A MODEL-DRIVEN BUILDING INFORMATION MANAGEMENT SYSTEM FOR LOW ENERGY BUILDING OPERATION

Hasan Ufuk Gökçe[1], PhD / Assistant Professor, Ufuk.Gokce@okan.edu.tr
Kamil Umut Gökçe[2], PhD / Visiting Professor, Umut.Goekce@cib.bau.tu-dresden.de
Raimar J. Scherer[2], PhD / Head of Department, Raimar.J.Scherer @cib.bau.tu-dresden.de
[1]Okan University, Department of Energy Systems Engineering, Istanbul, Turkey
[2]TU Dresden, Institute for Construction Informatics, Dresden, Germany

ABSTRACT

Wireless monitoring and optimisation of buildings' energy consumption is of central importance for the renovation and energy-efficient operation of buildings since it allows the identification and correction of inefficient energy usage. However, the adoption of monitoring and control systems for building management and control applications is hampered by the unavailability of appropriate tool environments. In this paper an integrated model-driven approach that automates the design from component to application level will be presented to provide optimized building operations. The aim is to create a holistic environment for wireless embedded monitoring and control systems to increase the efficiency of the overall system development process and to exploit their potential for reduction of building energy consumption. To reach this objective, new methods, tools and equipments were researched and integration methods covering integrated design, energy simulation models and data warehouse technologies were developed.

Keywords: Energy-efficient buildings, BIM, Data Warehouse Technology, Intelligent and Integrated Control.

1. INTRODUCTION

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 (Gaterall & McEvoy 2005).
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 industrialized 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 (Gökçe 2010).
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 (Gökçe 2010).
As contribution to the "Kyoto-Protocol-Process" the EU outlined the objective to reduce energy consumption by 20 % until 2020. As buildings account for almost 40 % of the total energy usage in Europe (EC 2006) (Itard 2008) the European Commission undertakes much effort to reduce the energy consumption of buildings (EC 2006) emphasizing on energy rating to inform and stimulate subsequent building renovation activities.

About 85 % of the European buildings are older than 20 years; 60 % are older than 40 years and 30 % 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 % of these buildings will be renovated in the next 20 years opening the potential to improve their energy performance (Gökçe 2010).

Wireless monitoring and optimisation of buildings' energy consumption is of central importance for the renovation and energy-efficient operation of buildings since it allows the identification and correction of inefficient energy usage (Gökçe 2010). Current studies show that improved building control systems can contribute to the reduction of energy-consumption of buildings by 5 to 30%. In addition, it is often faster and less costly to automate building systems than it is to insulate building shells. Thus, flexible and easy to handle monitoring control technologies are essential. Presently, many sophisticated building services systems are available for facilities management. However, their focus on energy performance rating of buildings is at best sporadic, often comprising an ad-hoc combination of off-the-shelf building management systems (BMS) with some extensions. Such systems provide many problems to building owners with regard to interoperability. The optimisation of these systems for energy management adds another layer of complexity to the design and management procedures. It requires analysing the system, developing new interfaces, replacing devices, newly adjusting and optimising parameters and so on.

To address the above issues, in this research we focus on (1) establishing a new model-driven development approach that strongly automates the systems from component to application level, and (2) the creation of an integrated system concept for optimised building operations. A specific objective, addressed in the paper, is the development of a holistic multi-dimensional data aggregation system for flexible and automated creation of a range of applications and services for energy monitoring and control using modern Data Warehouse technologies.

We suggest a new integrated data aggregation and building operations system coupled with open and extensible information exchange facilities to support tool interoperability. It shall offer e-services for energy monitoring and control using data warehouse, data mining and web service technologies. These services structure and aggregate so called "Fact Data" using "Dimensional Data" and are thus capable to respond to complex query profiles required for sophisticated decision support. The information structure is pre-defined in so-called dimensions (e.g. location dimension: building, floor, room) that are used to define cubes. The specific data content, such as HVAC system information and Location information is imported from other data sources, preferably and predominantly via BIM. The proposed system extracts sensor data from the basic BMS and from a wireless sensor network. 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. Concurrently, data gathered from the building information model, e.g. via a BIM-CAD system, is loaded to the dimensional data section of the data warehouse. Loaded fact data and dimensional data is then aggregated with regard to different stakeholder requirements in the data warehouse system and presented through context sensitive Graphical User Interfaces.

2. FUNDAMENTAL CONCEPTS

This section is an overview of the fundamental concepts involved in order to create a model driven building information management system for low energy building operation. Initially, current building performance frameworks will be introduced in order to develop awareness for current regulations and ongoing/completed similar research activities. Furthermore, wireless embedded sensor technologies coupled with Wireless Sensor Networks (WSN) will be summarised. Since BIM is the primary information source for describing the sensor measurements, basics of BIM will be briefly discussed. Finally, Data warehouse technology and its fundamental terminology will be introduced.

2.1 BUILDING PERFORMANCE ASSESSMENT AND MONITORING 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 German Sustainable Building Council "Deutsche Gesellschaft für Nachhaltiges Bauen" (DGNB), 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). In order to overcome this issue building performance monitoring research projects were initiated recently. These projects are Metracker (LBNL 2009), Building EQ (Building EQ 2009), BeyWatch (Beywatch 2009), DEHEMS (Dehems 2009), AMI-MOSES (AmiMoses 2010), SmartHouse-SmartGrid (Smart 2010) and BEAWARE (BeAware 2010) These research projects are the result of the Directive 2002/91/EC by the European Parliament for energy performance of buildings. The directive requires owners to quantify the energy usage of their buildings against benchmarks set by government agencies throughout the building life cycle.

2.2 WIRELESS EMBEDDED DEVICES AND WIRELESS SENSOR NETWORKS

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.
Wireless Sensor Network (WSN) is a wireless network consisting of spatially distributed autonomous devices using sensors that allow the physical environment to be monitored at high resolution. These sensors also called motes, are installed in particular locations or can be sprayed in a particular zone to gather information such as temperature, humidity, CO_2, Lux level, etc.
Sensors are not powerful. The real functionality of sensors comes with wireless sensor networks when these tiny sensors start communicating with each other through wireless protocols. WSN can shuffle the information collected through thousand of sensors and transfer it to the public internet and or a local area network. Finally, the information is collected in the data warehouse where it is analysed. Figure 1 depicts a sample WSN.

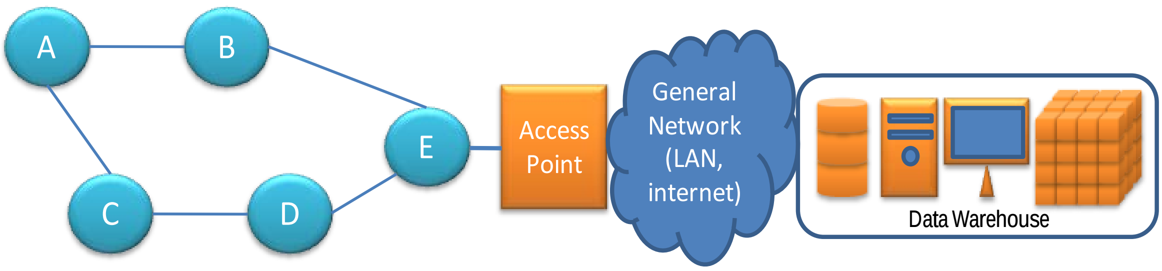

Figure 1: A Sample Wireless Sensor Network (Gökçe 2009)

Although Wireless Sensor Networks (WSN) technology is rapidly evolving and significant progress has been made in many areas, such as power management (Ramanathan et al. 2005) (Caldas et al. 2005) (Klues et al. 2007), network algorithms (Yarvis et al. 2005) (Yaqing et al. 2008) and architecture (Shangwei et al. 2006) (Asim et al. 2008) the area of sensor network still requires much more attention. There are a number of benefits associated with WSN that have prompted a rapid increase in its popularity for many applications including environmental and habitat monitoring (Juang et al. 2002) (Cerpa et al. 2001) (Mainwaring et al. 2002), healthcare (Zhang et al. 2008) (Fischer et al. 2008) (Zaho et al. 2005) and traffic control (Wenije et al. 2005) (Jingyu et al. 2006). The advantages of adapting wireless technologies for energy efficient building operation include the limited need for modifications of the existing building infrastructure; low cost for installation and maintenance, flexibility and a much faster deployment than the traditional wired Building Management Systems.

Although these benefits are highly desirable there remain some limitations that obstruct the deployment of large scale WSN including quality of service (QoS), transmission delays, message losses, and reliability. These drawbacks are intensified as a result of substandard design.

Currently there are a number of European projects investigating aspects of wireless sensor networks for various applications, but there is little focus on the wireless embedded systems emphasising on building automation and control. GAWIND is a project investigating the development of software tools and design methodologies to assist in the planning and optimisation of broadband wireless access networks, focusing on the utilisation of grid computing to enable resource intensive optimisation (Gawind 2006). Another European project called FEEDNETBACK involves research related to the development of a software tool set to support a co-design framework for networked control (Feednetback 2007). This framework will be applied to two industrial case studies: a smart camera network for surveillance and motion capture, and an underwater inspection system.

2.3 BUILDING INFORMATION MODELLING

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 BIM exchange formats were developed. The most established BIM exchange formats are IFC (Industry Foundation Classes) (ISO 16793) and aecXML (Bentley 1999). While the IFC model initially focused on graphic data, aecXML is designed for non-graphic data involved in construction industries, and has a place alongside IFC. All major CAD tools support at least IFC (Holnes 2008). Especially, several tools allow the rapid modelling of CAD models from paper drawings (Autodesk 2009).

BIM have a quite large scope and specify many objects. Individual end-user applications usually implement only a subset relevant to their specific use case (Weise et al. 2003) (ProIT 2005). In result, the risk that other tools erase or corrupt other project data is omnipresent (Nour et al. 2007) and partial models were developed. The suggestions dealing with partial models have been proposed in COMBINE 2 (Augenbroe et al. 1995) (Lockley 2000). A repository called integrated data model (IDM) was used to derive subsets of information. Although it can be accepted as a sufficient approach, it does not comprise well dynamic, ad-hoc view specification. The BLIS project (Hietenan 2002) developed a more structural concept starting with high-level classes, such as wall, beam etc., which are then detailed step by step to low-level classes. The ProIT project provides the basis for IFC view definitions (ProIT 2005). The IDM project developed a principal methodology for the creation of partial model views and their binding to processes through so-called functional parts (Wix 2005). All three projects BLIS, ProIT and IDM harmonized their efforts by developing the Model View Definitions (MVD) that was finally adopted as the official format to define views for IFC in 2005 (BuildingSmart 2009).

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 (Gökçe 2010).

2.4 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 or fact tables (Elmasri & Navathe 2004).

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. 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 (Gökçe 2010).

In addition, advanced data analysis techniques like Knowledge Discovery and Data Mining (KDD) (Han 2006) are often used on top of a Data Warehouse. Data Warehouse technology has a high potential for energy performance analysis (Tso et al. 2007) (Augenbroe 2005) since it includes powerful tools for performance data aggregation.

Service-Oriented Architecture (SOA) is an approach to organize IT resources and data collectively in order to enable integration between different technologies and allow for standardised data interaction (Mensah 2005). SOA focuses on interoperable, robust, reusable, and compassable 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 are partially integrated in Building Management Systems, a consistent SOA is still missing.

3. 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.

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).

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 2) 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 (Gökçe 2010).
The system extracts sensor data from building management systems and from a wireless sensor network. 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 is loaded to the dimensional data section of the data warehouse. Loaded fact data and dimensional data is aggregated concerning different stakeholder requirements in the data warehouse system and presented through specific Graphical User Interfaces (GUIs).

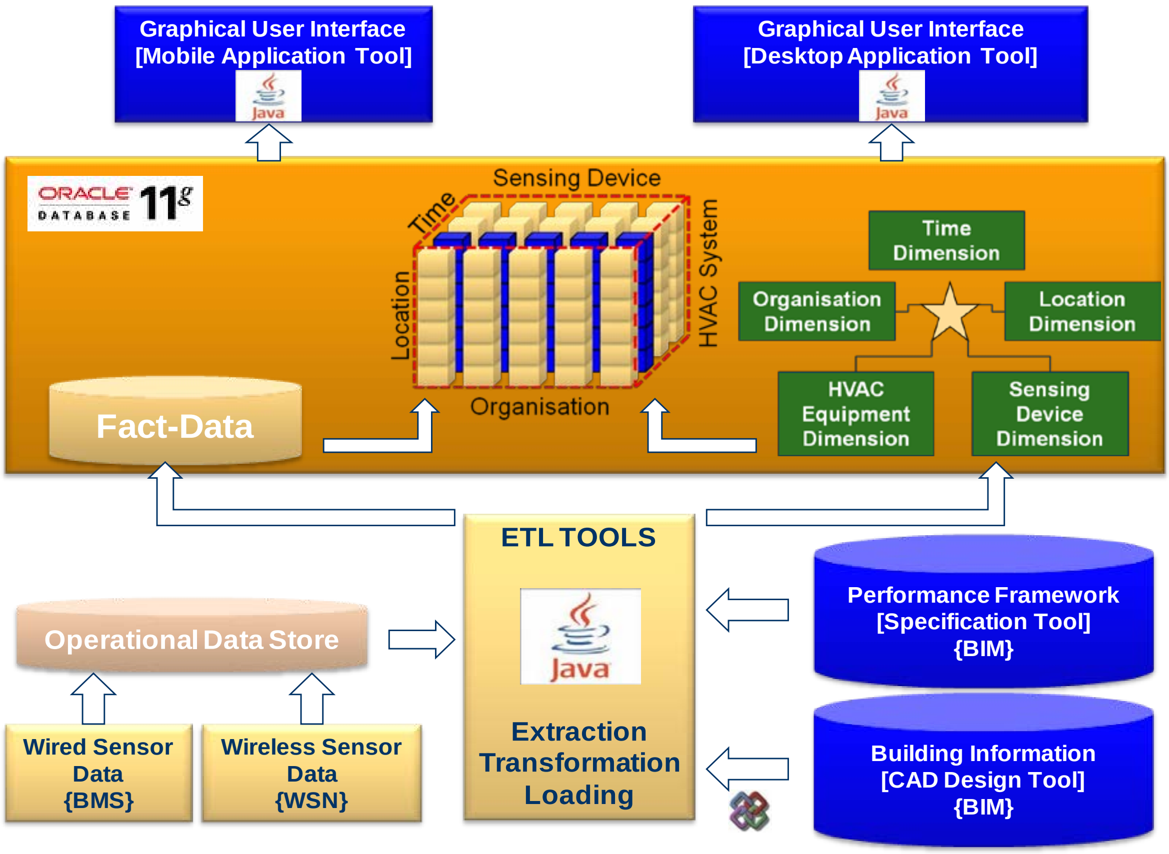

Figure 2: Architecture for Holistic Multi-Dimensional Information Management System for Building Performance Data (Gökçe 2010).

The system consists of three integrated main components, which will be explained in the following sections. These components are: (1) Data Warehouse Core, (2) Extraction, Transformation, Loading (ETL) Layer, and (3) Information Representation Layer.

3.1 DATA WAREHOUSE CORE

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.
Components of the Data Warehouse Core are briefly described as;

- *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.
- *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, and 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.
- *Dimensional Data:* As explained above 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. 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 Energy Systems Engineering Department staff in the Engineering Building for the last 3 months" is only achieved with time, location, sensing device and organisation dimension attributes.
- *Aggregated Data:* Aggregated data is the decision support level of the multi-dimensional data warehouse core. 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.

3.2 EXTRACTION, TRANSFORMATION, LOADING (ETL) LAYER

Data need to be loaded to the data warehouse core 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 are 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:

(1) Extracting data from multiple sources such as wired/wireless sensor/meter readings and BIM tools.

(2)Transforming it to fit data warehouse requirements which might be inconsistent with the outside data sources, e.g., data type inconsistencies and (3) 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. In addition, the ETL tool is used to populate Dimensional Tables, which store persistent data extracted from BIM tools.

3.2.1 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. For test purposes, a BMS with 100 sensors and 180 actuators is used. 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.

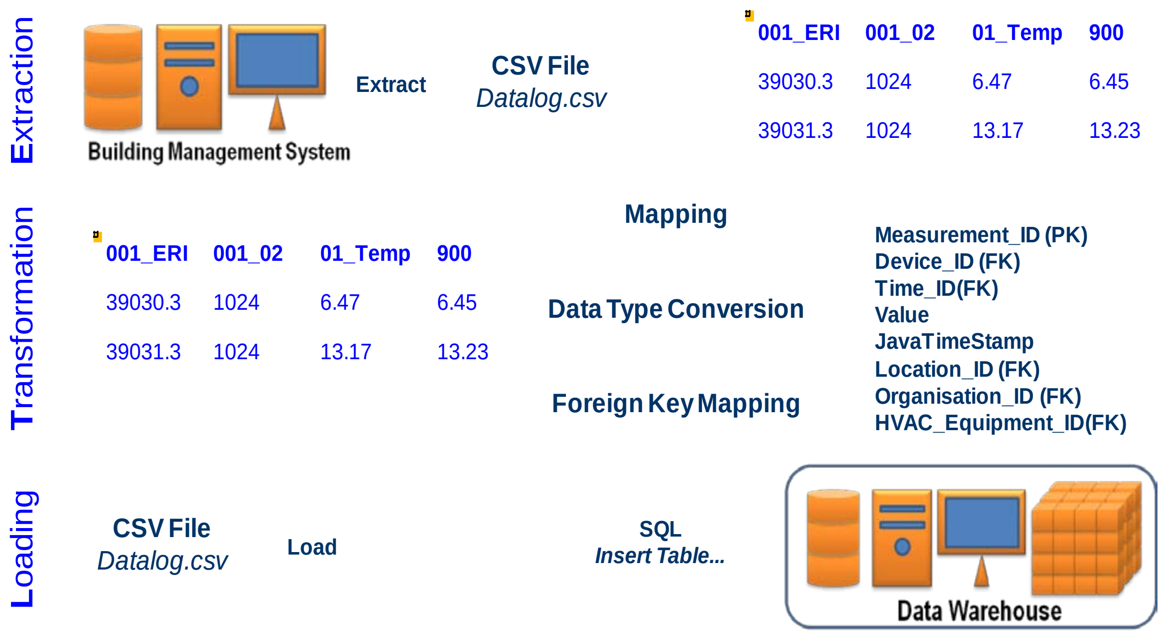

Figure 3: Extraction, Transformation and Loading (Gökçe 2010).

Figure 3 depicts the ETL process developed for a wired BMS in order to populate the fact data table which extracts data from the current BMS comma separated values (CSV) file archive and eliminates inconsistencies such as duplicate rows. Then, transforms the CSV file structure to the data warehouse fact data table structure and finally loads the CSV files to the data warehouse fact data table.

3.2.2 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.

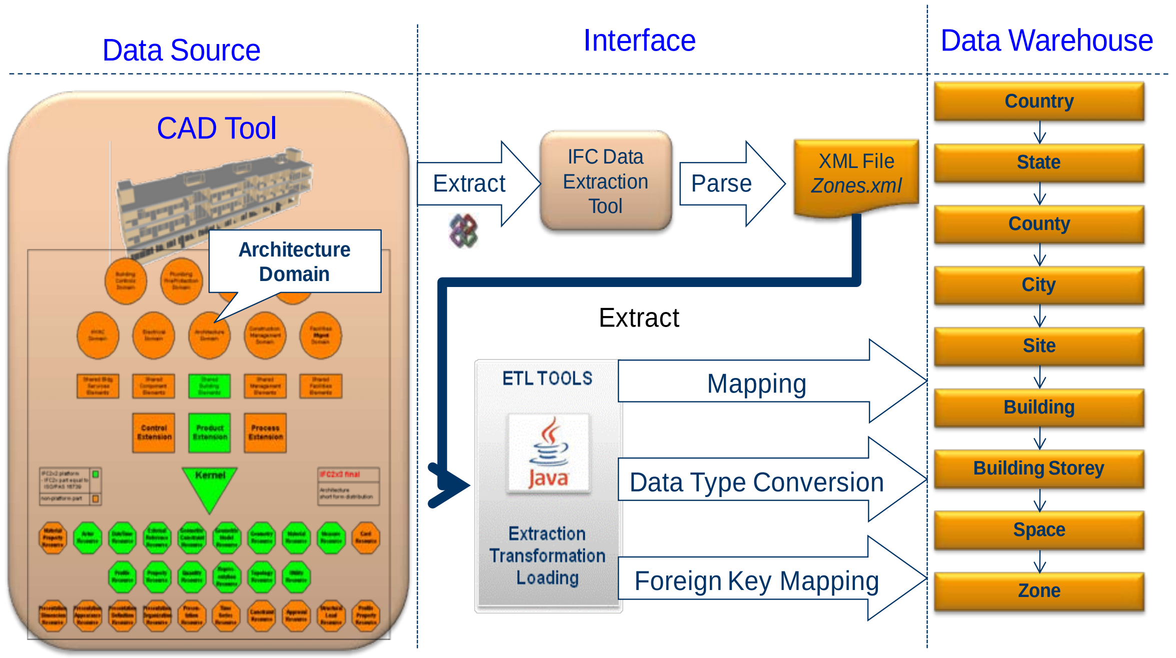

Figure 4: The ETL Process for Populating Location Dimension Table (Gökçe 2010).

Figure 4 depicts the developed system's ETL process to populate the Location_Dimension table of the data warehouse core.
This process involves: (1) Extracting architectural building information by using IFC (Industry Foundation Classes) data extraction tool. (2) Parsing the extracted data to a file in XML format, e.g., Zones.xml. (3) Extracting the data from the XML file. (4) Transforming the extracted data by proving necessary mappings, data type conversions and foreign key associations. (5) Loading the pre-processed data to the data warehouse's location dimension table.

3.3 INFORMATION REPRESENTATION LAYER

The common goal of the graphical user interfaces is to represent the building performance information to the end users (stakeholders) concerning their roles and functions. The aim of the proposed system's information representation section is designing and implementing user friendly Graphical User Interfaces (GUI). In order to achieve this, a Java based interface is developed which enables end users easy querying without dealing with complex SQL statements. In addition, this GUI is capable of representing query results both in graphical format and/or in tabular format regarding to stakeholder preferences.
Stakeholders include any person or organisation that may be affected by the success or failure of the software (Marinilli 2006). Four principle stakeholders identified for the developed system. 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.

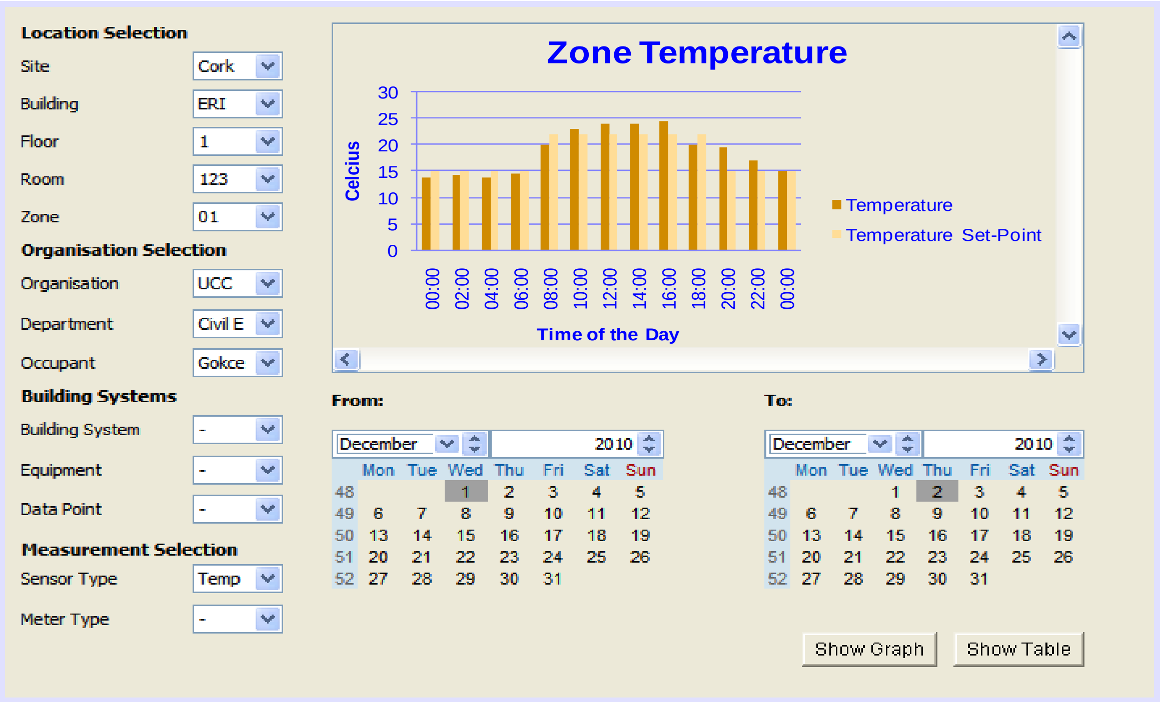

Figure 5: Facility Manager Graphical User Interface (Gökçe 2010).

Figure 5 depicts a Graphical User Interface developed for Facilities Manager. 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.

4. FUTURE RESEARCH AND CONCLUSIONS

In this research, an integrated, holistic system approach is described in order to create an extensible architecture for energy efficient building operation, to increase the productivity of the overall system development process, to exploit the potential for reduction of building energy consumption and to cope with the gaps in the interoperability of existing tools. New methods and tools are established that increase system development productivity covering wireless embedded systems and networks, and integration into backend systems. The result is an innovative model-driven development approach that strongly automates the design from component to application level to create a highly efficient integrated system importing and aggregating information from existing systems and reusing information from previous steps.

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. In addition, the developed system can be further expanded for scheduling and management of maintenance activities. Furthermore, the developed system can be improved 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.

5. REFERENCES

AMI-MOSES (2009) “AmI-MoSES - Project overview.” Available at: http://www.ami-moses.eu/en/index [Accessed November 17, 2009].

Asim, M.; Mokhtar, H.; Merabti, M. (2008) “A Fault Management Architecture for Wireless Sensor Network”, International Wireless Communications and Mobile Computing Conference, 6-8 August 2008.

Augenbroe, G. /ed/ (1995b) “Combine 2, Final Report CEC-JOULE program”, Brussels. 2009.

Augenbroe, G.; Park, C. (2005) “Quantification methods of technical building performance.” Building Research and Information, Routledge, part of the Taylor & Francis Group, vol. 33, no. 2, pp. 159-172, 2005.

Autodesk (2009) “Revit Architecture”, http://www.revit.com, 2009.

Bentley Systems (1999) “aecXML Preliminary Specification”, Working draft 0.81, Aug. 1999.

BEYWATCH (2009): Welcome to BeyWatch. Available at: http://www.beywatch.eu/index.php [Accessed November 17, 2009].

buildingSMART (2009) “Model View Definition (MVD)”, http://www.iai-tech.org/products/ifc_specification/ifc-view-definition, 2009.

Caldas, R.B.; Correa, F.L. Jr.; Nacif, J.A.; Roque, T.R.; Ruiz, L.B.; Fernandas, A.O.; da Mata, J.M.; Coelho, C., Jr. (2005) “Low Power/High Performance Self-Adapting Sensor Node Architecture”, Emerging Technologies and Factory Automation, 2005, 10th IEEE Conference 19-22 September 2005

Cerpa, A., Elson, J., Estrin, D., Girod, L., Hamilton, M., and Zhao, J. (2001) “Habitat monitoring: application driver for wireless communication technology”, ACM Sigcomm Workshop on Data Communication, San Jose, Costa Rica, April 2001.

Cohen, R., Bordass, W. & Field, J. (2004) “Energy performance of non domestic buildings: closing the credibility gap”. In *Building Performance Congress*.

DEHEMS (2009) “About the project: DEHEMS Project”. Available at: http://www.dehems.eu/about [Accessed November 17, 2009].

EC (2006) “A European Strategy for Sustainable, Competitive and Secure Energy” Brussels: Commision of the European Communities.

Elmasri, R. & Navathe, S. (2004) “Fundamentals of Database Systems Fourth Edition”, Boston: Pearson Education, Inc. ISBN: 0-321-20448-4.

EnOcean Alliance (2007) “Energy for free”, White paper, 2007.

FEEDNETBACK (2007) “Feedback design for wireless networked systems”, Funded under 7th FWP (Seventh Framework Programme) ICT-2007.3.7 Network embedded and control systems

Filippn, C. (2000) “Benchmarking the Energy Efficiency and Greenhouse Gases Emissions of School Buildings in Central Argentina.” *Building and Environment*, 35 (5) (1 July), 407-414.

Fischer, M.; Yen Yang Lim; Lawrence, E.; Ganguli, L. K. (2008) “ReMoteCare: Health Monitoring with Streaming Video”, seventh International Conference on Mobile Business, 7-8 July 2008.

Gaterell, M. & McEvoy, M. (2005) “The Impact of Climate Change Uncertainties on the Performance of Energy Efficiency Measures Applied to Dwellings.” Energy and Buildings, 37(9), 982-995.

GAWIND (2006) “Grid-enabled automatic wireless network design”, Funded under MOBILITY-1.3.1 Marie Curie Host Fellowships - Transfer of knowledge (TOK) - Development Scheme, 2006-08-01.

Gökçe H.U (2010) “Multi-Dimensional Analysis of Building Performance Data for Energy Efficient Building Operation”, PhD Thesis, National University of Ireland, Cork, Ireland.

Han, J.; Kamber, M. (2006) “Data mining: concepts and techniques.” Morgan Kaufmann, 2006

Hietanen J. (ed.) (2002) “Building Lifecycle Interoperable Software (BLIS)”, http://www.blis-project.org/index2.html, 2002.

Howley, M. & O'Gallachoir, B. (2006) “Energy in Ireland 1990 – 2004”. Trends, issues, forecasts and indicators. Sustainable Energy Ireland (SEI).

ICC (2000) “Final Draft ICC Performance Code for Buildings and Facilities”, *International Code Council*. Falls Church, VA.

Inmon, W. (1992) “Building the Data Warehouse”, First Edition. John Wiley and Sons. ISBN: 0471569607.

Itard, L., Meijer, F., Vrins, E., Hoiting, H. (2008) “Building Renovation and Modernisation in Europe: State of the art review”. ERABUILD, TU Delft.

Jagemar, L.; Olsson, D.; Schmidt, F. (2007) “The EPBD and Continuous Commissioning, Project Report”, Building EQ, EIE/06/038/SI2 .448300, Oct. 2007.

Jingyu Liu; Yanjun Fang (2006) “Urban Traffic Control System Based on Wireless Sensor Networks”, Proc. IEEE International Conference on Information Acquisition, August 2006.

Klues, K.; Handziski, V.; Lu, C.; Wolisz, A.; Culler, D.; Gay, D.; and Levis, P. (2007) “Integrating concurrency control and energy management in device drivers,” Proc. 21st ACM SIGOPS Symposium on Operating Systems Principles, pp. 251-264, 2007.

LBNL (2009) “High Performance Commercial Building Systems: Metracker.” Available at: http://eetd.lbl.gov/BT/hpcbs/Element_2/Metracker/02_E2_Metracker.html [Accessed October 19, 2009].

Lockley S., Augenbroe G. (2000) “Data Integration with Partial Exchange in: Proc. International Conference on Construction Information Technology”, INCITE 2000, Hong Kong, pp. 277-291.

Mainwaring, A.; Polastre, J.; Szewczyk, R. Culler, D.; and Anderson, J. (2002) “Wireless Sensor Networks for Habitat Monitoring”, WSNA, Atlanta, USA, September 2002.

Mensah, K. (2005) “Oracle Database Programming Using Java and Web Services.” Digital Press, 2005.

PeBBu (2005) “PeBBu 2nd International SOTA Report.” Volume 2005.

Price, L. et al. (2006) “Sectoral Trends in Global Energy Use and Greenhouse Gas Emissions”, Lawrence Berkeley National Laboratory. USA.

ProIT (2005) “Product Model Data in the Construction Process”, Project Report, founded by Confederation of Finnish Construction Industries RT, 2005.

Ramanathan, N., Yarvis, M., Chhabra, J., Kushalnagar, N., Krishnamurthy, L., and Estrin, D. (2005) "A stream-oriented power management protocol for low duty cycle sensor network applications", Second IEEE Workshop on Embedded Networked Sensors (EmNetS-II), Sydney, Australia, May 2005.

Shangwei Duan and Xiaobu Yuan (2006) "Exploring Hierarchy Architecture for Wireless Sensor Networks Management", Wireless and Optical Communications Networks, 2006 IFIP International Conference, 11-13 April 2006

SmartHouse/SmartGrid (2009) "Smart Houses Interacting with Smart Grids to achieve next-generation energy efficiency and sustainability." Deliverable 1-2009.

Tso, G. K. & Yau, K. K. (2007) "Predicting electricity energy consumption: A comparison of regression analysis, decision tree and neural networks." Energy, vol. 32, no. 9, pp. 1761 - 1768, 2007.

US-DOE (2002) "High Performance Building Metrics Project Framework", US Department of Energy, Washington, DC. Available at: http://www.nrel.gov/buildings/highperformance/metrics/pdfs/framework.pdf. [Accessed October 1, 2009].

Weise M., Katranuschkov P. (2003) "Supporting State-based Transactions in Collabrative Product Modeling Environments", in Scherer R.J. (ed.): W 78 22nd Conference on Information Technology in Construction, Inst. of Applied Computer Science in Civil Engineering, Dresden University of Technology, Germany, pp 269, 2003.

Wenjie, C.; Lifeng, C.; Zhanglong, C.; Shiliang, T. (2005) "A realtime dynamic traffic control system based on wireless sensor", International Conference on Parallel Processing Workshops, 14-17 June 2005.

Widom, J. (1995) "Research Problems in Data Warehousing. International Conference on *Information and Knowledge Management"*. Baltimore, Maryland.

Wix J. (ed.) (2005) "Information Delivery and Framework", Presentation at the IAI International Council in Oslo, Norway, 31 May 2005. http://www.nibs.org/FMOC/71305/2_InformationDeliveryAndFramework.pdf, 2005.

Yaqing, L.; Layuan, L.; Chunyan, W. (2008) "A Multipath Routing Algorithm Based on Link Multi-metrics for Wireless Sensor Networks", Computing, Communication, Control, and Management, CCCM '08. ISECS International Colloquium, August 2008.

Yarvis, M., Kushalnagar, N., Singh, H., Rangarajan, A., Liu, Y., and Singh, S. (2005) "Exploiting heterogeneity in sensor networks", IEEE International Conference on Computer Communication (INFOCOM 2005), Miami, FL, March 2005.

Zhang, P.; Chen, M. (2008) "A Remote Health Care System Based on Wireless Sensor Networks", 12th International Conference on Computer Supported Cooperative Work in Design, 16-18 April 2008.