for DHW and pre-heat of heat pump aquifer loop
2. Geothermal Systems
• 88 kW Heat Pump with aquifer open loop, Aquifer water source system for the heat pump
3. Cooling and Air Handling
• 6 heat pumps (2,2 kW) for cold rooms
• 4 AHUs for Labs (incl. heat recovery section)
4. Back-Up for Renewable Systems
• Gas Fired Boiler (163 kW)
5. Under floor heating system.
6. High frequency lighting.
• Advanced lighting controls.</td></tr>
<tr><td>BMS</td><td colspan="2">1. Cylon Controls
• Individual room thermostats and controls.
• 100 sensors, 180 actuators</td></tr>
</table>

Table 6. 1: The ERI Building Overview.

6.3 The ERI Building Demonstrator– Objectives

The main objective of the ERI Building Demonstrator is to implement and validate the Holistic Multi-Dimensional Information Management System to monitor and analyse the performance of the ERI Building with regards to different stakeholder requirements by using the data collected from wired/wireless sensor and meter network.

As the environment in the ERI is controlled by a wired Building Management Systems, it provides an ideal benchmark and comparison point towards wireless building management. The choice of sensors and the wireless sensor network design are complementary to the current wired BMS installation but will also be evaluated in a standalone fashion to demonstrate the value of a wireless solution compared to a wired with regard to retrofitability, flexibility, and cost efficiency. Table 6.2 gives an overview of the demonstrator.

Requirements	1. Monitoring of consumption data. • Electricity • Water • Gas 2. Monitoring of CO_2 emissions. 3. Monitoring a particular zone. • Passive Infrared Occupancy • Radiant Temperature • Temperature • CO_2 occupancy • Lighting Level • Humidity • Electricity Meter • Lighting Electricity Meter
Implementation	1. Mains Meters 2. Zone Meters 3. Room Sensors 4. Building System Sensors and Meters
Selected Zones and Building Systems	1. Open plan office (Room 1.23) in the ERI-Building is selected for “in depth” analysis of the User Comfort Parameters. 2. Under Floor Heating Manifold (UHF 1.03) is selected for monitoring and analysing the performance of the building systems.

Table 6. 2: Demonstrator Overview

6.4 Implementation Scenarios

The multi-dimensional analysis of a selected building performance scenario will be introduced for the ERI Building Demonstrator

The structure of the implementation scenarios is as follows:

1. *Description:* The scenario specification starts with a short textual description of the scenario and its goals.
2. *Graphical Description:* This part of the scenario specification contains a graphical representation of the scenario in order to illustrate the major actors (acting components) and activities supported by the scenario. A UML use case diagram which shows use cases, actors, and their interrelationships (Scott 2004) is developed for illustration.
3. *Use Cases:* The fourth part briefly describes potential use cases in order to show the interaction of packages to solve the use cases. A UML Sequence Diagram (Scott 2004) which models the sequential logic, in effect the time ordering of messages between classifiers is developed for illustration purposes.
4. *Demonstrators:* It is envisaged that each scenario "materializes" in the demonstrator installed in UCC's Environmental Research Institute (ERI) building.

6.4.1 Scenario: The Multi-Dimensional Analysis of Building Performance

This scenario addresses the collection, aggregation and representation of different data streams to various stakeholders (e.g. owner, facility manager, user/tenant, building technician) in order to perform multi-dimensional analysis of building performance data. Data acquisition is based on the current BMS system's wired sensor network and a first prototype implementation of Buildwise and ITOBO projects' wireless sensor/meter network. Compiled performance data includes:

- Energy Consumption Data (conventional and renewable sources)
- User Comfort Data (Temperature, CO_2-level, Humidity, Lux-Level)
- Environmental Impact Data (CO_2-Footprint)
- Building systems performance data (Under Floor Heating System)

6.4.1.1 Graphical Description

Figure 6.1 depicts the use case diagram for the specified scenario. In this diagram, four main actors such as Building Owner, Facility Manager, Occupant/Tenant and Building Technician are illustrated with their roles. Also, the Holistic Multi-Dimensional Information Management System is depicted as the system component.

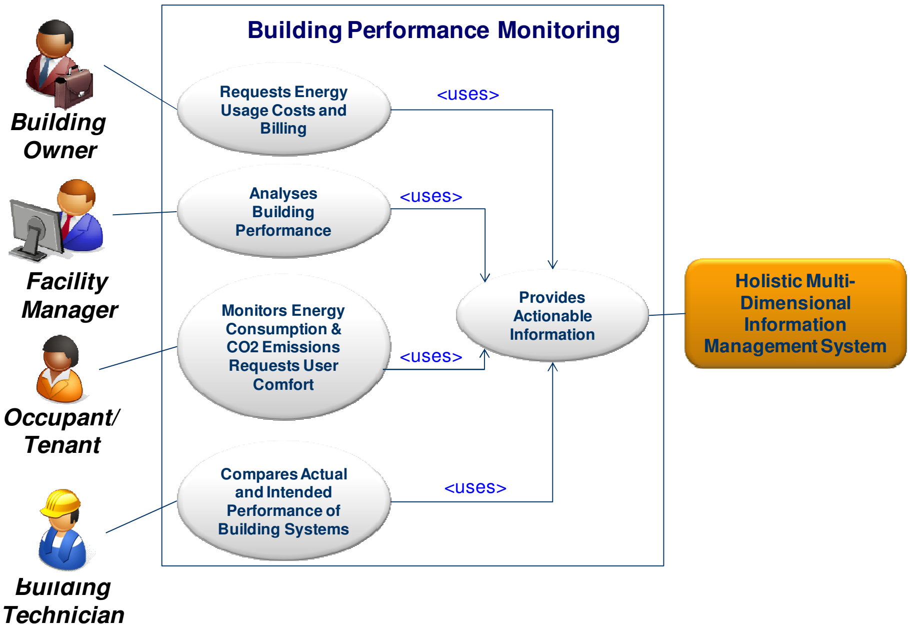

Figure 6. 1: Use Case Diagram for the Scenario: Building Performance Monitoring

6.4.1.2 Use Case Definitions

In this section three different use cases will be introduced in relation to the Building Performance Monitoring Scenario. In order to illustrate these use cases UML sequence diagrams are used to specify relationship between the different components of the Holistic Multi-Dimensional Information Management System described in the Chapter 5.

Use Case 1: Extracting Data from WSN and Populating Fact Data

Sensor data needs to be extracted from the wired/wireless sensor and meter network (WSN) and loaded to the Fact Data table of the Data Warehouse core. Figure 6.2 depicts a UML sequence diagram to illustrate data extraction from WSN and populating the fact data. There are four system components such as WSN, Operational Data Store (ODS), Extraction Transformation and Loading (ETL) Tool and Fact Data are depicted. These system components were explained in Chapter 5.

Data collected from the WSN initially stored in the ODS which acts as a preliminary data repository for data cleaning and integrity checks. ETL tool extracts this pre-processed sensor data, transforms data into fact data table structure and loads (populates) to the Fact Data table.

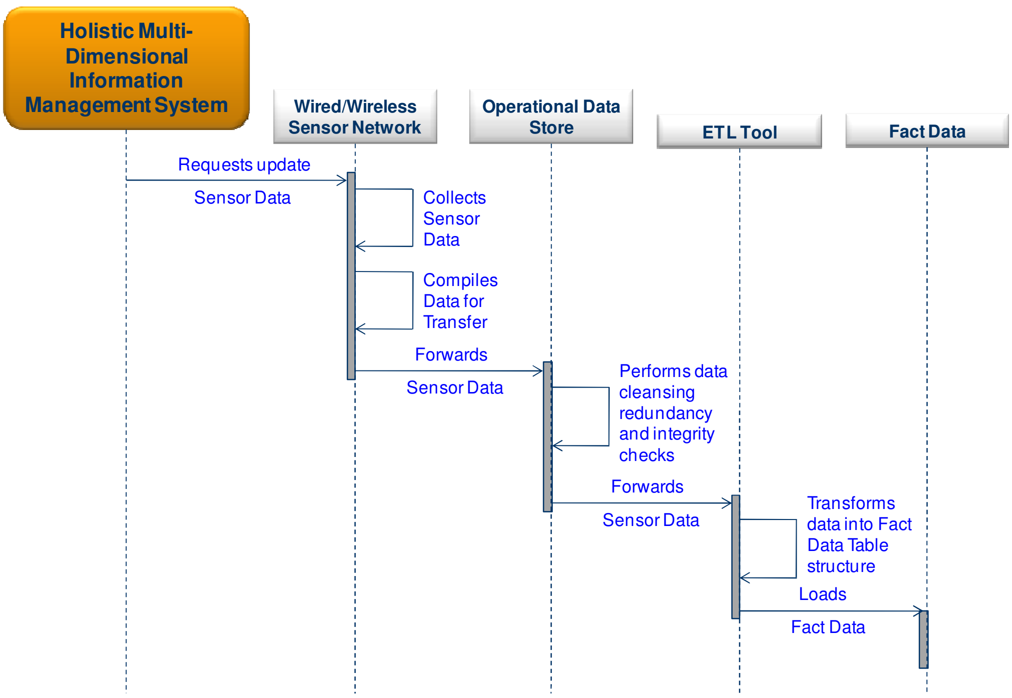

Figure 6. 2: Extracting Data from WSN and Populating Fact Data

Use Case 2: Populate Dimensional Data

The dimensional data (e.g. rooms in a building and their usage) which is categorises and classifies the fact data needs to be updated on regular intervals from the BIM tools. There are three system components: IFC Data Extraction Tool, ETL Tool, Dimensional Data and a BIM component such as a CAD Tool are illustrated in the sequence diagram (Figure 6.3).

The update process is initiated automatically by the system itself with regards to pre-programmed intervals and/or in case of alterations being made within the Building Information Model.

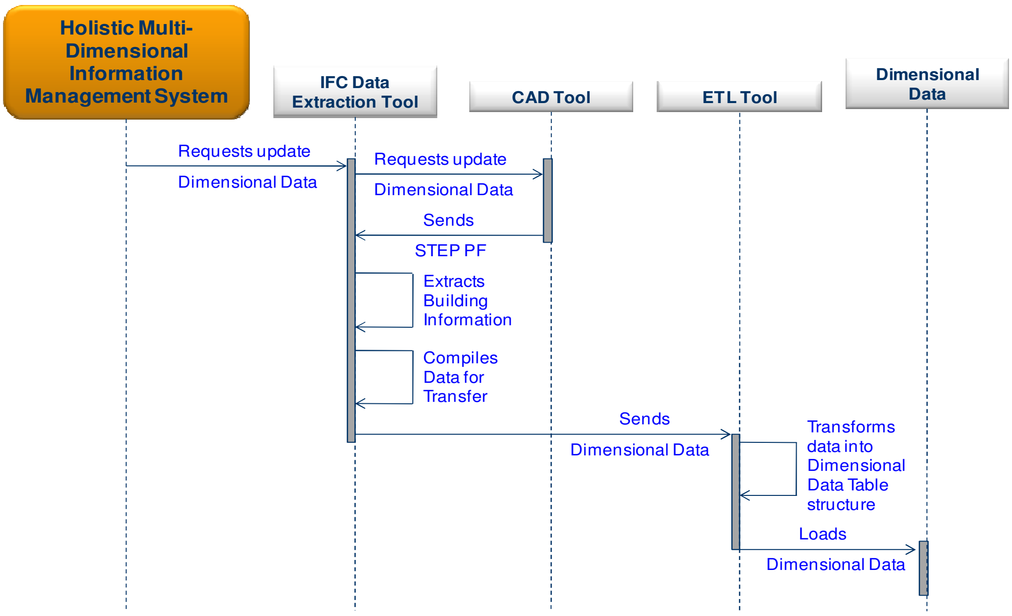

Figure 6. 3: Extracting Data from the BIM and Populating Dimensional Data

Use Case 3: Information Representation

Information representation is maintained through context sensitive graphical user interfaces (GUI) developed for Building Owner, Facility Manager, Occupant/Tenant and Building Technician. These GUIs provide access to the data stored in the Data Warehouse supporting the different views defined by the cubes. The developed GUIs support a data warehouse interface. This maintains that all interaction with the Data Warehouse is accessible through a generic mechanism supporting service oriented architecture. Figure 6.4 depicts the UML sequence diagram for the GUIs developed for different stakeholders.

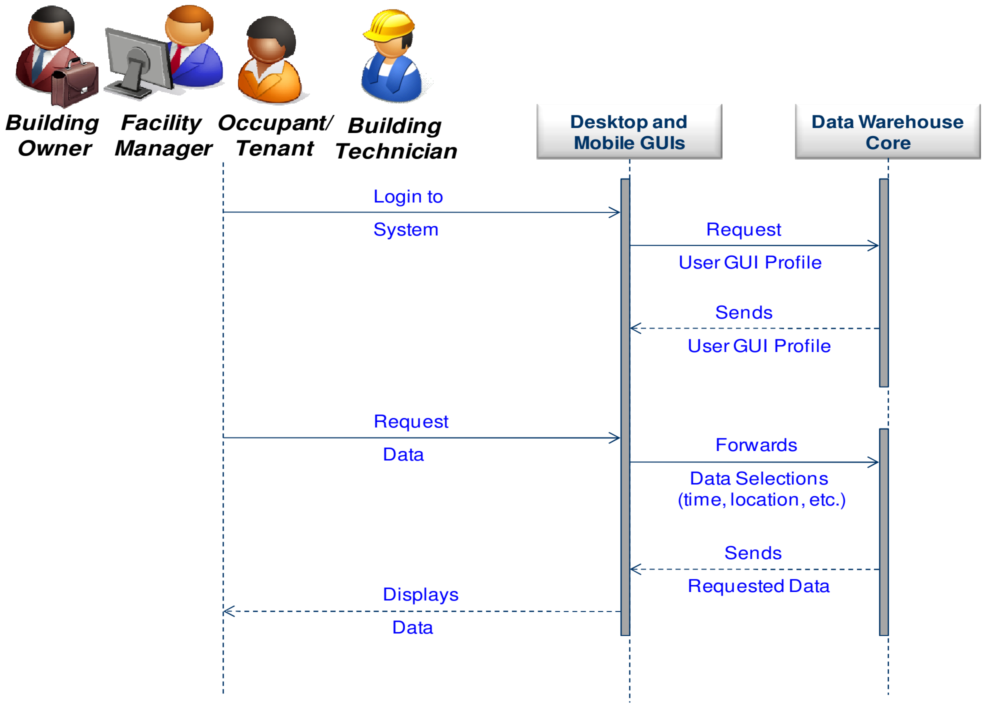

Figure 6. 4: Information Representation

6.5 System Requirements

In the scope of the scenario description, the system requirements for the ERI Building demonstrator are introduced in this section.

The BuildWise and ITOBO projects provide software and hardware for mesh networking, management and middleware functionality.

In the first phase, the project team will deploy Tyndall (Tyndall 2010) sensor nodes and an open source software stack in order to collect basic environmental data – heat, light, humidity and mains/sub-metering data.

In the second phase, off-the-shelf component sensors and meters will be deployed to collect sensor and meter data.

In the final phase, the data collected from the wired/wireless sensor and meter network will be aggregated in the developed system for monitoring and analysis purposes.

The sensor network IEEE802.15.4 based physical layer consists of Tyndall Zigbee motes (Ó Mathúna 2008) (Tyndall Mote 2010) that contains three basic layers, these are RF transceiver, Sensor and Power layers which are covering the open plan office 1.23 in the ERI Building.

The sensor nodes sample their sensors (radiant temperature, room temperature, relative humidity and CO2) update every 1 to 3 minutes depending on the sensor reading settings and send the readings over IEEE802.15.4 wireless link to the particular base mote. The base mote is connected over USB link to a gateway (GW) device.

The GW devices, providing a wireless backbone layer based on ad-hoc networking using OLSR based routing, are Soekris embedded PCs with IEEE802.11 (WiFi) based wireless network interfaces. The GWs relay sensor data into a database.

The PC server layer is running an Oracle 11g database for storing the data from the sensors. In order to get convenient access to the stored data over internet set up web services is used as service oriented architecture

The Operating System is also being customised to be incorporated with the BuildWise/ITOBO application specific multi sensor systems which are being developed and incorporated into the heterogeneous Wireless Sensor Network.

Table 6.3 below depicts the hardware and software requirements for the validation of the system in the ERI Building. These requirements are collected under four main headings. These are: mains metering, zone metering, building systems sensors, zone sensors and software.

Hardware/Software Requirements		Description	Type
Mains Metering	Incoming Electric Meter	Used for metering the whole building electricity consumption. Data extracted from the BMS	Cylon
	Incoming Water Meter	Used for metering the whole building water consumption. Data extracted from the BMS	Cylon
	Incoming Gas Meter	Used for metering the whole building gas consumption. Data extracted from the BMS	Cylon
Zone Metering	Electricity Meter	Used for metering the electricity consumption of a particular room/zone	Archmeter PA 310
	Lighting Electricity Meter	Used for metering the lighting electricity consumption of a particular room/zone	Archmeter PA 311
Building Sys Sensors	Water Flow Rate Sensor	Used for metering the liquid flow quantity from outside of a pipe	Sheinitech STUF-300EB
	Water Flow Temp. Sensor	Used for measuring the liquid flow temperature outside of a pipe	Sheinitech STUF-300EB
Zone Sensors	Passive Infrared Occupancy	Used for detecting the human presence in a particular room/zone	AMN 44122
	Radiant Temperature	Used for the measurements of thermal environments in spaces where radiation has a major influence on perceived temperature.	Cylon
	Temperature	Used for measuring the temperature	Thermistor
	CO_2 occupancy	Used for detecting the ocuupancy level. The difference between the indoor CO2 concentration and the level ouside the building indicated the occupancy and/or activity level in a space and thus its ventilation requirements.	Airtest CO2
	Lighting Level	Used for capturing indoor/outdoor light in order to make decisions on if the level of natural light is sufficient to provide the full indoor illumination level required, or if an artificial light is needed	Cylon
	Humidity	Used for measuring air quality in buildings. Extremely low or high humidity levels (the comfort range is (30 - 70% RH)) can cause discomfort to workers and can reduce building longevity. Humidity control also dictates building energy consumption during heating seasons.	STH 11
	Sensor Mote	This prototyping system enables easy integration of sensors using the modular layers available from Tyndall.	Tyndall 25 mm Mote
Software	Autodesk Revit Arch.	The ERI Building is modelled. This provides architectural building information for the Dimensional Data	
	Autodesk Revit MEP	The ERI Building systems (e.g. HVAC Sytems) is modelled. This provides information for the Dimensional Data	
	Wireless Sensor Network Design Tool	Virtual deployment of these sensors is done automatically by the WSN Design Optimisation Tool developed by CIT AWS group. This tool contains sensing device information required by the Dimensional Data.	
	Oracle 11 g	The Data Warehouse core is developed by using Oracle 11g for data storage and aggregation purposes.	

Table 6. 3: System Requirements

6.6 Sensor and Meter Deployment

The open plan office (Room 1.23) in the ERI Building is selected for validating the implementation scenarios. Figure 6.5 depicts the location of the selected room 1.23.

In total, eight sensors (3 Radiant Temperature, 2 Lighting Level, 2 Passive Infrared Occupancy, 1 CO_2 Occupancy) and two meters (1 Zone Electricity Meter, 1 Lighting Electricity Meter) are deployed for multi-dimensional analysis of a specific zone performance. Figure 6.6 depicts the positioning of the sensors and meters in the room 1.23.

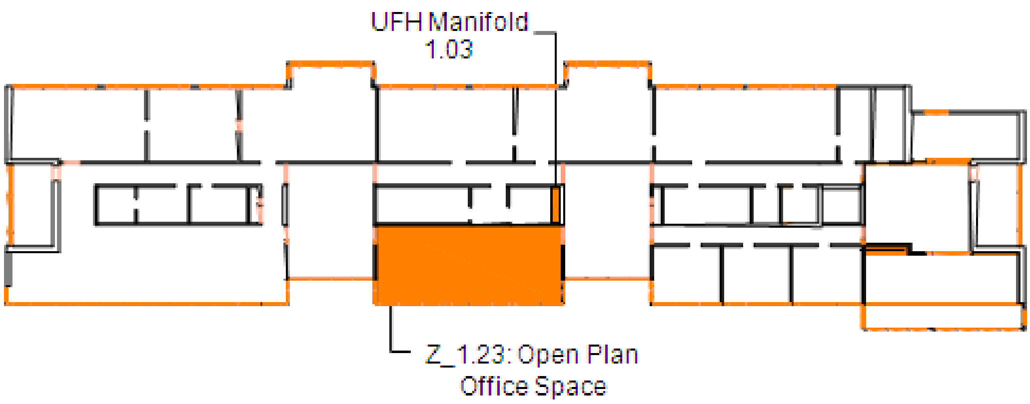

Figure 6. 5: The ERI Building first floor layout.

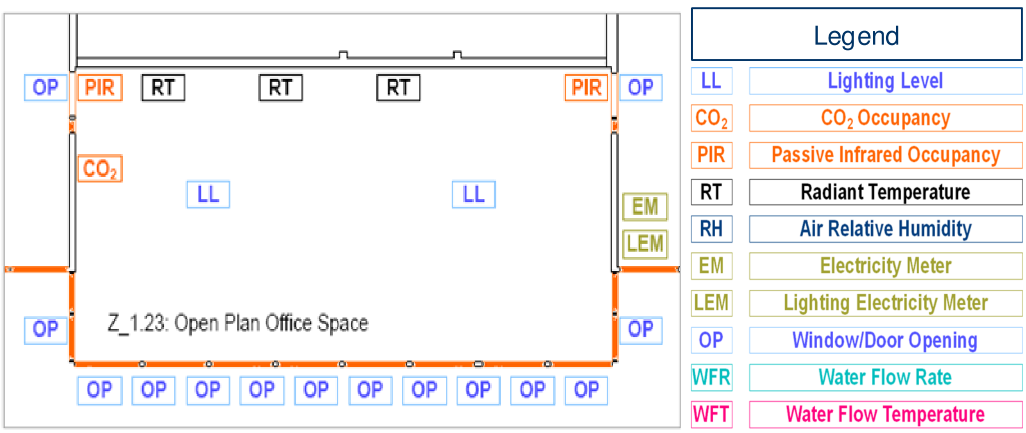

Figure 6. 6: Positioning of the sensors and meters in the room 1.23

Under floor heating manifold (UHF) 1.03 is selected as an implementation sample for monitoring and analysing the performance of the specific building systems in the ERI Building. In total five Water Flow Temperature (WFT) sensors (1 WFT sensor is deployed to the main supply, 4 WFT sensors are installed to the four different loops' return pipe) and one Water Flow Rate (WFR) sensor is installed to the main supply. Also one Relay Controller (RC) is installed for controlling. Figure 6.7 depicts the schematic of UHF 1.03 and the sensor placement.

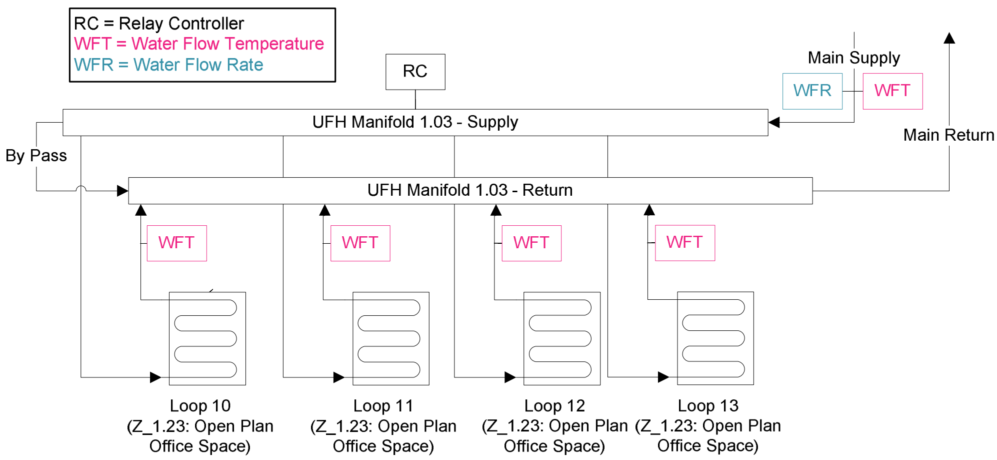

Figure 6. 7: Schematic of the under floor heating circuit (UHF 1.03)

6.7 The Holistic Multi-Dimensional Information Management System

The dynamic data collected from the wired/wireless sensor/meter network and the persistent data extracted from the BIM tools should be stored, aggregated and represented to the stakeholders for performing multi-dimensional analysis of the building performance.

In order to address these issues, the Holistic Multi-Dimensional Information Management System (Chapter 5) is used. The system extracts sensor data from building management systems and from wireless sensor/meter network. Collected sensor/meter data is stored in the operational data store for data cleansing and redundancy check processes. This pre-processed data is loaded to the fact data section of the data warehouse system via an Extraction, Transformation, and Loading (ETL) tool. Simultaneously, data gathered from the building information model is loaded to the dimensional data section of the data warehouse. Loaded fact data and dimensional data is aggregated with regards to different stakeholder requirements in the data warehouse system and presented through specific Graphical User Interfaces.

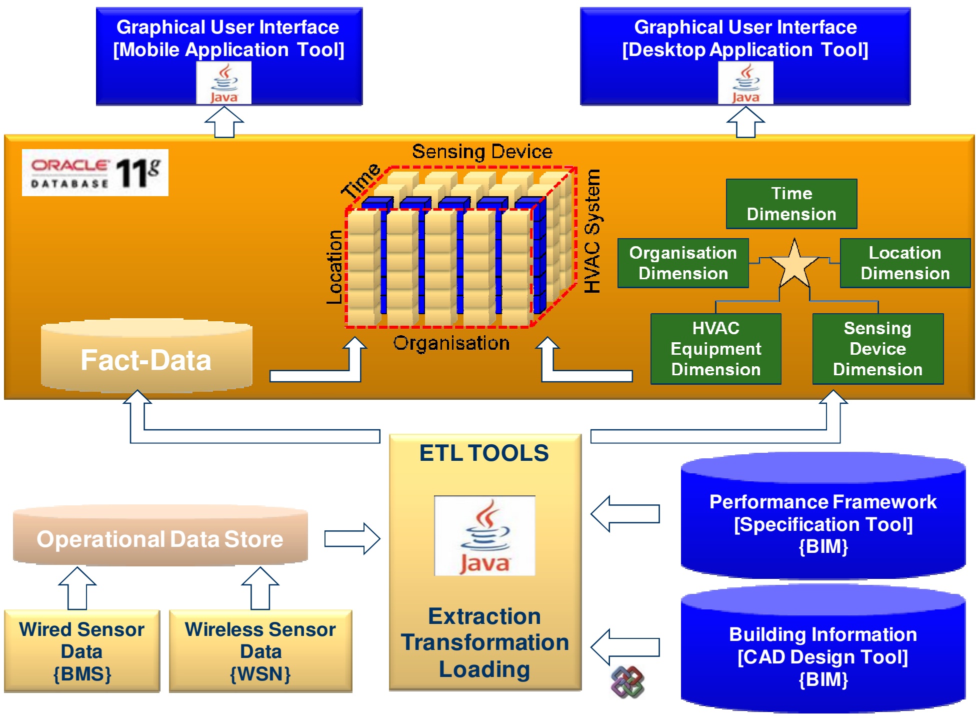

Figure 6. 8: Architecture for the Holistic Multi Dimensional Information Management System

The system architecture to support multi-dimensional analysis of building performance data is depicted in Figure 6.8. The system consists of three integrated main components which were explained in detail in Chapter 5.

These components are:

- Data warehouse core
- Extraction, Transformation, Loading (ETL) Layer
- Information Representation Layer (Graphical User Interfaces)

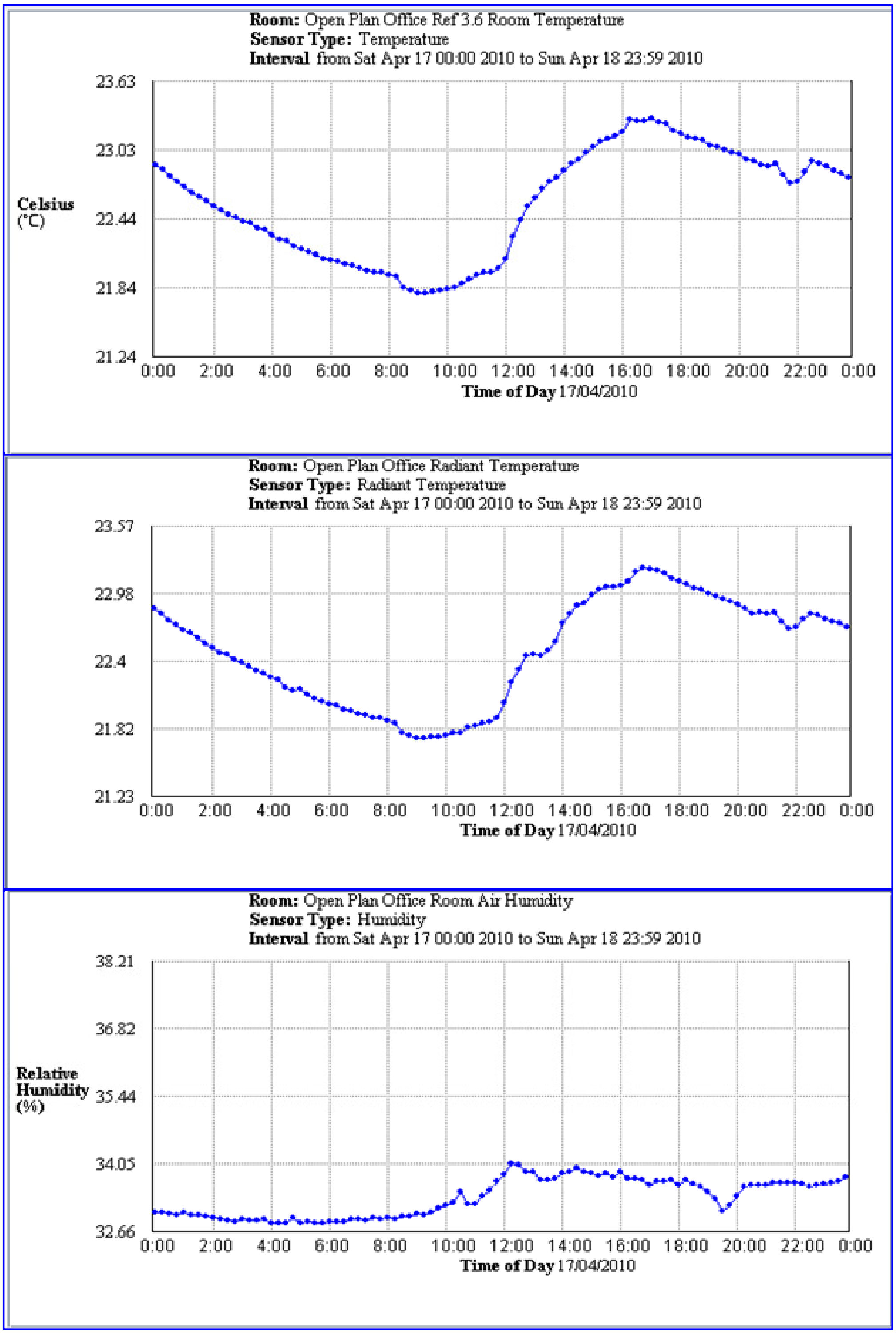

Figure 6. 9: Graphical Representation of the Sensor Readings

Information is represented through stakeholder specific GUIs for monitoring and analysis. GUIs developed for the stakeholders such as occupant/tenant, facility manager, building owner and building technician, were introduced in Chapter 5.

Figure 6.9 depicts the graphical representation of the sample sensor readings collected from the room 1.23. The graphs represent temperature, radiant temperature and air humidity level readings collected from the relevant sensors deployed in the sample open office space. 17-Apr-2010 and 18-Apr-2010 are specified as the time interval for the readings. As illustration purposes daily readings for the 17-Apr-2010 are depicted in the figure. The developed GUIs have build-in functionalities to visualise each specific day separately for the given time interval. For the demonstrator plot style graphs are implemented for more detailed visualisation. It is also possible to implement other graph styles e.g. bar charts as depicted in the Chapter 5 for the less technical end users.

Expected data volume for the ERI Building demonstrator is given in the table 6.4a. Building Performance Data is provided by 8 wireless sensors (3 Radiant Temperature, 2 Lighting Level, 2 Passive Infrared Occupancy, 1 CO_2 Occupancy) and 2 wireless meters (1 Zone Electricity Meter, 1 Lighting Electricity Meter). Additionally, the expected data volume figures which cover the overall ERI building performance data is provided in table 6.4b to demonstrate amount of records logged annually.

Sensing Devices	**Sensing Interval**	**Reading (Daily)**	**Readings (Annually)**	**Quantity of the Devices**	**Records (Annually)**
Wireless Sensors	1 min.	1440	525,600	8	4,204,800
Wireless Meters	1 min.	1440	525,600	2	1,051,200
Total Records					5,256,000

Sensing Devices	Sensing Interval	Reading (Daily)	Readings (Annually)	Quantity of the Devices	Records (Annually)
Wired Sensors	15 min.	96	35,040	180	6,307,200
Wireless Sensors	1 min.	1440	525,600	80	42,048,000
Meters	15 min.	96	35,040	65	2,277,600
Total Records					50,632,800

Table 6. 4: Expected Data Volume Figures (Table a and b)

6.8 Analysis of the Similar Products

In this section, the Holistic Multi-Dimensional Information Management System is analysed with the similar products/systems currently available. These products/systems are grouped under the five main domains; Building Control Automation, Monitoring &Targeting, FM, Management & Consultancy and System & Component manufacturer.

As a result of the interviews carried out with the Buildwise and ITOBO projects' industry partners; Cylon Controls, Vector FM, HSG Zander (HSG Zander 2010), Arup (Arup 2010) and Intel (Intel 2010), nine system features have been outlined as the critical and innovative features to evaluate the developed system with regards to the available products/systems. These features are; (1) Web Services (2) Real Time Analysis (3) Wireless Data Logging (4) Desktop Application (5) Mobile Application (6) Multi-Dimensional Data Analysis (7) Performance Benchmark (8) Stakeholder Specific Configuration (9) Multiple stakeholder application.

As depicted in the Table 6.5, the developed system is capable of satisfying all of these critical and innovative features outlined by the industry partners.

	Company	Web Services	Real Time Analysis	Wireless Data Logging	Desktop Application	Mobile Application	Multi Dimensional Data Analysis	Performance Benchmarking	Stakeholder Specific Configuration	Multi Stakeholder Application
Building Control Automation	Lightwave Technologies	Yes	Yes	No	No	No	No	Historical Data	No	No
	Cylon	Yes	Yes	Yes	Yes	No	No	Historical Data	No	No
	Siemens	Yes	Yes	Yes	Yes	Yes	No	Historical Data	FM/Field Crew	No
	TAC Satcwell	Yes	Yes	Yes	No	Yes	No	Historical Data	No	No
	Johnson Controls	Yes	Yes	Yes	Yes	Yes	No	Historical Data	No	No
Monitoring and Targeting	ResourceKraft	Yes	Yes	No	No	No	No	Historical Data	No	No
	Wirelite	Yes	Yes	Yes	No	No	No	Historical Data	No	No
	Hawksbury Esighenergy	Yes	No	No	No	No	No	Historical Data	Expert and Basic	No
FM	Vector FM/Spokesoft	Yes	Yes	No	No	Yes	Not Relevant	Not Relevant	Manager/ Technician	No
Mngmt. Consult.	IBM Green Sigma	Not Relevant	Not Relevant	Not Relevant	Not Relevant	Not Relevant	Yes	Historical Data	Not Relevant	No
	Intel	Intranet	Yes	No	Yes	No	Yes	Normalised Historical	No	No
System/ Component Producer	EI Electronics	No	Yes	Fire Systems	No	Not Relevant	Not Relevant	Not Relevant	Not Relevant	No
	EPI Sensor	No	No	Yes	No	No	No	Not Applicable	No	No
	Enocean	No	No	Yes	No	No	No	Not Applicable	No	No
The Holistic Multi-Dimensional Information Management		Yes	Yes	Yes	Yes	Yes	Yes	Multiple Sources	Yes	Yes

Table 6. 5: Comparison of the developed system with the similar products. (Data extracted from (BuildWise 2010)).

6.9 Business Case: Wireless Energy Performance Monitoring and Heating/Lighting Control System for Residential Buildings

In this section, an affordable wireless energy management system which is derived from the Holistic Multi-Dimensional Information Management System will be introduced coupled with requirements and cost analysis. Also, a Return on Investment (ROI) analysis will be introduced in the final part of this section.

The proposed system enables visualization of historical/real-time energy consumption and CO_2 emissions. Also it provides wireless heating/lighting controlling of the individual zones (rooms) within an apartment flat.

Three different types of apartment flats from different market segments have been examined for the business case. These flats are;

- Four bedroom luxury apartment flat for high income segment.
- Three bedroom apartment flat for medium income segment.
- Two bedroom social apartment flat for low income social housing segment.

In the next sections use case scenarios, system requirements and pricing information will be introduced.

6.9.1 Use Case Scenarios

The proposed system will support three scenarios in order to visualise building consumption data to the stakeholders and optimise building energy use. These are: (a) Energy consumption monitoring, (b) Heating System Controlling and (c) Lighting System Controlling.

Energy Consumption Monitoring

Objective: Real time visualisation of energy consumption.

Data Source: Wireless Gas/Electricity/Water meters.

Data Aggregation: Time based (hourly/daily/weekly/monthly/yearly)

Heating System Controlling

Objective: Controlling the temperatures of individual zones (rooms) via controlling wireless controllers/actuators for panel radiators in each zone (room). For example, "Maintain 24 C of room temperature unless occupant leaves the room for longer than X amount of minutes."

Data Source: (a) Wireless temperature sensors. (b) Temperature set point entered by the end user (occupant).

Actuators: Wireless Controllers/Actuators for Panel Radiators.

Constraint: (a) Temperature set point (b) Presence

Lighting System Controlling

Objective: Controlling the lighting levels (Lux Levels) of individual zones (rooms) via controlling wireless adjustable lighting switches. For Example "Maintain 500 Lux in the room unless the room is not occupied."

Data Source: (a) Wireless lux level sensors (b) Presence sensors.

Actuators: Wireless adjustable lighting switches.

Constraint: (a) Lux level set point (b) Presence

6.9.2 Required Installations

The list of required installations for the system is provided in the Table 6.6.

Each flat contains	Required Replacements
Electricity Meter	Wireless Electricity Meter
Gas Meter	Wireless Gas Meter
Water Meter	Wireless Water Meter
Panel Radiators in each room	Wireless Controllers/Actuators for Panel Radiators in each room
Lighting Switches in each room	Wireless adjustable switches
Wall Hung Natural Gas Boiler	Wireless Controller/Actuators for Wall Hung Natural Gas Boiler
	Wireless Temperature Sensors for each room
	Wireless lux sensors
	Wireless presence sensors
	Wireless touch panel monitors with processing capability for energy consumption monitoring and control of the system (one monitor for each flat)

Table 6. 6: List of required installations within the flats.

6.9.3 Simplified System Architecture

This section introduces the simplified system architecture (Figure 6.10) for monitoring and optimisation of the energy performance of specific apartment blocks.

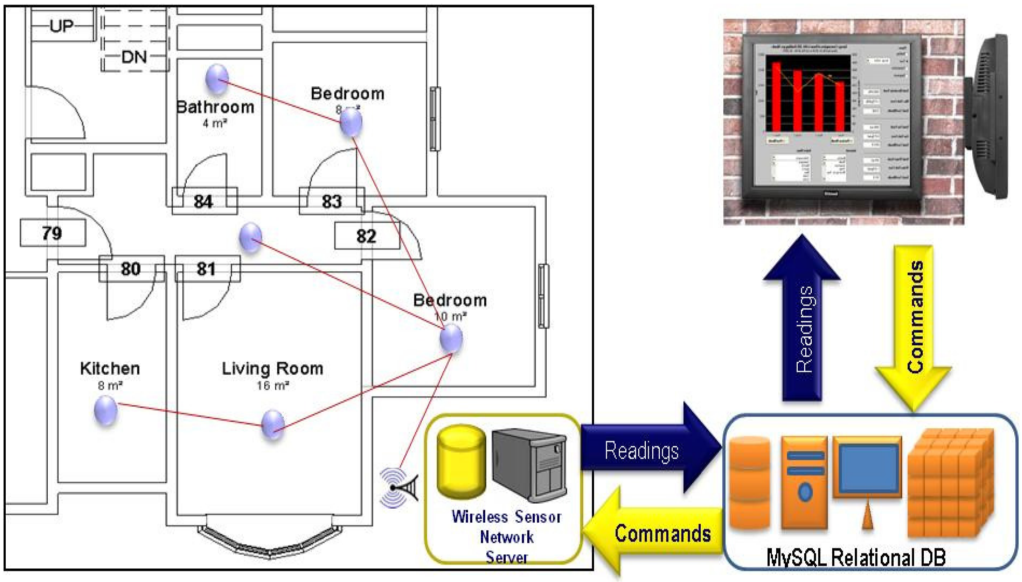

Figure 6. 10: Simplified System Architecture

In this architecture dynamic data collected from wireless sensors and meters are stored and aggregated in the DW. Aggregated data is visualised through specifically developed GUIs and touch screen monitors to the residents. This aggregated data is also used for energy use optimisation of the flat through the actuators installed.

6.9.4 System Deployment

The following is a wireless system for a 4 bedroom apartment. The apartment flat has four bedrooms each with a radiator and temperature sensor. The main living room is also equipped with three radiators and two temperature sensor. The gas boiler in the kitchen is enabled by the wireless control and gas consumption is metered, also there is a radiator and temperature sensor present. The water is also metered from the kitchen. There are three bathrooms in the apartment. One is on-suite to the master bedroom which has a radiator and temperature sensor. The main communal bathroom also has a radiator and temperature sensor. The electricity is being monitored from at the meter coming into the apartment.

Figure 6. 11: Placement of the sensors, meters and actuators.

Figure 6.11 depicts the location off all control elements. The main control panel and the display panel have not been positioned on the drawing as this would be a matter of choice. The locations for the Electricity/Water and Gas meters have been assumed. This could also be moved as a matter of choice. Also the locations of the wireless transmitters and receivers have been placed on the drawing for illustration purposes and may not be the final location of these system elements. The locations have only been placed on one apartment on the drawing as these can be mirrored.

The following table is a breakdown of the points required for the deployment of the wireless devices:

		4 Bedroom Apartment Flat		3 Bedroom Apartment Flat		2 Bedroom Apartment Flat	
Description	**Type**	**No. Virtual Inputs**	**No. Virtual Outputs**	**No. Virtual Inputs**	**No. Virtual Outputs**	**No. Virtual Inputs**	**No. Virtual Outputs**
Temperature Sensor	*Virtual Analog*	11		8		5	
Lux Sensor	*Virtual Analog*	12		9		6	
Presence Sensor	*Virtual Digital*	12		9		6	
Electricity Meter	*Virtual Digital*	1		1		1	
Water Meter	*Virtual Digital*	1		1		1	
Gas Meter	*Virtual Digital*	1		1		1	
Single Gang Light Switch	*Virtual Digital*	10		7		4	
Double Gang Light Switch	*Virtual Digital*	3		3		3	
Radiator Actuator	*Virtual Digital*		12		9		6
Lights	*Virtual Digital*		11		8		5
Boiler Enable	*Virtual Digital*		1		1		1
Total		***51***	***24***	***39***	***18***	***27***	***12***

Table 6. 7: Breakdown of the points required for the wireless devices.

6.9.5 Cost Analysis

The following table depicts the component costs of the developed system for different options. Component prices are taken from the Cylon Controls 2010 Irish Euro pricelist. The items make with an asterisk (*) are not supplied by Cylon Controls and a put in for guide prices only.

These prices indicate the prototype cost of one system for three different segments. Therefore, using these R&D aimed guide prices for business oriented cost analysis is deceptive.

		4 Bedroom Apartment Flat		3 Bedroom Apartment Flat		2 Bedroom Apartment Flat	
Description	**Unit Price**	**Q**	**Total Price**	**Q**	**Total Price**	**Q**	**Total Price**
Controller (e.g. Cylon UC32.net K/ELC/WEB)	€650.00	1	€650.00	1	€650.00	1	€650.00
Touch Screen Monitor (e.g. Cylon Site Guide)	€650.00	1	€650.00	1	€650.00	1	€650.00
Wireless Transmitter/ Receiver	€252.00	3	€756.00	1	€252.00	1	€252.00
Wireless Temperature Sensor	€86.11	11	€947.21	8	€688.88	5	€430.55
Wireless Radiator Relay	€127.43	12	€1,529.16	9	€1,146.87	6	€764.58
Radiator Actuator*	€50.00	12	€600.00	9	€450.00	6	€300.00
Lux/Presence Sensor	€50.00	12	€600.00	9	€450.00	6	€300.00
Single Gang Light Switch	€87.00	10	€870.00	7	€609.00	4	€348.00
Double Gang Light Switch	€89.50	3	€268.50	3	€268.50	3	€268.50
Light Relay	€127.43	11	€1,401.73	8	€1,019.44	5	€637.15
Meter Input	€124.20	3	€372.60	3	€372.60	3	€372.60
Boiler Enable Relay	€127.43	1	€127.43	1	€127.43	1	€127.43
Total		**€8,772.63**		**€6,684.72**		**€5,100.81**	
Total (35% Discounted)		**€5,702.21**		**€4,345.07**		**€3,315.53**	

Table 6. 8: Cost Analysis

According to the interviews with the component suppliers these prices can be reduced by 30-40% in the case of increase in the quantities supplied. This assumption is also consistent with the “Economies of Scale” principle of micro-economics. These are the cost advantages that a business obtains due to expansion. They are factors that cause a producer’s average cost per unit to fall as scale is increased. For example output can be doubled for less than a doubling of cost (Pyndyck & Rubinfield 2001). Therefore, in the Table 6.8 35% discounted prices are also included for a more realistic cost analysis.

In addition to the systems presented a low cost option (Option B) for the two bedroom social apartment flats is also developed. In this system the lighting control scenario is cancelled to reduce costs. The total cost of Option B is €2,305.65.

The likely installation costs for a single apartment were determined using a number of assumptions as given:

Electrician Wiring and Installation:	€60
Main Contractor Builders Work:	€100
Total:	€160

This rough estimation has been made using the following assumptions;

- Irish supply of controls equipment
- Typical EU electrician labour cost of €60 for electrician & apprentice
- Builders works assuming minimal concrete disturbance

This estimation gives very general cost estimation for a single independent apartment.

Costs would be further reduced if the building was taken as a whole and controlled centrally. This would be achieved for both systems by requiring less controllers and wireless receivers.

6.9.6 Return on Investment Analysis

Energy prices and energy consumption facts (typical practice) of residential buildings are as follows:

Household electricity price in Ireland[1]:	€ 0.19
Household natural gas price in Ireland[2]:	€ 0.061
Electricity consumption for residential buildings[3]:	60 kWh/m^2
Fossil Fuel consumption for residential buildings[4]:	201 kWh/m^2

Calculation of the energy consumption costs per m^2 for residential buildings:

Electricity cost: € 0.19*60 kWh/m^2 = 11.40 €/m^2

Fossil Fuel cost: € 0.061*201 kWh/m^2 = 12.26 €/m^2

Total Energy Consumption Cost: 23.66 €/m^2

Calculation of the total energy consumption costs of the demonstrator apartment flats:

2 Bedroom Flat: 100 m^2* 23.66 €/m^2 = € 2366.10 per annum

3 Bedroom Flat: 150 m^2 * 23.66 €/m^2 = € 3549.15 per annum

4 Bedroom Flat: 250 m^2 * 23.66 €/m^2 = € 5915.25 per annum

[1] Per kWh, including tax, Sustainable Energy Ireland, List of Energy Prices, 4th Quarter 2009
[2] Per kWh, including tax, Sustainable Energy Ireland, List of Energy Prices, 4th Quarter 2009
[3] Per annum, CIBSE Energy Benchmarks: Typical Practice for Northern Ireland Residential Buildings
[4] Per annum, CIBSE Energy Benchmarks: Typical Practice for Northern Ireland Residential Buildings

Calculation of the monetary value of the energy savings:

2 Bedroom Flat: € 2366.10 per annum * 20% saving [5]= €473.22 per annum

3 Bedroom Flat: € 2366.10 per annum * 20% saving = €709.83 per annum

4 Bedroom Flat: € 5915.25 per annum * 20% saving = €1183.05 per annum

Net Present Value Analysis:

The net present value (NPV) of a time series of cash flows, both incoming and outgoing, is defined as the sum of the present values (PVs) of the individual cash flows.

Each cash inflow/outflow is discounted back to its present value (PV). Then they are summed. Therefore NPV is the sum of all terms $\frac{R_t}{(1+i)^t}$, where

t - the time of the cash flow

i - the discount rate (the rate of return that could be earned on an investment in the financial markets with similar risk.)

R_t - the net cash flow (the amount of cash, inflow minus outflow) at time *t*

If the NPV is greater than 0, it means the investment would add value to the investor and the investment should be accepted. If the NPV is less than 0, it means the investment would subtract value from the investor and it should be rejected. In case of the NPV is equal to 0, it means the investment would neither gain nor lose value for the investor. In this situation, other criteria, e.g. legislative drivers should be taken into consideration for the investment decision.

[5] This is an estimation based on research findings and case studies of (Salsbury 2000), (Mills et al. 2004) and (DIN EN 2007). The actual saving quantity can only be confirmed after the system deployed and tested properly.

The assumptions for the NPV calculation are:

Inflation Rate: 5%

Rate of Return: 7%

Product Life Cycle: 8 years

Table 6.9 below depicts the NPV calculation of the system.

Years	4 Bedroom Flat	3 Bedroom Flat	2 Bedroom Flat	2 Bed. Flat (Opt. B)
T0	-€5,702.21	-€4,345.07	-€3,315.53	-€2,305.65
T1	€1,159.85	€695.10	€463.94	€463.94
T2	€1,137.11	€681.47	€454.84	€454.84
T3	€1,114.81	€668.11	€445.93	€445.93
T4	€1,092.96	€655.01	€437.18	€437.18
T5	€1,071.52	€642.16	€428.61	€428.61
T6	€1,050.51	€629.57	€420.21	€420.21
T7	€1,029.92	€617.23	€411.97	€411.97
T8	€1,009.72	€605.12	€403.89	€403.89
NPV	€2,964.20	€848.69	€151.04	€1,160.91

Table 6. 9: Net Present Value (NPV) Calculation.

NPV >0 means that this project will add value to the investor. As depicted in the table all three types of the proposed system adds value to their investors which makes the proposed systems feasible for the stakeholders.

6.7 The Chapter Conclusion

In this chapter, implementation and validation of the Holistic Multi Dimensional Information Management System was described in order to test and demonstrate its capabilities in an appropriately selected research building.

The multi dimensional analysis of the building performance data is selected as the implementation scenario for the developed system. This scenario covered the collection, aggregation and representation of different data streams to various stakeholders.

The open plan office space (Room 1.23) and the under floor heating circuit (UHF 1.03) located in the ERI Building were selected as implementation samples for the scenario described.

In total, 13 sensors, 2 meters and 1 relay controller were installed for monitoring the performance of the selected zone and the building system.

The data collected from the wired/wireless sensors and meters is aggregated within the developed system and the results presented through context sensitive GUIs.

The demonstrator validated the developed system's capabilities for the described scenario definition. Also, this proved that the system can be used as a nucleus for various end-product developments in the area of energy monitoring and optimisation.

In the second part of the chapter, an affordable residential building specific wireless energy monitoring and optimisation system which is derived from the research findings presented in this work were introduced.

Three different end products were introduced to target three different income segments such as luxury, middle class and social housing projects. For each segment the cost and the investment analysis were introduced. The NPV method was applied for the investment analysis. The results of the NPV analysis proved the feasibility of the proposed products.

About 85 percent of the European buildings are older than 20 years; 60 percent are older than 40 years and 30 percent are pre-war buildings (Itard 2008). Most of them are not equipped with advanced building management and control systems (Jagemar 2007). It is estimated that about 50 percent of these buildings will be renovated within the next 20 years. From a business perspective this creates a significant market potential for the developed system.

Chapter 7

The Thesis Conclusion

Chapter 7 introduces the summaries and conclusions of the research objectives undertaken in this thesis. Also, the potential future research topics will be discussed in the final section of this chapter.

7.1 Introduction

The objective of this thesis is to research and develop a methodology leading to a system which is appropriate to process and analyse building performance data for energy efficient building operation. In order to reach this objective, initially in Chapter 2 the building energy use and its environmental impact were discussed coupled with a review of international environmental drivers such as the Kyoto Protocol, the accord of the Copenhagen Summit and the European Union Directive on Energy Performance of Buildings. In Chapter 3, current building performance assessment and monitoring systems were reviewed to give a general definition of the domain as well as identify the deficits and weaknesses in current practices. Also, building performance monitoring related research projects were introduced to create awareness for future projections and to underline the requirements. In Chapter 4, the standardisation and integration efforts for the AEC/FM industry were analysed in order to define the requirements for developing an integration concept for using the BIM data to categorise and classify the building performance data in the Data Warehouse core. In Chapter 5, the Holistic Multi-Dimensional Information Management System for energy efficient building operation was introduced with its sub-components. Finally in Chapter 6, the implementation of the proposed system was defined with a technical demonstrator description in order to validate and test its capabilities in an appropriately selected research building. Also, an affordable residential building specific wireless energy monitoring and optimisation system which is derived from the research findings presented in this work was introduced coupled with a possible business case.

In the following sections of this chapter the essential contributions and findings of the thesis are summarised based on the research objectives. In the final section of this chapter, the potential future research topics will be introduced.

7.2 The Summary of the Research Objectives

In the preceding chapters, motivation (Chapter 2), requirements analysis (Chapter 3&4), proposed solution (Chapter 5) and validation of the proposed solution (Chapter 6) are presented. In this section, essential contributions and findings of the thesis are summarised based on the main objectives which were introduced in Section 1.3.

Objective 1: Identifying the significance of building energy use and its environmental impact with a historical analysis and future projections. Specifying the requirements for energy efficient building operation through reviewing the international regulations.

The global warming facts and figures have clearly established a link between a rise in global mean air temperature and atmospheric CO_2 levels. If emissions continue along their present trajectory it is estimated that by the end of this century average global temperatures are likely to have risen by 4^oC and possibly by 6^oC. Such increases bring with them potentially catastrophic consequences.

It is possible to ease climate change without affecting the progress of economic development with a worldwide emphasis on energy efficiency and renewable energy sources. For example, both USA and Germany have similar Gross Domestic Product (GDP) per capita figures but when it comes to GHG per capita figures, USA (23.5 Tonnes of CO_2e per capita) has nearly double emission levels in comparison to Germany (11.9 Tonnes of CO_2e per capita). As the world's third biggest economy, Germany have been continuously focusing on energy efficiency and renewable energy resources. This policy resulted as lower GHG emissions without limiting the economic growth of the country.

Currently buildings account for 25-30% of total energy related CO_2 emissions. Future projections indicate that in 2030, buildings will be responsible for 35.6% of primary energy use in the World and continue to maintain its importance. Therefore, efforts for saving energy in buildings are very crucial to cope with climate change.

Objective 2: Analysing existing building performance assessment and monitoring systems to identify the deficits and weaknesses in current practices.

An internationally accepted standardised solution has not been agreed to quantify the performance of buildings.

Current practices do not support Energy Performance of Building Directive and continuous commissioning which are the prerequisite for long term energy efficient building operation.

In the scope of the current practices building performance data is not evaluated from multiple stakeholder perspectives.

A process and a methodology leading to a system appropriate to process and analyse building performance data is required to address these deficits. Therefore, in Section 3.5 a monitoring and analysis process was introduced to develop a basis for the Holistic Multi-Dimensional Information Management System.

Objective 3: Analysing the standardisation and integration efforts of the AEC/FM industry in order to develop a flexible, standardised and extensible integration concept to maintain data exchange between the BIM tools and the DW.

At present, a full integration and interoperability among various product models is not achieved in the AEC/FM industry due to the fact that a model trying to encapsulate the entire AEC/FM industry is a huge and very complex model which demonstrates difficulties with mapping between domains.

Therefore, integration of specific tools for certain processes instead of a full BIM integration is likely to produce more accurate results for interoperability.

In this context, the Holistic Multi-Dimensional Information Management System addresses these problems by focusing on specific BIM tools and particular information within these tools which is required for building performance monitoring and analysis.

Since the IFC is the only broad building level object schema and most of the BIM vendors offer IFC compatibility with building model repositories that support integration of the data generated by multiple applications. IFC data exchange methodology is used to extract required information from the BIM tools. This extracted information will then be used within the developed system in order to classify and categorize building performance data.

Objective 4: Specifying the proposed Holistic Multi-Dimensional Information Management System with a unique data aggregation layer and web services specifically designed for building performance monitoring and analysis.

A methodology leading to a system which is appropriate to process and analyse building performance data is developed.

The Holistic Multi-Dimensional Information Management System based on data warehouse technology in order to support multi-dimensional analysis of building performance data is introduced in Chapter 5.

The system architecture is depicted in Figure 7.1. The system consists of three integrated main components which were explained in detail in Chapter 5.

These components are:

1. Data Warehouse Core
2. Extraction, Transformation, Loading (ETL) Layer
3. Information Representation Layer (Graphical User Interfaces)

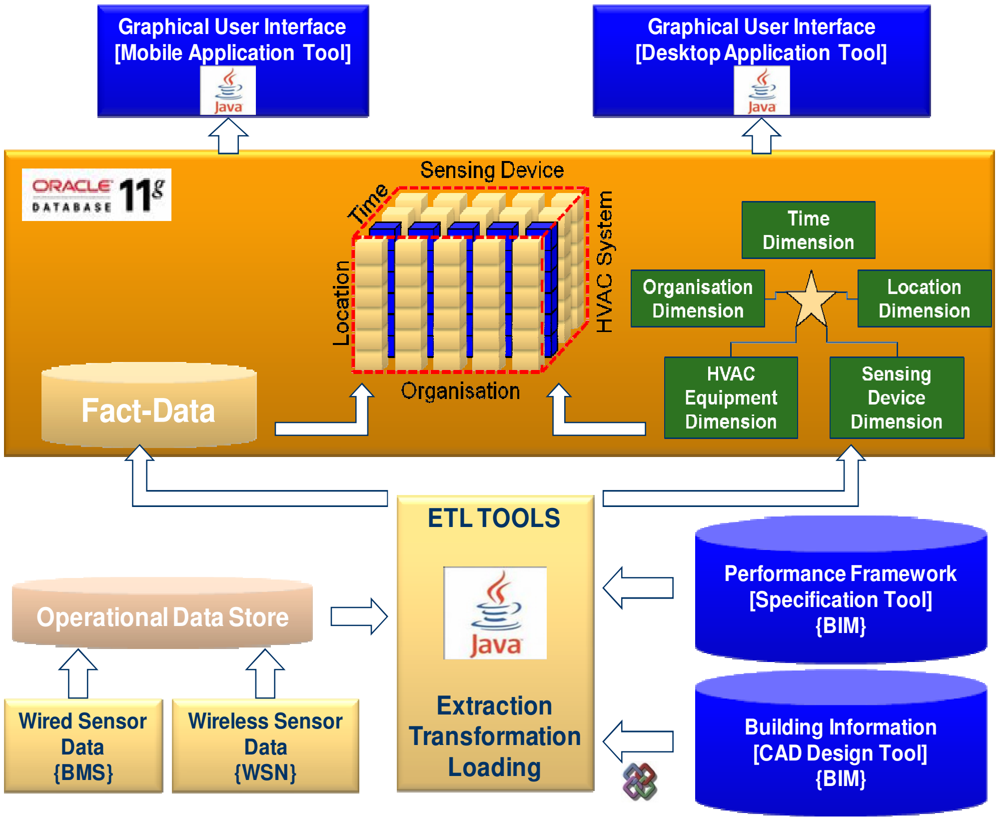

Figure 7. 1: Architecture for Holistic Multi Dimensional Information Management System for Building Performance Data

Objective 5: Demonstrating the implementation of the specified system and validating its capabilities in an appropriately selected research building.

Implementation of the Holistic Multi Dimensional Information Management System was described in Chapter 6 in order to demonstrate and test its capabilities in an appropriately selected research building.

The Environmental Research Institute (ERI) Building which is denoted as “the living laboratory” is used as a test bed for the system validation and implementation purposes within the scope of Buildwise and ITOBO projects.

The multi dimensional analysis of the building performance data is selected as the implementation scenario for the developed system. This scenario covered the collection, aggregation and representation of different data streams to various stakeholders.

The open plan office space (Room 1.23) and the under floor heating circuit (UHF 1.03) located in the ERI Building were selected as implementation samples for the scenario described.

In total, 13 sensors, 2 meters and 1 relay controller were installed for monitoring the performance of the selected zone and the building system.

The data collected from the wired/wireless sensors and meters is aggregated within the developed system and the results presented through context sensitive GUIs.

The demonstrator validated the developed system's capabilities for the described scenario definition. Also, this proved that the system can be used as a nucleus for various end-product developments in the area of energy monitoring and optimisation.

Objective 6: Introducing an affordable residential building specific wireless energy monitoring and optimisation system which is derived from the research findings presented in this work.

An affordable residential building specific wireless energy monitoring and optimisation system which is derived from the research findings presented in this work, were introduced in Section 6.2.

Three different end products were developed to target three different income segments such as luxury, middle class and social housing projects. For each segment the cost and the investment analysis were introduced in Section 6.9.5. The NPV method was applied for the investment analysis (Section 6.9.6). The results of the NPV analysis proved the feasibility of the proposed products.

7.3 Future and Ongoing Research

The research findings and developments in this thesis create the possibility of future development and research. The potential future and ongoing developments will be introduced below.

The developed system is open to further expansions. Since the system stores all building related information, it offers a high potential for building performance monitoring and multi-dimensional analysis as a powerful tool for data aggregation. This aggregated data can be used and be further developed for more advanced data analysis techniques like Knowledge Discovery (KDD) and Data Mining.

Also the developed system can be further expanded for scheduling and management of maintenance activities. The operation of a building can only be sustainable and optimised if the building infrastructure, sub-systems and components are working efficiently and safely, which requires effective planned and reactive maintenance of the building. Many maintenance policies exist (Wang 2001) so in general there are three general approaches to maintenance planning (Budai, Dekker & Nicolai 2006):

Corrective Maintenance is a classification of maintenance that occurs in response to a break-down, request or other malfunction that inhibits the building operation. Maintenance tasks are carried out in direct response to a failure and are defined to solve the failure event in a prescribed manner.

Time-based Preventative Maintenance is a series of scheduled inspection routines on building plant. In this case failures can be seen before a failure may occur. Building elements need to be classified to ensure an optimal inspection routine interval is chosen as there is a trade off between inspection costs and failure cost.

Condition-based Maintenance is similar to time-based preventative maintenance but provides a more optimal solution as the interval is relative to the decreasing performance of the building systems. Implementations tend to focus on information details of equipment such as lifetime, running hours and levels of production rates. Mathematical models can be used in order to calculate the optimal inspection strategy (Chelbi & Ait-Kadi 1995).

Combining a well defined maintenance plan with a coordinated layout of a wireless sensor network (WSN) relative to key monitoring aspects of a building's equipment provides a basis for a remote monitoring scheme. With this flow of information from building elements the solution must alert the Facility Manager when failures occur or reach a threshold at which an inspection should be performed. A new complexity is added to the FM activities as the WSN must be maintained and changes in building equipment must be accounted for (Gökçe 2009).

Maintenance actions will be derived from (a) regular maintenance requirements and processes, (b) user reports and (c) building performance data and diagnosis. The actions will be scheduled to optimise energy efficiency, cost and user satisfaction, while respecting constraints and preferences over resources, engineer availability, and building use. The schedule will be updated continuously as tasks are completed, as engineers report their locations, and as new tasks are generated. Particular attention will be paid to the roles of multiple service teams, requiring negotiation of contracts and service levels, and coordination of activities between the teams. Relevant technical documentation and work orders will be compiled. Information will be displayed in a context sensitive way to the individual maintenance clients (mobile and desktop). This possible future development might addresses that need.

Moreover, the developed system can be further expanded for intelligent building control. Through the implementation of KDD and data mining methodologies, the data aggregated within the DW core can be used to discover predictive patterns such as the user preferences and the weather predictions.

An Intelligent Control module which contains algorithms including AI (Artificial Intelligence) and machine learning approaches interacts with the user preference analysis, predictive analysis, and DW core to compute control parameters, which are then passed to the wireless network for actuation. It also can feed information to the diagnosis module regarding control problems (i.e., the control system is not behaving as expected), as well as the Maintenance Management System, to request repairs of known faults. Also, information from the maintenance management and diagnosis systems may be used to influence the control policy (ITOBO 2010).

Furthermore, Java based Graphical User Interfaces (GUI) developed in this thesis act as a bottle neck for the system. The developed GUIs are designed for the stakeholders who are not familiar with the Structured Query Language (SQL). Therefore during the design phase of these GUIs "user friendly" design was taken as the primary design feature in order to increase the level of easy utilisation. On the other hand, user friendly GUIs limit the multi dimensional analysis capability of the developed system. In order to solve this issue, dynamic automatically updating GUIs which would increase analysis capabilities while reducing the end user complexities, will be considered as a future research area.

In conclusion, the developed Holistic Multi-Dimensional Information Management System for energy efficient building operation possesses a significant potential for further improvements and developments with its flexible, standardised and extensible architecture.

Appendix A: Data Warehouse Table Definitions

These appendixes present Data Warehouse table definitions. The Data Warehouse schema is introduced in Chapter 5 (Section 5.3.4).

The table definitions are provided under:

1. Fact Data Table Definition
2. Fact Data Table: SQL
3. Sensing Device Dimension Table Definition
4. Sensing Device Dimension Table: SQL
5. Location Dimension Table Definition
6. Location Dimension Table: SQL
7. Organisation Dimension Table Definition
8. Organisation Dimension Table: SQL
9. HVAC Equipment Dimension Table Definition
10. HVAC Equipment Dimension Table: SQL
11. Time Dimension Table Definition
12. Time Dimension Table: SQL

Fact Data Table Definition

Column Name	Data Type	Constraints	Explanation	Example
MEASUREMENT_ID	Number	Primary Key	Surrogate Key	From 1 to ~
DEVICE_ID	VARCHAR2 (15 Char)	Foreign Key (Rf: Sensing_Device_Dimension)	This is provided to join the Fact_Data table to Sensing_Divece_Dimension table	S00001
TIME	VARCHAR2 (15 CHAR)		Microsoft Time Stamp used in CSV files	39634.01042
TIME_ID	Number	Foreign Key (Rf: Time_Dimension)	This is provided to join the Fact_Data table to Time_Dimension table	T00001
JAVATIMESTAMP	Time Stamp		Conversion of MS Time Stamp to Java Time Stamp. Required to deal with “time level”	04-May-08 04.45.00.187000000
VALUE	Number (10,3)		Sensor/Meter Readings	65
LOCATION_ID	VARCHAR2 (15 Char)	Foreign Key (Rf: Location_Dimension)	This is provided to join the Fact_Data table to Location_Dimension table	L00001
ORGANISATION_ID	VARCHAR2 (15 Char)	Foreign Key (Rf: Organisation_Dimension)	This is provided to join the Fact_Data table to Organisation_Dimension table	O00001
HVAC_EQUIPMENT_ID	VARCHAR2 (15 Char)	Foreign Key (Rf: Organisation_Dimension)	This is provided to join the Fact_Data table to HVAC_Equipment_Dimension table	E00001

Fact Data Table: SQL

```
REM UFUK FACT_DATA

  CREATE TABLE "UFUK"."FACT_DATA"
   (  "MEASUREMENT_ID" NUMBER NOT NULL ENABLE,
      "DEVICE_ID" VARCHAR2(15 CHAR),
      "TIME" VARCHAR2(12 CHAR),
      "TIME_ID" NUMBER,
      "VALUE" NUMBER(10,3),
      "LOCATION_ID" VARCHAR2(15 CHAR),
      "ORGANISATION_ID" VARCHAR2(15),
      "HVAC_EQUIPMENT_ID" VARCHAR2(15 CHAR),
      "JAVATIMESTAMP" TIMESTAMP (6) WITH LOCAL TIME ZONE,
       CONSTRAINT "FACT_DATA_PK" PRIMARY KEY
("MEASUREMENT_ID")
  USING INDEX PCTFREE 10 INITRANS 2 MAXTRANS 255 COMPUTE
STATISTICS
  STORAGE(INITIAL 65536 NEXT 1048576 MINEXTENTS 1 MAXEXTENTS
2147483645
  PCTINCREASE 0 FREELISTS 1 FREELIST GROUPS 1 BUFFER_POOL
DEFAULT)
  TABLESPACE "USERS"  ENABLE,
       CONSTRAINT "FD_HVAC_DIM_FK" FOREIGN KEY
("HVAC_EQUIPMENT_ID")
        REFERENCES "UFUK"."HVAC_EQUIPMENT_DIMENSION"
("HVAC_EQUIPMENT_ID") ENABLE,
       CONSTRAINT "FD_LOCATION_DIM_FK" FOREIGN KEY
("LOCATION_ID")
        REFERENCES "UFUK"."LOCATION_DIMENSION" ("LOCATION_ID")
ENABLE,
       CONSTRAINT "FD_ORG_DIM_FK" FOREIGN KEY
("ORGANISATION_ID")
        REFERENCES "UFUK"."ORGANISATION_DIMENSION"
("ORGANISATION_ID") ENABLE,
       CONSTRAINT "FD_SENS_DIM_FK" FOREIGN KEY ("DEVICE_ID")
        REFERENCES "UFUK"."SENSING_DEVICE_DIMENSION"
("DEVICE_ID") ENABLE,
       CONSTRAINT "FD_TIME_DIM_FK" FOREIGN KEY ("TIME_ID")
        REFERENCES "UFUK"."TIME_DIMENSION" ("TIME_ID") ENABLE
   ) PCTFREE 10 PCTUSED 40 INITRANS 1 MAXTRANS 255 NOCOMPRESS
LOGGING
  STORAGE(INITIAL 65536 NEXT 1048576 MINEXTENTS 1 MAXEXTENTS
2147483645
  PCTINCREASE 0 FREELISTS 1 FREELIST GROUPS 1 BUFFER_POOL
DEFAULT)
  TABLESPACE "USERS"
```

Sensing Device Dimension Table Definition

Column Name	Data Type	Constraints	Explanation	Example
DEVICE_ID	VARCHAR2 (15 Char)	Primary Key	Manually generated ID	S00001
SENSING_DEVICE_CATEGORY	VARCHAR2 (15 Char)		Top level hierarchy for the sensing devices (Sensing device, meter, actuator)	Sensing Device
SENSING_DEVICE_SUB_CATEGORY	VARCHAR2 (15 Char)		Second level hierarchy for the sensing devices	Wireless Sensor
SENSING_DEVICE	VARCHAR2 (15 Char)		Third Level hierarchy for the sensing devices	Lux level Sensor
DEVICE_LOCATION	VARCHAR2 (15 Char)		Location of the sensing device (Also HVAC equipment if applicable)	L00001/H00001
METRIC_UNIT	VARCHAR2 (15 Char)		Metric units for measurements	Lux
SENSING_DEVICE_DESCRIPTION	VARCHAR2 (100 Char)		Description of the sensing device	Cylon Controls Lux Level Sensor. Type 3100

Sensing Device Dimension Table: SQL

```
REM UFUK SENSING_DEVICE_DIMENSION

  CREATE TABLE "UFUK"."SENSING_DEVICE_DIMENSION"
   (  "DEVICE_ID" VARCHAR2(15 CHAR) NOT NULL ENABLE,
      "SENSING_DEVICE_CATEGORY" VARCHAR2(15 CHAR),
      "DEVICE_LOCATION" VARCHAR2(15 CHAR),
      "METRIC_UNIT" VARCHAR2(15 CHAR),
      "SENSING_DEVICE_DESCRIPTION" VARCHAR2(100 CHAR),
      "SENSING_DEVCE_SUB_CATEGORY" VARCHAR2(15),
      "SENSING_DEVICE" VARCHAR2(15),
       CONSTRAINT "SENSING_DEVICE_DIMENSION_PK" PRIMARY KEY
("DEVICE_ID")
  USING INDEX PCTFREE 10 INITRANS 2 MAXTRANS 255 COMPUTE
STATISTICS
  STORAGE(INITIAL 65536 NEXT 1048576 MINEXTENTS 1 MAXEXTENTS
2147483645
  PCTINCREASE 0 FREELISTS 1 FREELIST GROUPS 1 BUFFER_POOL
DEFAULT)
  TABLESPACE "USERS"  ENABLE,
       CONSTRAINT "SENSING_DEVICE_DIMENSION__FK1" FOREIGN KEY
("DEVICE_LOCATION")
        REFERENCES "UFUK"."LOCATION_DIMENSION" ("LOCATION_ID")
ENABLE
   ) PCTFREE 10 PCTUSED 40 INITRANS 1 MAXTRANS 255 NOCOMPRESS
LOGGING
  STORAGE(INITIAL 65536 NEXT 1048576 MINEXTENTS 1 MAXEXTENTS
2147483645
  PCTINCREASE 0 FREELISTS 1 FREELIST GROUPS 1 BUFFER_POOL
DEFAULT)
  TABLESPACE "USERS"
```

Location Dimension Table Definition

Column Name	Data Type	Constraints	Explanation	Example
LOCATION_ID	VARCHAR2 (15 CHAR)	Primary Key	Manually generated ID	L00001
COUNTRY	VARCHAR2 (15 CHAR)		Counrty Name	Ireland/European Union
STATE	VARCHAR2 (15 CHAR)		State name (if applicable)	Ireland
COUNTY	VARCHAR2 (15 CHAR)		County name (if applicable)	Cork
CITY	VARCHAR2 (15 CHAR)		City name	Cork City
SITE	VARCHAR2 (15 CHAR)		Name of the site	UCC
BUILDING	VARCHAR2 (15 CHAR)		Name of the building	ERI
BUILDING STOREY	VARCHAR2 (15 CHAR)		Floor in the building	-1
SPACE	VARCHAR2 (15 CHAR)		Space/Room code	LG04
SPACE_NAME	VARCHAR2 (15 CHAR)		Space/Room name	IRUSE Lab
ZONE	VARCHAR2 (15 CHAR)		Specifies the different zones within a room/space. (i.e. under floor heating loops)	1

Location Dimension Table: SQL

```
REM UFUK LOCATION_DIMENSION

  CREATE TABLE "UFUK"."LOCATION_DIMENSION"
   (  "LOCATION_ID" VARCHAR2(15 CHAR) NOT NULL ENABLE,
      "COUNTRY" VARCHAR2(15 CHAR),
      "STATE" VARCHAR2(15 CHAR),
      "COUNTY" VARCHAR2(15 CHAR),
      "CITY" VARCHAR2(15 CHAR),
      "SITE" VARCHAR2(15 CHAR),
      "BUILDING" VARCHAR2(15 CHAR),
      "BUILDING_STOREY" VARCHAR2(15 CHAR),
      "SPACE" VARCHAR2(15 CHAR),
      "SPACE_NAME" VARCHAR2(15 CHAR),
      "ZONE" VARCHAR2(15 CHAR),
       CONSTRAINT "LOCATION_PK" PRIMARY KEY ("LOCATION_ID")
  USING INDEX PCTFREE 10 INITRANS 2 MAXTRANS 255 COMPUTE
STATISTICS
  STORAGE(INITIAL 65536 NEXT 1048576 MINEXTENTS 1 MAXEXTENTS
2147483645
  PCTINCREASE 0 FREELISTS 1 FREELIST GROUPS 1 BUFFER_POOL
DEFAULT)
  TABLESPACE "USERS"  ENABLE
   ) PCTFREE 10 PCTUSED 40 INITRANS 1 MAXTRANS 255 NOCOMPRESS
LOGGING
  STORAGE(INITIAL 65536 NEXT 1048576 MINEXTENTS 1 MAXEXTENTS
2147483645
  PCTINCREASE 0 FREELISTS 1 FREELIST GROUPS 1 BUFFER_POOL
DEFAULT)
  TABLESPACE "USERS"
```

Organisation Dimension Table Definition

Column Name	Data Type	Constraints	Explanation	Example
ORGANISATION_ID	VARCHAR2 (15 Char)	Primary Key	Manually generated ID	O00001
ORGANISATION	VARCHAR2 (15 CHAR)		Organisation name	UCC
BRANCH	VARCHAR2 (15 CHAR)		Branch name	Civil & Engineering
DEPARTMENT	VARCHAR2 (15 CHAR)		Department name	IRUSE
GROUP	VARCHAR2 (15 CHAR)		Group name	ITinAEC
INDIVIDUAL	VARCHAR2 (15 Char)		Individual	Ufuk Gokce
LOCATION	VARCHAR2 (15 Char)	Foreign Key (Rf: Location_Dimension)	Specifies the location of the individual	L00001

Organisation Dimension Table: SQL

```
REM UFUK ORGANISATION_DIMENSION

  CREATE TABLE "UFUK"."ORGANISATION_DIMENSION"
   (  "ORGANISATION_ID" VARCHAR2(15) NOT NULL ENABLE,
      "ORGANISATION" VARCHAR2(15),
      "BRANCH" VARCHAR2(15 CHAR),
      "DEPARTMENT" VARCHAR2(15 CHAR),
      "GROUP" VARCHAR2(15 CHAR),
      "INDIVIDUAL" VARCHAR2(15 CHAR),
      "LOCATION" VARCHAR2(15),
       CONSTRAINT "ORGANISATION_DIMENSION_PK" PRIMARY KEY
("ORGANISATION_ID")
  USING INDEX PCTFREE 10 INITRANS 2 MAXTRANS 255 COMPUTE
STATISTICS
  STORAGE(INITIAL 65536 NEXT 1048576 MINEXTENTS 1 MAXEXTENTS
2147483645
  PCTINCREASE 0 FREELISTS 1 FREELIST GROUPS 1 BUFFER_POOL
DEFAULT)
  TABLESPACE "USERS"  ENABLE,
       CONSTRAINT "ORGANISATION_DIMENSION_LO_FK1" FOREIGN KEY
("LOCATION")
        REFERENCES "UFUK"."LOCATION_DIMENSION" ("LOCATION_ID")
ENABLE
   ) PCTFREE 10 PCTUSED 40 INITRANS 1 MAXTRANS 255 NOCOMPRESS
LOGGING
  STORAGE(INITIAL 65536 NEXT 1048576 MINEXTENTS 1 MAXEXTENTS
2147483645
  PCTINCREASE 0 FREELISTS 1 FREELIST GROUPS 1 BUFFER_POOL
DEFAULT)
  TABLESPACE "USERS"
```

HVAC Equipment Dimension Table Definition

Column Name	Data Type	Constraints	Explanation	Example
HVAC_EQUIPMENT_ID	Number	Primary Key	Manually generated ID	H00001
HVAC_SYSTEM_NAME	VARCHAR2 (50 Char)		Top level hierarchy for the HVAC system installed in the building	Ventilation
HVAC_EQUIPMENT _ CATEGORY_NAME	VARCHAR2 (50 Char)		Second level hierarchy for the HVAC system installed in the building. Specifying the name of the HVAC Equipment.	AHU(Air Handling Unit)1
HVAC_EQUIPMENT_NAM E	VARCHAR2 (50 Char)		Third level hierarchy for the HVAC system installed in the building. Specifying the data points of the HVAC Equipment.	AS1
HVAC_EQUIPMENT_ DESCRIPTION	VARCHAR2 (100 Char)		Contains descriptive information about the HVAC Equipment	Air Supply Temperature
HVAC_EQUIPMENT_ LOCATION	VARCHAR2 (15 Char)	Foreign Key (Rf: Location_Dimension)	This is provided to join the HVAC_EQUIPMENT table to Location_Dimension table	L00001

HVAC Equipment Dimension Table: SQL

```
REM UFUK HVAC_EQUIPMENT_DIMENSION

  CREATE TABLE "UFUK"."HVAC_EQUIPMENT_DIMENSION"
   (  "HVAC_EQUIPMENT_ID" VARCHAR2(15 CHAR) NOT NULL ENABLE,
      "HVAC_SYSTEM_NAME" VARCHAR2(50 CHAR),
      "HVAC_EQUIPMENT_CATEGORY_NAME" VARCHAR2(50 CHAR),
      "HVAC_EQUIPMENT_NAME" VARCHAR2(50 CHAR),
      "HVAC_EQUIPMENT_DESCRIPTION" VARCHAR2(100 CHAR),
      "HVAC_EQUIPMENT_LOCATION" VARCHAR2(15 CHAR),
       CONSTRAINT "HVAC_EQUIPMENT_DIMENSION_PK" PRIMARY KEY
("HVAC_EQUIPMENT_ID")
  USING INDEX PCTFREE 10 INITRANS 2 MAXTRANS 255 COMPUTE
STATISTICS
  STORAGE(INITIAL 65536 NEXT 1048576 MINEXTENTS 1 MAXEXTENTS
2147483645
  PCTINCREASE 0 FREELISTS 1 FREELIST GROUPS 1 BUFFER_POOL
DEFAULT)
  TABLESPACE "USERS"  ENABLE,
       CONSTRAINT "HVAC_EQUIPMENT_DIMENSION__FK1" FOREIGN KEY
("HVAC_EQUIPMENT_LOCATION")
        REFERENCES "UFUK"."LOCATION_DIMENSION" ("LOCATION_ID")
ENABLE
   ) PCTFREE 10 PCTUSED 40 INITRANS 1 MAXTRANS 255 NOCOMPRESS
LOGGING
  STORAGE(INITIAL 65536 NEXT 1048576 MINEXTENTS 1 MAXEXTENTS
2147483645
  PCTINCREASE 0 FREELISTS 1 FREELIST GROUPS 1 BUFFER_POOL
DEFAULT)
  TABLESPACE "USERS"
```

Time Dimension Table Definition

This table is automatically generated by the ORACLE built in function.

Column Name	Data Type
TIME_ID	NUMBER
DAY	DATE
CODE	NUMBER
START_DATE	DATE
END_DATE	DATE
TIME_SPAN	NUMBER
JULIAN_DATE	NUMBER
DESCRIPTION	VARCHAR2 (200 Char)
NAME	VARCHAR2 (25 Bytes)
DAY_OF_CAL_WEEK	NUMBER
DAY_OF_CAL_MONTH	NUMBER
DAY_OF_CAL_QUARTER	VARCHAR2 (4000 Bytes)
DAY_OF_CAL_YEAR	NUMBER
CAL_MONTH_NUMBER	NUMBER
MONTH_OF_QUARTER	NUMBER
MONTH_OF_YEAR	NUMBER
CAL_QUARTER_NUMBER	NUMBER
QUARTER_OF_YEAR	NUMBER
CAL_YEAR_NUMBER	NUMBER

Time Dimension Table: SQL

```
REM UFUK TIME_DIMENSION

  CREATE TABLE "UFUK"."TIME_DIMENSION"
   (  "TIME_ID" NUMBER NOT NULL ENABLE,
      "DAY" DATE,
      "CODE" NUMBER,
      "START_DATE" DATE,
      "END_DATE" DATE,
      "TIME_SPAN" NUMBER,
      "JULIAN_DATE" NUMBER,
      "DESCRIPTION" VARCHAR2(2000 CHAR),
      "NAME" VARCHAR2(25),
      "DAY_OF_CAL_WEEK" NUMBER,
      "DAY_OF_CAL_MONTH" NUMBER,
      "DAY_OF_CAL_QUARTER" VARCHAR2(4000),
      "DAY_OF_CAL_YEAR" NUMBER,
      "CAL_MONTH_NUMBER" NUMBER,
      "MONTH_OF_QUARTER" NUMBER,
      "MONTH_OF_YEAR" NUMBER,
      "CAL_QUARTER_NUMBER" NUMBER,
      "QUARTER_OF_YEAR" NUMBER,
      "CAL_YEAR_NUMBER" NUMBER,
       CONSTRAINT "TIME_DIMENSION_PK" PRIMARY KEY ("TIME_ID")
  USING INDEX PCTFREE 10 INITRANS 2 MAXTRANS 255 COMPUTE
STATISTICS
  STORAGE(INITIAL 65536 NEXT 1048576 MINEXTENTS 1 MAXEXTENTS
2147483645
  PCTINCREASE 0 FREELISTS 1 FREELIST GROUPS 1 BUFFER_POOL
DEFAULT)
  TABLESPACE "USERS"  ENABLE
   ) PCTFREE 10 PCTUSED 40 INITRANS 1 MAXTRANS 255 NOCOMPRESS
LOGGING
  STORAGE(INITIAL 65536 NEXT 1048576 MINEXTENTS 1 MAXEXTENTS
2147483645
  PCTINCREASE 0 FREELISTS 1 FREELIST GROUPS 1 BUFFER_POOL
DEFAULT)
  TABLESPACE "USERS"
```

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