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Self-Aware Buildings

An evaluation framework and implementation technologies for improving building operations

by Raymond Sterling Garay

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in the College of Engineering and Informatics

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ABSTRACT

Significant advances have been made in developing national and international policies aimed at improving the energy efficiency of buildings that address both new construction and retrofitting activities in buildings. However, policy measures targeting operational optimisation of buildings are few and indirect.

The research community is very active in developing methodologies and tools for reducing energy consumption in buildings. However very few developments achieve broad market acceptance. As with policy, this reduces the impact of such developments.

What policy makers and researchers have failed to take into account is that the general public is not well prepared to make energy efficient decisions on their own. There is a recognised lack of educational programmes that appropriately advise the stakeholders on the different aspects of energy efficiency in building operations.

A common scenario in non-residential buildings is the existence of a facility manager that monitors a building management system which is in charge of automatically controlling the significant energy consuming systems such as air conditioning, heating, ventilation, domestic hot water, among others. By their very nature, building management systems represent a complex integration of software and hardware and in most cases the facility manager is not knowledgeable enough to make decisions that support energy efficiency operation of buildings systems. In this scenario, buildings are operated sub-optimally leading to energy waste.

For different reasons, it is unrealistic to assume that facility managers will become experts in building physics and the technologies underpinning automated and optimised building operations. Such expert knowledge must then be incorporated in the building systems as embedded knowledge.

Targeting the integration of expert knowledge in building systems, this research work introduces the concept of a Self-Aware Building (SAB). A SAB is a building that is not necessarily highly automated but instead incorporates four general characteristics that support optimal operation without adding overhead to the facility manager. These characteristics are: (i) performance prediction; (ii) automated reaction of building systems to predicted performance; (iii) automated detection of performance reduction and diagnosis of root causes and; (iv) support of the facility manager tasks by providing information in a way suitable to the typical skill set.

This thesis begins with a deep study of the political, social and market drivers required to deliver energy efficient operations followed by a review of the technologies required to achieve the SAB concept.

Based on the political, social, market and technological aspects identified, this research work develops and discusses a methodology to evaluate buildings in advance of incorporating the technologies required to integrate the SAB characteristics. Next, these evaluation methodology and identified technologies are presented and discussed in real and simulated scenarios involving four different case studies. The case studies demonstrate a roadmap for achieving the SAB concept that include: (i) building performance prediction; (ii) automated reaction of building systems to predicted performance; (iii) automated detection of building performance reductions and diagnose of root causes and; (iv) building systems supporting facility managers tasks by providing information in a way suitable to his/her typical skill set.

Finally, this thesis presents a comprehensive discussion regarding the advantages and disadvantages encountered with each technology used and recommendations for the implementation of measures to support SAB.

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DECLARATIONS

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

Raymond Sterling Garay

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

Raymond Sterling Garay

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To my family and friends for their support in the good and the bad.

DEDICATION

A Tatiana

List of abbreviations

AHU	Air Handling Unit
AI	Artificial Intelligence
ANN	Artificial Neural Networks
APAR	AHU Performance Assessment Rules
ASHRAE	American Society of Heating, Refrigeration Air-Conditioning Engineers
BAS	Building Automation System
BCVTB	Building Controls Virtual Test Bed
BMS	Building Management System
BRIICS	Brazil, Russia, India, Indonesia, China and South Africa
CDM	Clean Development Mechanism
CEN	European Committee of Standardisations (French: Comité Européen de Normalisation)
CHP	Combiner Heat and Power
CO_2-eq	CO_2 equivalent
DDC	Direct Digital Controller
EEB	Energy Efficiency in Buildings
EEI	Energy Efficiency Indicators

EIA	U.S. Energy Information Administrator
EIT	Economies in Transition
EoS	End of Set-back
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certification
EPI	Energy Performance Indicators
EU	European Union
FL	Fuzzy Logic
GA	Genetic Algorithms
GHG	Greenhouse gases
HVAC	Heating, Ventilation and Air Conditioning
ICT	Information and Communication Technologies
IEA	International Energy Agency
KBS	Knowledge-Based System (knowledge representation)
KET	Key Enabling Technology
KPI	Key Performance Indicator
MAS	Multi-Agent Systems
MS	Member State
O&M	Operation and Maintenance
OECD	Organisation for Economic Co-operation and Development
PID	Proportional, Integral and Derivative
PLC	Programmable Logic Controller
QMBD	Qualitative Model-Based Diagnosis
QUAD	1 quad is equivalent to 10^{15} BTU or $1.055 \cdot 10^{18}$ Joules.

R&D	Research and Development
RTU	Roof Top Unit
SAB	Self-Aware Buildings
SVM	Support Vector Machines
SWOT	Strengths, Weaknesses, Opportunities and Threats
U.S.	United States of America
UN	United Nations
UNEP	United Nations Environmental Programme

CHAPTER 1
INTRODUCTION

Buildings are responsible for approximately 30% of the world's energy use. However, their operation is highly inefficient leading to as much as 50% of the energy consumed being wasted. It is widely perceived that a well-designed building should be energy efficient, but the reality shows otherwise and buildings consistently underperform when compared with intended design conditions. An important factor for this underperformance lies in the way building systems are operated. A wealth of methodologies and tools exist to tackle particular energy optimisation issues in buildings. Nevertheless, decision makers lack standardised methodologies and tools that will support them in understanding the real possibilities for each facility to incorporate technologies aiming at the operational optimisation of the energy use.

In this lack of understanding by decision makers, in particular facility managers, lies a deep knowledge gap between the typical facility manager skill set and the optimisation opportunities existing in the different systems incorporated in buildings (e.g. electrical, mechanical or safety). In bridging this knowledge gap, this thesis presents and discusses the concept of Self-Aware Building (SAB). A SAB is a building that is not necessarily highly automated but instead incorporates basic characteristics that support optimal operation without adding overhead to the facility manager. These characteristics are: (i) performance prediction; (ii) automated reaction of building systems to predicted performance; (iii) automated detection of performance reduction and diagnose of root causes and; (iv) support facility manager tasks by providing information in a way suitable to the typical skill set.

To support the SAB concept, this thesis proposes a standard classification and evaluation procedure to audit building management systems in advance of integrating energy efficient optimisation technologies. Furthermore, in the course of the thesis, the high impact energy efficiency technologies are defined and their incorporation capabilities are evaluated against the proposed classification of building management systems. Finally, four case studies are described to investigate the application of the SAB evaluation procedure and the incorporation of the technologies in real and simulated scenarios.

This chapter establishes the research context, concisely defines the research questions, describes the proposed approach in addressing the research question and outlines the thesis structure.

1.1 THE NEED FOR ENERGY EFFICIENCY IN BUILDINGS

Worldwide, the buildings sector consumes the largest share of global energy and is the main contributor to the emission of greenhouse gases (GHG). Estimates show that buildings are responsible for over 30% of the final energy consumption generating over six gigatonnes of CO_2 emissions (International Energy Agency, 2014). Developed countries show statistics even greater at this time. In the European Union (EU), the building sector is responsible for over 40% of total energy consumption and over 25% of the overall CO_2 emissions (EUROSTAT, 2010; European Environment Agency, 2010).

Buildings represent the largest potential for energy and GHG emissions reductions, even more than all other energy consuming sectors together (Levine et al., 2012). In cost-effectiveness terms, buildings also represent the highest low-cost possibilities for GHG reduction as shown in Figure 1-1. For example, in Figure 1-1 is can be seen that between 5 $GtCO_2$-eq and 6 $GtCO_2$-eq emissions can be avoided yearly with measures that cost less than 20US$ per tCO_2-eq mitigated.

Concerned by the statistics and encouraged by the potential in reducing GHG shown by the building sector, governments and international organisations have set in motion measures to reduce energy consumption and CO_2 emissions. In this regard, the EU has published the Directive on the energy performance of buildings (*Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of* *buildings (recast)*) aimed at assessing static energy consumption in buildings as a first step measure to evaluate the performance of the building sector. The recent Europe 2020 flagship initiative (European Commission, 2011), place incentives towards a reduction of 20% of energy consumption and CO_2 emissions by the year 2020 and 50% by the year 2050. The United States (U.S.) have enacted two Federal Acts, the Energy Policy Act of 2005 (*Pub.L.109 - 58. An act to ensure jobs for our future with secure, affordable, and reliable energy*) and the Energy Independence and Security Act of 2007 (*Pub.L.110 - 40. Energy Independence and Security Act of 2007*) aiming at improving energy efficiency, with special focus on Federal and commercial buildings. The Energy Policy Act of 2005 targets a minimum of 20% of use from renewable energies by 2015 while the Energy Independence and Security Act of 2007 requires all new commercial buildings to have zero-net-energy balance by 2025. China for its part has adopted a National Green Building Action Plan aiming at achieving one billion square meters of green buildings by 2015 (International Energy Agency, 2014). Other countries have assumed similar measures.

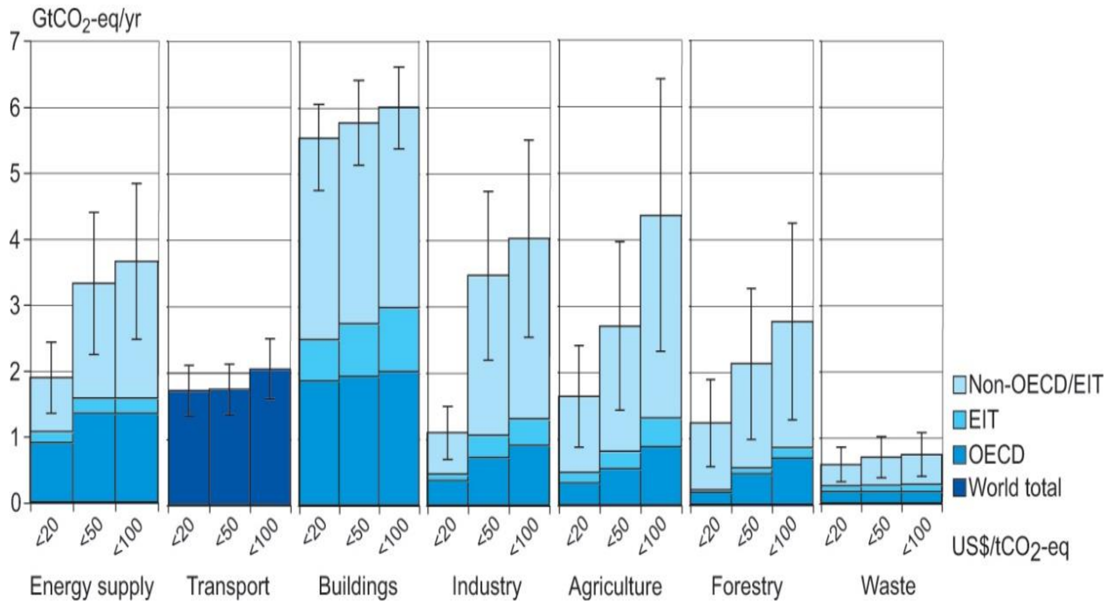

Figure 1-1. Estimated economic potentials for GHG mitigation at a sectorial level in 2030 for different cost categories. Note: estimates do not include non-technical options, such as lifestyle changes. Source: (Intergovernmental Panel on Climate Change, 2007).

Even with all the international efforts in place, buildings are not on track to meet their carbon reduction goals as reported by the International Energy Agency (International Energy Agency, 2014). It is quite opportune thus to investigate the root cause for this delay.

As will be explained in detail in Chapter 2, this delay in achieving energy and GHG reduction objectives for buildings, does not seem to be due to a lack of appropriate technologies for implementing energy efficiency measures. In fact the case is the opposite. Technologies for achieving the required levels of energy efficiency exist, are available in the market, and have shown to be mature enough to meet the requirements. The issue then lies in two distinct aspects:

- Policy measures are based on the principle that a well-designed building will operate optimally (Raftery, 2011). Thus policy assumes that people are ready to take energy efficient decisions. Based on this, policy developments worldwide focus on new buildings and the refurbishment of existing buildings rather than operational optimisation of existing buildings. In Europe, for example, 92% of the building stock from 2005 will still be there in 2020 and 75% in 2050 (European Commission, 2012). Given these numbers, it is unrealistic then to expect the whole building stock to be refurbished by 2050[1]. Nevertheless, there are very few enforceable policy mechanisms that target existing buildings not undergoing renovations and focus on the operation aspect of the building lifecycle where, according to the World Business Council for Sustainable Development (World Business Council for Sustainable Development, 2007), over 80% of the energy consumption occurs.
- In relation to the above, there is a lack of educational programmes worldwide aiming at raising general public capabilities for enforcing energy efficient measures (Harrigan & Curley, 2010). Nevertheless, the World Business Council for Sustainable Development (World Business Council for Sustainable Development, 2009) has shown that while on the one hand, people's behaviour can increase the impact of energy efficiency measures by 30% at no extra cost; on the other hand, people's behaviour may reduce building's performance by 60%, even when energy efficiency measures are in place.

In conclusion, even with well-designed buildings, the average stakeholder lacks the required skill set to behave in an energy efficient manner and policy does not takes this into consideration. As a result, and to avoid the socio-political implications, current policy efforts try to evaluate buildings *as-built* rather than *as-operated*. Chapter 2 provides

[1] Even if the totality of the building stock was refurbished, the embodied and disposal energy and GHG emissions coming of such refurbishments might offset the benefits in the long term (García Casals, 2006).

a discussion as per the advantages and disadvantages of such approach in facing energy reduction goals.

1.2 THE NEED FOR IMPROVED BUILDING OPERATIONS

Policy mechanisms have been largely centred on building improvements to achieve the necessary levels of energy efficiency but focusing on two aspects: (i) use of renewable energy sources and, (ii) improved insulation in buildings. Even when these are important aspects to take into consideration, there are other aspects that should take precedence such as optimised operation of systems and behavioural aspects of building users.

Energy consumption does not need to be translated into GHG emissions. In this regard, it is important to understand how much of this energy is necessary for human activities in buildings, how much is being wasted and how much energy consumption can be optimised cost-effectively. The issue then lies in optimising building operations while complying with the constraints of comfort, health and cost. In Figure 1-2 it is shown what cost-effective measures are likely to have the greatest impact in reducing GHG emissions from buildings if such measures are pursued aggressively.

It can be seen that measures relating to buildings are among the most cost-effective. Although improved building insulation appears as the best approach, the accuracy of what is shown in Figure 1-2 can be discussed in terms of whether it includes the GHG emissions due to fabrication, transportation, installation and disposal of the insulation materials. If the focus is reduced to the non-residential sector only, and assuming that Figure 1-2 is accurate in all aspects, Figure 1-3 shows that the best measures are those pertaining to heating, ventilation and air conditioning (HVAC) systems, lighting and energy management. Therefore, at least for the non-residential sector, operational optimisation, which includes heating, cooling and energy management, comprises the most cost-effective set of measures that could be taken in order to achieve energy and GHG reduction targets with over 75% of the possible measures.

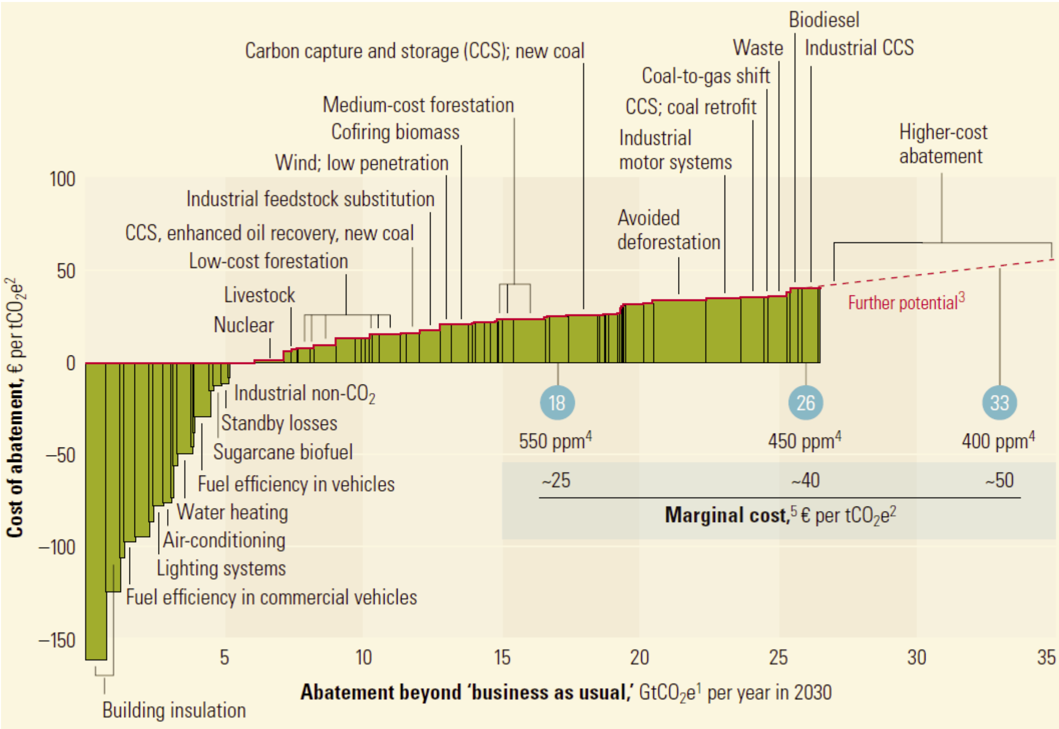

Figure 1-2. Global cost curve for GHG abatement measures beyond business as usual by 2030. Source: (Enkvist et al., 2007).

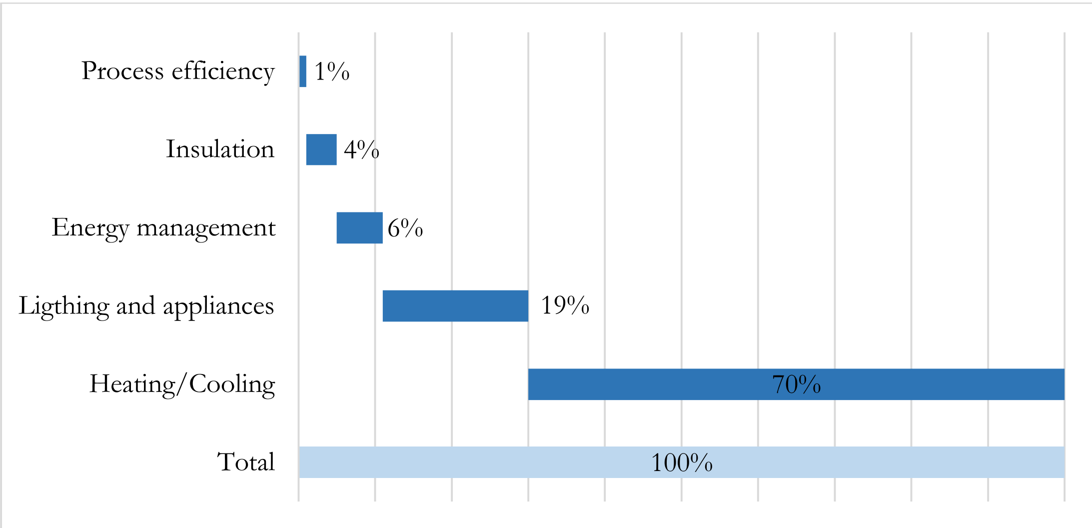

Figure 1-3. Cost-effective (upfront cost offset by energy savings) energy efficiency measures carbon abatement potential in existing non-domestic buildings in the UK. Source: (Carbon Trust, 2009).

1.3 Problem statement

Optimising operations in existing non-residential buildings requires integrated solutions to offset the cost of the incorporation of such upgrades (International Energy Agency, 2014). In this research thesis, the focus is kept on buildings that incorporate the means for controlling and monitoring, manually or automatically, the energy systems and the heating, ventilation and air conditioning (HVAC) systems. These control and monitoring systems are normally known as Building Management Systems (BMS). The HVAC systems are known for being inefficient and sources of energy waste for reasons spanning from inappropriate dimensioning, incorrectly implemented controls and even the existence of undetected issues that reduce the performance of energy systems for long periods of time (Bruton et al., 2014). For buildings that incorporate BMS to control HVAC systems, methodologies and tools that aim at overall operational improvements face a series of barriers for their implementation, such as:

- Diversity and lack of standardisation of building systems which translates into high upfront costs for implementing methods and tools since they need to be fitted to the specific facility;
- Building managers' time availability and technical skill set not matching that required to effectively implement energy efficient measures and thus missing opportunities;
- There exists a wealth of technologies available for improved building operations but decision makers are often not informed as per all possibilities available. Furthermore, many technologies are seen as redundant by decision makers (e.g. incorporated alarm system vs. fault detection and diagnosis);
- Lack of auditing tools to evaluate the likelihood of an effective integration of new technologies in building operations;
- Energy is still seen as a utility and not as an asset. In this sense energy is largely used to accomplish a task but not continuously managed and monitored to improve its use before, during and after the accomplishment of the task;
- Policy measures not directly supporting continuous improved operations but rather one-off prescriptive approaches.

In summary, the high-level problem to be investigated in this thesis work is:

How can building operations be optimised, prior to any major refurbishment, with the incorporation of existing methodologies and tools and overcoming the above mentioned barriers?

1.4 RESEARCH QUESTIONS

In addressing the problem stated in the previous section, the following specific questions will be investigated in this thesis work:

- How can building systems be *characterised* not in terms of its automation, but of their readiness to incorporate more advanced energy efficiency capabilities?
- What technologies aimed at optimising building operations can be *incorporated* in building systems depending on their characteristics?
- How can *tool selection* be performed to match the existing or envisioned building infrastructure?
- What are the steps to be followed for the *cost-effective integration* of new technologies in building operations?
- How can *integration* of technologies for optimised building operations effectively help the decision making process of the building manager?
- Why is there still little implementation of policies directly targeting optimised building operations? How can this situation be improved?

1.5 PROPOSED SOLUTION

The proposed solution to answer the identified research questions is provided by the *Self-Aware Building* concept and the supporting tools and technologies as described below.

Table 1-1 shows the current approaches aimed at tackling the problems identified during the course of this thesis (section 1.3) and also includes the solutions proposed by this research work under the umbrella of the SAB concept.

Current approaches to integrate energy efficiency technologies in building operations require the study and development of solutions that solve the issue for the specific building but lack the standardisation necessary for a broad implementation.

In this research thesis, a standardised approach is proposed to answer the questions that address the problem statement. This approach is based on three pillars:

- Development of a common framework to characterise BMS in relation to their suitability to implement energy efficiency measures in HVAC systems;

- Development of a standardised auditing methodology and a tool to evaluate BMS in advance of integrating technologies to increase HVAC systems energy efficiency;
- Development of an integration roadmap for technologies that assist building managers and facility operators in continuously monitoring and improving building operations and provide information in a manner that matches the different skill sets of these individuals.

Table 1-1. Contrasting current and proposed approaches to the research problems.

Problem	**Current Approach**	**Proposed solution**
Policy not able to drive reduced energy consumption effectively	Policy geared towards one-off measures	Implementation of outcome-based policy that enforces continuous energy management. (section 2.1.5)
Lack of linkage between energy consumption and processes	Energy seen as utility to be paid for	Active energy management to treat energy as an asset to be optimised rather than as a utility to be consumed (sections 2.2.1 and 3.4)
Wealth and complexity of information and data produced by buildings	Continuous training of facility manager	Embedding knowledge in building systems (section 2.2.2) The Self-Aware Buildings concept (section 2.3)
Lack of standard tools to characterise building systems	Ad-hoc and case-to-case evaluation	Strengths, Weaknesses, Opportunities and Threats standard analysis (section 3.5)
Technologies and possibilities not known to decision makers	Vendors marketing campaigns	Matching building system's status with possibilities (section 3.5.3)

For the common framework, building management systems were broadly categorised in four clusters named building ages that represent the evolution of what is known today as building management systems and the characteristics these should have to implement energy efficiency measures.

Once the categorisation was in place, an auditing tool was developed based on a standardised methodology to evaluate building management systems in order to classify them in one of the four ages of evolution. Such a tool is based on a traditional project management assessment methodology known as analysis of strengths, weaknesses, opportunities and threats (SWOT). The outputs of the SWOT analysis provide useful information as per the qualities of the building's systems open for exploitation and the issues to be solved.

Before developing the integration roadmap for energy efficiency technologies, it was necessary to understand the actual needs of facility managers and what technologies would really support those needs. Findings from the literature review of this research thesis (Chapter 2), showed the existence of a knowledge-gap between the typical building manager and the rapidly developing technologies for energy efficiency in building operations. The solution to bridge this knowledge-gap is to embed the necessary knowledge into the building systems. In this way these systems become aware of their use and performance creating a new concept of buildings that are self-aware. The technologies to accomplish the Self-Aware Building (SAB) concept must provide the building with the following characteristics:

- Allow the building to keep track, monitor and predict its performance;
- Act in consequence of the predicted performance;
- Automatically detect performance reductions and diagnose root causes;
- Support the automated processing of information so it can be presented in a way that matches the skill set of every user.

As can be seen, a SAB building does not necessarily require a high level of automation but incorporates elements that automatically adapt and improve building operations with time (including memory of past performance) and also diagnose issues with building systems. The technologies that support or directly incorporate SAB characteristics in buildings that are researched in this thesis are:

- Communication systems and automated data management to provide the necessary data for monitoring building operations and relaying information to the users appropriately;
- Artificial intelligence and machine learning techniques to implement intelligent characteristics including fault detection and diagnosis;
- Modelling and simulation to monitor and predict building's performance.

Finally, the developed SWOT analysis is applied to different case studies implementing each of the SAB characteristics through the identified technologies.

1.6 Thesis Structure

The thesis is structured as shown in Figure 1-4:

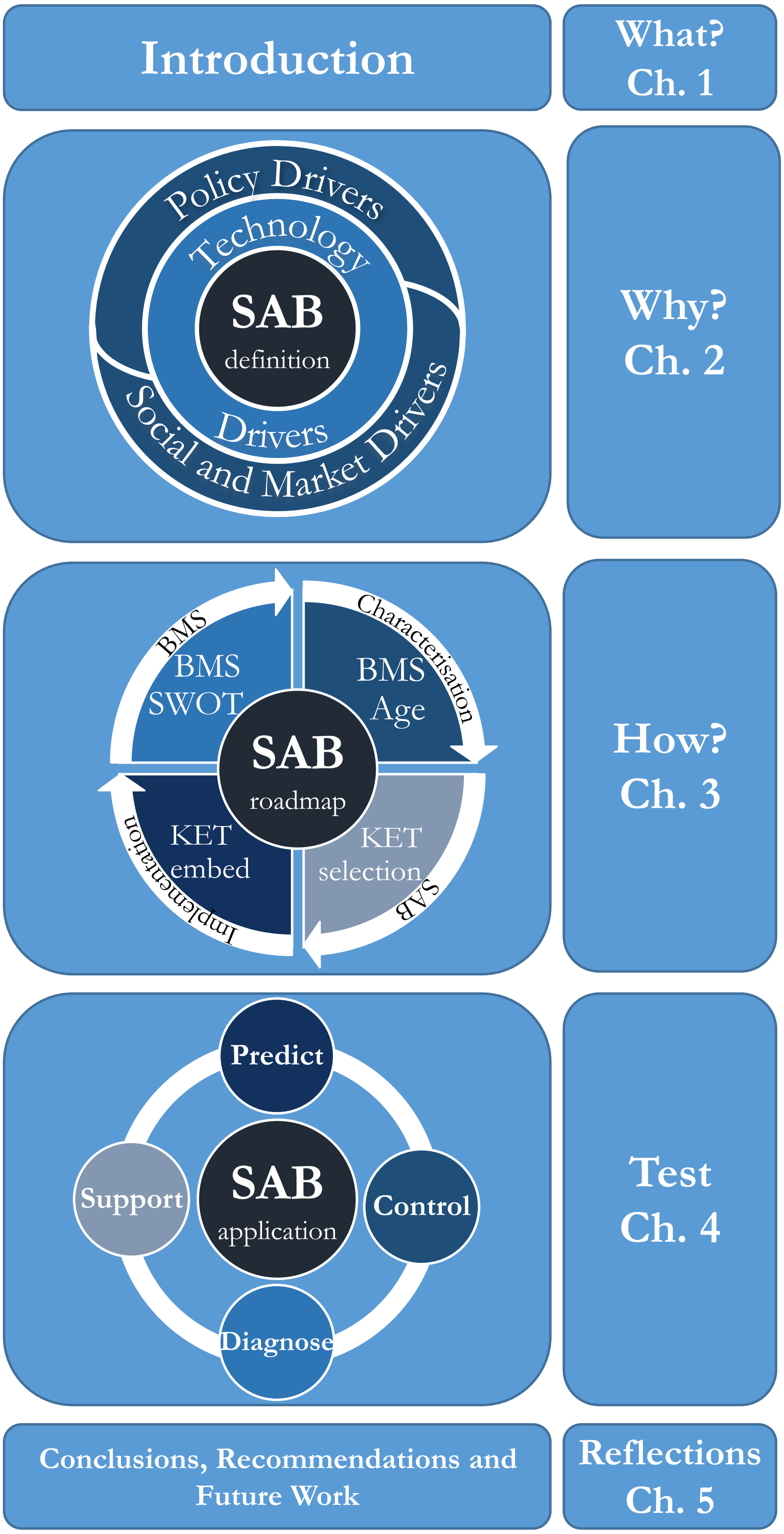

Figure 1-4. Graphical thesis structure.

- Chapter 1 presents the introduction to the research work and states **What** will be discussed in the rest of the thesis.
- Chapter 2 presents and discusses a detailed literature review of the main drivers for energy efficiency for building operations focusing on four broad areas: policy, socio-human, market and technology. The chapter works through the different needs currently facing the buildings when aiming at achieving energy efficiency goals and synthetises these needs into the definition of a *Self-Aware Building* (SAB). Chapter 2 aims at contextualizing the research and provide the reasons **Why** the research was carried out;
- Chapter 3 describes the evolution of building management systems (BMS), their impact on energy efficiency in building operations and defines a methodology for evaluating BMS (BMS SWOT + ages) in face of integrating the key enabling technologies supporting the SAB concept. Chapter 3 discusses **How** the SAB idea is applied to real facilities;
- Chapter 4 describes and discusses the implementation of the different aspects of SAB in four demonstrator buildings, one for each SAB characteristic: prediction, control, diagnostics and decision support. Chapter 4 presents case studies to **Test** the hypothesis regarding SAB characteristics;
- Chapter 5 presents the detailed conclusions from all the aspects this thesis work. Furthermore, it discusses recommendations to generally improve and foster energy efficiency in building operations and finishes by providing a roadmap for future work.

1.7 PUBLICATIONS

During the course of this research work, several peer-reviewed journal con conference publications have been successfully published.

1.7.1 Peer-reviewed journal publications

Sterling, R., Provan, G., Febres, J., O'Sullivan, D., Struss, P., and Keane, M. M. (2014). *Model-based Fault Detection and Diagnosis of Air Handling Units: A Comparison of Methodologies*. Energy Procedia, 00(0), pp.686–693.

Kouveletsou, M., Sakkas, N., Garvin, S., Batic, M., Reccardo, D., & **Sterling, R**. (2012). *Simulating energy use and energy pricing in buildings: The case of electricity*. Energy and Buildings, 54 (0), 96-104. doi:10.1016/j.enbuild.2012.07.031

1.7.2 Peer-reviewed conference publications

Sterling, R., Provan, G., Febres, J., O'Sullivan, D., Struss, P., and Keane, M. M. (2014). *Model-based Fault Detection and Diagnosis of Air Handling Units: A Comparison of Methodologies*. Proceedings of the sixth International Conference on Sustainability in Energy and Buildings. SEB 14. 2014. Cardiff. UK.

Sterling, R., Coakley, D., Messervey, T., and Keane M. M. (2014). *Improving Whole Building Energy Simulation with Artificial Neural Network and Real Performance Data*. Proceedings of the second IBPSA-England Conference. BSO 14. Building and Optimization. 2014. London. UK.

Struss, P., **Sterling, R.,** Febres, J., Sabir, U., and Keane M. M. (2014). *Combining Engineering and Qualitative Models to Fault Diagnosis in Air Handling Units.* Proceedings of the 21st. European Conference on Artificial Intelligence ECAI 2014. 2014. Prague. Czech Republic.

Febres, J., **Sterling, R**, Keane, M. M. (2014). *A novel calibration methodology for heating coil models using real data and Modelica models.* Proceedings of the 2014 ASHRAE/IBPSA-USA Building Simulation Conference. September 10-12, 2014, Atlanta. GA. US.

Struss, P., Sabir, U., **Sterling, R**., Febres, J. and Keane M. M. (2014). *Diagnosis of Air Handling Units based on Engineering and Qualitative Models.* Proceedings of the 8th International conference on Intelligent Systems and Agents. 2014. Lisbon. Portugal.

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Sterling, R., Costa, A., Messervey, T., Mastrodonato, C., & Keane, M.M. (2012). *Swimming Pool Hall HVAC Modelling, Simulation and End of Setback Neural Network Prediction: A Detailed Case Study*. Proceedings of the 5th National Conference of IBPSA-USA. SIMBUILD 2012. Madison, WI, USA.

Sterling, R., Costa, A., & Keane, M. M. (2012). S*wimming Pool Hall HVAC End of Setback Artificial Neural Network Prediction.* Proceedings of the 5th International Conference on Energy Research. ICERD5 2012. Kuwait City, Kuwait.

Costa, A., **Sterling, R.,** Messervey, T., & Keane, M.M. (2011). *Value of building simulation in sports facilities management.* Proceedings of the 12th International IBPSA Conference. BS 2011. Sydney, Australia

CHAPTER 2

DRIVING FORCES FOR ENERGY EFFICIENCY IN BUILDING OPERATIONS

In order to understand the outlook for energy efficiency in building operations in 2014, it is important to:

1. Identify, understand, and discuss the approach different countries and regions have adopted in developing policy concerning energy efficiency in buildings;
2. Analyse the economic impact and market reactions of such policy measures;
3. Understand the social context and public reaction to the different policy mechanisms and technologies;
4. Monitor and review how policy has driven the technological developments;
5. Identify the main policy, market, social and technological gaps still to be covered to achieve energy efficiency in buildings goals.

The next section provides a background and relevance of the problem of energy efficiency in building operations. The reminder of the chapter will present and discuss the different aspects affecting the way in which energy is used in buildings (e.g. political, social, economic, technological, etc.), concluding with a description of the envisioned evolution of buildings operations.

After reading chapter 2 it is expected the reader to have a full understanding of the following main points:

- The distortion generated by current policy approaches that promote retrofitting by replacing practice instead of optimising operation of existing systems;
- The necessity to implement energy management in building operations and the change in the conceptual view of energy as an asset to be continuously optimised and not as a utility to be paid for;
- The market potential of energy management that translates not only into efficient operations but also into reduced operational costs;
- The need to improve educational programmes to provide people with the necessary knowledge and skills to start making effective energy efficient decisions;
- The recognition that the targets for energy efficiency in building operations will not be achieved by refurbishment and increased training of building managers but needs also the incorporation of technology aiming at providing effective operational support;
- Identification of the key enabling technologies expected to deliver effective operational support for improved building energy use;
- Recognition of the necessity to implement standardisation in different levels of building operations.

2.1 Policy drivers: Towards outcome-based building operations

Policy is the main driver for improved building performance. In the case of building operations, even when technology is in place, it is only when it is brought to the attention of policy makers that it can be fostered and made economically available, thus increasing its adoption.

In the light of this research work, the term 'policy' refers to the set of mechanisms policy makers and stakeholders utilise to address the need to improve buildings energy performance. Such mechanisms include, but are not limited to: international agreements, codes, standards, legislation, financial schemes, etc.

Policy can be addressed at different levels, from a global point of view to a regional point of view passing through national and international levels. At the international level, there are energy efficiency goals and international directives, treaties, protocols and similar mechanisms that define the main guidelines for energy policy in the fore coming years, both at national and international levels.

At both, national and international levels, policy mechanisms can be grouped in the following categories according to the approach they take for achieving energy efficiency in buildings:

- **Direct policy mechanisms** that have a direct impact on improved energy efficiency in buildings such as:
  - Standards, codes and regulations that establish the minimum set of measures a facility needs to comply with. Although these are minimum, common practice is that they become the maximum to be aspired to;
  - Certifications and labelling approaches that provide information on the expected energy performance of the building. These mechanisms also aim at incentivise measures for energy efficiency in buildings;
- **Indirect policy mechanisms** that aim at incentivise public and market uptake of measures for improved energy efficiency in buildings such as:
  - White certificates and obligation schemes that impose obligations on energy services providers to apply energy efficiency measures on their customers;

- Financial mechanisms such as grants, loans, tax exemption, research and development funding etc., used to foster the innovations that policy makers consider fundamental for achieving energy efficiency goals;
- Public engagement mechanisms that aim at involving user on energy efficiency in buildings measures. People are the final users of the buildings and their contribution is paramount for achieving energy efficiency goals.

The rest of section 2.1 consists of a presentation and discussion of the policy mechanisms mentioned before, the different points of view for policy making and the overall influence policy has in buildings operation.

2.1.1 Global energy efficiency goals

As previously stated energy efficiency goals give the basic guidelines, which are the umbrella under which the energy policy develops in time. These goals can be defined at different levels, from global to national and regional. In the case of international agreements, these provide general mechanisms and principles that should be implemented in national regulations of associated countries, thus providing a framework for national/regional regulations.

At global level, the most important agreement on energy efficiency to date (2015) is the Kyoto Protocol (United Nations Framework Convention on Climate Change, 1998). The Kyoto Protocol was promoted by the United Nations (UN) and is a mechanism that aims to reduce the negative effects of climate change by reducing the amount of polluting greenhouse gases (GHG) that are released into the atmosphere. Although it was devised in 1998, it was not until 2005 that it entered into full force. The first reduction period for the Kyoto Protocol was 2008-2012 with the goal of reducing GHG emissions by 5% under 1990 levels. Even though the Kyoto Protocol strives to have a real impact on climate change, it does not directly include the building sector. The actual success of the Kyoto protocol is outside the objectives of this research, it is presented as an example of an international agreement.

A report published in 2008 by the United Nations Environment Programme (UNEP) (Cheng et al., 2008) discusses the need to adopt measures to make the building sector more efficient. Cheng suggests the use of the Clean Development Mechanism (CDM)[2]

[2] The CDM "allows a country with an emission-reduction or emission limitation commitment under the Kyoto Protocol to implement an emission-reduction project in a developing country. Such Project can earn saleable certified emission reduction credits, each equivalent to one tonne of CO_2, which can be

to foster projects aiming at GHG reductions in buildings. A contrary point of view argues that the actual cost-effectiveness and impact of the CDMs is low when compared with more direct mechanisms such as labelling and certification programmes and building codes (Carassus, 2013). However, labelling and certification programmes fall under the responsibility of national authorities and thus outside UNEP's field of action. Finally, Cheng recognises the issues arising from the diversity of the building sector such as the lack of standardised management and monitoring tools for energy efficiency and the lack of metrics, regulations and standards that evaluate buildings based on actual performance.

In 2009, the UNEP published a summary report for decision makers (United Nations Environment Programme, 2009) signalling at buildings as having the biggest potential for energy consumption and GHG emission reduction by making use of already available technologies. In this regard, the summary takes on the idea previously presented by Cheng (Cheng et al., 2008) and recommends that CDMs support investment in energy efficiency in buildings if countries are to meet their GHG emission reduction targets. The summary report also identifies six barrier categories that the building sector face when pursuing energy efficiency measures, none of which are related to the lack of technologies but with the combination of economic factors with lack of or poor policy mechanisms (regulations, certifications, etc.) in place and behaviour and misinformation of end-users.

The International Energy Agency (IEA) has provided statistics showing building's energy demand worldwide will increase by 50% by 2050 when compared to 2013. However, in order to keep global temperature rise to less than 2ºC, a 77% reduction in total GHG emissions in buildings is necessary by 2050 (International Energy Agency, 2013). In Figure 2-1 it can be seen that the contribution to energy reduction of different buildings elements in order to reach the targeted GHG emission reduction (77% reductions overall, from 15.2GtCO_2 to 2.3GtCO_2). Figure 2-1 depicts in time the impact different energy efficiency measure might have in reducing GHG emissions. For example, starting from the baseline emissions projected for 2050 of 15.2 Gt of CO_2 in a business as usual scenario, each energy efficiency measure reduces that amount to a

counted towards meeting Kyoto targets." (United Nations Framework Convention on Climate Change, n.d.).

total of 2.6 Gt of CO_2 if aggressive policy towards reducing energy consumption is implemented and enforced.

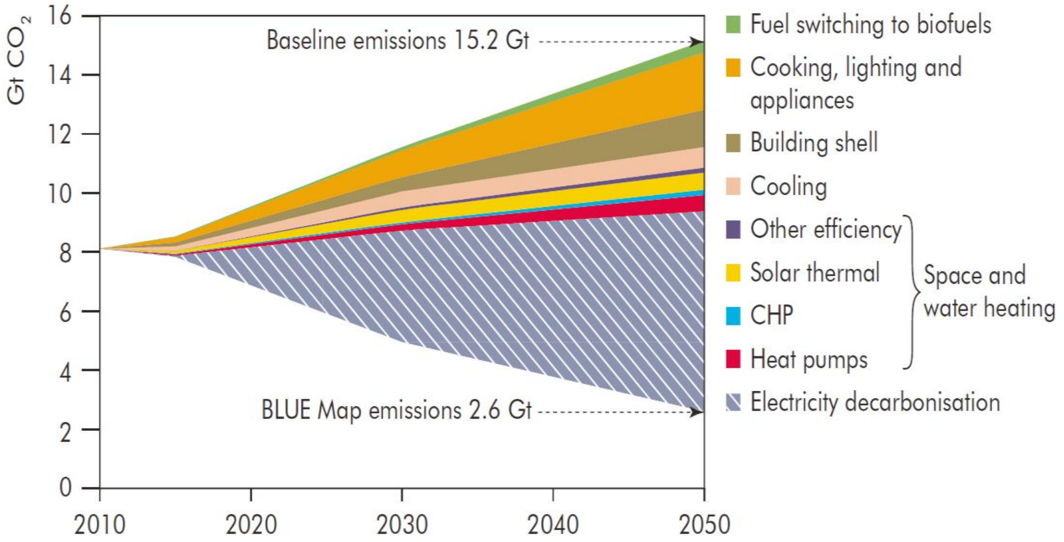

Figure 2-1. Emission reduction in the building sector compared to business as usual[3]. Source: (International Energy Agency, 2010b).

Figure 2-2 shows the projected thermal consumption in buildings in a "business-as-usual" scenario compared to exploiting the energy consumption potential to the maximum. For example, for North America in 2050, when compared to 2005, the moderate scenario (blue + black) only marginally reduces energy consumption while the deep scenario (black only) reduces energy consumption by more than a half.

From the Figure 2-2 is important to note that developed countries will, in both scenarios, reduce their thermal energy use by 2050. However, in developing economies there is a mixed scenario. Also, it can be seen in Figure 2-2 that the highest potential in preventing high energy use comes from the Americas, Europe, Russia and China.

So far it has been shown that statistics and international agencies recognise that although difficult, the goals are reachable if the right combination of policy, technology and behaviour change comes into place.

[3] IEA's Baseline scenario assumes governments introduce no new energy and climate policies while BLUE Map scenario sets a goal of reduction of emissions across all sectors by 50% in 2050 compared to 2005 levels.

Before analysing the approach that policy has taken in different regions in the world (section 2.1.4) it is important to fully understand direct (section 2.1.2) and indirect (section 2.1.3) policy mechanisms.

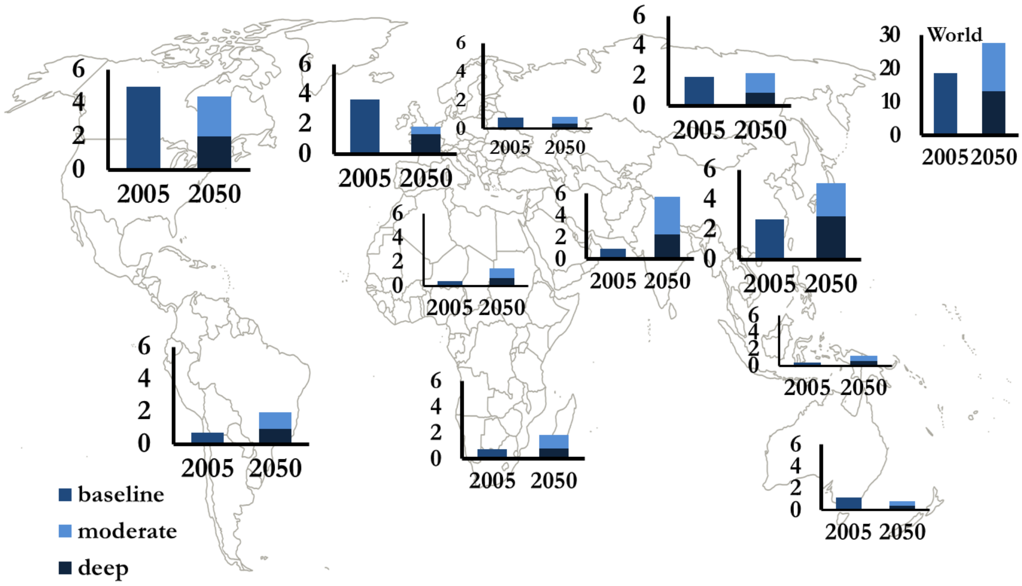

Figure 2-2. Projected thermal energy use in PWh ($x10^{15}$) in buildings in 2005 and 2050 for different regions and scenarios. Baseline corresponds to energy use in 2005. In the moderate scenario all buildings comply with codes and regulations. In the deep scenario, all buildings comply with best practices. Source: (Global Buildings Performance Network, 2013).

2.1.2 Direct policy mechanisms for energy efficiency in buildings

The main mechanisms policy makers have to directly influence energy efficiency in buildings are codes, standards and certification schemes. These mechanisms play an important role in achieving global energy efficiency goals. According to the U.S Department of Energy (U.S Department of Energy, 2010): "More stringent building energy codes are part of the solution" for achieving the goals of energy consumption and GHG emission reduction, improving energy security and delivering net cost savings.

Before embarking in a discussion on the benefits, drawbacks and potentials of different energy efficiency in buildings policy mechanisms, it is important first, to know what these mechanisms are; second, to understand what they can do when properly implemented, including the effect on the market and people's behaviour and; finally, have an overview on the main codes, standards and certifications schemes worldwide.

Definitions for building energy codes, standards and certifications are as follows:

- **Energy codes**: "specify how buildings must be constructed or perform, and are written in mandatory, enforceable language" (Bartlett et al., 2003).
- **Energy standards**: "describe how buildings should be constructed to save energy cost-effectively. They are published by national organizations such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). They are not mandatory, but serve as national recommendations, with some variation for regional climate" (Bartlett et al., 2003).
- **Energy certifications**: are mechanisms that "must include reference values, such as current legal standards, in order to make it possible for consumers to compare and assess energy performance. They must also be accompanied by recommendations for cost-effective improvement options to raise the performance and rating of the building" (Bio Intelligence Service et al., 2013).

The scope of each mechanism is clear, while codes provide the minimum a building must comply with, standards provide the desired scenarios and certificates try to promote compliance with or beyond the standards rather than merely settling for the code minima.

Compliance with these three mechanisms can be achieved through one or more of the following paths:

- **Prescriptive Approach**: following this path requires materials and equipment in buildings comply with certain characteristics. This is traditionally accomplished by setting a minimum requirement for thermal performance level such as U-factors (for walls, doors, windows, and roof), requirements on HVAC systems, lighting, etc. (Liu et al., 2010). This approach is the easiest to develop and enforce since it can be written in mandatory and enforceable code language.
- **Performance-based Approach**: in a performance compliance path, instead of regulating specific elements of the buildings, it requires that the proposed design can be shown to perform better than a certain parameter (normally annual energy consumption being equal or less than the building following a prescriptive approach) (*Performance-based Building Energy Code*). The performance approach is normally optional for many types of buildings in most codes and is presented as an alternative to the prescriptive approach. The performance-based compliance path is more flexible than the prescriptive path as it allows to offset effect of low-performing characteristics by some other high-performance characteristics.

- **Outcome-based Approach**: this path regulates the actual consumption of the whole building over a period of time (typically 12 months) and requires this consumption to be below the allowed maximum annual (Northeast Energy Efficiency Partnerships, 2012). The outcome-based approach is based on the actual performance of the building in real operation, it thus inherently also regulates building's users who have to demonstrate that performance targets were met in a certain period to avoid some penalisation (Conover et al., 2011). It is also the most flexible of all approaches as it does not include limitations during building design but rather during building's operations.

Table 2-1 presents building types addressed by each compliance approach.

Table 2-1. Building type and main code compliance approaches.

Approach	**New Buildings**	**Buildings Undergoing Renovations**	**Existing Buildings**
Prescriptive	x	x	
Performance-based	x	x	
Outcome-based		x	x

Compliance paths for energy in buildings policy differ from country to country. The IEA recommends the enforcement of performance-based regulations (based on building's estimated energy performance) and certificates that account for the whole building's life-cycle as means for achieving energy efficiency goals (International Energy Agency, 2011). The IEA considers energy certification schemes as key to unlock the potential in energy efficiency in the building sector. Nonetheless, in another report (International Energy Agency, 2010a), the IEA recommends prescription-based certification (based on building's as-built characteristics) for new buildings and buildings with high rate of occupant's change (e.g. households) so the rating is independent from the users and also recommends performance-based certification for large and complex buildings. However, it has been demonstrated that certifications do not accurately reflect energy consumption in building as they miss the actual operational consumption of the building which can be more than two times higher than the one reflected in the certificate (Burman et al., 2014)

Worldwide, most building regulations, codes and standards follow a prescriptive compliance path and in some countries building regulations allow for a performance-based compliance path (see Table 2-2). Some certification schemes like the Leadership in Energy and Environmental Design (LEED) have outcome-based compliance path for existing buildings (International Energy Agency, n.d.). An outcome-based compliance code is in proposal phase as per 2014 by the International Code Council and is expected to be released in the 2014 International Green Construction Code (National Institute of Building Sciences, 2014).

From Table 2-1 it can be seen how the approaches to evaluate building's performance in current policy tools are largely devoted to new buildings and those buildings undergoing renovations. However, a large part of the building stock still remains without any enforceable mechanisms to reduce energy consumption (those old and not undergoing significant renovations). One possible solution to assess and regulate energy consumption in the existing building stock that is not going through renovations is to enforce outcome-based compliance paths, however this solution faces the barrier of requiring to know the energy performance history of the building (Denniston et al., 2010). Another possible solution is requiring some form of retrofit to be carried out at a particular time (e.g. when selling) (United Nations Industrial Development Organization, n.d.).

The rest of the section discusses the different compliance approaches followed by different countries and regions. Table 2-2 is informative in nature and provides an overview on which are the main standards, regulations, codes and certifications currently being used worldwide.

Table 2-2. Overview of standards, regulations/codes and certifications dealing with energy efficiency in buildings worldwide. Sources: (International Energy Agency, n.d.; Buildings Performance Institute Europe, 2010; Andaloro et al., 2010; Global Buildings Performance Network, 2013).

Country / Region	**Code / Standard**	**Type**	**Compliance**
EU	EU Directive on Energy Performance in Buildings	Code	N/A
U.S.	ASHRAE Standard 90.1, International Energy Conservation Code	Standard	Prescriptive, Performance
U.S. – California	Building Energy Efficiency Standards	Code	Performance

Country / Region	**Code / Standard**	**Type**	**Compliance**
U.S.	LEED, Energy Star, Home Energy Score, Home Energy Rating Scheme, bEQ Building Energy Quotient	Certification[v]	Prescriptive, Performance, Outcome
Canada	National Energy Code for Buildings	Standard	Prescriptive, Performance
Canada	LEED, BOMA BESt	Certification[v]	Prescriptive, Performance Outcome
United Kingdom	Building Regulations (England and Wales), Technical Handbook for The Building Regulations (Scotland). The Building Regulations (Northern Ireland)	Code	Prescriptive Performance
United Kingdom	EPBD Energy Performance Certificate	Certification[m]	Performance
Ireland	Building Regulations	Code	Prescriptive Performance
Ireland	Building energy Rating	Certification[m]	Performance
France	RT 2012 (New buildings), RT 2005 (Refurbishing)	Code	Performance
France	Building Base Consumption (BBC)	Certification[m]	Prescriptive, Performance
Spain	Technical Code for Buildings	Code	Prescriptive (only in certain cases), Performance
Spain	Energy Efficiency in Buildings Certificate	Certification[v]	Prescriptive
Germany	Energy Conservation Regulations	Code	Prescriptive, Performance
Germany	Energy Performance Certificate	Certification[m]	Performance
Australia	Building Code of Australia	Code	Performance
Australia	NABERS (Non-residential), NatHERS (Residential)	Certification	Outcome
India	Energy Conservation Building Code	Code	Prescriptive Performance

Country / Region	Code / Standard	Type	Compliance
India	Bureau of Energy Efficiency (BEE) Star Rating for Buildings, Green Rating for Integrated Habitat Assessment, Indian Green Building Council (several certificates), LEED	Certification[v]	Prescriptive, Performance, Outcome
China	Design Standard for Energy Efficiency (for different types of buildings and climate zones)	Code	Prescriptive, Performance
China	Passive House	Certification[v]	Performance
Russia	Thermal Performance of Buildings	Code	Prescriptive, Performance
Russia	Green Standards, Energy Efficiency Class of Multifamily Building	Certification[v]	-
Japan	Rational Use of Energy within Buildings (Residential), Standards of Judgment for Construction Clients and Owners of Specified Buildings on Rational Use of Energy for Buildings (Non-residential)	Standard	Prescriptive, Performance
Japan	Passive House	Certification[v]	-
Brazil	LEED, Qualiverde	Certification[v]	-

[m] mandatory, [v] voluntary.

From Table 2-2 it is obvious that only Europe is consistently enforcing energy efficiency in buildings in some way while largely in other regions, even when the infrastructure is in place (e.g. standards and voluntary certificates), there is no way of enforcing a path towards reduction of consumption in buildings. This is a problem especially in the regions of expected high growth in energy consumption in the northern hemisphere (Figure 2-2) and where there is no possibility to cover energy demand from renewables (e.g. China, Russia and the U.S.). For other regions like South America, Africa or India, where renewables are already covering an important percentage of the energy demand (Dube et al., 2010), programmes to incentivise the full exploitation of the renewable potential could prove easier to implement and have a bigger impact.

2.1.3 Indirect policy mechanisms for energy efficiency in buildings

Indirect policy mechanisms for energy efficiency in buildings aim at *incentivising* users to carry out energy efficiency measures. These are indirect as the outcome depends on third parties (e.g. users) engaging with the mechanisms and modifying their energy consumption patterns. Indirect policy mechanisms can be divided in three tiers as shown in Figure 2-3.

The first tier of these incentive mechanisms correspond to trading schemes like white certificates and energy supplier obligations (also known as demand-side management). "White certificates place a legal obligation on energy suppliers, retailers and/or distributors to encourage investments that produce energy savings on their customer's premises" (Obara, 2009). One important characteristic of white certificates is that they may be tradable thus allowing regulated organisations to sell certificates if they have accomplished their target in excess or buy certificates otherwise. White certificates can be combined with other mandatory measures (e.g. such as green certificates that impose obligations on the quota of renewables) to achieve their target energy consumption reduction (Bertoldi & Rezessy, 2006; Oikonomou et al., 2009).

Energy supplier obligations are enforceable mechanisms expressed in terms of targets such as market shares, percentage of energy demand, peak demand, percentage of renewables, etc., that should be met by energy suppliers to avoid penalisation.

In the countries that have applied these mechanisms, white certificates and energy supplier obligations have proven to be very effective in terms of companies delivering beyond targets savings at lower than market costs and they have also shown to have a positive impact in energy reduction (mainly electricity consumption) in the residential sector (Bertoldi et al., 2010; Mundaca & Neij, 2009).

Table 2-3, is informative in nature, and provides an overview of significant energy efficiency obligations in selected countries.

Table 2-3. Overview of energy efficiency obligations in selected countries. Source: (Lees, 2010).

Country	**Target company**	**Eligible Customer**
Belgium	Electricity Distributors	Residential/non-energy intensive industry/service
Brazil	Electricity distributors/suppliers	All except transport
Denmark	Electricity, gas, oil/heat distributors	All except transport and those covered by EU ETS
France	All suppliers of energy	All except those covered by EU ETS
Italy	Electricity & gas distributors	All
UK	Electricity & gas suppliers	Residential only

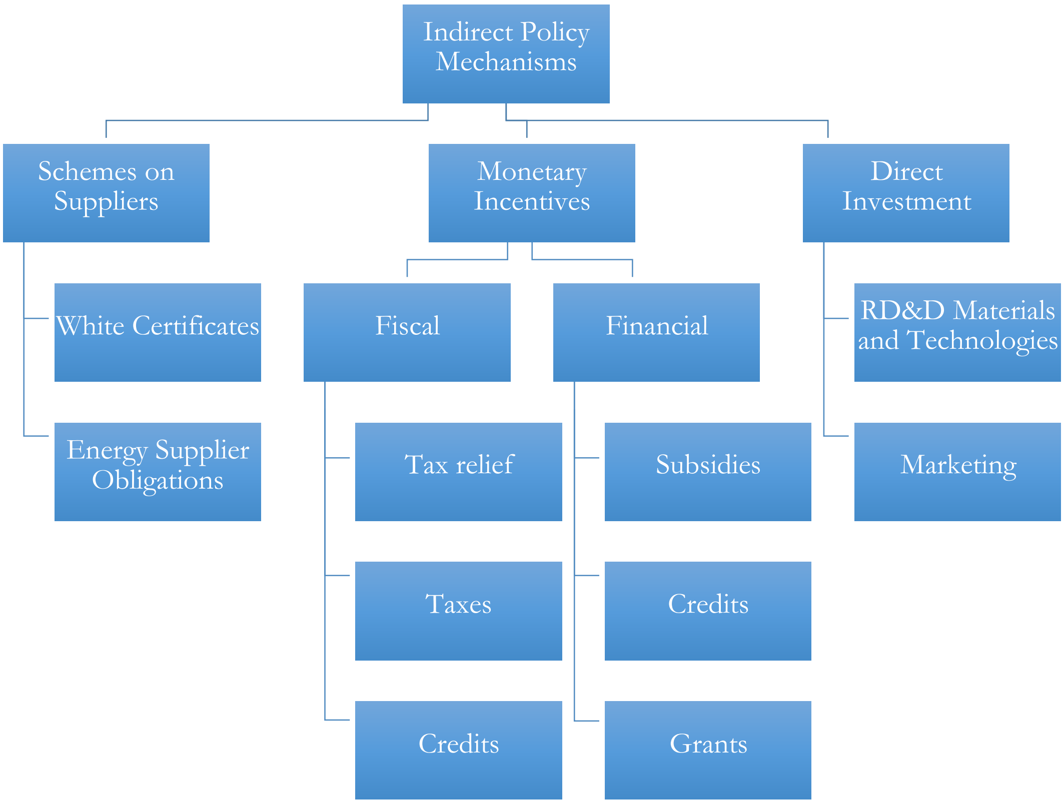

Figure 2-3. Tiers of indirect policy mechanisms.

The second tier of indirect policy mechanisms corresponds to monetary incentives that aim at stimulating the final users. Such mechanisms include grants, loans, rebates, subsidies and/or tax incentives. These incentives may be targeted to the construction sector or to the house-owners, to the residential sector or the commercial sector, to new buildings or existing buildings, be national or local, engage private funding, being completely from public funding or from public-private partnerships. The number and variety of these types of measures makes it difficult to compare and estimate the energy savings. Also, many of these programmes are promoted by the governments so they usually change with new governments. Some of the considered to be most successful monetary programmes are shown in Table 2-4.

Table 2-4. Energy efficiency in buildings incentive programmes. Sources: (Levine et al., 2012; International Energy Agency, n.d.; Association for the Conservation of Energy, 2009).

Country	Program	Incentive type	Funds origin	Target sector
Germany	KfW Loans for Energy Efficient Construction	Loan, Grants and Tax Rebates	Public Banks	House owners, municipalities and welfare associations
Austria	Federal Promotion of Extraordinary Efficiency in Buildings	Grants	Government	Residential
U.S	Tax deductions for energy efficient commercial buildings	Tax rebate	Government	Commercial
India	MNRE incentive program for GRIHA-rated buildings	Refund of costs for project highly rated in energy efficiency	Government	All
China	Interim Administrative Method for Incentive Funds for Heating Metering and Energy-Efficiency Retrofit for Existing Residential Buildings	Grant	Government	Residential

Finally, the third tier concerns direct investment for the stimulation of the innovation and marketing of new technologies. This is achieved by supporting, with public funds, research and development of energy efficiency technologies and materials for energy efficiency in buildings. Although there are no official figures, direct funding on research and development is seen by several countries as a high-impact and cost-effective approach to drive innovation and market uptake of technologies and materials targeting improved building operations (International Energy Agency, 2009, 2013, 2014). More and better marketed innovation translates in larger impact of all other policy mechanisms as more means will be available to deliver the targets of improved performance in buildings. Ultimately, these instruments aim at incentivise private financial markets to fund energy efficiency either by translating research into marketable products or by the creation of the so-called public-private partnerships where funds from both sectors are brought together (Hilke & Ryan, 2012).

Research and development (R&D) funding mechanisms are used mainly in the EU and in the U.S. aiming at maintaining their global technological and market leadership and, at the same time, as means for creating and fostering employment in the energy efficiency sector. Other effect of direct investment is that of creating a driving force towards better energy security and a more stable energy market (International Energy Agency, 2009).

In Figure 2-4 it is shown the investment directly related to R&D for energy efficiency in buildings for the decade 2001-2011. It can be clearly seen how Europe and the U.S. are the ones providing the biggest amount of funding (combining public and private funds).

For the upcoming years, and directly from public funds, the EU through the European Commission has allocated a tentative budget of €600 million during the period 2014-2020 (Horizon 2020 programme[4]) for directly funding research and innovation activities related to energy efficiency in buildings (European Commission, 2013b).

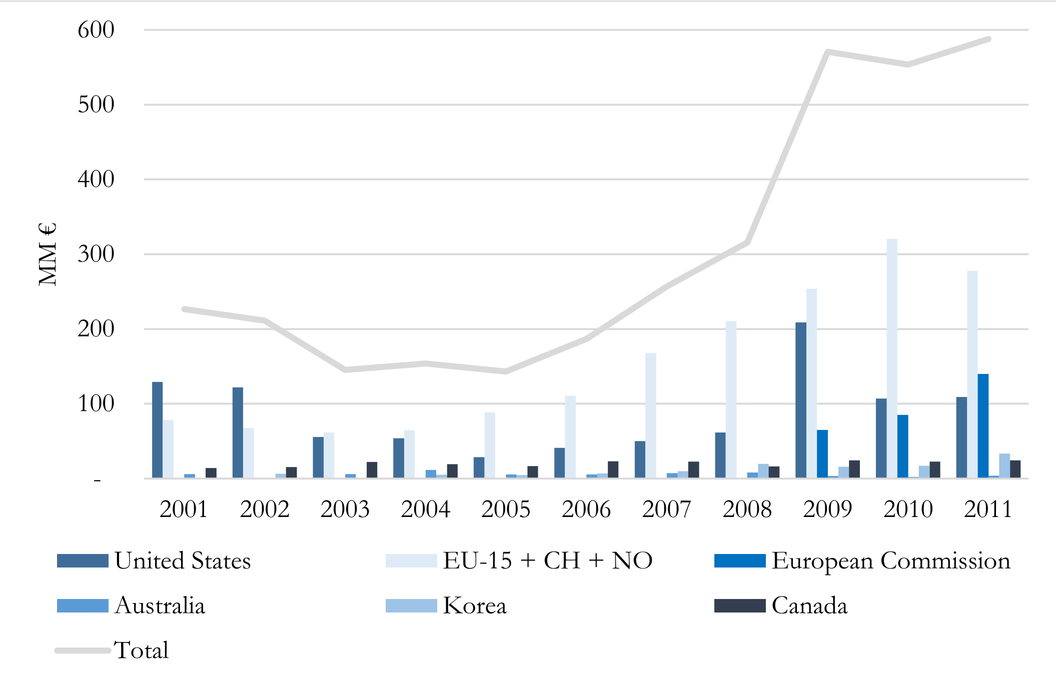

Figure 2-4. Total R&D in million Euro (2012 prices and exchange rates) for residential and commercial buildings, appliances and equipment. Source: IEA data.

[4] http://ec.europa.eu/programmes/horizon2020/

2.1.4 Energy efficiency in buildings policy outlook in selected regions

2.1.4.1 European Union

The European Union is pioneer in realising the energy efficiency potential in the building sector. This realisation is collected in the *EU Energy Performance of Buildings Directive (EPBD)* (*Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast)*) which aims at providing cost-effective measures for the improvement of energy efficiency of buildings.

The EPBD establishes the framework under which the EU Member States (MS) ought to develop national regulations and certification mechanisms concerning energy efficiency in buildings. The EPBD also provides a reference for minimum energy performance requirements of new buildings and buildings with a floor space above 1000 m^2 undergoing major renovations. The most tangible requirement of the EPBD is for MS to implement E*nergy Performance Certification* (EPC) schemes. An EPC must be issued by an independent entity and provide clear information on the energy performance of a building as well as recommendations on possible modifications to be carried out in order to improve such performance. EPCs are mandatory in most EU MS (see Table 2-2) however their validity period differs from one MS to another and furthermore, there is no obligation to carry out the improvements recommended in the EPC. As a result, an EPC acts as an independent assessment to be supplied to potential buyers or tenants so they can make better informed decisions without any compromise imposed on any of the parties to improve building's performance. Other requirement to comply with the EPBD is to perform a periodic inspection of medium to large size heating and air conditioning facilities in order to monitor and optimise operations.

Even when the initial EPBD was published in 2002 and it should have come into full force by 2006, in 2010 the full implementation of the Directive was still lacking in some MS (Andaloro et al., 2010). Moreover, most MS have not adopted appropriate accompanying measures to improve building energy performance and enhance the reach of the EPC schemes (measure of excellence Figure 2-5). Such measures would provide better guaranties to property owners, buyers, landlords and tenants on expected energy use in the buildings being occupied. Also, since the EPBD has left MS to implement the requirements in a way that suit specific country necessities and culture, this has resulted in a lack of standardisation of the approaches that makes comparison between countries difficult (measure of uniformity in Figure 2-5).

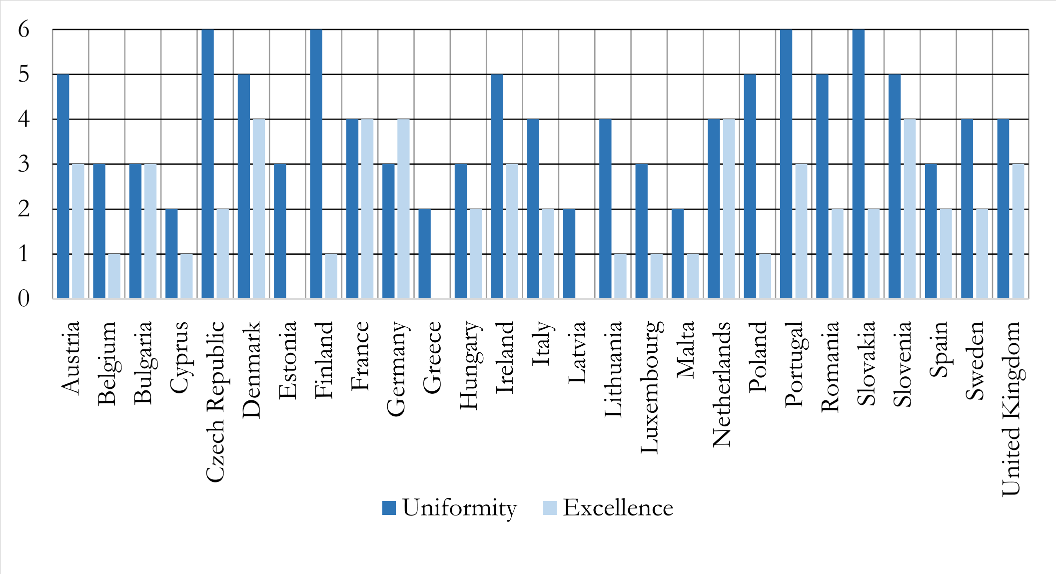

Figure 2-5. Indicators of EPBD energy certification implementation on the Member States of the European Union in 2010. Qualitative scale from 1 to 6 being 6 the best Source: (Andaloro et al., 2010).

One weak point of the EPBD is that its actions are focused on improving current building operational energy consumption and CO_2-eq emissions without accounting for the whole life-cycle of the building and its components (e.g. form cradle to grave including embodied energy of materials and energy necessary for disposal and recycling) (Szalay, 2007). In the same line current energy regulations and certifications in Europe may not reach the expected impact when analysed in the whole building life-cycle (García Casals, 2006). Reasons for this issues are seen by García-Casals, with especial emphasis on Spanish regulations, as two-fold:

- Energy certification and regulations seem to encourage building material refurbishing rather than systems operational optimisation by the merely fact that they do not account for life-cycle analysis;
- Lack of concise, clear and appropriate definition of energy performance indicators.

Another barrier to improved building operations is the conservative approach the building industry has towards implementing energy efficient measures (Ryghaug & Sørensen, 2009).

Szalay, Ryghaug and Sørensen and García-Casals provide a view that to reach energy efficiency and GHG emission reduction objectives, policy measures must be innovative and account for long-term impact of the building sector. Their critiques also explain the findings of Andaloro, whereby the lack of unified energy performance indicators and even the translation of the text of the EPBD to other languages has led to deviation in the original intended application of the directive: that of improved operational performance.

2.1.4.2 The United States of America

The United States of America has a similar layout to the European Union in the sense that general guidelines are given at the Federal level, but actual implementation of building regulations is competence of individual States. In 2005, the Federal Government signed the Energy Policy Act of 2005 (*Pub.L.109 - 58. An act to ensure jobs for our future with secure, affordable, and reliable energy*) in a centralised attempt to foster energy efficiency nationwide. Specifically to the building sector, it establishes tax reductions for facilities undergoing renovations or new facilities conforming with ASHRAE 90.1 standard (ASHRAE, 2004). The Act also brings about a number of mandatory energy efficiency measures to Federal buildings such as (Dixon et al., 2010):

- Advanced metering for all Federal buildings;
- Designed to perform 30% better than standards for new Federal buildings and;
- Minimum of 20% of use for renewable energies by 2015.

Reinforcing the Energy Policy Act of 2005, the Energy Independence and Security Act of 2007 (*Pub.L.110 - 40. Energy Independence and Security Act of 2007*) requires that all new commercial buildings have a zero-net-energy balance by 2025 and that all buildings do so by 2050 (Sissine, 2007).

In the U.S., the share of potential energy savings in buildings nationwide is evenly spread between new building construction, retrofitting and building equipment. However, the main focus of policies is new buildings and building equipment (Amecke et al., 2013). This opposed to the EU case where the rate of new constructions is very low and the biggest opportunities are in retrofitting (including improved operations) which is reflected in regulations targeting retrofitting. Also, since the adoption of building energy codes is left to the individual States to define, it is the case that a number of States have adopted codes that regulate primarily building envelopes while only a few make provisions for energy efficient operations and even some States do not have regulations at all[5] (Amecke et al., 2013).

[5] An interesting point to note is that the State of California has probably the highest level of standards and requirements for buildings worldwide and a long tradition for building energy efficiency (Laustsen, 2008). This drives many countries to look at California's regulations when developing own codes.

Unlike the EU, energy labelling in the United States of America is not mandatory and there is no unified version. Nonetheless, several approaches for energy labelling of residential and commercial buildings are in operation: Home Energy Rating System, Energy Star, Home Energy Score, ASHRAE Building Energy Quotient, LEED (International Energy Agency, n.d.).

In the U.S., the standards and codes are largely based on two main standards: The International Energy Conservation Code (*2012 International Energy Conservation Code*), mainly for the residential sector, and the ASHRAE Standard 90.1 2004 for all sectors (ASHRAE, 2004; Doris et al., 2009). Both standards are largely prescriptive in nature and address mostly new construction or large renovations with some specification for buildings in normal operation (Laustsen, 2008).

2.1.4.3 Developing countries

Developing countries represent the bulk of constructed floor area growth in the upcoming years. It is expected that these countries will produce the almost totality of population growth by 2050 (see Figure 2-6 left). Moreover, the urban population in developing countries is expected to double by 2050 while that of developed countries will increase only marginally (see Figure 2-6 right) (Department of Economic and Social Affairs, 2012).

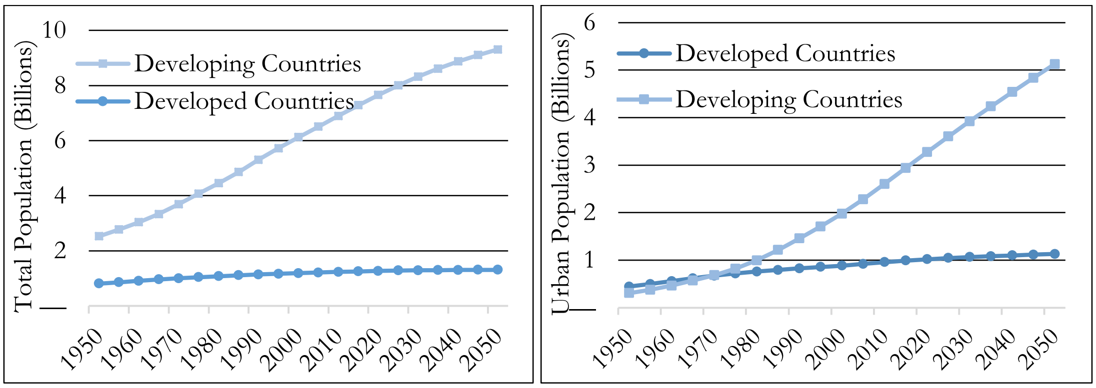

Figure 2-6. Left: Total population growth developed vs developing countries. Right: Urban population growth developed vs. developing countries. Source: UN Department of Economic and Social Affairs Population Division Data.

In economic terms, developing economies are expected to drive the world's economic growth in the years to come, especially the group formed by Brazil, Russia, India, Indonesia, China and South Africa (BRIICS) (OECD, 2012) Figure 2-7.

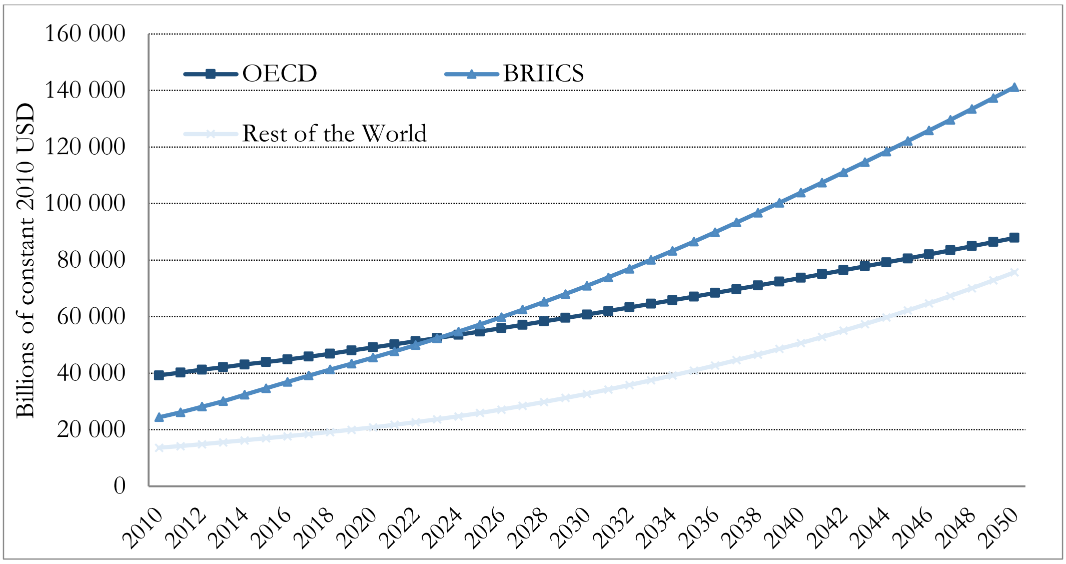

Figure 2-7. Projections for real gross domestic product: Baseline, 2010-2050. Source: Organisation for Economic Co-operation and Development (OECD) Environmental Outlook Baseline, output from ENV-Linkages.

The combined population and gross domestic product (GDP) growth is expected to impact the buildings sector as follows:

- New residential buildings (being these both new built and re-built) will be needed to accommodate the increase in population;
- Increase in GDP leads to a higher energy demand in buildings to accommodate increased standards of comfort;
- Increase in commercial floor space is expected to be proportional to the GDP (Ürge-Vorsatz et al., 2011).

Given this growth, developing economies represent a big opportunity for the implementation of energy efficiency policies from scratch. In particular, policies aimed at new buildings and retrofitting can have the largest impact on energy efficiency in developing countries.

Developing countries also show all the different scenarios for the existence of standards on building energy efficiency (residential and/or non-residential). As per 2009 some did not have any standard (e.g. Venezuela, Argentina, Iran), some had proposed but not yet implemented any standard (e.g. Brazil, India, Morocco), others had voluntary or mixed mandatory-voluntary standards (e.g. Taiwan, South Africa, Russia) and only a few did have mandatory standards in place (e.g. Mexico, Singapore, Vietnam, China) (Janda, 2009).

The implementation of energy efficiency policies in developing economies presents a series of barriers that must be overcome such as (Iwaro & Mwasha, 2010):

- Many developing countries lack baseline consumption data. This situation makes it very difficult to quantify the reach and outcome of the implementation of any energy efficiency measure;
- An important part of the population will not be able to afford the price increase that is still attached with improved efficiency, especially upfront costs;
- Lack of appropriate production technologies which translates in these countries having to import energy efficient products with the corresponding increase in price;
- Behavioural and organisational issues like corruption, electricity theft, tradition to ignore small energy efficiency measures;
- Overall lack of information and population facing more pressing problems than energy efficiency.

However, even with the above mentioned barriers in place, a starting point to both, test the applicability of energy regulations and educate population on energy efficiency in buildings issues, consists on the implementation of government-led programs in large building of public use (Yan-ping et al., 2009), particularly those buildings owned and/or managed by the State as done in the U.S.

2.1.5 Discussion of policy outlook for energy efficiency in buildings

Policy is fundamental in improving energy efficiency in buildings and achieving consumption and GHG reduction goals. Different mechanisms are at the disposition of policy makers to drive the how, when and what energy efficiency measures need to take place in buildings. Some mechanisms are global or international (e.g. Kyoto Protocol, EPBD) and some are national or regional and have either direct (standards, codes, regulations and certifications) or indirect (white certificates, financial mechanisms, public engagement) influence in the energy use in buildings.

The EU is pioneer in the implementation of regulatory energy efficiency in buildings policy measures in its member states while the United States of America leads the development of standards and together with the EU, both lead research investment for improved operations.

Standards, codes and regulations have the greatest potential for delivering cost-effective energy efficiency and carbon reduction measures (Levine et al., 2012). In addition, improving energy efficiency in existing buildings can have the greatest impact in the overall reduction of GHG emissions in the buildings sector, as can be seen in Figure 2-8 for the UK where the potential reduction gap is around 90 $MtCO_2$ while that for new construction is around 60 $MtCO_2$. This has been demonstrated by the results of the application of indirect policy mechanisms such as white certificates and supplier obligations in countries like Italy, U.K. and Denmark.

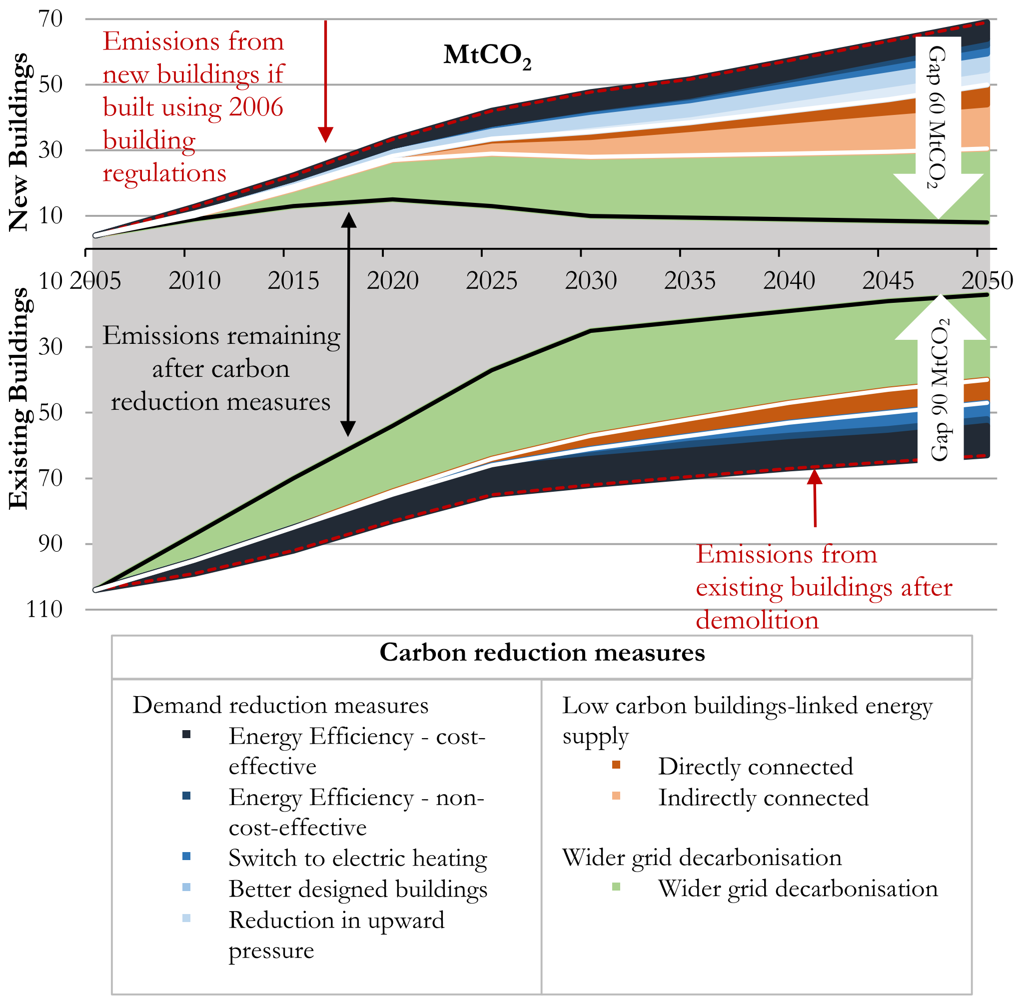

Figure 2-8. Potential GHG emissions reduction for new and existing buildings in UK. Source: (Carbon Trust, 2009).

Contrary to the need to regulate and exploit the potential of existing buildings, most of the standards and regulatory mechanisms around the world (developed mainly in OECD countries) concern primarily with new buildings or those undergoing important renovations and not directly targeting the problem of high-energy use of existing buildings. The goal in terms of primary energy consumption reduction imposed by regulations and standards to the type of buildings they target is high (towards net-zero). As a result, current standards and regulations may be preventing the exploitation of the full potential of optimisation of existing building operations by directly requiring extensive renovations (Ries et al., 2009). Even if such renovation takes place, a deep renovation in an existing building may prove to cause more GHG emissions and consume more energy when the whole building life-cycle is taken into account as discussed by García-Casals (García Casals, 2006).

In Table 2-5, an ideal match can be seen between policy goals, policy mechanisms and response and desired policy response:

Table 2-5. Matching policy goals with desired and actual policy response.

Policy goals	**Policy mechanisms**	**Desired policy response**	**Actual policy response**
Establishing goals for GHG reduction	Energy efficiency goals and international directives	Enforceable agreements	Mixed voluntary/mandatory agreements
Integrating energy efficient practices in all aspects of the building life-cycle	Standards, codes and regulations Certification and labelling People engagement	Mandatory labelling and certification of all buildings	Mixed voluntary/mandatory labelling and certification of new buildings or buildings undergoing large renovations
Identifying and integrating energy saving technologies and materials	Funding mechanisms	Financial incentives	Tax exemptions Tax rebates R&D funding Grants Loans
Gathering data for energy benchmarking	Certification and labelling	Mandatory certificates and labels of all buildings with short expiration	Mixed voluntary/mandatory certification and labelling of some buildings with long term expiration

In this light, it is important for regulations to set the focus on a rational balance between refurbishing and optimisation of building operations. This is particularly true for OECD countries for in these countries the growth in floor space in the next 30 years is minimal if compared with the expected growth of developing economies. Also, as shown in Figure 2-8, the highest potential for GHG abatement in developed economies lies in existing buildings.

For developing economies the outlook is partially different. These countries will see a pronounced growth in population which will translate in increased floor area. Also an increase in GDP will reflect in a higher demand for better comfort conditions thus requiring more energy. If the problem is not addressed in a timely fashion, the combination of the above mentioned factors could result in an important increase in GHG emissions as shown in Figure 2-1. For developing economies it is important that policy enforces mechanisms targeting new construction and renovations. Although these countries face barriers such as lack of information and education on energy efficiency matters, lack of economic resources to assume high cost of energy efficient solutions and/or social issues such as corruption or energy theft. Developed economies and policy makers should integrate efforts for incorporating energy efficiency measures in developing countries.

In both, developed and developing economies, the introduction of an outcome-based path for compliance with building regulations, standards and certifications may be the appropriate approach to ensure optimal building operations, even before retrofitting. Such compliance path is complementary to the existing policy targeting new construction and renovations. The outcome-based approach agrees with the concept of actual energy efficiency as it could quantify the ratio between energy input to service output (energy used to maintain comfort) (Pérez-Lombard et al., 2009) and may produce necessary data to understand and overcome other barriers for the effective implementation of building regulations such as lack of standardisation, misinformation, high cost of retrofitting, etc. Other barriers that need to be overcome to support adapting policy measures to the real need of improved building operations are:

- Lack of standardisation including the choice of key performance indicators;
- Lack of inclusion of embodied energy of materials and disposal energy in the calculations of the whole building-life cycle;
- Lack of continuity in the certification process as certificates, once issued are valid for long periods;
- Lack of user’s information.

If policy takes into account these needs, and we add to that the conclusion that refurbishing could end up producing more emissions when compared to the whole building life cycle, we can see, according to Figure 1-2, that building insulation may not prove as beneficial as initially thought. This leads to optimisation of building systems operation (e.g. HVAC, lighting, etc.) being the most cost-effective way to support energy efficiency in buildings.

Finally, recent research shows that all policy mechanisms can be implemented cost-effectively and environmentally effective on the societal level, especially if programmes reinforce one another (Boza-Kiss et al., 2013).

2.2 BUILDING OPERATIONS AND ENERGY MANAGEMENT: SOCIAL AND MARKET DRIVERS AND BARRIERS

In section 2.1 it was discussed how policy has been developed around the world to face the need to reduce energy consumption in buildings. Policy evolution has not only been driven only from the need to improve energy efficiency in buildings (EEB) but from a mixture of diverse factors such as market needs, social response, and technological availability. In this section, an overview of the main market and social drivers for EEB will be presented and discussed.

Market and social drivers, when properly accounted for and integrated into energy efficiency measures, have the potential to boost the impact of EEB measures. For example, people's behaviour can increase the impact of energy efficiency measures by 30% at no extra cost. But also, people's behaviour may reduce building's performance by 60%, even when energy efficiency measures are in place (World Business Council for Sustainable Development, 2009).

One of the main conclusions from the previous section was that policy seems biased towards measures aimed at new buildings or buildings undergoing renovations but little seems foreseen for the operational optimisation of existing buildings. In addition, there is a lack of proper studies on the application and impact of measures that aim at creating consciousness among the population.

To optimise building operations, the first step is to understand how energy is consumed in buildings. Figure 2-9 shows the average split of energy end-use in buildings for the US, projected to 2035. In Figure 2-9 it can be seen that Heating, Ventilation and Air Conditioning Systems (HVAC) (including domestic hot water and refrigeration) represent over 50% of the energy consumed in buildings today and will continue to do so in the years to come.

In addition, the suitability of the sub-sector relating to buildings of public use (e.g. offices, sport facilities, libraries, universities, hospitals, airports, etc.) as demonstrators for methodologies, technologies and education on EEB, proposed in the previous section, is reinforced by the fact that these type of buildings represent over 70% of the non-residential building stock in the EU (Figure 2-10) and they also have one common element: they normally incorporate HVAC. In this sense, results and lessons learnt in this sub-sector can be replicated in the rest of the buildings sector (including residential as this sector drives toward net-zero energy consumption).

Another common element of public use buildings is the existence of automated control of their systems known as Building Controls (also Building Management Systems, Buildings Automation Systems, etc.). Building Controls, among other uses, are in charge of controlling HVAC systems to maintain comfortable and healthy environmental conditions inside buildings[6].

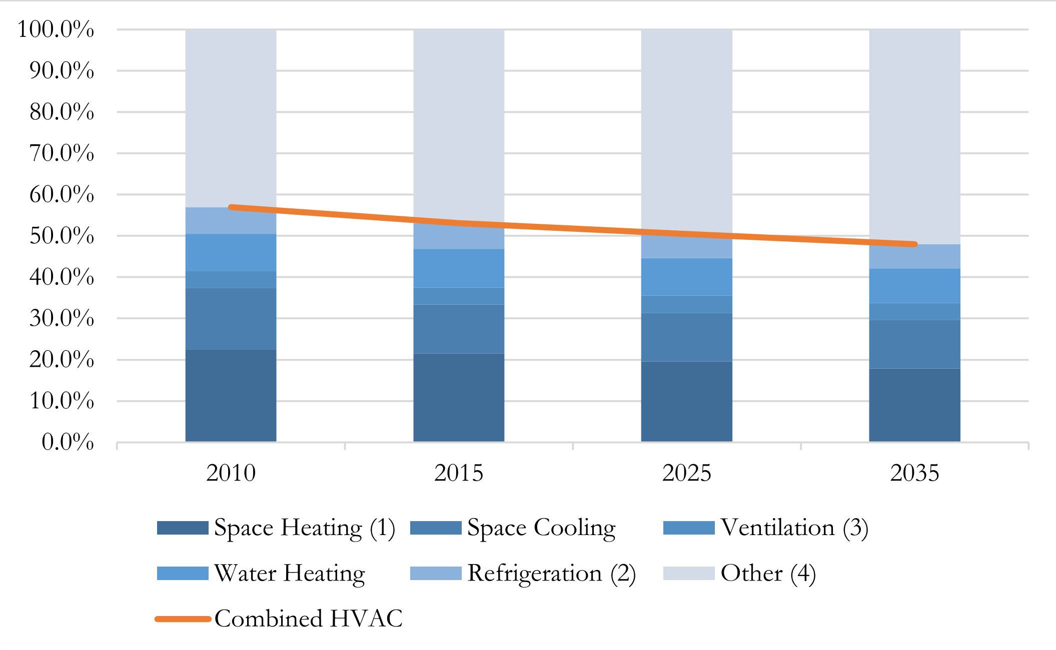

Figure 2-9. U.S. Buildings energy end-use splits. Source: (US DOE, 2011). Notes: 1) Includes furnace fans (0.44 quad[7]). 2) Includes refrigerators (2.21 quad) and freezers (0.26 quad). Includes commercial refrigeration. 3) Commercial only; residential fan and pump energy use included. 4) Include electronics, lighting, computers, cooking, wet cleaning, residential small electric devices, heating elements, motors, swimming pool heaters, hot tub heaters, outdoor grills, and natural gas outdoor lighting. Includes commercial service station equipment, ATMs, telecommunications equipment, medical equipment, pumps, emergency electric generators, combined heat and power in commercial buildings, and manufacturing performed in commercial buildings and energy adjustment EIA uses to relieve discrepancies between data sources. Energy attributable to the residential and commercial buildings sector, but not directly to specific end-uses.

[6] Building Controls are also in charge of controlling other systems like lighting, emergency, energy generation, etc.
[7] 1 quad is equivalent to 10^{15} BTU or $1.055 \cdot 10^{18}$ Joules.

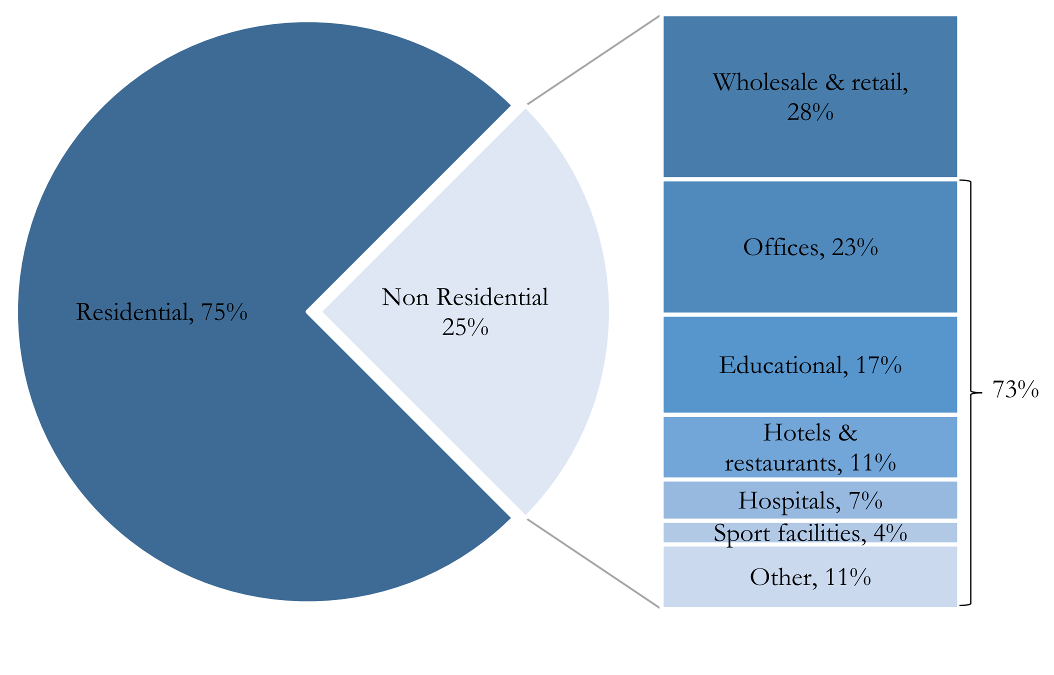

Figure 2-10. European building stock (m²). Source: (Buildings Performance Institute Europe, 2011).

The importance of building controls in a global context can be understood by the market size and projections in the EU and the U.S. as shown in Figure 2-11.

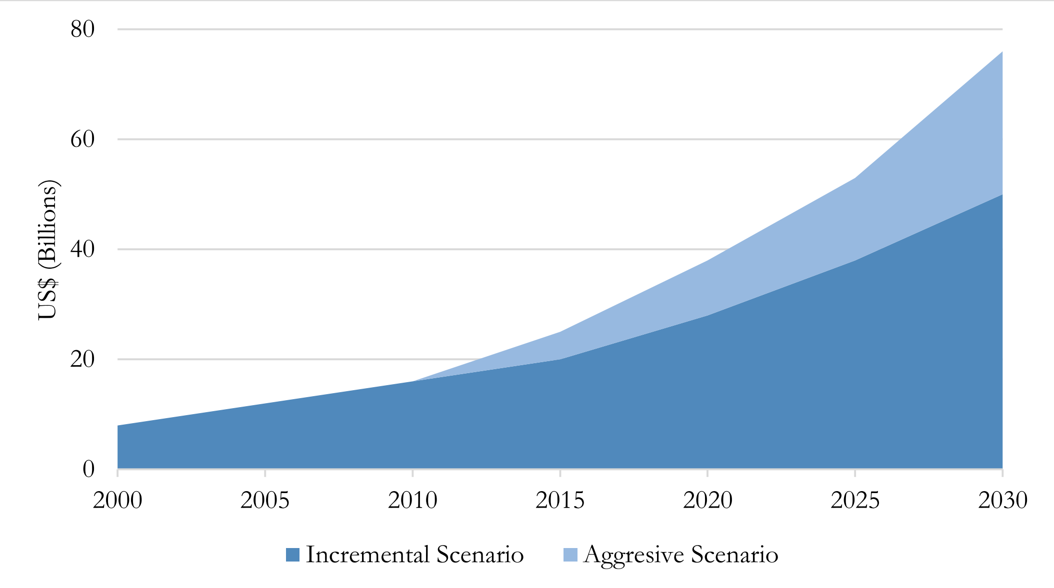

Figure 2-11. Actual and forecast of combined building controls market size in the EU and the U.S. for the period 2000-2030.The incremental scenario focuses on current and planned policies, while the aggressive scenario assumes more ambitious public policy is developed and enacted resulting in a higher demand for building controls. Source: (Mulki & Hinge, 2010).

A discussion on the role of building control systems in delivering energy efficiency goals can be found in Chapter 3. For the purposes of this section it is important to highlight that the existence of such systems provide a technical stepping stone to drive a change in concept of energy use. Building control systems are normally in charge of managing the HVAC systems and in doing so they control the usage of an important part of the energy used in buildings as show in Figure 2-9. The use of automated building control systems will increase worldwide as shown in Figure 2-11 and represent a potential opportunity for implementing energy efficiency measures. In this regard, building controls could also serve to manage energy as an *asset* rather than as a *utility*. This conceptual change can drive measures at management level to optimise energy use, after some barriers are overcome, such as:

- Traditional view of energy as a utility to be paid for rather than as an asset that, if optimised, can deliver great savings;
- Lack of understanding about building's energy use, building's systems use and possibilities to improve it by those in charge of monitoring and managing building controls (building managers);
- Lack of general knowledge on energy efficiency by the building's occupants and;
- A consumption-driven market not embracing the opportunities that energy efficiency brings and remains with old practices of replacing before optimising.

The above mentioned points will be further discussed in the rest of the section.

2.2.1 Energy use vs energy management: Utility or asset

Energy management, which inherently leads to energy efficiency, is still largely seen as a high-cost commodity needed to comply with environmental demands. This vision remains today despite the fact that facilities undertaking energy efficiency programmes have shown that, in the long term, energy management practices are cost-effective in terms of monetary savings and increased productivity (McKane et al., 2010). The key for making an energy management programme cost-effective lies in the continuity of the programme. In this way, instead of approaching energy use as an expense, it is managed as an asset like production, quality, and safety (Vikhorev et al., 2013). On the contrary, implementation of several one-off energy efficiency projects is likely to fail in delivering continuous savings unless monitoring and improvements are carried out continuously (Therkelsen et al., 2013).

Standards such as the ISO 50001 (ISO, 2010), provide tools and methodologies to integrate energy management in the overall facility management. Nonetheless, their application requires a level of resources normally unavailable in commercial buildings, especially given that the training of the appointed energy manager may not be adequate for an optimal buildings management role (O'Donnell et al., 2013). In addition, O'Donnell states that commonly used tools such as building management systems (BMS) or energy information systems lack the necessary data transformation and standardisation to provide efficient support in the decision-making process. One way in which such deficiencies are reflected in BMS is in the way they present information about systems operations. Normally BMS provide simple graphics and trends but lack advanced data manipulation capabilities (Costa et al., 2013a). This BMS deficiency creates a gap that needs to be filled by the building manager who has the task to transform the information into knowledge and enforceable actions. However, it is often the case that building managers lack knowledge and/or the time to optimally carry out building performance analysis.

With the above mentioned issues, it is clear that capacities need to be built, either in people managing building or in the building systems themselves. The next section argues sustaining the latter case.

2.2.2 Capacity building: People or machines

Capacity building has been discussed in literature in relation to the implementation and enforcement of energy efficiency policies and the need to appropriately train individuals that enforce policy (e.g. building auditors issuing building energy certificates) for the successful outcome of the measures (OECD, 2012; United Nations Environment Programme, 2009; International Energy Agency, 2011, 2013). Similarly, in building operations, there is a recognised need for building managers to possess a series of highly technical and informatics skills in order to be able to effectively implement energy efficiency measures. Consequently, tools have been proposed and developed to help them in the process (Torrens et al., 2011; Costa et al., 2013a; O'Donnell et al., 2013; Costa et al., 2012). Most of the supporting tools make use of computer simulation to embed the "capacity" into the solution. This ultimately aims to bridge the gap between the wealth of data provided by buildings and the information that can be generated from such data. However, the truth remains that the building manager needs to interpret this information to take actions. A task for which building managers are still under-skilled. The need lies thus in building system's having the capacity to *automatically* transforming data into actionable tasks or knowledge without the need to be interpreted.

To date the integration of such automated transformation capacity in building systems has been hampered by the diversity and fragmentation of the building sector. In particular, building systems that are designed for purpose, leading to building management tools that are still being developed ad-hoc and specific for purpose as opposed to standard and generic. The consequence is that in the end, each building still needs to be studied individually for the implementation of energy efficiency tools. This prevents the development of tools suitable for a wide range of applications with the capacity already built-in in the software. This has often resulted in a barrier against the implementation of many technologies aimed at optimising building operations.

The current situation does not necessarily need to continue into the future. Technologies and methods exist so that *embedding capacity* in the building systems and making the building *self-aware* is a possibility (see section 1.3). The main issues for existing buildings involve, knowing what can be implemented and what the real possibilities for improving operations cost-effectively. In other words, to be informed about the existing market technologies and the real integration possibilities of such technologies on each building.

So far the discussion has been centred on the building systems and the people managing such systems. It has been said that there is a need to implement measures to educate the public on energy efficiency, and that buildings of public use are ideal for such measures. Even if the focus of this work is not on how to influence people's behaviour towards more sustainable energy use, the next section provides, with the hope to encourage further research in the area, a short overview on the importance of public engagement and awareness to achieve energy efficiency targets.

2.2.3 Public behaviour, engagement and awareness

Most of the energy consumption in the building's lifecycle occurs through the operation phase as shown in Figure 2-12. During this phase it is not only important to improve the way buildings are designed and operated, but also the actions people utilising buildings take and which have an impact on building operations (e.g. opening windows to cool down before turning down thermostat or closing radiator valves).

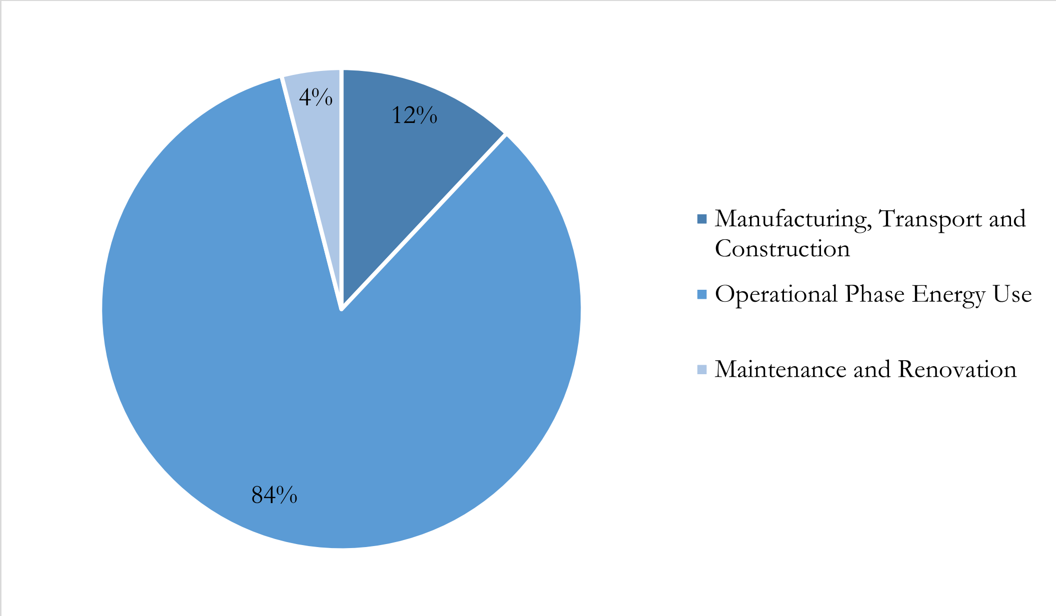

Figure 2-12. Building life cycle energy use. Source: (World Business Council for Sustainable Development, 2007).

The tenant, owner and general building users make decisions on usage, operation and maintenance on an ongoing basis. Many of these decisions negatively affect energy usage and provide an opportunity to improve energy efficiency (Managan et al., 2012). In fact, it was previously established, in the introduction of section 2.2, that people's behaviour can improve energy efficiency by 30% at no extra cost or compromise building's performance by 60%.

Contrary to what energy policy expects, many of people's decisions in building operations follow an idiosyncratic rather than a reasoned and predictable behaviour. In consequence, the actual impact of building's users in the built environment is poorly understood and often overlooked (Janda, 2011). This may lead to missing out on no-cost energy efficiency opportunities. Janda also highlights how policy assumes that people are prepared and trained to participate in energy efficiency decisions. In this regard, energy efficiency has been shown to be under-represented in national and international environmental education programmes so policy assumptions on people's readiness to make energy-efficiency decisions are unreal (Harrigan & Curley, 2010).

The issue lies in that most awareness campaigns and energy efficiency measures focus on technical aspects and economic benefits. Nonetheless, population and especially GDP growth in some regions reduce the economic impact of efficient building operations and invariably lead to better and more comfortable buildings, even at the expense of less than optimal operations in terms of energy efficiency. As a result, building energy consumption is expected to keep growing in the foreseeable future (Figure 2-13). Nonetheless, increased energy consumption does not necessarily needs to translate into increased GHG emissions.

Current policy approaches aiming and reduction of GHG, promotes changing primary energy sources with renewable energy, the installation of energy efficient equipment and the provision of more detailed or even personalised energy consumption information[8]. However, these measures do not directly translate into actual energy efficiency (Ek & Söderholm, 2010) but may even have a rebound effect since people facing a reduced energy cost, consumes even more[9] (Gillingham et al., 2013). To avoid this, policy measures ought to also promote behavioural changes.

Finally, programmes should not only promote awareness on energy efficiency and reduction of consumption, but should also be complemented with education on health related problems derived from inefficient operation of buildings, and emphasize on the negative impacts of non-optimal operations. As an example, intermittent local heating (e.g. heating living room but not the bedroom) can have a negative impact on health as sharp changes in temperature can cause a sudden blood pressure drop that can result in death by apoplexy or anaemia. To prevent this, it is necessary to maintain a reasonable level of thermal comfort throughout the inhabited spaces of the building. In fact, once users get accustomed to it, keeping the whole living space a few degrees cooler in winter and a few degrees warmer in summer, combined with appropriate clothing, can provide equivalent or even bigger savings that conditioning a single area to higher levels of comfort and leaving the rest of the space unconditioned (Ürge-Vorsatz et al., 2012).

[8] An example of good educational policy has shown that measures raising awareness about the *negative* impact of reduced building performance can induce more intensive response from users that campaigns than focus on economic benefits (Ek & Söderholm, 2010).

[9] It is important to note that this rebound effect does not defeat the purpose of energy efficiency measures but reduces its effect and proper education in energy efficiency is key in preventing such rebound effect.

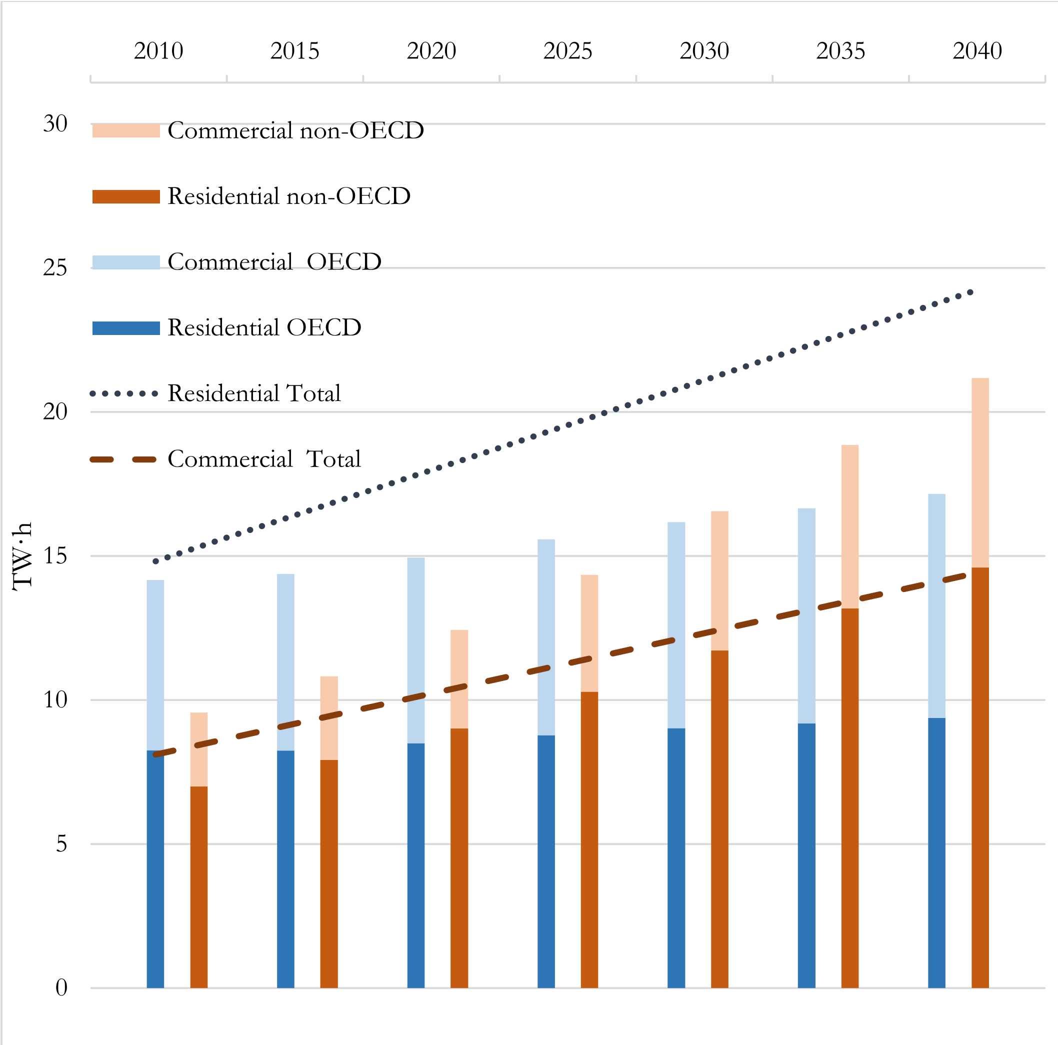

Figure 2-13. Total world delivered energy consumption in buildings, 2010-2040. Source: Energy Information Agency (EIA) data.

2.2.4 Market drivers and barriers

It has been recognised that energy efficiency in the building sector offers the greatest potential for cost-effective GHG emission reductions than any other major sector, and using already available technologies (United States, 2009) as shown in Figure 2-14. In fact, from Figure 2-14 it can be concluded that most GHG emission reduction actions in buildings would have negative cost (<0$) and thus actually save money.

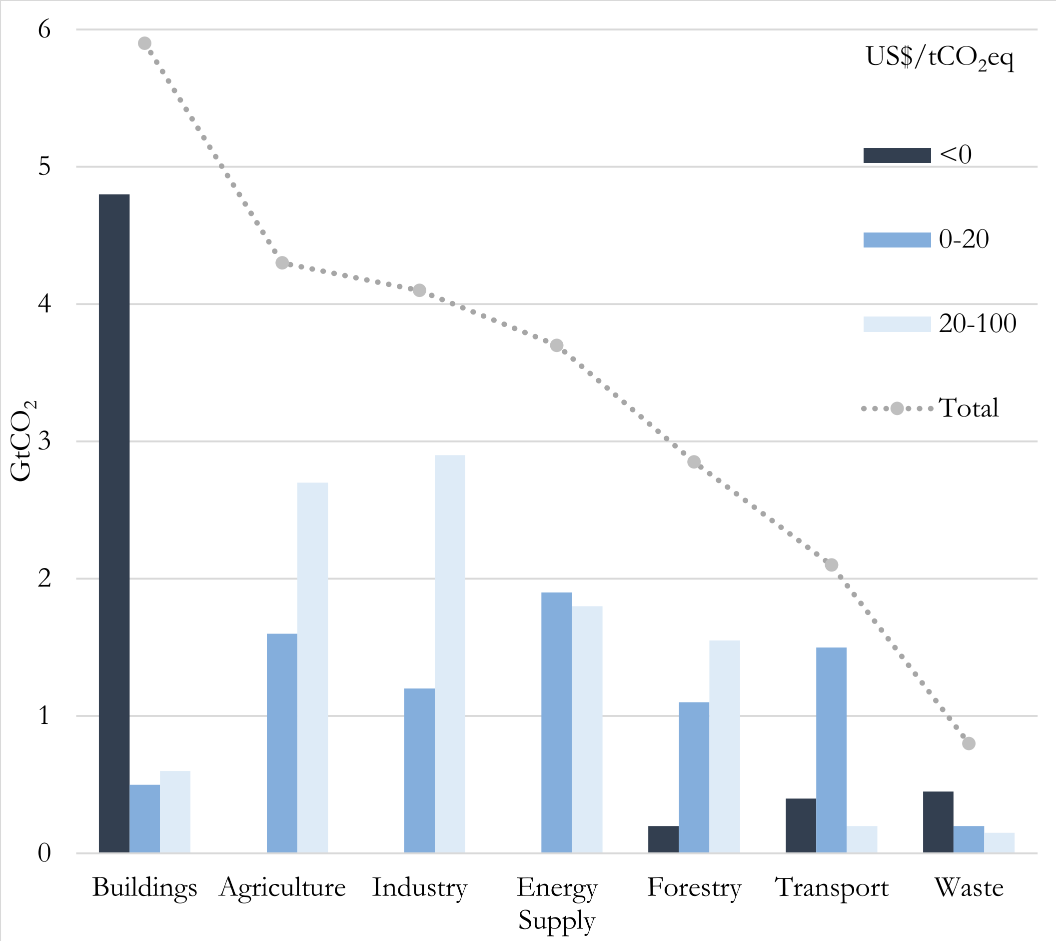

Figure 2-14. Estimated potential for GHG mitigation at a sectorial level in 2030 in different cost categories. Source: (Ürge-Vorsatz & Novikova, 2008).

The market value and business opportunities of energy efficient building operations can be grasped from the example of the energy performance contracting model[10], as shown in Figure 2-15. In Figure 2-15 it is shown that once the performance contract is enforced, the energy consumption is reduced, which translates to net monetary savings. Throughout the duration of the contract, part of these savings are what the contracted company charges for theirs services and the rest is what the contracting entity actually saves. At the end of the contract, all the savings are net for the contracting entity.

[10] According to the Energy Efficiency Directive (2012/27/EU), 'energy performance contracting' means a contractual arrangement between the beneficiary and the provider of an energy efficiency improvement measure, verified and monitored during the whole term of the contract, where investments (work, supply or service) in that measure are paid for in relation to a contractually agreed level of energy efficiency improvement or other agreed energy performance criterion, such as financial savings.

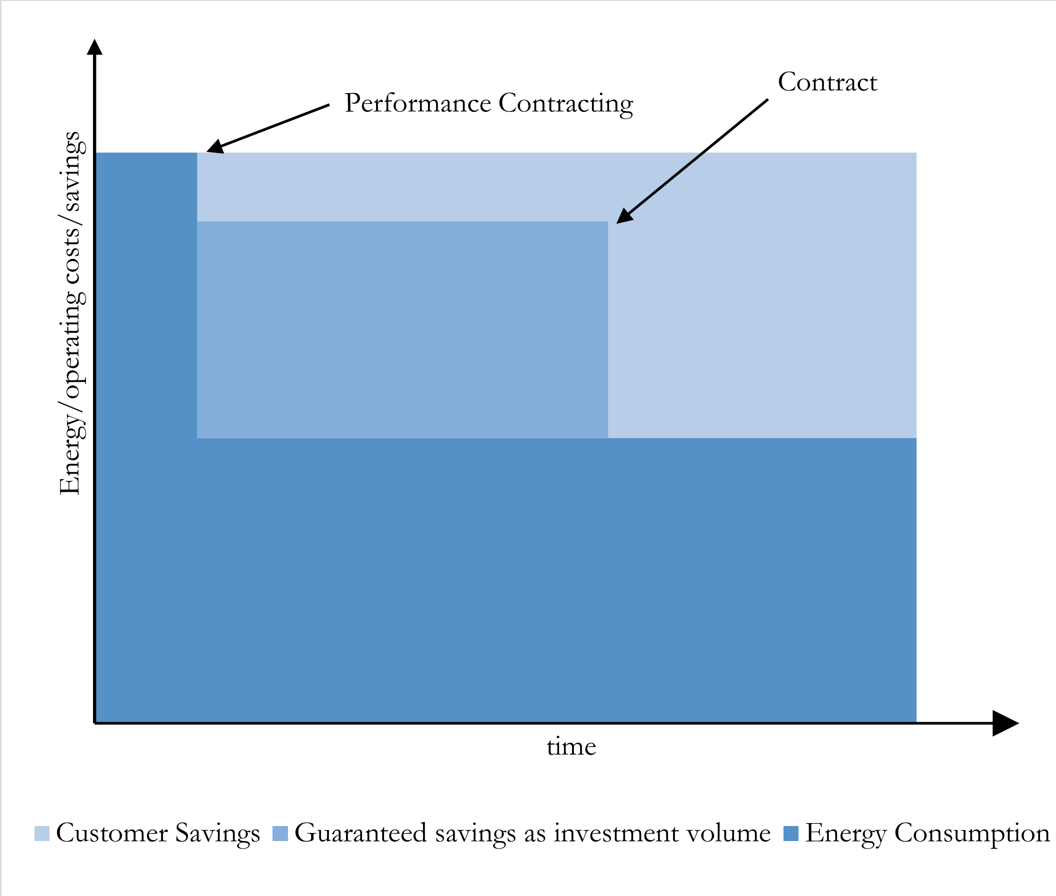

Figure 2-15. Energy performance contracting business model. Source: (Managan et al., 2012).

Research shows that inside organisations, including personnel cost, the implementation of energy management programs have a payback period of around 2 years (Therkelsen et al., 2013). Furthermore, Therkelsen shows that many hidden no- or low-cost operational energy performance improvements can be uncovered by energy management programmes.

Keeping the focus on operational optimisation of buildings, specifically on space conditioning systems (HVAC) incorporating BMS, as existing in most buildings of public use, it can be seen in Figure 2-16 how measures directly targeting systems optimisation such as continuous commissioning, retro commissioning and building energy information systems represent three of the greatest potential for energy savings (Navigant Consulting Inc., 2011). As an example, retro commissioning typically achieves savings around 15%, compared to previous energy consumption and with paybacks of less than one year (Mills et al., 2004), while a proper commissioning or continuous commissioning would prevent the energy waste.

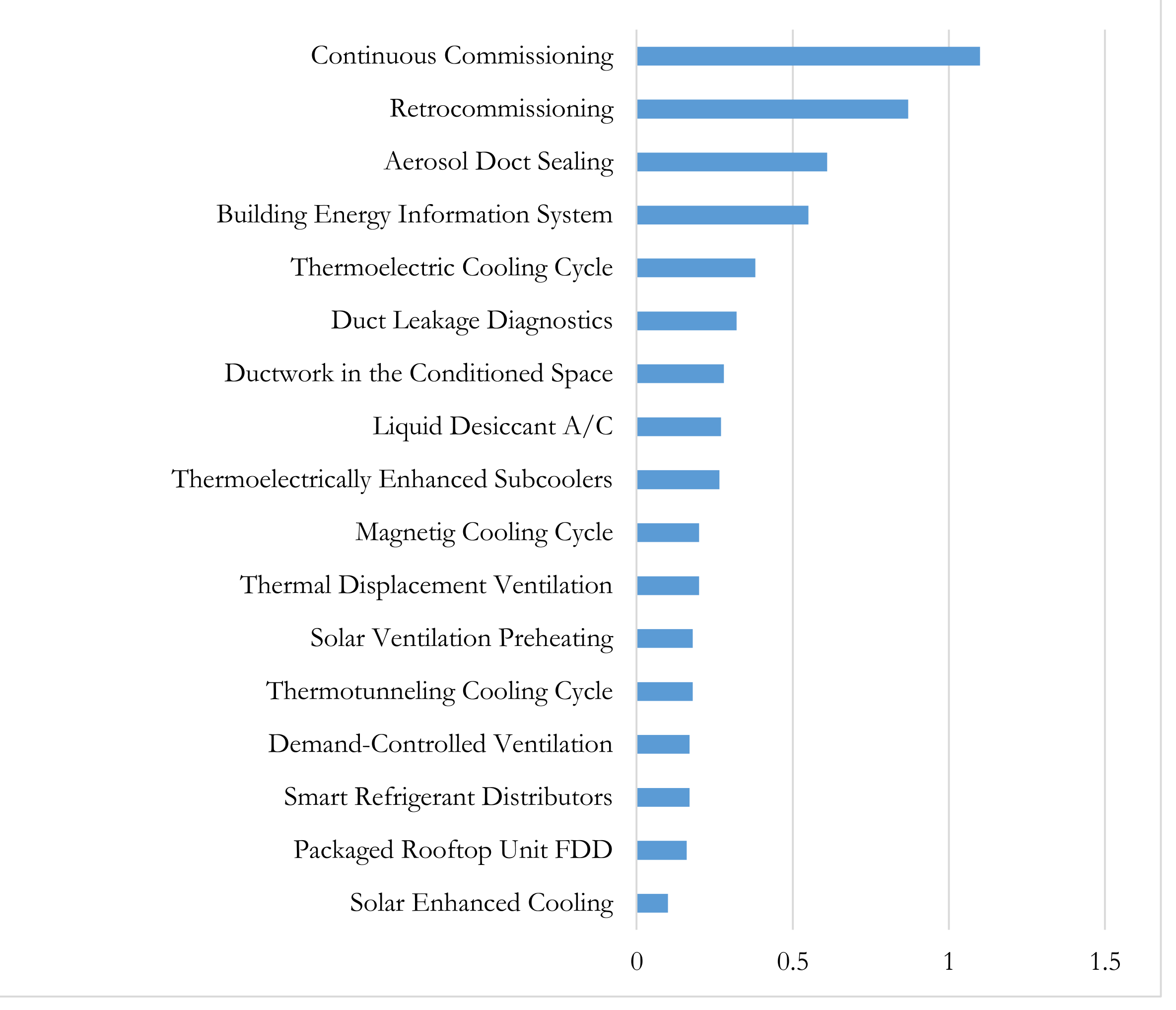

Figure 2-16. Energy savings potential (Quads/yr.) of various energy efficiency measures. Source: (Navigant Consulting Inc., 2011).

There even seems to be an under-exploited market for energy efficiency in buildings operations (Peterson et al., 2010). Nevertheless, actual efficient operation of buildings is still not current practice as barriers exist preventing implementation of technology and methodologies for achieving optimal building operation. Some of these barriers are (McKane et al., 2010; Prill et al., 2009; Managan et al., 2012; Mulki & Hinge, 2010; Peterson et al., 2010; United States, 2009):

a. Lack of awareness of financial benefits from energy efficiency measures;
b. Lack or disaggregation of incentives;
c. Capital constrains and corporate culture leading to more investment in new production capabilities rather than energy efficiency;

d. Current practice aiming at replacing rather than optimising;
e. Lack of expertise in efficient building operations and maintenance;
f. Lack of perceived repeatability for energy efficiency measures;
g. Lack of clearly defined products and services to enhance building operations;
h. Lack of standardised assessment tools for understanding optimisation possibilities in building operations.

Barriers *a* and *b* require public campaigns to raise the awareness regarding opportunities, benefits and available financial tools for optimising building operations. Barriers *c* and *d* require a paradigm and mind-set change to perceive energy as an asset rather than as a utility. Barrier *e* demands either for more and better training of building manager or, maybe preferably, simplification of the operation of buildings by increasing the level of intelligence and automation. Barriers *f* and *g* require projects and incentives for implementing building optimisation in different facilities and standardised indicators to compare results and effort. Barrier *h* requires the development of tools aimed at identifying and integrating low to no cost optimisation measures in a continuous fashion rather than current tools that aim at one-off rating of the building and limit themselves at providing recommendations.

2.2.5 Discussion of social and market findings

The beginning of this section showed the potential for improvement in building systems' operations and the impact it may have in the overall energy consumption and GHG emissions of the building sector. With a particular focus on building of public use, it was highlighted how efficient operation of HVAC systems and Building Management Systems can provide high-impact opportunities, not only technically but also in the form of educational and awareness campaigns. However, the fact remains that energy, in the building sector, is still seen as a utility rather than as an asset and the benefits of energy management are not well known.

Even if research on energy management has demonstrated that treating energy as an asset and incorporating it in the management level as production, quality or security, can result in monetary savings and overall increase in people's productivity, there is still no broad uptake of energy management practices worldwide.

Barriers still facing the integration of energy management in building operations include the required technical skills and a deep knowledge of the building that are seldom found in building operators, least in users. To date, solutions to this knowledge gap rely on the incorporation of software tools that aim at easing the work of the building manager. However, such solutions merely transform data into information, not yet into knowledge. With the diversity of the building sector, solutions are normally tailor-made for particular buildings and "a standardised approach to evaluate buildings in the face of incorporating measures to improve operations is still lacking" (United States, 2009) as is lacking the inclusion of methodologies to embed capacity. The remaining issue for building managers is to realise the realistic and cost-effective opportunities for improving operations that are available to him/her including the accompanying products and services.

On a side note, the impact of people's behaviour and their response to policy measures aimed at delivering energy efficiency is poorly understood and overlooked even by international organisations that do not include energy efficiency in their educational environmental programmes. With improved life-styles it seems that highlighting economic benefits of reduced energy consumption might have less impact than highlighting its environmental consequences. Educational programmes might incorporate building of public use and offices as case studies for different approaches to raise awareness among users.

The building sector is lagging in delivering energy efficiency and GHG emission reduction goals and people using buildings are key for reversing this tendency.

2.3 TECHNOLOGY DRIVERS AND BARRIERS: BRIDGING THE CAPACITY GAP AND BUILDING SELF-AWARENESS

In the previous sections the need for improving operation of existing buildings has been discussed. Also, it has been demonstrated how policy and people's behaviour influence building's performance. It has been suggested the use of public use buildings incorporating HVAC systems controlled by some form of building automation system (BAS) to show the impact of educational and technical programmes aiming at delivering improved building operations at low to no-cost.

The relevance of building controls and HVAC systems in terms of energy consumption has been also established. HVAC systems represent over 50% of the building's energy consumption and building controls, in charge of managing these HVAC systems, determine if that 50% of consumption is used optimally or not. Furthermore, it is estimated that 90% of HVAC building controls are inadequate[11] (Carbon Trust, 2007). Reasons for reduced performance of building controls and HVAC systems are various: presence of faults in some component of the system, inadequate control logic, scheduling problems, lack of sensor calibration, under- or over-sizing of systems, etc. (Costa, 2010). Correcting these performance issues, although it may prove time-consuming, can prevent between 4% and 45% of energy waste (Treado & Chen, 2013). Integrating methodologies and technologies that prevent these issues, either automatically or manually, will prevent energy waste.

Up to now it has been discussed how buildings normally perform below optimal conditions, even those integrating automatic building controls systems. Also, the existence of a knowledge gap between skills required to fully exploit BMS and the actual skill set of most building managers is leading the perpetuation of this under-performance. It is unrealistic to expect building managers to become experts on informatics systems. The reason lies in the fact that technology advances at a high pace, and even if managers become experts on technology at some point in time, their knowledge will become obsolete quickly.

To overcome these issues it seems necessary to bridge this knowledge gap by introducing 'intelligence' in building systems so that buildings become 'self-aware' and

[11] Inadequate building controls translate directly into energy waste and increased GHG emissions.

more robust. In this way the building can provide useful information[12] about its performance to the building manager.

Under the conditions previously stated, a Self-Aware Building (SAB)[13] does not necessarily need to be highly automated but instead the building incorporates elements that automatically adapt and improve itself with time (including memory) and also diagnose issues with its systems. A SAB incorporates the following characteristics such as it:

- Predicts, keeps track and monitors building's performance;
- Controls and adapts building's actions to the monitored/predicted performance;
- Diagnoses root causes of building's performance reductions;
- Supports building managers by providing information about building's operations in a way that matches their typical skill set.

In order to incorporate the SAB level of intelligence in buildings, two broad aspects should be studied:

- **Key Performance Indicators** (KPI). KPIs use and standardisation is important as KPIs have several uses including but not limited to (Shah et al., 2010): assessing the impact of measures, transforming raw data into useful information, comparison with other building, benchmarking, measure compliance with regulations, etc.;
- **Key Enabling Technologies** (KET). KETs should be incorporated in building systems. These KETs are technologies that support or introduce the desired intelligence in building operations such as (Roth et al., 2005b): communication systems, automated data management, artificial intelligence and machine learning techniques, fault detection and diagnosis, modelling and simulation, etc.

The remaining of the section gives an overview of the main functions of BMS[14] [15] with the pros and cons of typical implementation; following this, there is a discussion on KPIs and KETs for bridging the knowledge gap between building systems and building manager in developing a SAB.

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[12] Information that is in accordance to the typical building manager skill set, which does not need interpretation and that can lead to real performance optimisation actions.
[13] Term taken from (Mahdavi et al., 2001).
[14] For the purpose of this research, BMS, Building Automation Systems (BAS), Building Energy Management Systems (BEMS) and Building Automation and Control Systems (BACS) are similar terms.
[15] BMS already incorporate basic technology and infrastructure needed for SAB.

2.3.1 Building management systems

Previous sections have introduced the idea of a BMS as being a supervisory system in charge of monitoring and managing (including controlling) a range of services in buildings. In this regard, the main tasks of a BMS are normally defined as:

- Monitoring environmental and technical variables in the controlled areas;
- Controlling electrical and mechanical components;
- Optimising the operation of the facilities.

All of these tasks are aimed at maintaining predefined indoor comfort conditions and levels of safety and efficiency of the system. Services normally under the scope of a BMS include, but are not limited to those shown in Figure 2-17 that include:

- Mechanical systems such as: HVAC, heat generation (including refrigeration), shading and windows control;
- Electrical systems such as: Lighting, lifts, power generation (e.g. CHP, Gas Turbine);
- Communication systems;
- Fire and Security Systems.

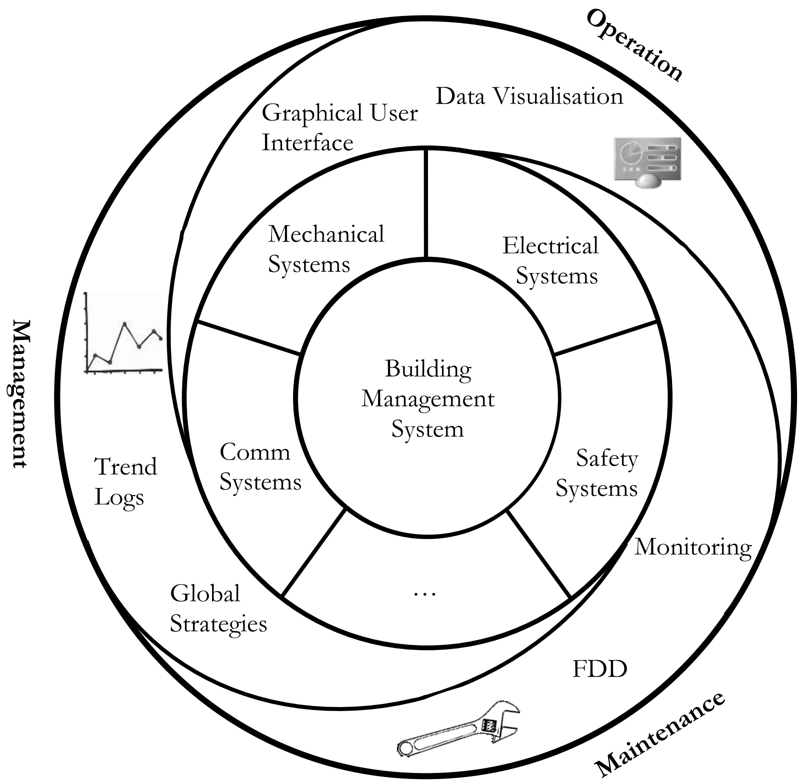


Figure 2-17.Functional aspects of BMS. Source: (Kastner et al., 2005).

A BMS manages these wide range of systems by a combination of software and hardware modules. Hardware modules normally comprise sensors, actuators, communication networks, controllers (PLC, DDC), etc. Software modules include control algorithms, communication protocols, supervisory software, graphical user interface, data bases, etc. Main classifications of BMS in relation to architectural topology and infrastructure are:

- Centralized, if a control unit supervises the whole system;
- Distributed, if sensed information is locally processed by autonomous controllers, each supervising specific appliances and/or areas;
- Mixed, e.g. peripheral controllers are able to acquire and process information for groups of devices while a central building supervising unit acts as coordinator among local controllers.

Regardless of the architecture, BMS offer the opportunity to develop and implement control and energy efficiency measures of diverse complexity[16]. Given the impact BMS can have in building operations, some standards exist to guide the optimal implementation of automation in buildings. The main standard that supports building management and automation is EN 15232 (CEN, 2007).

2.3.1.1 EN 15232 Energy Performance of Buildings – Impact of Building Automation Control and Building Management

The aim of EN 15232 is to support the EPBD to enhance energy performance of buildings in the MS of the EU. EN 15232 specifies methods to assess the impact of Building Automation and Control Systems (BACS) on the energy performance of buildings, and a method to define minimum requirements of these functions to be implemented in buildings of different complexities (Siemens, 2012). The standard divides Building Automation and Controls Systems into four energy efficiency classes according to the installed systems, as presented in Table 2-6. EN 15232 makes it possible to qualify and quantify the benefits of BACS.

[16] The complexity will depend on the KPIs and the KETs incorporated in the BMS. More discussion about this matter can be found in Chapter 3.

Table 2-6. Function list and assignment to energy performance classes. Source: ABB in (CEN, 2007).

Class	**Heating / Cooling control**	**Ventilation / Air conditioning control**	**Lighting**	**Sun protection**
A	• Individual room control with communication between controllers • Indoor temperature control of distribution network water temperature • Total interlock between heating and cooling control	• Demand or presence dependent air flow control at room level • Variable set point with load dependant compensation of supply temperature control • Room or exhaust or supply air humidity control	• Automatic daylight control • Automatic occupancy detection manual on / auto off • Automatic occupancy detection manual on / dimmed • Automatic occupancy detection auto on / auto off • Automatic occupancy detection auto on / dimmed	• Combined light/blind / HVAC control
B	• Individual room control with communication between controllers • Indoor temperature control of distribution network water temperature • Partial interlock between heating and cooling control (dependent on HVAC system)	• Time dependent air flow control at room level • Variable set point with outdoor temperature compensation of supply temperature control • Room or exhaust or supply air humidity control	• Manual daylight control • Automatic occupancy detection manual on / auto off • Automatic occupancy detection manual on / dimmed • Automatic occupancy detection auto on / auto off • Automatic occupancy detection auto on / dimmed	• Motorized operation with automatic blind control

Class	Heating / Cooling control	Ventilation / Air conditioning control	Lighting	Sun protection
C	• Individual room automatic control by thermostatic valves or electronic controller • Outside temperature compensated control of distribution network water temperature • Partial interlock between heating and cooling control (dependent on HVAC system)	• Time dependent air flow control at room level • Constant set point of supply temperature control • Supply air humidity limitation	• Manual daylight control • Manual on/off switch + additional sweeping extinction signal • Manual on/off switch	• Motorized operation with manual blind control
D	• No automatic control • No control of distribution network water temperature • No interlock between heating and cooling control	• No air flow control at room level • No supply temperature control • No air humidity control	• Manual daylight control • Manual on/off switch + additional sweeping extinction signal • Manual on/off switch	• Manual operation for blinds

Estimation of the impact of BACS in energy performance of buildings can be done using a factor-based calculation that gives a rough estimate or a detailed methodology.

The detailed methodology provides a more accurate estimation of the impact but also implies a deep knowledge of all automation, control and management functions for the selected building. Deep discussion on EN 15232 falls outside the scope of this research work. However as an example, based on the BACS efficiency factors mentioned in the standard, Table 2-7 gives an idea of the potential energy savings that can be reached when switching from a class C or D system to a class A system.

Table 2-7. Energy savings potential. Source: (CEN, 2007).

Facility	**Electrical savings potential**		**Thermal savings potential**	
	D→ A	C→ A	D→ A	C→ A
Offices	21%	13%	54%	30%
Schools	20%	14%	33%	20%
Hotels	16%	10%	48%	32%
Restaurants	12%	8%	45%	32%
Residential buildings	15%	8%	26%	19%

Even with standards in place, BMS have become complex and difficult for the average operator to understand. In general, BMS complexity is beyond the technical profile of the building manager and in many cases they fail to address organisational and managerial issues that also affect utilisation on the system (O'Donnell et al., 2013).

Finally, the objectives of the standards on HVAC are restricted to an increased automation of systems but do not address the integration of technologies supporting building operators, especially when operational performance is reduced such as when there is the presence of a fault. In this sense, BMS conforming to standards may be highly automated but they are yet to become intelligent or self-aware.

2.3.2 Key performance indicators

The role of Key Performance Indicators (KPIs) is to transform the wealth of data coming from buildings into useful information for the decision making. In the area of energy efficiency, KPIs are metrics associated with observed building characteristics that can be translated into better or worse than expected environmental and energy performance (New Buildings Institute, n.d.).

KPIs are an essential part of the energy efficiency in buildings process. They are the metrics used to measure the effectiveness of any energy efficiency and/or GHG emissions reduction action and should not be taken lightly. KPIs can also serve to benchmark and make comparisons between different facilities and even the impact of different policies at national and international levels. However, there is a lack of international standardisation when developing the KPIs that makes it difficult to perform a cross-country comparison of implemented energy efficiency measures as discussed in section 2.1.4.1 (Andaloro et al., 2010).

KPIs can be divided into three subgroups, those relating to energy consumption (and GHG emissions), those relating to economic aspects and those considering indoor environmental aspects of the building. Another subgroup of KPIs relates to health issues and the regulatory framework for the prescription of minimum acceptable levels to maintain healthy conditions in buildings is well established.

Any assessment on the impact of any measure to improve energy efficiency in buildings will require a compromise between the three KPIs subgroups, and it is well known that the choice of KPIs can have a big impact on the assessment results. Therefore, the selection of the appropriate KPIs is a big challenge (Shah et al., 2010).

The rest of the section will briefly provide an overview on each KPIs subgroup.

2.3.2.1 Indoor environmental related key performance indicators

Building occupant's comfort directly impacts health and productivity as well as energy consumption (Kemenade, 2013). Comfort can be thermal, visual and acoustic (Steskens & Loomans, 2010). This research focuses on thermal comfort. The most used thermal comfort KPI is the Predicted Mean Vote Index (PMV) (Fanger, 1973), which estimates the average response of a large group of individuals to the environmental conditions. It takes into account, apart from environmental conditions such as temperature, relative humidity and air velocity, factors relating to the metabolic activity of the people.

These KPIs are mostly used for evaluating approaches to control HVAC systems, especially as a boundary condition in the optimisation process of implemented control algorithms (Dounis, 2010). Regardless of the index used to measure comfort, higher comfort conditions translates into higher energy consumption.

2.3.2.2 Energy related key performance indicators

Energy related KPIs are often referred to as Energy Performance Indicators (EPIs) or Energy Efficiency Indicators (EEIs). EPIs provide a ratio between the energy used to deliver a specific service and a measure of the value of that service (Vikhorev et al., 2013). Constructing efficient EPIs requires a compromise between the completeness of the information provided and the compactness of such information in relation to the skills of the EPIs' user. Furthermore, development of EPIs is closely related to standards and regulations (Pérez-Lombard et al., 2011).

A formal methodology for the development of HVAC EPIs could be as follows (Pérez-Lombard et al., 2012a):

1. Definition of the required minimum quality of the different services provided by the HVAC system (heating, cooling, ventilation, humidification, etc.);
2. Division of the HVAC system into the different equipment (coils, valves, fans, dampers, etc.);
3. Aggregation of information from each equipment into subsystems (heat/cold generation, air transport);
4. Aggregation of the subsystems into services (e.g. heating, cooling);
5. Aggregation of the services at the global level;
6. Assign energy use indicators to each HVAC system and component compared to the primary energy required by the overall building;
7. Definition of the energy demand indicators as floor area, thermal energy and delivered volume.

In this way the distribution and allocation of the information follows a natural path in the energy consumption of the HVAC system (Perez-Lombard et al., 2011).

Following the methodology, EPIs can be constructed at different levels (from equipment to overall HVAC system) and by combining energy use indicators with energy demand indicators in a structured fashion.

O' Brien (O'Brien, 2010) discussed the difficulties in developing HVAC EPIs given the diverse nature of the systems. Nonetheless, O' Brien proposes EPIs for components commonly found on any HVAC such as fans in ventilation systems. Also, he proposes metrics that are independent of the installed system such as the use of the degree-day analysis[17] and the use of the coefficient of performance (COP) of the system.

Ó Gallachóir (Ó Gallachóir et al., 2007) proposes EPIs at the level of cluster of buildings by linking energy demand data from utilities to variables such as users, floor space, installation of new equipment, etc. The main goal of Ó Gallachóir is to demonstrate how, even with segmented or inadequate data, the construction of EPIs that deliver useful information for policy and decision making can be made.

Escrivá-Escrivá (Escrivá-Escrivá et al., 2011) proposes a number of indices and accompanying methodology for characterising building operations. He suggests a combination of audits and direct measures for gathering the necessary data for calculating the EPIs. For direct measures the methodology requires the existence of an Energy Control and Management System where there exists the possibility to separate whole building energy consumption from that of HVAC systems. Also, information about occupancy is required to calculate some EPIs.

O'Sullivan (O'Sullivan & Keane, 2004) proposed a framework for the integration of performance metrics through the whole building's life cycle, but with particular focus on the operational phase. This framework is based on the Building Information Model idea where all information about geometry, materials and real time data is gathered. O'Sullivan adds to the framework whole building energy simulation models to act as benchmark for operations. O'Sullivan suggests a hierarchy of EPIs in a top-down approach, where the building is split in systems and these in components. These EPIs are the ones used for the comparison between real-time operations and simulation.

Harris (Harris & Higgins, 2012) proposes the construction of EPIs based on system-level metering and design information. The idea is to provide a set of EPIs that would enable comparison between different buildings using whole-building approaches.

Perez-Lombard's (Perez-Lombard et al., 2011) and O'Brien's (O'Brien, 2010) approaches provide the highest level of useful information. However, they are also the most difficult to implement compared to a system or whole-building only approach as presented by Harris & Higgins (Harris & Higgins, 2012). The reason lies in the need to increase the level of monitoring and its associated costs and issues. On the other hand,

[17] Degree day analysis is a method of assessing the performance of a building or HVAC system in terms of the heat consumption relative to the ambient temperature.

methods using already existing information such as that proposed by Ó Gallachóir (Ó Gallachóir et al., 2007) are easier and cheaper to implement and might provide the necessary information, depending on the circumstances. Regardless of the approach, the use of KPIs can be enhanced if they are recalculated periodically to continuously inform decision makers (Escrivá-Escrivá et al., 2012).

2.3.2.3 Economic related key performance indicators

Energy efficiency measures are evaluated against economic aspects[18] (economic KPIs). Economic KPIs include direct cost and initial investment, annual charges, life cycle cost, return of investment, net present value, internal rate of return, etc. (Kolokotsa et al., 2011). These metrics are not different when evaluating the incorporation of intelligence in building operations (Wong et al., 2005).

Regardless of the KPIs, it has already been discussed that the actions aimed at optimising operational energy use are more cost-effective than those aimed at replacement and refurbishment (Escrivá-Escrivá, 2011). This can be better explained if the scope of the cost-benefit analysis is broaden to the whole building's life-cycle, which includes manufacturing and disposal of the improvement brought by such actions (García Casals, 2006). Nevertheless, more visibility is given to actions aimed at improving by replacement rather than starting with system's optimisation, since it fits better the business models of some stakeholders.

2.3.3 Key enabling technologies for building self-awareness

In this section, the KETs that are expected to deliver a high impact on building optimisation are presented (Roth et al., 2005b). Supporting measures to enhance the applicability and diminish the barriers for the implementation KETs are also discussed. The focus is in the developing and supporting technologies for achieving SAB.

2.3.3.1 Communication protocols

Building elements communicate among themselves and with the central control using communication protocols. Protocols are defined by the data structures that explain the format and meaning of data[19]. Both devices have to know the data structure in order to

[18] The impact of the economic evaluation depends on the point of view of such evaluation. For example, a tenant will benefit directly from any energy efficiency measure in the form of reduced bills but the owner, who will normally have to pay for such improvement, won't necessarily find it profitable.
[19] Almost like a dictionary that explains a word's spelling and meaning.

facilitate the exchange of information. Key characteristics for communication protocols in BMS are (Singh, 2011):

- **Being open-source or proprietary**: A protocol is open-source when the creator of the protocol makes it readily available to everyone. Proprietary protocols are those that make the protocols restricted to the creator of the device by not sharing the data structure, thus preventing others from using it or developing devices that can communicate through that protocol.
- **Standard**: A standard protocol requires all parties, from developers to end-users, to agree on a data structure that can be implemented on their respective devices. If there is consistency across an industry, then the protocol becomes an industry standard like BACnet or Modbus.
- **Interoperability**: A protocol is interoperable when a component from one vendor can be replaced with a component from a different vendor.

According to the European Committee of Standardisations (CEN), BMS architecture, in relation to communications, is divided in three levels as shown in Figure 2-18 (European Committe of Standardisations, 2000).

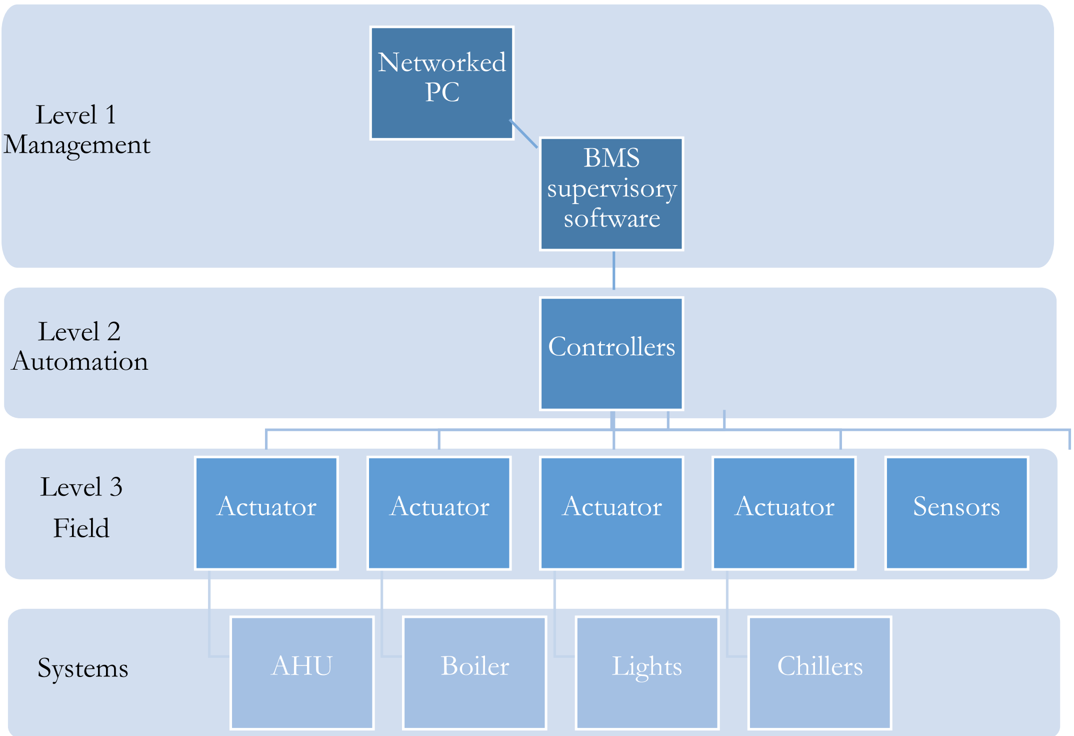


Figure 2-18. BMS architecture. Source: (Sustainable Energy Authority Ireland, 2007).

Communication protocols often used in BMS include: BACnet, ModBus, Lontalk (LonWorks), KNX, ZigBee, Ethernet and Internet. Basic characteristics of these protocols are presented in Table 2-8.

Table 2-8. Basic characteristics of most common communication protocols. Source: (CASCADE Consortium, 2012c).

Protocol	Characteristics
BACnet (Building Automation and Control Network)	Developed by an ASHRAE committee composed of representatives from industry, end-users and consulting engineers. May be used by head-end computers, general purpose direct digital controllers, application specific or unitary controllers, and smart sensor/actuator devices with equal effect. Defines data communication services and protocol for computer equipment used for monitoring and controlling HVAC, refrigeration and other building systems. Defines an abstract, object-oriented representation of information communicated between such equipment; Provides a comprehensive set of messages for conveying encoded binary, analogue, and alphanumeric data between devices. Its communication media is defined to be Ethernet devices, ARCnet devices, or an especially-defined RS-485 asynchronous protocol for twisted-pair wiring that will operate at up to 78,000 bits per second.
ModBus	Developed by Modicon and published in 1979 for use with PLC. Developed for industrial applications, it is openly published and is royalty free. Places little restrictions on vendors, as moves raw bits/words easily. Allows for communication between devices (up to 247) connected in same network, in a master/slave protocol. Its communication media is defined to be over a serial EIA-345 physical layer. There are many variants of protocol versions, including: Modbus RTU (compact, binary) Modbus ASCII, Modbus TCP/IP, Modbus Plus, Modbus PEMEX, and Enron Modbus. Large binary objects are not supported. No securities against interception of data. Can consume large bandwidth as Master must continuously poll slave for data.
M-Bus	Light weight message-orientated protocol. Provides automatic location of communication peers and subject based addressing. Protocol is layered on IP multicast and is specified for IPv4 and IPv6. No mechanism for congestion control, use is limited to single network link. Messages sent using either unreliable transport or reliable, depending on system complexity and bandwidth. Security includes messages with a return digest based on shared secret key value. Prevents unauthorised messages. Encryption also possible. European standard (EN13757-2 / -3). Commonly used for remote reading of gas, heat or power meters. Other applications: alarm systems, flexible illumination, heating control etc. Very cost effective two wire bus (or wireless). Battery driven systems are possible.

Protocol	Characteristics
KNX	It is based on three existing protocols: EIB (European Interconnection Bus), EHS (European Home Systems) and BatiBus. Interoperable with BACnet through the ISO 16484-5. Provides specifications that are not only used for the automation of electrical installation equipment but also for HVAC applications. Supports several communication media: Twisted pair, power line, radio frequency, infrared and IP/Ethernet.
LonTalk	Developed by Echelon as part of the LonWorks product line to provide low-cost distributed control and communication sensor and actuator networks used in building, home, factory, and instrumentation applications. Presented to programmers and installers as a collection of services that may be optionally invoked. Services may be chosen by the programmer and fixed at compile time. Follows the ISO-OSI reference Model, containing all seven layers. Designed to support twisted-pair wiring, power-line wiring, radio frequency and infrared communication, and coaxial and fibre optic media. Since LonTalk protocol is designed for multiple physical media to be interconnected within the same network and components are available for speed ranges from 5 kbps to 1.25 mbps, a wide range of application and cost points can be addressed. The ability to create flexible bandwidth as needed allows the same protocol to be used to solve problems ranging from interconnecting high-level controllers to economically interconnecting low-level sensors and actuators. Implemented in a dedicated VLSI component, the Neuron chip (offered by Motorola and Toshiba) for computing and communication. Supports numerous transceivers for different physical media. LonWorks products include extensive development tools, software, physical layer transceivers and network management tools.
OPC (Object Linking and Embedding for Process Control)	More than a protocol is a suite of protocols which purpose is to interface industrial devices with Microsoft Windows based software. The most recent versions are platform-independent. OPC is an open standard thus can be implemented in a wide range of devices while the server can rest on any type of platform. Very scalable from smart sensors and smart actuators up to mainframes. Produce specifications for a range of applications from handling alarms and events, real-time data access, historical data access, data exchange between servers. Supports several different physical layers such as Ethernet, Serial, Radio frequency.
ZigBee	Wireless communication architecture developed on top of the IEEE 802.15.4 reference stack model. IEEE. 802.15.4 is a low-rate wireless personal area network (LR-WPAN) solution. It is designed to be simple for low-power devices and lightweight wireless networks. As per 2014, it is the only BACnet approved wireless mesh network standard for commercial buildings.

A comparison of the KNX, LonWorks and BACnet is presented in Table 2-9.

Table 2-9. KNX, BACnet and LonWorks comparison. Sources: (Ferreira et al., 2010; Merz et al., 2009).

	KNX	**LonWorks**	**BACnet**
Standard	EN50090, ISO/IEC 14543	ANSI/CEA-709, ISO/IEC 14908	ISO 16484-5
Control architecture	Decentralized	Decentralized	Centralized
Network architecture	"Bottom Up" solution Low speed free topology	"Bottom Up" solution Common communication Protocol Peer-to-Peer	"Top Down" solution Multiple communication protocol Tiered network topology
Device architecture	Initially used a 68HC05 processor	Neuron Chip Neuron C (Programming language)	Processor independent Programming language independent
Communication	TP, PL, Wireless, optical fibre	Single protocol: LonTalk TP, PL, Wireless, optical fibre	Multiple protocols supported: Ethernet, ARCNET, MS/TP, LonTalk, PTP, ZigBee HA
Internet support	KNXnet/IP	LonWorks/ IP i.LON – Web service device	BACnet/IP BACnet/WS

Regardless of the protocol, data exchange between components usually happens over some physical wire (such as on a twisted pair RS485 or Ethernet CAT5 cable). Research suggests that 70% of costs associated with BMS relate to wiring (Jang et al., 2008). Improvements and additions to the BMS such as those aiming at introducing necessary sensors and actuators for SAB, normally require substantial re-wiring. The cost associated with the rewiring is often halting implementation of novel developments.

The introduction of wireless sensor technologies and associated protocols (e.g. ZigBee) serves to greatly reduce the cost associated with improving the BMS in this regard. A robust and cheap wireless platform will surely foster incorporation of FDD into BMS by reducing the probability for economic reasons preventing such incorporation.

2.3.3.2 Data access and management

Transformation of existing buildings into SAB requires for access and in some cases manipulation of the data incorporated in the BMS by an external software. In this regard, BMS data access can present one of three scenarios (CASCADE Consortium, 2012c):

- **Easy access**: in this scenario, an external software module can access the same data used by the BMS. This offers the possibility to perform simultaneous real time control, analysis and scheduling of the data. A BMS using BACnet will present this scenario;
- **Average access**: in this case, there is no direct access to the data used by the BMS, however a standard protocol is being used by the BMS. In this scenario an external software will have to go through the BMS for accessing the necessary data. A typical solution incorporates a database in which the BMS stores all the data and the external software links to this database. A BMS using ModBus will fall in this scenario;
- **Difficult access**: is encountered when a proprietary protocol is used by the BMS. Two possibilities exist: the owner of the protocol is willing to cooperate and open its own protocol, in which case it is possible to program the data transfer to an external software or, the owner of the protocol is not willing to open the protocol, in which case the only solution is try to interface directly to the field equipment.

2.3.3.2.1 Data point naming

In a BMS, systems are often referred to as "points" (e.g. sensor measurement, actuator signal, etc.). As buildings become more and more automated the number of points under the scope of a BMS reaches the hundreds of thousands in commercial and industrial buildings (Butler & Veelenturf, 2010). Current BMS solutions normally introduce a point naming convention developed and designed in a case to case basis adapting to the blueprints and specificities of the project but without following any formal procedure. This lack of standardisation difficult the maintenance and managing of control systems and hampers the integration of external software to the BMS environment.

A standard naming convention provides a number of advantages such as: lower configuration and training costs; easier configuration and analysis applications (Lee et al., 2007); increased possibilities for automated data processing; enhancement of the capabilities of the KPIs and; the comparisons and benchmarks between different buildings and types of buildings. A proposed naming convention for standardization of the data point naming in the building sector, developed by the Fraunhofer Institute for Solar Energy, is presented in Table 2-10 (CASCADE Consortium, 2012c).

Table 2-10. Point naming convention. Source: Fraunhofer ISE.

#	Category	Abbreviation	Item	#	Category	Abbreviation	Item
1	Building	Free Choice	Building Name	6	Medium	HW	Hot Water
2	Zone	WBD	Whole Building			CHW	Chilled Water
		Free choice	All Other Zones			HCW	Hot / Chilled Water
3	System	DH	District Heat			DCW	Domestic Cold Water
		DC	District Cooling			FUEL	Any Kind Of Fuel
		ESUP	Energy Supply			OA	Outdoor Air
		WSUP	Water Supply			RA	Room Air
		WTH	Weather Station			SUPA	Supply Air
		WC.H	Water Circuit Heating			EXHA	Exhaust Air
		WC.C	Water Circuit Cooling	7	Position	PRIM, SEC	Primary or Secondary Side of System
		WC.HC	Water Circuit Heating / Cooling			SUP.(PRIM, SEC)	Supply
4	Sub-system_1	MTR	Meter For Fuel			RET.(PRIM, SEC)	Return
		MTR.H	Heat Meter	8	Kind	MEA	Measured Value
		MTR.C	Cold Meter			SEV	Set Value
		MTR.EL	Electricity Meter			SIG	Signal (Feedback from Component)
		MTR.W	Water Meter	9	Data Point	E	Energy
		GLOBSENS	Pyranometer			E.H	Heating Energy
		PU	Pump			E.C	Cooling Energy
		FAN	Fan			E.EL	Electric Energy
		HC	Heating Coil			VOL	Volume
		CC	Cooling Coil			T	Temperature
		PREHC	Pre-Heating Coil			RH	Relative Humidity
		PREHCC	Pre-Heating / Cooling Coil			SOL	Solar Irradiation
5	Sub-system_2	PU	Pump			CTRLSIG	Control Signal
		CTRV	Control Valve			STAT	Status (1/0)

2.3.3.3 Artificial intelligence potential for self-aware buildings

Previously in the introduction of section 2.3, the definition of a SAB was presented as a building that:

- Tracks, monitor and predict its performance;
- Adapts its action to the monitored/predicted performance;
- Detects performance reduction and diagnose root causes;
- Provides information about it operations in a way that matches the skill set of building managers.

Any of those characteristics requires for the building to react to its environment (including internal environment) in an efficient manner. But, traditional building controls are static in nature, they rely on predefined set-points and schedules to operate the building. At the most basic levels, BMS control strategies are on/off controls, proportional, integral and derivative controls and some optimal form of start/stop (Loveday & Virk, 1992). Although BMS companies are already incorporating intelligent tools and methods in their BMS (e.g. Johnson Controls, Siemens, etc.), the vast majority of the existing systems don't benefit from these characteristics. Many don't even have the necessary infrastructure to incorporate such technologies.

When the appropriate infrastructure exists, Artificial Intelligence (AI)[20] techniques provide means for achieving the SAB goal in a cost-effective manner. The main advantages of AI over traditional monitoring and control techniques are their memory, learning, reasoning and optimisation capacities. In the rest of the section the main areas in which AI can have impact in building operations are presented and discussed.

The following sections build in the developments of AI for optimisation of building operations and discuss particular applications that I consider to be of high-impact in energy efficiency.

2.3.3.3.1 Performance estimation and prediction: Tracking, monitoring and predicting performance

From an AI modelling point of view, performance estimation and prediction are similar terms. Literature on AI for building performance prediction is extensive and several

[20] AI is a branch of computer science that, among other definitions, aims at reproducing human's rationality in a software. In an AI system, the rationality involves perceiving the environment and taking actions that maximise the chances of success. Introducing and describing AI techniques is outside the scope of this research work and vast amounts of information can be found online or at libraries. The interested reader will find a free, online and comprehensive starting point at (Poole & Mackworth, 2010)

reviews have been made to date (Zhao & Magoulès, 2012a; Dounis, 2010; Krarti, 2003; Kalogirou, 2006, 2000). Main AI techniques used in performance estimation include:

- Artificial Neural Networks (ANN) (Karatasou et al., 2006; González & Zamarreño, 2005; Yang et al., 2005);
- Support Vector Machines (SVM) (Xuemei et al., 2009; Dong et al., 2005; Li et al., 2009; Zhao & Magoulès, 2010);
- Fuzzy Logic (FL) (Edwards et al., 2012), and GA (Li et al., 2011).

Most literature about performance prediction using AI is concerned with the accuracy of the predicted performance (Neto & Fiorelli, 2008; González & Zamarreño, 2005) and the selection of suitable inputs (Karatasou et al., 2006; Ismail et al., 2011; Zhao & Magoulès, 2012b). The reason for this is that the real value of these techniques lies in the balance between accuracy and generalisation of the predictor (Yang et al., 2005). However, integration of intelligent systems in building operations still remains largely ad-hoc due to the diversity of techniques and lack of standardised approach to the overall development of the AI methodology (e.g. selection of type, architecture, inputs/outputs selection, etc.).

2.3.3.3.2 Set-back and end of set-back optimisation: Adapting actions to the predicted performance

A typical energy saving strategy is that of night/weekend set-back of the HVAC systems in any non-residential building. This set-back means a turning off or reducing the set point of the systems during unoccupied periods and is estimated that it produces savings in the range of 12%-34%, depending on the building's load (ASHRAE, 2007; Costa et al., 2011). Normally there is a fixed schedule for this set-back and the subsequently re-start of the systems. However, research shows that optimising the end of set-back (re-start time) so it is variable and depended on current conditions, can provide further 10% energy savings without having any effect on occupant's comfort (Carbon Trust, 2007). Optimal Set-Back time selection may have a similar impact. Figure 2-19 shows an example of potential savings using an optimised end of set-back. In addition, if the optimisation aims at bringing indoor temperature within the comfort range (e.g. 18ºC) instead of the set point (e.g. 20ºC) further savings can be achieved.

Optimisation of set-back is a particular case of performance prediction and fulfils the SAB characteristic of adapting actions to predicted performance. Artificial intelligence methodologies, especially ANN have proven to be effective in optimising set-back scheduling in facilities (Yang & Kim, 2004; Yang et al., 2003; Ben-Nakhi & Mahmoud, 2002). These methodologies offer the added advantage of being able to continuously learn and adapt themselves, if properly programmed, to the changes and aging of the facility and its systems (Sterling et al., 2012b).

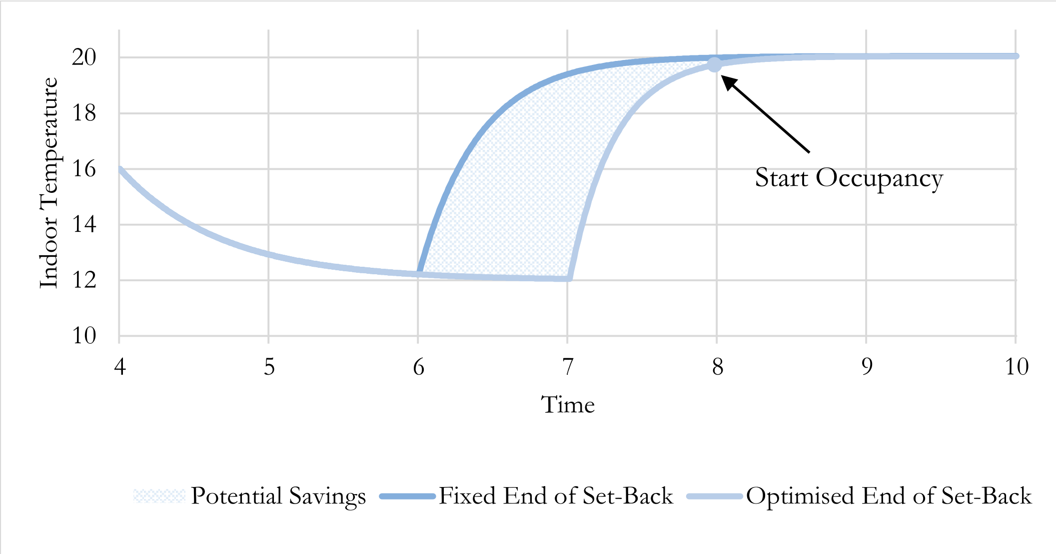


Figure 2-19. Fixed vs optimised end of setback.

2.3.3.3.3 Fault detection, diagnosis and prognosis: Detecting and diagnosing performance reductions

Estimates give an average range of 15% to 30% for the energy waste in commercial buildings due to poorly maintained, degraded and improperly controlled buildings (Le et al., 2005; Bruton et al., 2012). These issues, apart from deriving in energy waste and reduction of equipment life, can also represent reduced performance and even health problems for the building's occupants (Mumma & Issues, 2003).

In general terms, a fault is considered as any issue or state that causes a reduction of the performance, even if it is not perceived immediately by humans (e.g. in a car, a dirty sensor might cause the air-fuel mixture to be wrong and translate into more fuel consumption). Detecting a fault is the process by which, using available information, there is a realisation of this reduction of performance (e.g. in the faulty car sensor scenario, after filling the tank a couple of times with the dirty sensor one realises that fuel consumption is higher than it should be). Diagnosing a fault is determining the root(s) cause(s) of the loss of performance (e.g. after checking everything else is working correctly, the sensor is isolated as the cause of the reduced performance). Fault Detection and Diagnosis (FDD) is the field within control engineering that studies the automated detection and diagnosis of faults.

Research shows that a proper FDD implementations can reduce HVAC energy consumption by 5%-40% (Piette et al., 2001; Westphalen et al., 2003; Roth et al., 2005a), especially if faulty operations are timely rectified for the most frequent and high-impact faults (e.g. economizer malfunction, faulty sensors, inadequate airflow, coil valves faults, cycling elements, etc.) (International Energy Agency, 2006; Heinemeier, 2012; Lee & Yik, 2010).

One step forward that could be taken to increase savings is the introduction of automated prognosis in the FDD process (FDD&P). A building incorporating prognosis is capable of predicting its future performance based on current conditions, even under faulty operation. In order to deliver prognosis, the BMS must be equipped with some form of computer simulation models that will enable the prediction capabilities. This process can be automated so the FDD&P tool acts as a decision support system (DSS) for the facility manager providing advice as per actions to take in order achieve optimal building operation under a broad range of operation scenarios.

However, while in critical systems such as those encountered in automotive or aerospace applications, where safety considerations of faulty operations drive the necessity for integration of FDD, in buildings the issue of faulty operations rarely entails safety considerations. In building operations, the impact of a fault is considered in economic rather than safety terms. These economic considerations have driven current practice where faults are mostly identified manually during routine inspections, due to persistent alarms, or as a result of a noticeable degradation of performance. The problem with this approach is that many faults can be undetected for long periods of time thus leading to a considerable energy and monetary waste (Haves et al., 2009). Automated FDD can help with this problem by providing timely indications of the existence and root cause of the fault, and possibly also suggest correctives actions. This automation embeds the SAB characteristic of detecting and diagnosing performance reduction problems into the software This in turn relives the burden from the building manager to have to analyse and interpret the vast amount of data provided by modern BMS, a task for which in many cases is under-skilled (House & Kelly, 1999).

Nevertheless, the economic impact of faulty operation of building HVAC systems has not been considered sufficient enough to encourage its broad integration in building operations. The reason appears to lie in the fact that in the building sector, FDD tools are assessed against economic considerations (Li & Braun, 2004), but their impact is underestimated. Underestimation of the impact of FDD in building operations is a multifaceted problem: (i) the amount of case-studies is still low so the technology remains unknown; (ii) FDD characteristics are confused with those of the normal BMS and therefore considered redundant; (iii) lack of BMS standardisation obliges FDD solutions to be developed on a case-to-case basis which may prove a costly enterprise. These result in BMS incorporating only the most basic forms of FDD (limits and alarms) and therefore failing to achieve its potential for energy efficiency.

On the technical side, automated FDD requires a-priori knowledge of the normal and faulty behaviour of the systems to be embedded in the methodology. In this sense, FDD techniques can be classified as rule-based or model-free (Donca, 2010) methodologies, model-based methodologies and history-based methodologies, as shown in Figure 2-20 and explained as follows:

- **Rule-based FDD methodologies** incorporate the knowledge as a set of if-then-else rules to be applied on the data. Limits and alarms are widely used as rule-based FDD to prevent or highlight potentially harmful operations. Expert systems, on the other hand, compile knowledge from real experts of the system in the rule-set (House et al., 2001; Schein et al., 2006).
- **Model-based approaches** use a mathematical model of the relationships between system's components and possibly an indication of the expected behaviour under faulty conditions. Within model-based approaches two tiers can be defined, white box and black box. White box models provide a mathematical representation of the physical relationships influencing the system's behaviour such as, for example, models based on first principles of energy and mass conservation (Sterling et al., 2014b; Yu et al., 2002; Müller et al., 2013). In black box models this mathematical representation is derived directly from data such as for example, linear regression, ANN, etc. (Yan, 2013; Yoshida et al., 2001).
- **Process history-based methods** use past performance data to derive input-output information. Black box methods are similar to those in the model-based approach, and the grey box models combine white box and black box (e.g. first principle models with parameter determined by ANN) (Wang et al., 2012b; Li, 2004; Qin, 2006).

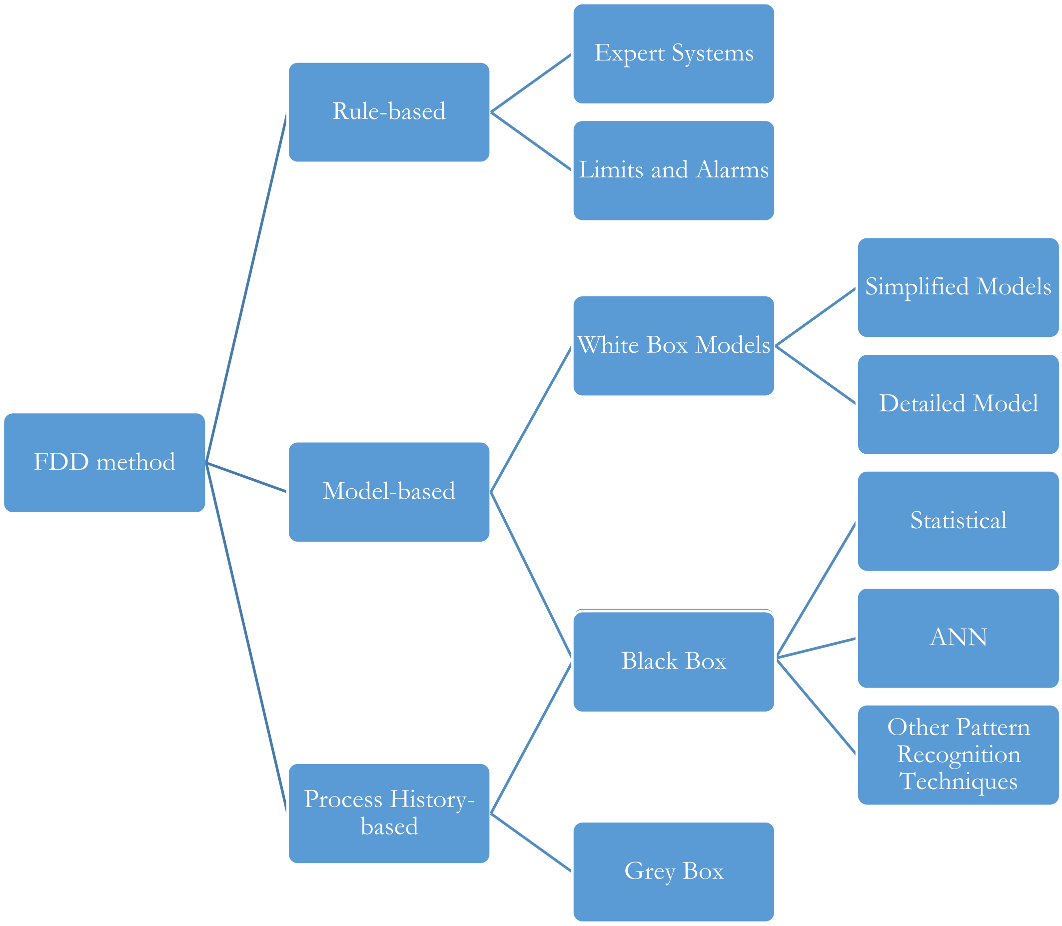


Figure 2-20.Classification of FDD methods according to a-priori knowledge. Source: (Katipamula & Brambley, 2005a).

From experience, automated diagnosis is little used in building operations, but when used it is normally in the form of a collection of rules named AHU Performance Assessment Rules (APAR) (House et al., 2001) which target Air-Handling Units (AHU) specifically. Although the APAR rule-set approach is simple to implement, it certainly lacks flexibility and requires a high degree of knowledge of the building for its tuning and utilisation. Furthermore, while APAR can be robust in fault detection, it only provides guidance information as per the root cause of those faults. Other issues with APAR is that it was only developed for temperature related issues and does not account problems with humidity. Finally, since APAR assumes a predefined control sequence in the facility, it only identifies faults corresponding to the sub-set of rules of the particular operation mode (e.g. heating, cooling, ventilation, etc.) in which the unit is believed to be operating in (Bruton et al., 2014).

Automated FDD approaches can also utilise AI techniques. The main AI techniques for FDD found in literature are shown in Table 2-11.

Table 2-11. AI automated techniques for HVAC FDD with examples.

Branch	Technique	References
Machine Learning	ANN	(Lee et al., 2004; Magoulès et al., 2013; Zhu et al., 2012; Subbaraj & Kannapiran, 2010; Du et al., 2009)
	SVM	(Liang & Du, 2007; Dehestani et al., 2011; Yan et al., 2014; Namburu et al., 2007)
	GA	(Wang et al., 2012b)
Data Mining	Decision Trees	(Katipamula & Pratt, 1999; Mulumba et al., 2014)
	Clustering	(Zucker et al., 2014; Khan et al., 2013; Seem, 2007)
KBS	Expert Systems	(Wang et al., 2012a; Schein et al., 2006; Song et al., 2008)
	Consistency Checking	(Sterling et al., 2014c)
Probabilistic	FL	(Lo et al., 2007; Dexter & Ngo, 2001)
	Kalman Filters	(Bonvini et al., 2014)

The above mentioned literature is not comprehensive nor exhaustive, but it does provide an overview of the current research in the area of AI for FDD. Moreover, Table 2-11 provides indication on which techniques have received more attention form the research community. Classifiers such as ANN and SVM and expert systems are the most researched methodologies as they naturally fit the FDD problem and are the easiest to implement. Fuzzy Logic (FL) is often combined with genetic algorithms (GA) to improve diagnosis capabilities by using the GA to optimise and adapt the fuzzy sets.

AI methods on FDD applications avail of common strengths and suffer from common weaknesses as expressed by Katipamula (Katipamula & Brambley, 2005a). For data mining, machine learning and FL approaches, they are well suited for complex systems or systems where a mathematical representation of the interaction between elements is not feasible. Furthermore, these systems can improve and learn over time. However, they require fault-free (and sometimes faulty) training data that is not necessarily available or accessible. For knowledge based systems, the data requirements are much less, but they require a-priori knowledge (e.g. models, rules, etc.) of the normal and faulty operation of the systems to be introduced into the solution.

Nevertheless, there exists a greater barrier to the implementation of fault detection and diagnosis in building operations. This comes from the fact that facility manager and building operators are still sceptical as per the real advantages of the integration of fault detection and diagnosis techniques into their buildings (Heinemeier et al., 1999). Building operators often believe BMS functionalities overlap with those of FDD systems and thus consider the later redundant (Lee et al., 2007). These are managerial rather than technical problems as building energy managers may not be well informed and consequently, there is a lack of interest and proper incentives for this type of building optimisation (Herzog, 1997). An approach to overcoming this scepticism is to incorporate prognosis[21] so the impact of FDD is made clearly visible to building operators (Katipamula & Brambley, 2005a).

This barrier can be grasped by the low amount of FDD tools available in the market. Some market-available FDD tools that utilise AI approaches can be seen in Table 2-12.

Table 2-12. Commercially available FDD tools comparative table. Source: (Bruton et al., 2014).

Tool Name	**Company**	**FDD method**	**Remarks**
DABO	ADMS technologies	Expert System	Rule-based FDD
Cite-AHU	NIST	Expert System	-
PACRAT	Facility dynamics	N/A	Black-Box Models for baseline. Rule-based diagnostics
SciWatch	Scientific Conservation	ANN	-
SkySpark	SkyFoundry	Expert System	-
FDD Tools	NSIT	Artificial Intelligence and Statistical Modelling	-
Ezenics	Ezenics	Expert System	Rule-based FDD
Whole Building Diagnostician	Pacific Northwest National Laboratory	Expert System	Rule-based + Decision Trees

Other barriers to the incorporation of FDD in building operations are technological and include: data sufficiency, non-standard building systems, non-standard

[21] Prognosis estimates the condition of the systems at times in the future based in current conditions

communication protocols and poor data collection. All of these must be overcome for a successful integration of FDD in building operations (Lee et al., 2007).

As can be seen, the above mentioned technical problems relate directly to the needs identified in section 2.3.3.2 in relation to data access and management. Today's BMS generate vast amounts of data, but little of this data is transformed into useful knowledge. An approach to overcome this, apart from the already mentioned data-point naming standard, could be to model and deploy the data management using an object-oriented approach that sees the building as a collection of systems (classes) that perform determined tasks (methods) and possess a number of characteristics (arguments) (Xiao & Han, 1998; Maile, 2010). In this way data streams are not only a series of numbers but contain information about the systems, uses, access options, expected behaviours, etc. Maile (Maile, 2010), presented a hierarchy for representing the buildings as a series of objects that could serve as basis for the object-oriented data management for buildings in two ways, from a HVAC point of view and from a spatial point of view. This hierarchy is shown in Figure 2-21 below.

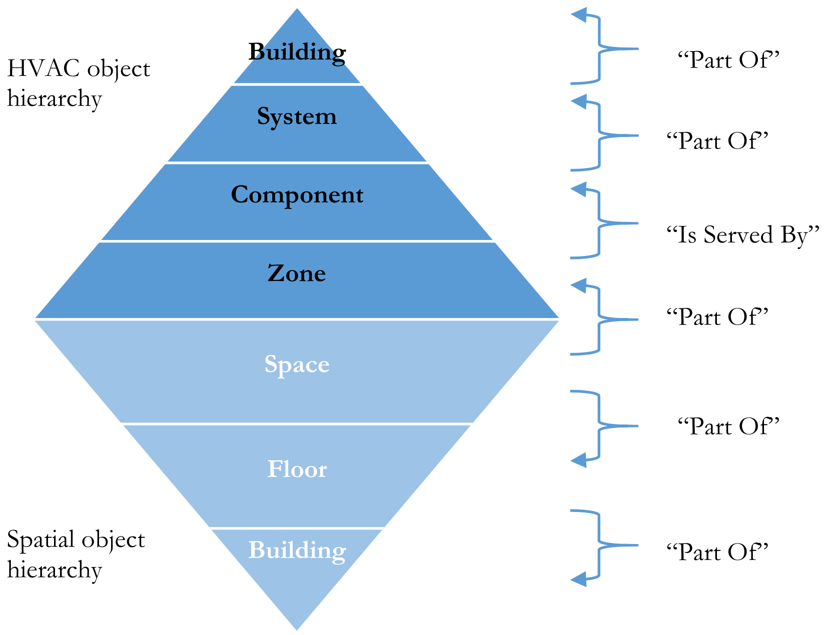


Figure 2-21. Pyramid representation of building object hierarchy. Source: (Maile, 2010).

Each element in Figure 2-21 can then have associated parameters and methods. For example, "Building" can have a pointer towards documentation, "Component" could have a method called "heating" or "Zone" could have a method called "Occupancy" and a parameter called "area".

2.3.3.3.4 Intelligent controls: Adapting actions to monitored and predicted performance

Improper control strategies are one of the main causes for energy waste in building operations, e.g. 15% - 35% in heating (Carbon Trust, 2007). Even if most of today's BMS incorporate microprocessors and direct digital controls (DDC), the truth remains that the possibilities of these pieces of technology are underused for reasons such as (Hatley et al., 2005):

- Improper design and application of the control system;
- Faulty installation, commissioning and government checkout of systems;
- Incompatibility between systems;
- Lack of maintenance of equipment and system;
- Lack of adequate capabilities from operators.

In part for the above mentioned reasons, it has been recognised that any intervention on the control system of a building is a time-consuming, expertise-laden and expensive task[22] (Treado & Chen, 2013). To this consequence follows that integrating intelligent controls in existing facilities requires high upfront costs that tend to hamper its implementation (Kolokotsa et al., 2011). In addition, there are also the same technical, market and societal barriers that have already been mentioned (e.g. lack of standardisation, scepticism, lack of qualified personnel, etc.). However, it has been demonstrated that correcting control issues in building systems offers a rapid return of investment (Mcmanus & Moore, 2013).

It is not the aim of this research to provide a deep discussion on the integration of intelligent control in BMS. Nonetheless, since intelligent controls also form part of a SAB characteristic (adapts actions to monitored and/or predicted performance), a brief presentation of technologies, opportunities and desired capabilities on intelligent control and decision support systems will follow.

The main advantages of the use of AI methods for building controls is their ability to deal with fragmented, incomplete or imprecise information (e.g. FL) and the adaptability inherent to their capability to learn behaviours from real data (e.g. ANN, SVM, etc.). In addition, studies have shown how AI-based controllers are capable of better maintaining room comfort conditions, over longer periods and over broader variations of conditions than traditional PID (proportional, integral, derivative)

[22] Especially if not carried out by the original developer and installer of the system.

controllers (Sterling Garay & Sanz, 2010; Moon et al., 2011). Other important advantage of AI-based control systems is their ability to conciliate energy efficiency with increased comfort, concepts that normally go in opposite directions in terms of energy consumption (Kolokotsa et al., 2009b; Diakaki et al., 2008; Kriksciuniene et al., 2014).

Until recently, intelligent control's research used traditional AI techniques such as FL (Kristl et al., 2008; Trobec Lah et al., 2006; Chiou et al., 2009; Shahnawazahmed et al., 2007); ANN (Atthajariyakul & Leephakpreeda, 2005; Sterling et al., 2012b; Sterling Garay & Sanz, 2010; Moon & Kim, 2010; Mohanraj et al., 2012); GA (Čongradac & Kulić, 2012; Mossolly et al., 2009; Pargfrieder & Jorgl, 2002; Sivapathasekaran et al., 2010); Expert systems (Orosa, 2011). However, in recent times there has been a move towards the use of Multi-Agent Systems (MAS)[23] (Dounis, 2010) for reasons such as:

- Their ability to cope with higher number of variables (e.g. user preferences, integration of different systems, etc.);
- By MAS definition, these systems comprise a distributed intelligence which reduces the need for high computational power;
- MAS are highly scalable and are better aligned with the idea of SAB given the definition of agents[24].

The advantages of using MAS over traditional AI techniques include their mechanisms for self-organisation, adaptation, evolution and learning (including reinforced learning) (A.I. Dounis et al., 2009). While traditional AI techniques try to emulate the decision-making process of a single human being, MAS strive to emulate the behaviour of biological systems composed of several individuals. The main application area for MAS within building operational optimisation seems to be decision support systems.

Given all the advantages, the barriers are still strong enough so the implementation of AI in building controls has yet to move from research environment to a market environment and broad uptake.

[23] The interested reader will find very useful references to the Multi-Agent Systems idea and design in (Ferber, 1999) and (Hoek & Wooldridge, 2007)

[24] "An agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors." (Russel & Norvig, 1995).

2.3.3.3.5 *A note on decision support systems: Providing information about building performance in a way that matches the skill set of building managers*

It has been discussed how most BMS provide vast amounts of data on building equipment and operations but it is the responsibility of the facility manager to analyse, interpret and act based on this data. This enterprise requires a skill set that, as has been previously stated, is lacking in most facility managers. Furthermore, achieving optimised building operations requires a decision making process whereby different options are evaluated and one (or several) are chosen for execution. This normally involves an iterative process as shown on Figure 2-22.

Regardless of the approach used in the decision making process, achieving a solution for optimal building operations requires solving a multi-objective and multi-criteria problem (Kolokotsa et al., 2009a). Automating this process requires an optimisation procedure. It is precisely in this area where MAS and evolutionary programming techniques such as GA can be fully exploited. The following AI-based decision support systems for building operations were found in literature:

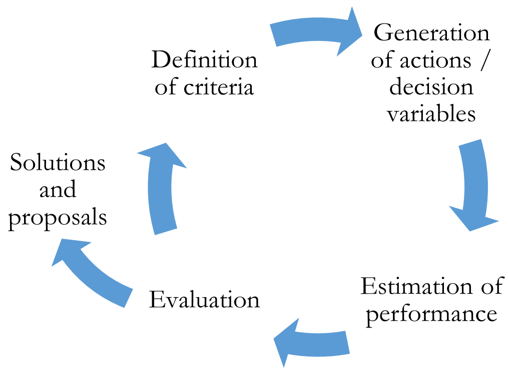


Figure 2-22. The iterative decision making process. Source: (Alanne, 2004).

- Shen (Shen et al., 2012), proposes a multi agent-based system targeted at facility operations and maintenance. He provides a service-oriented approach using web-services as agents. In this approach all entities are 'wrapped' as software services with a defined ontology and semantic for automated data discovery;
- Caldas and Norford (Caldas & Norford, 2003), demonstrate the use of GA in designing and optimising HVAC systems and controls;
- Fong (Fong et al., 2009), combines HVAC simulation with evolutionary programming for the selection of set point in both, primary and secondary HVAC systems.

In general, DSS are used either in the design phase or when some major refurbishment is being considered but much less in actual building operation. The actual use of AI-based DSS in continuous building operations is an area of research in its infancy. DSS for building operations might greatly leverage the use of simulation models as described in the next section.

2.3.3.4 Use of simulation in building operations: Prognosis

Computer modelling and simulation of the building as a whole or as separate components is a key enabling technology for the future of building energy efficiency (Pérez-Lombard et al., 2011). In the very basic scenario, computer simulations of buildings serves as means of self-assessing building performance and predicting and testing energy efficiency measures. In a more advanced scenario, building simulation is the core element of a decision support system providing building's prognosis and supporting control and maintenance activities.

Building simulation is being incorporated in different aspects of the building lifecycle, for example as a decision support tool during the design and retrofit phases by providing objective performance measures (Augenbroe, 2011) and as a policy-making tool to evaluate the expected impact of a proposed policy (Crawley, 2011), among other scenarios. However, current research challenge are:

- The level of detail and inputs necessary for the models to be both usable and reliable (Maile et al., 2010) and;
- The problems posed by the need to calibrate or adjust simulation outputs to match measured performance (Coakley et al., 2014; Sterling et al., 2014a).

In a view of the future of building performance simulation, Wetter (Wetter, 2011) highlights how today, simulation is still rarely used during operations. Wetter also argues that simulation tools will become increasingly more abstract and multi-purpose in order to fit the multi-domain nature of the building operation area. The lack of use of computer simulation during building operation creates an unexploited niche where the impact of simulation in reducing energy consumption is yet to be seen. But prior, some barriers must be overcome, such as complexity of simulation programs, lack of standardisation in the integration of systems in the building, lack of acceptance from facility manager, etc. The European Commission seems to have realised the potential value of the use of simulation during operations, as can be gathered from the multiannual roadmap for the contractual public-private partnership on energy efficiency in buildings under the Horizon 2020 research programme (European Commission, 2013a).

On the AI side, it has been previously discussed the use of AI in building operations and, in many cases, the development of simulation models was intrinsic within the AI techniques. For example, performance prediction is a form of simulating building's operational behaviour. Furthermore, simulation can be used to improve capabilities of FDD to deliver optimal control and to test operational scenarios as DSS.

2.3.4 Discussion on technologies for bridging the capacity gap for energy efficiency in building operations

Today's technologies possess the capability to act as a bridge between the complexity of building operations and the capacities of building operators. Especially AI methods encompass the desired capabilities that can be embedded in the building systems to achieve the SAB concept. In this sense the following technologies can be implemented in increased level of complexity of integration:

- Checking compliance with standards/regulations and ratings (Wang et al., 2005; Santamouris et al., 2007);
- Profiling consumption for new construction based on similar built facilities (Ekici & Aksoy, 2009);
- Load estimations (Mustafaraj et al., 2010; Ruano et al., 2006);
- Optimisation (e.g. an adaptive scheduling of start/stop according to predicted needs) (Sterling et al., 2012b);
- Fault detection, diagnosis and prognosis (Sterling et al., 2014b, 2014c);
- Control (e.g. comfort prediction to control HVAC systems) (Sterling Garay & Sanz, 2010);
- Decision support systems (e.g. if a renewable energy is in place with a storage system, decide whether to use energy, sell energy to the grid or store energy) (Kouveletsou et al., 2012).

In this regard, Table 2-13 shows the main AI techniques used in building operations.

Table 2-13. Main use of AI techniques in building operations. Source: (Krarti, 2003).

AI technique	**Usages**
ANN	Forecasting, Modelling, Controls, FDD
SVM	Forecasting, Modelling, Controls
FL	FDD, Controls
GA	DSS, Controls
MAS / Ambient Intelligence	Controls, DSS
KBS	FDD

However, before an effective integration of AI techniques can become widespread, the BMS infrastructure needs to evolve to be able to provide the relevant data for the AI techniques in an optimal fashion. Main steps of this evolvement include the incorporation of wireless technologies for increased number of data-points, standardisation of data-point naming conventions and communication protocols, as will be discussed in Chapter 3.

In addition, the study and development of relevant KPI will bring about a better understanding of the phenomena involved in building operations.

Finally, the use of building models and simulation can be very beneficial not only as a decision-making tool during design, but also as a decision-making tool during operations and supporting AI technologies.

2.4 CHAPTER SUMMARY

Figure 2-23 provides the high-level conclusions from the different section of this Chapter 2 and synthetises the need for the development and implementation of the SAB concept. The following paragraphs provide the summary conclusions from Chapter 2.

On the policy side, it has been stressed that the developments are only partially fulfilling the energy efficiency objectives due to over-conservative measures. The need to evaluate and regulate buildings based actual performance has been stressed as a means to achieving energy efficiency objectives. It has been shown that in order to gear policy towards measures that have a real impact on energy efficiency during building operations, the readiness and effectiveness of the technologies needs to be demonstrated. To do so, large, public-use buildings are ideal candidates to both, demonstrating innovative technologies and educating people on energy efficiency related matters. Building Management Systems are a technology element, common to most large buildings, which provides the means to carry out energy conservations measures. However, standardised means for auditing such systems is lacking today.

It is clear that the way people utilises buildings leads to elevated energy waste and not even facility or energy managers, making use of the BMS, are prepared to effectively implement long-term energy efficiency measures. The current mind-set is geared towards a view of energy as an utility that must be consumed and paid for, as opposed to the view of energy as an asset that must be exploited and optimised. While the former might prevent the successful application of energy efficiency measures, the later will be the real future driver for energy efficiency in buildings.

Adding to the problem, it has been recognised the existence of an ever-increasing knowledge gap between facility managers and BMS capabilities which leads to BMS being largely underutilised. Furthermore, new technologies aiming at improving building operations have a tendency to require increased skills from facility manager by providing them with new sources of information that needs to be processed and transformed into knowledge. In this sense, it is unrealistic to expect all facility managers to become experts in energy efficiency or even in optimised building operations and thus, technology must provide the necessary knowledge to fill the gap.

The needed technologies to support energy efficient operations of buildings, without requiring extended skills from facility managers, is in existence today, albeit in unlinked manner. Technological advances in many cases have been isolated from one another, creating thus different silos of knowledge and information that do not exchange information effectively.

The task is then to develop integration methodologies for technologies aiming at reducing energy consumption during operations of existing facilities with the Building Management System. This integration should be carried out without adding burden to the work of the facility manager. To solve the above mentioned issues, the Self-Aware

Buildings concept is proposed in this research work accompanied by the implementation methodology based on the three pillars:

- A common framework to characterise BMS systems in relation to their readiness to implement energy efficiency measures;
- A standardised auditing tool for BMS;
- A roadmap for the effective incorporation of energy efficiency measures in existing facilities that incorporate building management systems, taking into account the needs and ICT possibilities of each building and aiming at the integration of supporting technologies that embed knowledge in the systems rather than require more knowledge from the operator.

These three pillars provide a technical approach to address the main issues encountered in the three broad areas, political, socioeconomic and technologic discussed in this chapter by:

- Providing a tool to standardise the approach to audit buildings in face of implementing energy efficiency measures. This point reduces the associated risk preventing the implementation of outcome-based regulations;
- Homogenising the information provided by the facilities' systems and transforming such information into knowledge that can be understood by all the stakeholders. This further de-risks the implementation of outcome-based regulations and provides the bridging of the knowledge-gap between systems and users.
- Standardising building systems information so that the incorporation of new technical solutions is less costly and is not developed ad-hoc. Such standardisation improves the broad uptake of new and innovative technologies.

It is opportune to briefly comment on the difference between smart/intelligent buildings and SAB. The typical vision of an Intelligent Building is that of an automated building (e.g. a building incorporating a comprehensive building automation system). However, it was stated that a SAB is not necessarily highly automated but instead in comprises elements that transform the wealth of data generated by current BMS into supporting elements for optimised building operations. An intelligent building will transform the data generated by BMS into information that needs further interpretation. A SAB goes one step forward by transforming that information into knowledge and actions that do not require further analysis. At the end, an Intelligent Building tries to optimise building based on design condition but without taking into account user's behavioural impact on building operations. A SAB strives to optimise building operations including the impact of user's behaviour.

The following two chapters present the methodological framework and case studies on the implementation of the SAB concept as follows:

- Chapter 3 develops the methodology to characterise, audit and integrate technologies aiming at improving building operations in BMS. It also provides the roadmap for implementing the SAB characteristics in buildings based on the three pillars above mentioned.
- Chapter 4 presents case studies on the implementation of the different technologies to address each of the four SAB characteristics.

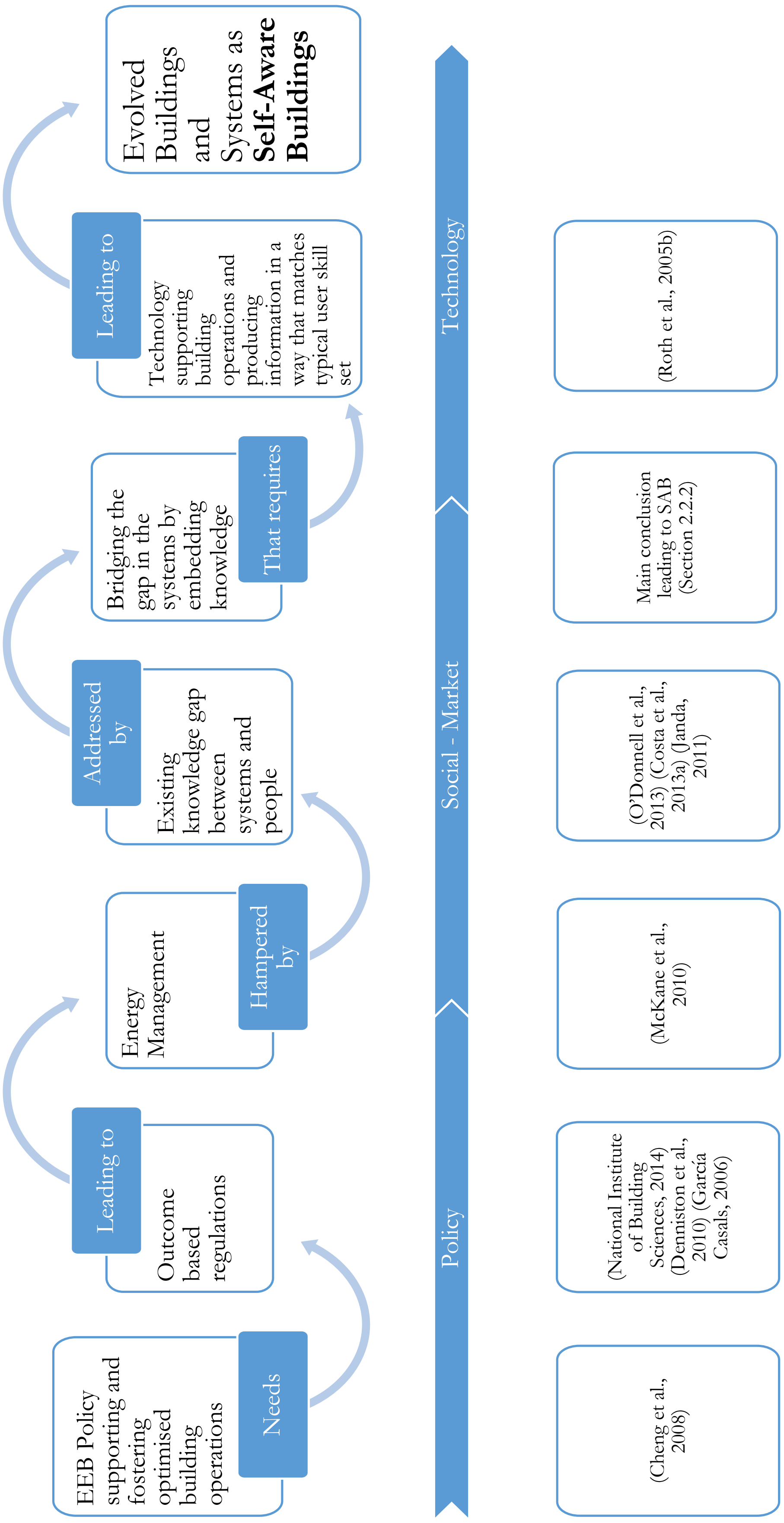
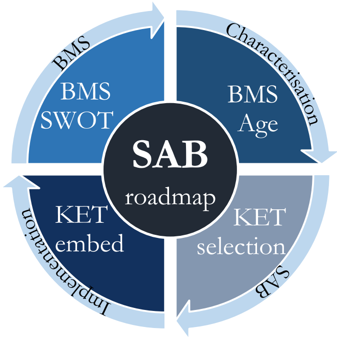


Figure 2-23. From policy needs to social barriers to self-aware buildings with selected literature.



CHAPTER 3

THE ROLE OF BUILDING MANAGEMENT SYSTEMS IN ACHIEVING SELF-AWARE BUILDINGS

This chapter: (i) develops and discusses an implementation toolkit for stakeholders responsible for current and future building management systems in realising the Self-Aware Building concept, (ii) defines a roadmap for the integration of innovative technologies in building operations to achieve SAB and, (iii) presents a view of an envisioned future for building management systems operation with specific goals relating to the opportunities provided by the energy systems in buildings and the incorporation of SAB capabilities. This chapter presents a past, present and future vision for the role of buildings management systems in contributing to achieving global energy efficiency goals with a focus on the opportunities for achieving Self-Aware Building capabilities. The evolution of building management systems is categorised into four ages, depending on the capabilities of the building management system for incorporating Self-Aware Building characteristics. Particular focus is given to systems that incorporate fault detection, diagnosis, prognosis and decision support tools in the context of energy efficiency in buildings. Furthermore, it is stressed how these two innovative technologies are needed in order to deliver on energy efficiency in buildings goals and also are cornerstone in achieving Self-Aware Buildings (section 2.3.3). A discussion on the advantages and issues, including barriers and needs, in order to achieve the presented vision of the future building management systems is provided. Furthermore, based on the evolution ages of building management systems identified in this research, a framework for assessing the capacity of a building management system for efficiently support SAB is proposed and discussed.

3.1 INTRODUCTION

Building management systems (BMS) are common place in different types of facilities (Lowry, 2002b). BMS are responsible for controlling environmental and safety conditions in buildings by maintaining comfort and security levels within predefined limits according to recognised standards. BMS, although mainly developed for control and comfort purposes, provide the opportunity to measure and improve energy efficiency as the existing infrastructure can be exploited for different energy efficiency actions. An overview of the functional aspects of a BMS is shown in Figure 3-1.

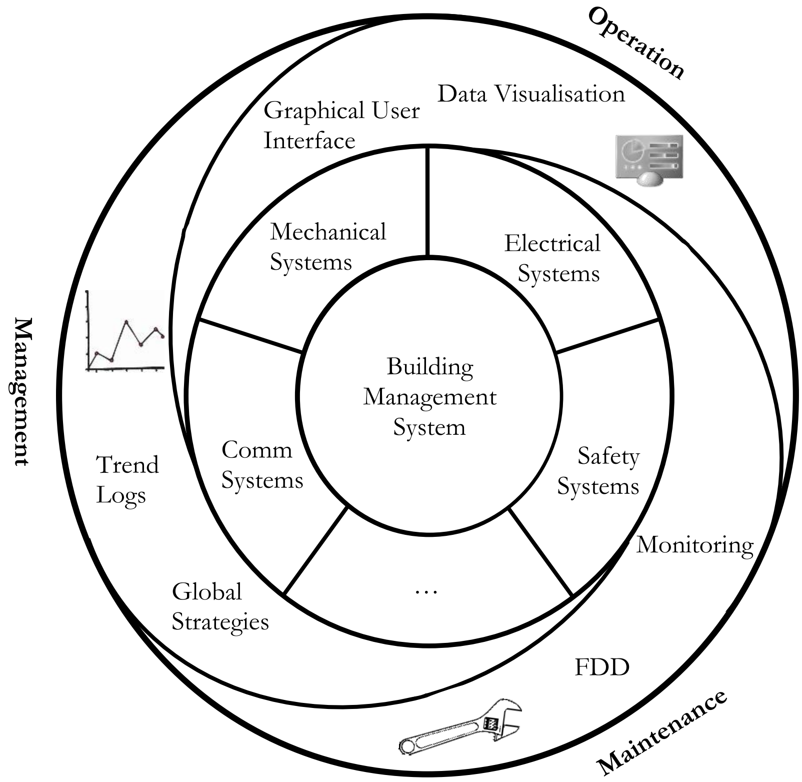


Figure 3-1. Functional aspects of BMS. Source: (Kastner et al., 2005).

BMS generate and utilise considerable amounts of data and information. However they also require specific educational and technical skills to monitor, analyse and to comprehend the data generated in order to translate raw data into energy saving activities. Furthermore, the required skills vary from manufacturer to manufacturer due to a lack of standardisation on features and information provided by BMS. For example, some BMS providers provide operational data in the form of text files while others utilise advanced data-base capabilities. Some BMS providers utilise proprietary protocols while others use standard protocols (e.g. BACnet, LongWorks) (Bushby, 1997).

BMS have established broad market uptake and have encouraging growth projections (Machinchick & Bloom, 2012). However, energy savings often fall short from what they are expected to achieve in the facilities. Surveys have identified that in the majority of cases BMS are underutilised, leading to higher operation costs due to suboptimal operational performance of the facilities (Lowry, 2002a). Among the reasons reported by Lowry, it is interesting to note that, to a large degree, these are related to the lack of user's skill (e.g. building manager or facility manager lacking technical skills to manage IT systems). The ideal situation would be for every facility manager to be an expert in building physics, energy efficiency and building management. However this is rarely the case. In many cases, a single person is in charge of managing several buildings at the same time. The above results in the facility manager only having enough time to maintain systems' operation so that predefined indoor conditions are met. Energy efficiency actions are not necessarily evaluated and/or implemented.

One cost-efficient way to overcome the above mentioned issue is to automate many of the tasks related to the management and control of the facility (see Figure 3-5 on IoT enabled Buildings). In this way, the work load of the facility manager is reduced and more time can be allocated to improving energy efficiency and actually applying energy conservation measures.

In this regard, embedding intelligence into BMS, including intelligent controls and automated diagnosis, is a key area for the future development of optimised building control and operations (Braun, 2007). In this case, we may already be talking of actual *intelligent buildings* or even *Self-Aware Buildings* (SAB) in which the functionalities of the BMS are exploited to the maximum so the building reacts optimally to its environment and predicted future conditions. As it was explained in Chapter 2 an intelligent building is not necessarily highly automated but instead incorporates elements that automatically adapt and improve itself with time (including memory). Building's also diagnose issues with their systems and provide prognosis on their expected future performance. All of this aiming at making the building self-aware and bridging the identified knowledge gap between BMS technologies and facility manager's typical skill set (House & Kelly, 1999). A Self-Aware Building (SAB) incorporates thus the following characteristics in it:

- Predicts, keeps track and monitors building's performance;
- Controls and adapts building's actions to the monitored/predicted performance;
- Diagnoses root causes of building's performance reductions;

- Supports building managers by providing information about building's operations in a way that matches their typical skill set.

Nonetheless, for SAB to become a reality, some key enabling technologies (KET) need to be incorporated into the building's operation. Most of these KETs are already available in the market and at affordable costs. The next step is to provide these KETs with the proper incentives (see section 2.3.3) in order to ensure their broad implementation in the building sector. These KETs have been described profusely in the U.S. (Roth et al., 2005b) and include low cost sensing and processing, improved communication structure, incentives on intelligence features including fault detection and diagnosis (FDD), automated prognosis, among others (see section 2.3).

The remainder of chapter discusses the evolution of BMS to date, how different technologies have been and can be incorporated in building's operation and, how the KETs described by Roth (Roth et al., 2005b) will benefit a SAB operations and how they should be integrated depending on the identified BMS age (CASCADE Consortium, 2012c).

3.2 Evolution of building management systems: The four ages of BMS

Controlling indoor environmental conditions is essential for maintaining levels of comfort, health and safety for persons and equipment in buildings. Although the technological evolution of the building sector has not kept pace with developments in other domains, like automotive or aerospace, it has certainly benefited from new technologies, developments and methodologies, particularly in the last 20 years (Katipamula & Brambley, 2005a). In this regard, during the course of this research work, four ages have been clearly identified for the evolution of the buildings in terms of the technical capabilities BMS possess for addressing energy efficiency measures in line with SAB characteristics. Evolution ages go from basic controls with no continuous monitoring, to a total automation, inter-facility integration and communication as shown in Figure 3-2 (Architectural Energy Corporation, 2007).

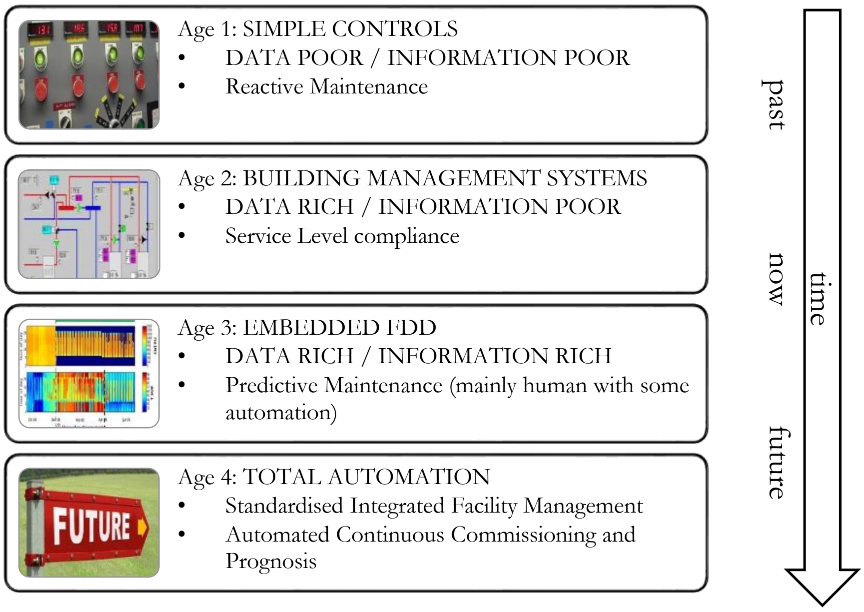


Figure 3-2. Ages of building management systems evolution.

Currently, most facilities incorporate BMS that fall in the transition between ages 2 and 3. The main characteristics and key issues in any of the ages are explained below.

3.2.1 Age 1: Simple controls

This is the very first and basic age of BMS. Control systems are very elementary, mostly mechanical and pneumatic/hydraulic elements with some analogue electronic actuators. BMS in age 1 are roughly comprised in the classification D of standard EN15232 (CEN, 2007). There is no automated collection of data and in general most of the information that can be gathered from the system comes from the knowledge of the system's operator. Maintenance is performed on a reactive basis after a severe reduction on performance or a component break is detected and only if the affected element is needed for continuing building's operation. System failure can only be detected by changes in the environment conditions while the diagnosis is performed by physically checking the system and in some cases comparing utility bills. Most residential buildings fall into this category. In terms of SAB, the lack of data provided by the building systems prevents any effective implementation of any SAB characteristic.

3.2.2 Age 2: Establishment of building management systems

BMS, also called building automation systems (BAS), are basically a software/hardware platform and computer based control system aiming at monitoring and controlling mechanical and electrical equipment to prescribed indoor environmental health and comfort conditions. In age 2, sensors and actuators have two-way communication with the centralized system. This enables the implementation of actions on the different systems to ensure appropriate indoor conditions including air quality. Even though vast amounts of data are exchanged between devices and central control/monitoring, little of this data is studied and/or used in any other way apart from maintaining predefined indoor conditions (IBM, 2012).

For the most part, in age 2 BMS, the visualization of data is limited to current conditions and potentially also include some access to past trends, but extraction of relevant information related to building operation requires skilled and experienced personnel (Hatley et al., 2005). This is not necessarily due to the lack of possibilities to incorporate such advanced visualisation in BMS, but is also related to a lack of user interest or customer demand for such tools (Blanes et al., 2014).

The robustness of these BMS when controlling indoor conditions[25], makes it difficult to detect and diagnose partial failure of systems since the effects of one broken element are normally offset by another element, thus making this failure invisible to the building's occupant (Hatley et al., 2005). This results in the added disadvantage that faulty operation can go unnoticed for long periods of time. In age 2 BMS, FDD activities are similar to those of age 1 but adding the possibilities of the improved visualisation capabilities.

In terms of SAB, data availability of age 2 BMS allows for the first two SAB characteristics: tracing, monitoring and prediction of building's performance and; basic adaptation of building actions to monitored/predicted performance (e.g. automated scheduling). However, age 2 systems normally lack the data quality and number of monitored points to incorporate further characteristics.

3.2.3 Age 3: Embedded FDD

The main steps forward to be taken in age 3 of BMS is the incorporation of fault detection and diagnosis capabilities, new visualization tools and novel performance indicators. Age 3 BMS exploit the rich data provided by the sensors, meters and equipment into an environment rich in information from which the actual behaviour of the system could both, as a whole and as a separate components of BMS, be quickly determined (Costa et al., 2013a). Maintenance of the systems ought to be based on the

[25] Robustness in the sense that indoor conditions are met even under non-optimal or faulty conditions.

actual performance of the elements but still keeping part of the maintenance based on schedules. Compliance with an energy management standard (e.g. ISO 50001 (ISO, 2010)) is also an important step to be taken for BMS to be considered age 3, as energy management standardisation supports the process of converting data into usable information for standardised energy management and FDD.

Although adoption of automated FDD is still very limited in age 2 (mainly due to lack of user confidence in FDD tools (Lee & Yik, 2010)), age 3 BMS must have FDD characteristics already embedded into their systems. Automated fault detection and diagnosis research for buildings and its systems has been in place for over two decades now (Le et al., 2005), with tools developed for almost all conceivable fault cases and uses (Katipamula & Brambley, 2005b, 2005a), but it is not until recently, with the increasing push for energy efficiency, that these tools are being incorporated into industrial grade building operations. However, barriers such as lack of user interest and demand for the technologies (section 2.2.4) and a lack of standardisation of the building information (section 2.3.2) have been preventing the general uptake of FDD due to the effort required to incorporate such systems in existing buildings (Zimmermann et al., 2012).

In terms of SAB, age 3 BMS can incorporate the characteristics of age 2 plus detection of performance reduction and diagnosis of root causes. This last characteristic is intrinsic to FDD tools.

3.2.4 Age 4: Automated FDD and prognosis

In age 4, advancements in BMS will focus on fully integrating automated FDD and prognosis on the technical side but also other organizational aspects (e.g. full incorporation of energy management standards such as ISO 50001), policies and human factors (see Chapter 2). The integration aims at the total automation of the building operational optimisation process[26] and it will be supported by the widespread use of smart meters, smart sensors, ambient intelligence and the internet of things, and their integration in the BMS infrastructure.

A way of integrating prognosis in the BMS can involve the incorporation of simulation and energy management tools based on ISO 50001, while adding automated

[26] A process that explicitly addresses policies, human factors, market drivers and key enabling technologies to push buildings towards achieving energy efficiency goals.

information exchange capabilities to/from the facility to enhance the interaction with other facilities and even with suppliers. Ideally, the BMS will allow for the automatic request of technical maintenance and/or replacing of parts, actively shifting heating or cooling loads to reduce overall energy consumption and even support access to a dynamic energy pricing market. The following key elements provide the foundations to achieve this ideal:

- **Standardised protocols and reporting systems**: to support portability and cross-platform integration of systems and information management and to reduce the re-training needs of facility managers;
- **Hierarchical alarm system**: the number of alarms should be reduced and identified faults need to be addressed or scheduled for intervention automatically by the BMS, thus relieving the operator from highly technical alarm managing tasks;
- **Customisation to support specific facility needs**: a modular approach will help systems to fit a broader range of facilities, depending on particular needs, and to have the possibility to add different capabilities at different times;
- **BMS serving a socio-technical system**: future BMS should use a holistic approach that integrates the technical, human, legal, political and organizational systems coherently. New BMS need to be integrated with Operations and Maintenance in practice in an automated fashion, thus improving the building operation while reducing human intervention and limiting human-induced errors. At the same time BMS will be integrated into the enterprise management;
- **Open Source Software**: nowadays, BMS software is traditionally proprietary and innovation is reduced to those functionalities provided by BMS companies. An open-source approach, or at least standardised inputs/outputs, will allow different specialists and developers to build upon already tested and working elements and thus provide new characteristics and services for the BMS underpinned by the existing ones.

This list is not all inclusive but instead represents a paradigm shift and needed characteristics to support age 4 BMS. Age 4 BMS incorporates all the characteristics of SAB, although for a full optimisation intelligent controls should be taken into account.

Table 3-1 shows a summary of the characteristics of each BMS age and incorporates an overview skill set a facility manager needs to operate and maintain the system.

Table 3-1. BMS characteristics and skill set needed by age.

Age	Characteristics	Skill set
1	Elementary controls, mostly on/off; No data collection; Reactive maintenance; No performance indicators apart from occupants comfort; No energy management.	No real skill set needed
2	Centralised control systems; Data provided mostly by bills; Manual data access; Scheduled maintenance; Alarm system; Utility costs and comfort are the only performance indicators.	Deep knowledge of the building and systems to interpret data, events, alarms, among others.
3	Distributed control; High frequency and quality data collection; Maintenance mainly based on actual system's performance with some scheduling for safety; KPI given by advanced visualisation techniques; Automated FDD; Manual energy management.	Deep knowledge of the building, systems and information systems; Interpretation of advanced visualisation techniques; Understanding of energy management standard (e.g. ISO 50001).
4	Predictive controls and embedded decision support systems; Near real time data collection and processing; Cloud-based data access and management; Predictive maintenance based on system's prognosis; Real-time KPI with automated performance monitoring; Automated FDD; Multi-facility automated energy management and smart grids.	Most of the skill set from age 3 is now embedded in the building systems. Building manager need to have a good knowledge of the buildings but most actions are generated automatically (e.g. via ISO 50001 implementation).

By looking at the above mentioned characteristics, it is possible to foresee the path that developments on FDD and automated prognosis must take, in conjunction with developments of BMS, in order to deliver the optimised building operation of the future: a full intelligent automation. As mentioned before, most BMS are in a transitional stage between ages 2 and 3, in this regard the next section discusses the developments that are needed for current BMS to fully become age 3 BMS.

3.3 Towards age 3: Improving performance indicators for embedding FDD

A computer with supervisory and control software, as exists in most modern BMS, is capable of providing performance indicators on system operations, energy consumption and fault detection. Current research studies show new developments and uses for novel key performance indicators (KPI) that exploit the already available information (see section 2.3.2). They aim at a better understanding of the energy state of the facility, as a whole or by the individual component, at any given time (Pérez-Lombard et al., 2012b; Escrivá-Escrivá et al., 2012). Also, the use of the capabilities of a BMS to monitor how energy is used in a building and to identify Energy Conservation Measures (ECM) has been proposed by Gonzalez (Gonzalez, 2006). Numerous published case studies also quantify significant savings of 5-25% which were identified using data acquired from BMS (Amundsen, 2000; Knight, 1995; World Business Council for Sustainable Development, 2008; Jones, 2006; Hirschfield et al., 2001).

Research has demonstrated that technologies have reached a maturity level where they can be already incorporated into industrial grade operations (section 2.3). However, technologies still need to obtain market recognition and broad uptake. A formalisation on the business approach that technologies that have reached research maturity need to take to effectively reach the market is outside the purpose of this research work. Nevertheless, Appendix A provides an example of the approach that could be taken for marketing research technologies.

In order to deliver energy efficiency goals, buildings need to be continuously evaluated on actual performance rather than on 'as-installed' characteristics. To evaluate building's performance effectively, a combination of a regulatory framework with the improved capabilities of BMS needs to be developed (section 2.4). This evolution is based on decision support system concepts as a combination of FDD, automated prognosis, KPI, Standards and regulations and Simulation. Figure 3-3 depicts this top-down approach for the evolution of the building management systems to support energy efficiency in buildings.

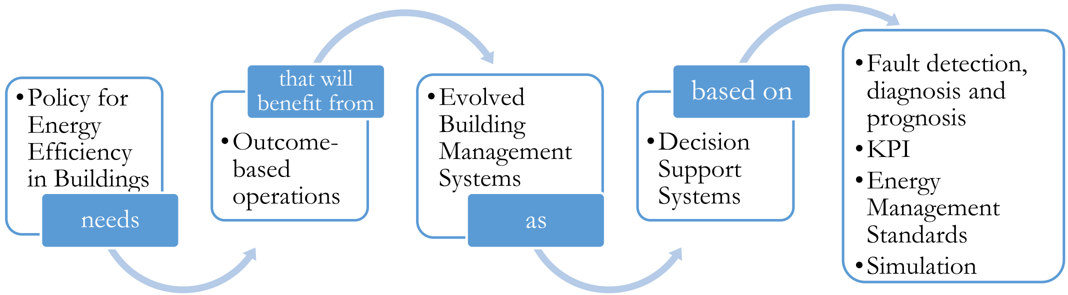


Figure 3-3. Evolution of BMS for energy efficiency in buildings. Top-down view.

From Figure 3-3, it can be seen that the main technical incorporation of the BMS for reaching age 3 is the embedding of FDD for supporting standards-based energy management (e.g. ISO 50001). This integration must be supported by an appropriate regulatory framework. Although it seems straight forward, there still exist a number of barriers, most of them non-technical, which prevent a widespread successful implementation and integration of FDD and prognosis in BMS.

3.3.1 Barriers for embedding fault detection and diagnosis in BMS

As was previously stated, FDD in building operations can have an impact in energy reductions between 5% and 25%. Also, FDD methodologies have already been demonstrated in real buildings (Dexter & Pakanen, 2001; Sterling et al., 2014b). Nonetheless, there is a great market barrier to the implementation of fault detection and diagnosis in building operations since facility managers and building operators are still sceptical as about the real advantages of the integration of fault detection and diagnosis techniques into their buildings (Heinemeier et al., 1999) as these capabilities are thought to overlap with the incorporated automated control and alarm systems of the BMS.

These are managerial rather than technical problems (Herzog, 1997) as building energy managers don't seem well informed and thus, there is a lack of interest and proper incentives for building optimisation.

Reasons for the lack of interest in improving operations, point towards the fact that the information provided to facility managers on energy conservation measures largely relates to equipment upgrade and replacement (Prill et al., 2009). Enforcing an improving-by-replacement approach misses the opportunity to view and develop energy conservation strategies in a holistic sense (e.g. managing energy as an asset rather than as a utility, see section 2.2.1). Replacement is only one of the many possible scenarios for improved operations which may prove suboptimal and lead, in the long term, to a greater energy consumption in the overall building's life-cycle (e.g. including energy to build and transport new components and decommission and recycle old ones).

The scepticism must be tackled by really demonstrating, in the long term, that FDD improves building operation without adding overhead to the building manager and/or by enforcing outcome-based regulations that make the incorporation of FDD more a necessity than a choice.

Apart from the market barrier, technological barriers such as data sufficiency, non-standard building systems, network protocols and poor data collection must be overcome for a successful integration of FDD in building operations (Lee et al., 2007). These technological barriers can be categorised into two subgroups: data and standardisation. Under 'data' we can encompass types of data, location, transfer, storage, visualisation, etc. Under 'standardisation' we can encompass naming conventions, BMS interactions and enterprise energy management standards (e.g. ISO 50001).

The technological barriers offer a set of key points to be taken into account when developing any FDD tool. In fact, if combined with the evolution ages of BMS they will provide an overview of the status of the building in facing the integration of FDD and will show weak points that need to be strengthened for successful integrations. On the other hand, the non-technical barriers offer a view on opportunities and threats that the integration of FDD in building operations may face.

3.3.2 Key points for integrating new KPI and FDD in existing BMS

Some of the common issues encountered in BMS deployments in real buildings when facing incorporation of FDD are (Raftery et al., 2010): insufficient measurement framework, poor electrical panel layouts, poor visualisation and analysis software, excessive 'value engineering', poor data quality and reduced personnel resources (included appropriate skill sets). Although BMS technologies, standards and guidelines at the management level are available, looking closely at building energy management, it is possible to observe that buildings rarely perform as well in practice as they should according to design. There are many reasons for this, including improper equipment selection and installation, lack of rigorous commissioning, improper maintenance and poor feedback on operational performance due to poor energy performance KPI (Piette et al., 2001). KPI are fundamental for the study and application of fault detection and diagnosis techniques since they provide, when properly applied, a metric for the optimal operation of the facility.

In order to provide with a robust and reliable fault detection and diagnosis platform, some key points must be studied so the FDD tools can be seemingly incorporated into BMS. These are:

- **Sensors**: type, availability and localization;
- **Visualization of data**: raw time series data, scatter plots, carpet plots, etc. KPI visualization, facility portfolio visualization;
- **Data transfer and storage**: wired/wireless; csv, MySQL, MS Access, etc.;
- **Communication protocols**: open-source, standard or proprietary;
- Possibility to **incorporate** new '**ad-hoc**' modules;
- Possibility to **define control actions**, **define alarms** to include new FDD rules.

In addition, non-technical key points should also be taken into account, which include:

- Experience of personnel in interacting with the system;
- Customizability of the implemented solution;
- Usability of the system;
- Integration with standard-based energy management systems;
- Security firewalls from manufacturers and facilities;
- Reliability and calibration of the system;
- Suitability of data for FDD.

The above mentioned points provide a framework for developing and comparing metrics for outcome-based operation in buildings and for developing technologies for improved building operation.

One way of developing such comparison metrics of outcome-based operations is to group the above-mentioned key points in categories, for example cost, user needs, simplicity, integration and availability, as proposed by Makarechi (Makarechi & Kangari, 2011), and then to use the categories and points to develop a survey/audit to be performed in the facility. Such approach can be used to place the BMS into one of the ages and consequently to provide a set of recommendations as per where energy efficiency measures and optimisation of operations could have the biggest impact. An example of an approach for auditing the facility is shown by Costa (Costa et al., 2013b) proposing the implementation of strengths, weaknesses, opportunities and threats (SWOT) analysis. The SWOT analysis (Humphrey, 2005) not only serves to demonstrate the status of the facility but also to compare and plan a path for its evolution into further ages.

3.3.2.1 On the improved data visualisation capabilities

Data visualisation in existing BMS is commonly simplified, offering simple line graphs and/or bar charts and at most tools for calculating mean, averaging, range, median, maximums, minimums and trends. In this sense, BMS visualisation tools omit critical analysis parameters such as outlier analysis and standard deviation, amongst others. Furthermore, they are not aligned with technical background and skill set of the users (e.g. facility manager). High quality visuals, including the previously mentioned and others such as carpet plots, are of imperative need in facilitating engineers and managers to effectively and efficiently parse through large quantities of data. By their very nature, these graphical methods highlight anomalies and allow staff to pinpoint problems at a much earlier stage, thus preventing significant energy loses due to suboptimal operation. Not only the people responsible for building operation will benefit from improved visualisation but also it will allow users of the building to help in energy reduction and to be involved in positively affecting building's performance (Center for Built Environment, 2009). Improved data visualisation is necessary for transforming the data-rich environment on which current BMS coexists, into the information-rich environment needed for improved building operations.

Improvement of the visualisation capabilities of the BMS is crucial in moving forward with the research application of FDD and automated prognosis tools, as it will provide valuable knowledge as per real building operations in relation to actual KPI that drive energy efficiency. In this regard, Blanes (Blanes et al., 2014) suggests a visualization platform for building diagnosis underpinned by whole building energy simulation. Raftery (Raftery & Keane, 2011) suggests a novel visualisation technique to summarize the large amount of information provided by buildings on a yearly basis by combining carpet and contour plots.

3.4 Towards age 4: Envisioned BMS, from fault detection and diagnosis to decision support systems

With the increasing needs of the building energy management market and the current deficit of highly skilled personnel in the area, a drive towards a more advanced suite of building automation systems is necessary. There is a need for greater visibility of energy consumption and this, in turn, forces the evolution of skill sets and knowledge required by facilities personnel. A building facilities manager's job has become increasingly complex due to the present multi-disciplinary requirements. Also, as the building community moves towards high-tech, it is important to also understand the information provided by an increased number of buildings and their associated data infrastructure. This translates into a need for actually 'managing' the building's information and technology systems adding to the already complex job of facility managers. At the end, the added complexity is in detriment of the availability of the facility manager for developing and implementing energy conservation measures.

It can be concluded then that it may prove difficult to find appropriate personnel to fully utilize the advantages brought by modern BMS, let alone to exploit envisioned BMS. Thus, it is straight forward to think about bridging this knowledge gap by embedding intelligence and knowledge in the BMS system itself. Previously, building management personnel must be trained to interpret building performance data generated by the BMS. New advances in artificial intelligence, incorporated in an automated FDD and prognosis suite within the BMS, can provide a systematic break-down of the problems occurring and through this 'knowledge', gained from previous similar events, it will be able to offer advice to the management personnel. This will greatly reduce both, workload of current staff, and training time of future staff and ensure optimal operation of the building's energy systems.

3.4.1 BMS integrated with on-going commissioning and decision support system

In the vision that follows, it is assumed that the proper infrastructure is in place (communication protocols, data availability and quality, KPI, etc.) and it is proposed that future building management systems will be the result of the convergence of the following KETs (Figure 3-4): Artificial Intelligence, Decision Support Systems and Simulation.

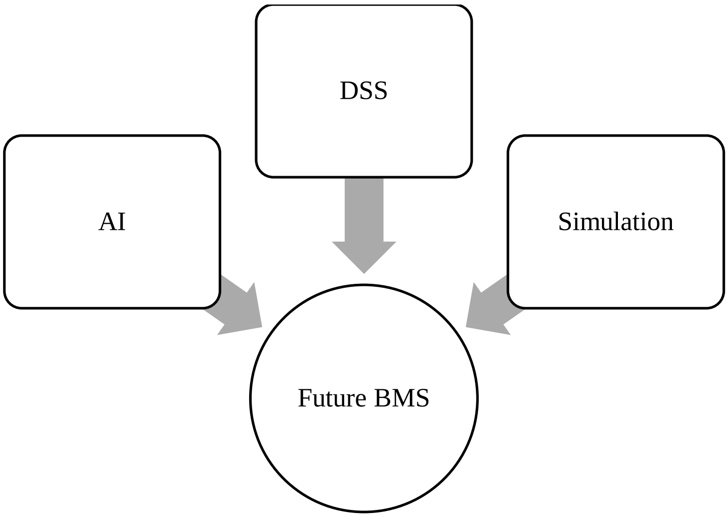


Figure 3-4. Supporting KET for future BMS.

3.4.1.1 Artificial intelligence (AI)

Over the past two decades, there has been an increasing interest in AI technologies for the energy efficient in building sector. AI advances are now moving out from the research laboratories into practical applications in many areas of building optimisation, ranging from design to diagnosis (Dounis, 2010). However to be practical, building control and management systems incorporating artificial intelligence must be designed in such a way that the existing knowledge can be integrated to it, independent of the building configuration. To achieve this, an optimal methodology seems to be the use of an object-oriented approach for defining the systems and labelling the data (Xiao & Han, 1998) through the use of ontologies (Tomašević et al., 2013). Object-orientation allows for a better understanding of the system as a whole as it will be subdivided in types of components (objects) and sub-systems (classes), and include information such as operational behaviour (methods) and characteristics (attributes). This approach for organising the data provided by BMS allows for a better use of the data, as useful information will be already embedded on each data point, thus easing the path for the transformation of the data into knowledge. Object orientation will also be a corner-stone in the future of building simulation and it is also expected that building system's definition and controls will follow this organisational paradigm (Wetter et al., 2013).

Furthermore, with the integration of artificial intelligence, the ability to learn from past behaviour may be introduced to the system thus improving its robustness and ensuring optimal operation during the whole building's operation life-cycle. Also, by introducing building system's automated performance diagnosis, buildings can achieve characteristics of the SAB concept by being able to provide timely and useful information about their performance, thus avoiding unnecessary energy waste and loss of comfort in some cases.

As an example of research in AI for building operations, Kalogirou (Kalogirou, 2006) recollected the use of artificial neural networks for energy applications in buildings with a predominance of energy consumption prediction, while Zhao (Zhao, 2011) developed and documented applications on fault detection and diagnosis and energy prediction of support vector machines, and Ahmed (Ahmed et al., 2011) implemented data-mining techniques in building operation optimisation.

Finally, distributed artificial intelligence techniques such as Multi-Agent System (A.I. Dounis et al., 2009) and Ambient Intelligence (Ducatel et al., 2003) will play a key role in exploiting the possibilities brought forward by the uptake of the concept of the Internet of Things (IoT) (Atzori et al., 2010) and the explosion on the amount and availability of data that will come from the interconnection of devices. New data streams will be available ranging from device specific consumption to occupant's location and behavioural patterns. These technologies will further enable the capabilities of a SAB, by providing extra data streams, to be even more aware of its environment and properly learn and understand occupant's behaviour. As can be seen in Figure 3-5, Moreno (Moreno et al., 2014) provides a layered platform for the SAB[27], where the key elements are the IoT devices (Layer 1) and the existence of a Context Ontology[28] (Layer 2) that allows to attach meaning to data streams, thus enabling the transformation of information into knowledge with the appropriate use of AI techniques (Layer 3), which in turn delivers Intelligent Building Services (Layer 4).

The sample of literature on application of artificial intelligence in building operations proves that research is mature enough for field operation and that integration in building operations could provide significant energy savings. A more comprehensive literature review can be found in section 2.3 of this research work.

[27] In Moreno's work SAB are referred to as Smart Building Management System.
[28] For a deep discussion on ontologies for building management and its potential please refer to (Tomašević et al., 2013).

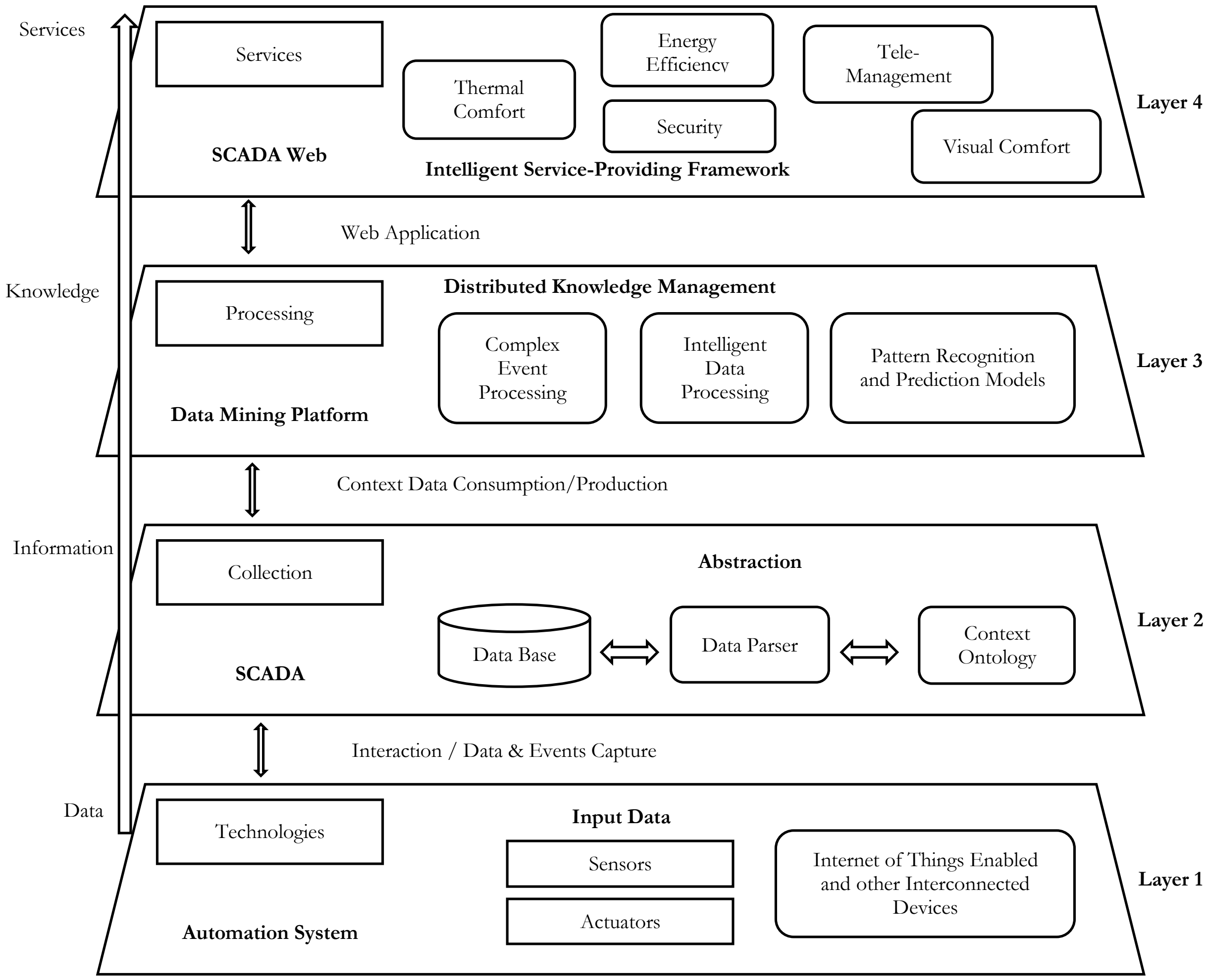


Figure 3-5. Layers of the base architecture for IoT enabled smart building management systems. Source: (Moreno et al., 2014).

3.4.1.2 Decision support systems (DSS)

Most BMS provide data on building equipment operations and is the responsibility of the engineer or technician to analyse and interpret this data. Regardless of how talented or knowledgeable this person may be, it is better if a software application can provide support in the analysis and decision making (Hatley et al., 2005). Future BMS must incorporate tools that inform facility managers regarding the energy efficiency measures that can be implemented in the facility *before* any replacement or upgrade takes place[29]. Such tools must seamlessly integrate with the building management system and perform continuous monitoring and reporting on the behaviour of the building and its systems. This integrated decision support system must cover basic activities (e.g. building monitoring), and innovative ones (e.g. system's prognosis and automated optimisation).

[29] Costa (Costa et al., 2009) proposed the use of simulation tools to provide advice on what energy conservation measures are more suitable for a determined facility.

A decision support system is much more than just representing energy consumption, cost data and deriving trends in usage. It also can be used to optimise building controls even under faulty operation and automatically schedule maintenance actions when needed, thus performing prognosis. An optimal decision support system is underpinned by a FDD framework, extending it to include prognosis and involving complete interoperability with the grid, renewable energy sources, storage and opportunities. This vision requires automated development of the scenarios for different responses, measurement and verification of results, and tracking of financial, energy and emissions effects. In this regard, simulation models must be also integrated with the DSS for providing a framework for scenario development.

3.4.1.3 Building performance simulation

Computer modelling and simulation of the building as a whole or as separate components is a KET for the future of building energy efficiency (Pérez-Lombard et al., 2011). In the very basic scenario, computer simulation of buildings serves as means of self-assessing and predicting building performance; testing energy efficiency measures and providing system's prognosis. Building simulation is being incorporated in different aspects of the building lifecycle. For example, as a decision support tool during the design and retrofit phases by providing objective performance measures (Augenbroe, 2011), as a policy-making tool to evaluate the expected impact of certain proposed policy (Crawley, 2011), as well as other scenarios. However, a current research challenge is how to manage the high level of detail and inputs necessary for the models to be both usable and reliable. In a view of the future of building performance simulation, Wetter highlights how today simulation is still rarely used during operation. Wetter also argues how simulation tools will become increasingly more abstract and multi-purpose in order to fit the multi-domain nature of the building operation area (Wetter, 2011). The lack of use of computer simulation during building operation creates an unexploited niche where the impact of simulation in reducing energy consumption is yet to be realised. However, some barriers must be overcome, such as the complexity of simulation programs, lack of standardisation in the integration of systems in the building or lack of acceptance from facility manager. The European Commission seems to have realised the potential value of the use of simulation during operation, as can be gathered from the multiannual roadmap for the contractual public-private partnership on energy efficiency in buildings under the Horizon 2020 research programme (European Commission, 2013a).

3.4.2 The vision for age 4 BMS

In age 4, BMS incorporating decision support systems must be fully integrated into the continuous commissioning schedule of the facility. In Figure 3-6, it can be seen how the different elements of this vision come together: after the installation or maintenance (1), initial commissioning (2) is performed in order to detect incorrect configuration, human-induced errors and to set up and calibrate any models that aid in the decision making process. Afterwards, condition based monitoring and fault detection, diagnosis and prognosis algorithms (3), are implemented in order to ensure continuous optimal behaviour of the facility according to the identified KPIs (4). In case some performance degradation is identified in the systems, or if some way of further optimisation is identified, prognosis will be activated feeding an energy management tool (5) (e.g. based on ISO 50001), which schedules maintenance or corrective actions (6), thus closing the cycle that is constantly repeated in an automated fashion (similar to the Continuous Commissioning® process (Hampton, 2003)). In summary, all the characteristics of SAB are incorporated in age 4 BMS.

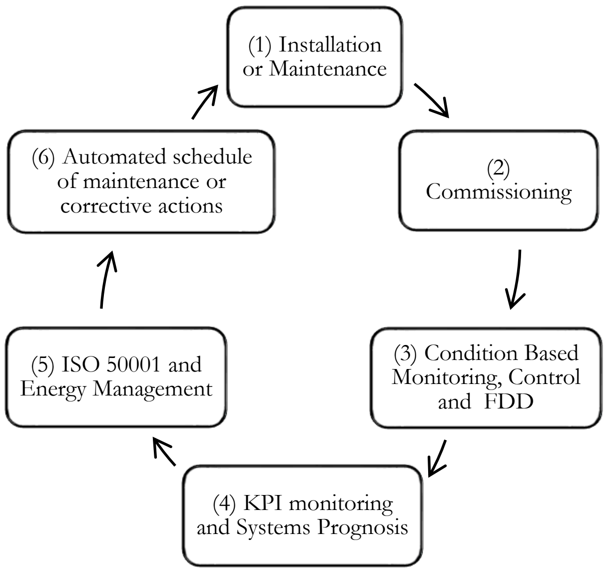


Figure 3-6. Continuous monitoring and maintenance with incorporated decision support.

The first step for building's commissioning (either first time or after maintenance) is to check that systems are working in good order. Installation, maintenance and commissioning are fairly standard procedures in the building's lifecycle and current practices includes them. However current practices also tend to stop there and, although room for improvement exists, building operation moves between installation/maintenance and commissioning on a schedule basis (Carbon Trust, 2009).

This non-optimal procedure will remain in place unless some external factor (e.g. regulatory framework demanding optimised operations) induces the necessary incorporation of optimisation measures.

In Figure 3-6, the building's commissioning process presented goes beyond initial assessment. In it, commissioning ensures that basic actions for energy efficiency, such as the ones proposed by Escrivá-Escrivá (Escrivá-Escrivá, 2011), are carried out and that an initial appropriate certificate, such as proposed by (Pérez-Lombard et al., 2009), is issued. This will be followed by condition-based monitoring, control and FDD ensuring building's efficiency is always at its best (Torrens et al., 2011). KPI as proposed by Ó Gallachoir (Ó Gallachóir et al., 2007) and Pérez-Lombard (Pérez-Lombard et al., 2012b) will become common place supporting energy management and system's prognosis, as these are necessary to keep building's energy performance within the rated parameters.

Standard-based energy management practices (e.g. based on ISO 50001), and associated technologies shall become an integral part of the overall facility management structure. Such practices will help offset the workload of the building manager by providing timely and accurate indicators of energy efficiency, helping decision makers to make better informed energy efficiency decisions. To achieve the above, policy should enforce the use of energy management concepts in buildings.

Finally, automated schedule of maintenance and corrective actions will be a natural output of the energy management framework, supported by modelling and simulation technologies and methodologies as depicted by Hull (Hull et al., 2009).

In the following section a framework is presented for assessing the readiness of the ICT infrastructure in a building management system in order to be able to incorporate SAB characteristics.

3.5 SWOT ANALYSIS APPROACH, TOOL SELECTION AND RECOMMENDATIONS

The acronym SWOT stands for *Strengths, Weaknesses, Opportunities and Threats*. It helps identifying internal and external factors that can be favourable or unfavourable to achieve the objectives proposed (e.g. integrating FDD). In Figure 3-7 a descriptive graph of the SWOT analysis is presented.

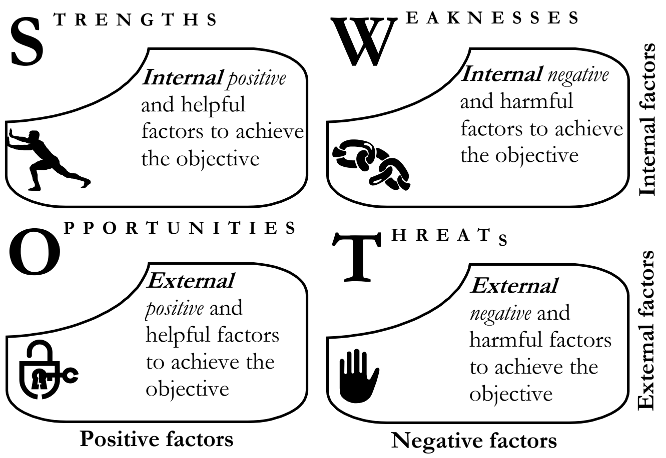


Figure 3-7. SWOT analysis graphically explained.

The SWOT analysis, as presented in this research work, focuses on the integration of SAB methodologies and tools in BMS to reduce energy consumption of HVAC systems. It focuses on FDD methodologies as an identified cornerstone in achieving SAB. Nonetheless, a similar approach can be taken for the rest of the systems and integration of other technologies. The SWOT also helps identify where FDD can have the biggest impact within the HVAC system by exploiting the recognised strengths and opportunities and creating contingency plans for weaknesses and threats.

In Figure 3-8, the proposed framework for performing the SWOT analysis can be seen. The approach proposes to follow two parallel routes, one for identifying internal factors (strengths and weaknesses) and other for spotting external factors (opportunities and threats). At the end, both results are combined into the assembled SWOT analysis in the form of a report.

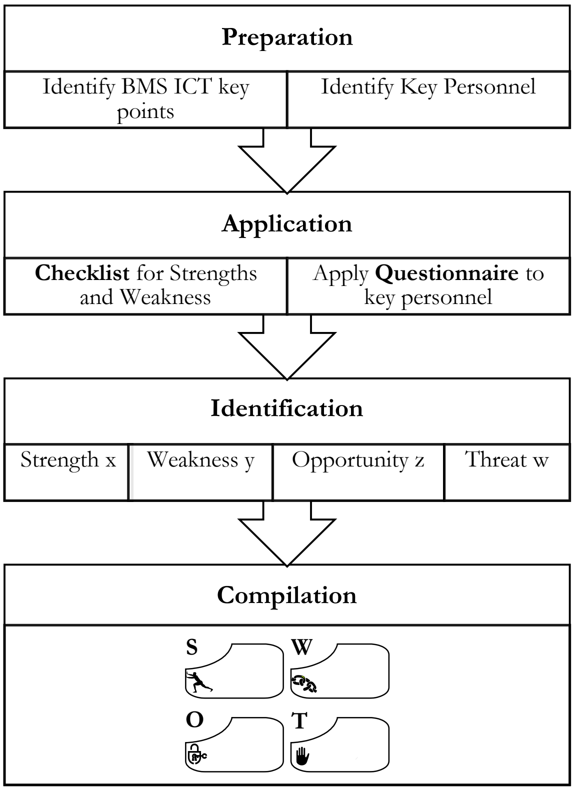


Figure 3-8. SWOT process.

3.5.1 Identifying internal factors: strengths and weaknesses

The steps to be carried out in order to identify the internal factors are:

1. The key technical elements of the BMS need to be identified with an audit;
2. A checklist based on the identified requirement for the four ages of the BMS is applied (see section 3.5.1.1);
3. The results from this checklist are to be analysed and conclusions will be drawn in the form of lists of strengths and weaknesses depending on the identified system age and the FDD solution desired;
4. The weaknesses of the system will need to be addressed to fully apply the solution.

Once the checklist is implemented in the facility, the following can be considered as a guideline to identify which points are strengths and which weaknesses:

- Every key point already in the age of the desired solution is considered a strength;
- Every key point below the age of the desired solution is considered a weakness and should be addressed promptly. If improvement is not possible and the solution can still be implemented without that particular point, then it should become a threat;

- Every key point above the age of the desired solution is considered as a strength point to be relied on and actions should be scheduled to fully exploit it;
- Every key point which status can't be established should be marked as a threat and steps should be scheduled to clarify the status and to be able to identify what it will represent in the desired solution.

3.5.1.1 Checklist for identifying strengths and weaknesses of the SWOT analysis

Identifying the strengths and weaknesses section of the SWOT analysis for the integration of innovative FDD tools into BMS systems can be done by applying a checklist like the one presented in Table 3-3 as a guideline. Next, some of the meanings of the items in the table are explained.

In relation to **BMS interactions**, the following aspects are considered:

- BMS code accessible: at least as pseudo code, to understand internal functioning of the BMS, control actions and rules;
- Control software modifiable: possibility to implement ad-hoc control functions within the BMS and/or embed software into the controller. This will also ease the path for automated optimal control;
- Interaction with BMS: possibility to communicate with the BMS in other way than the graphical user interface to read and write values and set parameters (this allows for further automation of the system).

Being **extensible** is analysed as follows:

- Manufacturer software and hardware modules: the manufacturer provides the software and hardware modules to enhance capabilities of the BMS;
- External software and hardware modules: the manufacturer provides an infrastructure to attach external modules to the system.

Sensors are analysed in relation to their degree of accuracy (indicative values in Table 3-2) and their robustness which is intended as the likelihood of the sensor to give an erroneous reading (this can be the effect of either a physical problem, a calibration problem or a connection problem).

Table 3-2. Sensors accuracy. Adapted from: CASCADE Deliverable 3.1 (CASCADE Consortium, 2012c).

Type of sensor	Low	Average	High
Temperature	> ± 1°C	> ± 0.1ºC and < ± 1°C. Typical ±0.5ºC	< ± 0.1 °C
Humidity	> ± 5 %	> ± 1 % and < ± 5 %. Typical ± 2 %	< ± 1 %
Volume flow (air)	> ± 5 %	> ± 1 % and < ± 5 %. Typical ± 5 %	< ± 1 %
Volume flow (water)	> ± 5 %	> ± 1 % and < ± 5 %. Typical ± 2 %	< ± 1 %
Electric power	> ± 1 %	> ± 0.1 % and < ± 1 %. Typical± 0,5 %	< ± 0.1 %
Light meter	> ± 10%	> ± 1% and < ± 10%. Typical ± 5 %	< ± 1%

Data availability is investigated according to:

- Data points: location, amount and suitability of the variables being measured, including standard naming convention;
- Data frequency: how often measurements and signals are measured and logged;
- Data visualization: means by which data can be visualised;
- Data accuracy: direct relationship with sensor accuracy plus verification of the consistency of measurement location.
- Data base availability and access.

Appropriate data availability will support the construction and exploitation of energy efficiency KPIs.

Data accuracy must be checked at different levels of the system to provide indications in relation to the reliability of the measured data. Furthermore, a framework might be implemented to properly adapt system's operation under conditions where data reliability is low (e.g. due to increased uncertainty).

Data format and Communication protocols are also studied at different levels, like field level (BACnet, LonWorks, Modbus, and M-bus), data transfer level (Ethernet, RS-232, Wireless) and data content level (csv, xml) which focuses on how data is structured and stored. For example: comma separated values (csv) format is useful for simple analysis but the extensible mark-up language (xml) is much richer for automated querying and data transferring.

Finally the **service level** aspect refers to elements of the facilities' system that are under the scope of the BMS:

- System: only controlling/maintaining/optimising the individual system (HVAC, lighting, single area of the facility);

- Facility level: managing the whole facility level and optimising the functioning of each system to improve the overall performance of the facility;
- Facility plus grid: same as facility plus optimising energy exchange with the grid for reducing costs/consumptions and emissions;
- Multi-facility: possibility to manage multiple facilities at sector, district, national or international levels.

The checklist can be completed after the audit on the systems infrastructure and taking into account any documentation from the facility that will support the information to be inputted in the list. However, this implementation for the strengths and weaknesses should be done on a case-to-case basis since the systems installed on the facilities must comply with particular needs and no standard solution exists for all implementations. Table 3-3 shows the structure of the checklist and how the technical BMS evolution, in terms of the ages previously defined, compares against these features.

Table 3-3. Strengths and weaknesses of BMS and their evolution.

System Characteristics	Key questions	Basic BMS solution Age 1	Most diffuse BMS solution Age 2	Transition BMS Solution Age 3	BMS of the Future Age 4
BMS Information		Manufacturer, Model			
BMS basics	**Systems under BMS**	HVAC	Age 1 + safety systems	Age 2 + energy, security and lighting systems	Age 3 + water management, IT systems
	Top-level variables controlled and monitored by the BMS	Air and Water Systems Temperature	Age 1 + Humidity Control, Overall Energy Consumption	Age 2 + Lighting and Sub-systems, Energy usage, Water usage, Occupancy	Age 3 + Visual and Thermal Comfort conditions. Energy generation, storage and use.
	Main key performance indicators used	None	Comfort conditions on conditioned areas and utility bills	Age 2 + detailed energy consumption	Age 3 + Multi-facility detailed energy and emissions management
	Weather station?	None	Temperature / Humidity measured by BMS	Full weather station installed on-site	Full high resolution and accurate weather station installed on site and live link with weather forecast

System Characteristics	Key questions	Basic BMS solution Age 1	Most diffuse BMS solution Age 2	Transition BMS Solution Age 3	BMS of the Future Age 4
BMS interactions	**BMS code accessible**	No BMS code	No access and proprietary software	Pseudo code available	Open source or standard based code
	Controller software modifiable	No software	No modifications allowed	Set points and schedules modifiable	Set points, schedules and control actions modifiable
	Interaction with BMS	No mean of interaction with BMS	Interaction via graphical user interface only	Incorporation of application programming interface (API) for scripting	Scripting, API incorporated and standardised
Extensible	**SW modules/elements**	No extension possible	Manufacturer developed modules	Manufacturer and External	Manufacturer and External
	HW modules/elements	No extension possible	Manufacturer developed modules	Manufacturer and External	Manufacturer and External
Sensors	**Sensors Accuracy**	Low	Average	High	High
	Sensors Robustness	Low	Medium	High	High
Data availability	**Data points**	None	Controlled Variables	Age 2 + control signals	Ubiquitous
	Data frequency	None	>15 minutes	< 15 minutes	< 5 minutes (near real-time)
	Data visualization	None	Trends	Fixed standard plots (e.g. carpet plots)	Configurable plots
	Data Accuracy	No data	Poor	Average	High
	Data base availability and access	No database	Manual	Automated / Reading Access	Automated / Full External Access
Data Format and Communication protocols	**Field level**	Ad-hoc or no protocol	Proprietary protocols	Standard (e.g. BACnet, Modbus, etc.)	Age 3 + Wireless/ Ethernet
	Data transfer level	RS-232/485	RS-232/485 Ethernet	Ethernet	Wireless / Ethernet
	Data content level	No data	Proprietary/ ad-hoc file format	Standard file format (e.g. csv/xml)	Standard file format optimised
Service Level		System	Facility	Age 2 + Grid	Multi-facility/Campus

3.5.2 Identifying external factors: opportunities and threats

The steps to be carried out in order to identify the external factors are:

- First, the key personnel operating the facility needs to be identified;
- Afterwards, a questionnaire must be completed by the key personnel;
- Last, conclusions from the questionnaire will form the list of opportunities and threats.

Results and conclusions drawn from this questionnaire are to be analysed on a case by case basis to determine the opportunities and threats of the facility. However, as a guideline, some threatening scenarios could be:

- Any recent or near future change in key personnel is to be considered a threat. This is due to the entropy created as the new member might have less experience than the departing one;
- Any difficulty or lack of functionality in the interaction with the BMS is a threat since it augments the effort to perform the tasks and it makes it less likely for energy conservation measures to be carried out;
- Old equipment, long time between maintenance operations, system providing large number false positives alarms, are threatening because it greatly reduces the reliability of the system;
- Others will become clear once the questionnaire is answered by the personnel.

3.5.2.1 Questionnaire to interview key personnel to identify opportunities and threats for the SWOT analysis

Opportunities and threats of the SWOT analysis correspond with external (out of our control), and often non-technical factors that can influence the implementation FDD tools. These factors can be extracted from interaction with key personal managing the facility. In light of this, a questionnaire (see example in Table 3-4) can serve as a basis to collect the necessary information from the key personnel that can be further analysed to extract opportunities and threats.

Table 3-4. Suggested questions to support opportunities and threats identification.

Name:		Role:
BMS interaction	How user-friendly is the graphical user interface of the BMS?	
	What difficulties in interaction with BMS have been encountered so far?	
	How could interaction with BMS be improved? (adding new features or improvement old ones)	
	What types of reports can be generated from BMS? (Excel sheets, full report diagrams, only text files, cost benefit analysis, yearly trends, etc.)	
	Can the report be modified to include or exclude features like key performance indicators?	
	Who is the intended receiver of the report?	
BMS operation	When was the BMS installed?	
	When was the last maintenance/calibration of the system performed?	
	How many false-positive and false-negative alarms the system reports per year/month/day?	
	What are the more common faults detected by the BMS?	
Energy management	Which plants are controlled/monitored by the BMS?	
	What types of key performance indicators are being used?	
	How are energy conservation measures being planned?	
	How are energy conservation measures being executed	
	How the implementation of energy efficiency measures being tracked and monitored?	
	Is information about number of occupants in the building being recorded? Can this information be included in the key performance indicators and reports?	
	Is there any report used for energy management?	
	Is the system useful for addressing Building's Energy Efficiency? Why?	
	What feature would you add to the system to address energy efficiency?	

After compiling the SWOT analysis it should be possible to identify which age the system under analysis must closely mirrors. This realisation will help in deciding the path to implement any SAB characteristic and what actions should be taken for the incorporation of the necessary tools and technologies. It is recommended to update the SWOT analysis periodically (or at least after any major change in the facility) and keep it available since it may be a very valuable decision making tool.

3.5.3 SAB characteristics selection depending on building's age

Selection of the best SAB characteristics will also be a case-to-case activity. As a general approach, Table 3-5 provides an indication for SAB characteristics best suited for each application given the readiness of the BMS. It is important to note that elements from a previous age can always be implemented in the following one.

Table 3-5. Building age vs. FDD approach, modelling and SAB characteristics.

Age	**1**	**2**	**3**	**4**
SAB Characteristics	None	Predicts, keeps track and monitors building's performance. Controls and adapts building's actions to the monitored/predicted performance.	Diagnoses root causes of building's performance reductions.	Supports building managers by providing information about building's operations in a way that matches their typical skill set.
What can be done?	Manual fault detection	Automated fault detection manual diagnosis	Automated fault detection and diagnosis	Automated fault detection, diagnosis and prognosis. Decision support systems
FDD Methodology Suggested	Limits and alarms	Statistical analysis, APAR rules, expert systems	Model based diagnosis, machine learning	Integration with BIM, ISO 50001 and similar standards
Modelling suggested	Expert knowledge	First principles, simplified physics, black box	First principles, detailed physics, black box, grey box	Same as age 3

Table 3-5 also provides some examples of modelling approaches that can be used to support FDD tools. Selection of modelling tools, FDD methodologies and other technologies must be carried out in a case-to-case basis at the moment depending on the skills of the people implementing the SAB.

3.5.4 General recommendations

In this section a set of best-practice actions to be performed on each facility regardless of the BMS age is presented. These actions will enhance the energy savings of any solution applied to the facility and are independent of the identified age of the system. The list of best-practice actions will also ensure that local regulations and industry standards are being followed. Some best-practice actions are (Escrivá-Escrivá, 2011):

- Gather local regulatory information on air quality and comfort;
- Gather standards applied during construction and commissioning phases;
- Check that set-points and schedules correspond with those contained in regulations and standards and plan actions to adjust if necessary;
- Creation, if not already in place, of a database to store building and BMS data.

- Set up of automated and periodic back up of data.
- Set up secure and possibly remote access to database.
- Ensure logging and completeness of database data.

Following these general recommendations and compiling a database with the collected information will ensure not only the best application of the desired solution, but also will help to monitor and maintain the whole system, both locally and remotely, while providing easy to access data for future necessities.

3.6 SWOT RESULTS

Raw results from the SWOT implementation on the audited BMS are in the form of the checklist and the questionnaire which can be compiled in a single report for future use.

Furthermore, the results can be represented graphically in two ways. The first way of graphical representation is achieved by filling with comments and points the sections of Figure 3-7. This representation offers clear advantages as it explains which items are considered for each SWOT section in the audited system and can provide further explanations about the reasons for considering certain BMS characteristic in one of the section or the other.

However Figure 3-7 does not provide information about the identified age of the system. Such information can be represented in a horizontal bar chart where each of the items from the checklist (strengths and weaknesses) are represented as shown in the dummy chart of Figure 3-9.

The information displayed in Figure 3-9 corresponds with the current age of the BMS together with expected results and evolution in ages from any programmed retrofitting as future characteristics. Finally, for opportunities and threats, the questionnaire must be presented as is.

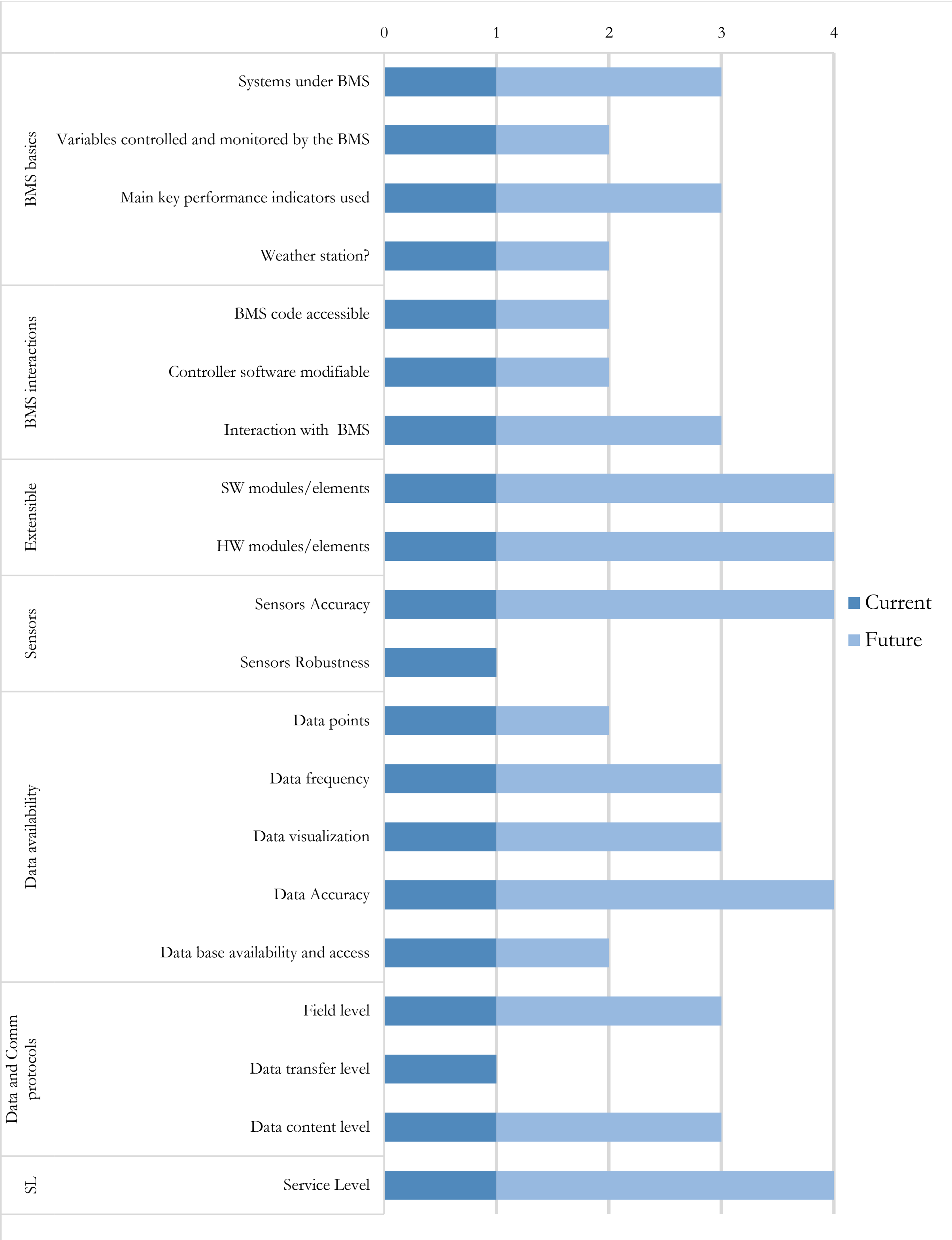


Figure 3-9. Strengths and weaknesses bar chart representation.

3.7 Chapter summary

Early stage BMS, such as those of age 2, can be defined as systems that operate on the premise of gathering data from local controllers (HVAC, fire protection, security, etc.) and relaying this data to a central computer for monitoring purposes. The data was then compared with standards, legislations and benchmarks. In cases where there was a significant deviation from the considered normal operation, an operator was alerted. Nonetheless operators were often not informed as to the why or what, merely that a problem existed.

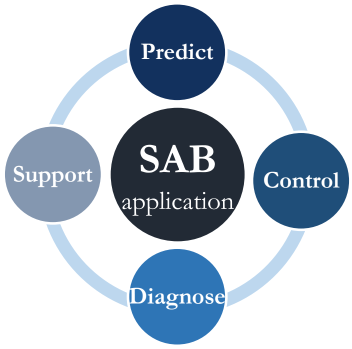
Today's BMS should improve over old systems by offering an automated and standardised approach to fault detection, diagnosis and prognosis such that the workload of the BMS operator is shifted from interpreting vast amounts of data to understanding how the system is operating based on information automatically processed from the data. This allows facility managers to act directly on specific reports and produce innovative energy efficiency measures. Furthermore, future BMS should transform the building into a self-conscious entity that, while maintaining comfort and safety conditions, always deliver optimised operations. This is the SAB paradigm.

However, improvements and additions to the BMS normally require substantial re-wiring which often proves a costly enterprise, halting implementation of novel developments. Current research suggests that 70% of costs associated with BMS relate to wiring. The introduction of wireless sensor technologies and associated protocols serves to greatly reduce the cost of BMS in this regard. Also, modern BMS utilises micro-processors in local controllers, which can be exploited as this serves to reduce the amount of data needed to be transmitted globally. Local processors are capable of deciding which data is pertinent to the central system and may send only a small fraction of the gathered data to the central controller. These systems allow more global control, greater monitoring and logging of data, provide fault detection and offer advice based on past events. Nonetheless, innovation is reduced to that provided by BMS companies since BMS are normally traditionally proprietary software and modifications to BMS code are not allowed.

It is evident how important standardisation is for overcoming barriers between research and industry. In this sense, industry is putting efforts in standardisation of technologies used, especially in communication technologies and research, to support standardisation increased commercialisation and exploitation. The SWOT analysis presented in this chapter is key in identifying the readiness of the hardware and the software of a building management system by framing the BMS in one of the four identified ages from which, by using Table 3-5, it is straight forward to identify what can be done and what is recommended to be done in terms of FDD, modelling and SAB characteristics.

Even if the scope of the SWOT implementation has been kept on the technical and personnel aspects of BMS and facility management, it is opportune to make a note on the economic aspects that impact the implementation of different energy conservation measures. It is straight forward to understand that the availability of a budget for implementing energy efficiency measures can be considered as an opportunity and its lack a threat. The implementation of energy conservation measures has shown reduced return of investment's times and, if continuously monitored and improved, even monetary savings in the long term (Section 2.2.1).Also, the incorporation of the different elements that would increase the age of the BMS entails an associated cost (e.g. rewiring as explained before). However such improvements are not to be evaluated against merely upfront costs but also in terms of potential implementation of energy conservation measures that will offset such costs and the opportunities arising from the conceptual change of energy as an asset.

The next chapter presents, through case studies, one approach for the implementation of each SAB characteristic in different facilities.



CHAPTER 4

CASE STUDIES: BMS AGES AND SAB CHARACTERISTICS

In this chapter, the main case studies used for this research work are presented. The case studies are part of collaborative work in different projects as will be made clear during the reading of each section. The chapter aims to demonstrate what SAB characteristic can be implemented in buildings depending on the identified age of their BMS. Each section of the chapter represents one case study. All sections follow a similar structure to provide a common framework for comparison. Sections start with an introduction of the particular case study and a short background on the main concepts needed to understand the case study. Following the introduction a description of the facility is provided. A SWOT analysis is applied to each facility showing results for the strengths and weaknesses as these are the ones defining the age of the BMS. Subsequently, the approach for implementing the SAB characteristic is explained on each case study and a presentation of the main results is made.

This chapter presents the case studies in an increasing order with relation to the identified age of BMS as shown in Table 4-1. The approach taken of each case study follows what presented in Table 3-5.

Table 4-1. Implementation of SAB characteristics through case studies.

SAB characteristic	Case study building	BMS age	Technologies used
Predicts, keeps track and monitors building's performance.	Nursing Library, NUIG, Galway, Ireland	2	First principle modelling, Artificial Neural Networks
Controls and adapts building's actions to the monitored/predicted performance.	Kingfisher Sports Club, NUIG, Galway, Ireland	2	First principle modelling, Artificial Neural Networks
Diagnoses root causes of building's performance reductions.	Cork School of Music, Cork, Ireland	3	First principle modelling, Qualitative Model-Based Diagnosis
Supports building managers by providing information about building's operations in a way that matches their typical skill set.	Satellite A Terminal 1, Malpensa Airport, Milano, Italy	4	Detailed physics modelling, Ontologies, Rule- and Model-based diagnosis, ISO 50001

4.1 AGE 2 BMS: PREDICTS, KEEPS TRACK AND MONITORS BUILDING'S PERFORMANCE

This section presents a case study focussed on the first SAB characteristic: "*Predicts, keeps track and monitors building's performance*". In this regard, the BMS with ICT systems that are in age 2 provide the necessary data and capabilities to accomplish this SAB characteristic. The methodology and results presented in this section have been published in (Sterling et al., 2014a).

4.1.1 The facility

The Nursing Library is a recently constructed building at the National University of Ireland, Galway (NUIG), in Ireland. It has a gross floor area of 700m^2 and was completed in 2009. The 3-storey building contains a library and study areas, as well as a computer room on the ground floor. It operates from 8:30 to 22:00 on weekdays and 9:00 to 17:00 on Saturdays/Sundays. Figure 4-1 shows a picture of this building.

Figure 4-1. Nursing library.

4.1.1.1 HVAC systems

The building has a mixed-mode ventilation system with a dedicated outside air system (DOAS) for forced ventilation and automatically (or manually) operated windows for natural ventilation in most areas. The DOAS draws air through an earth-hole system to temper the air in the winter and summer months. Stand-alone direct heat exchange units cool the computer rooms. Convective hot water baseboard heaters maintain indoor temperatures outside of the summer months. Campus-wide district hot water supplies all of the heating systems in the building.

4.1.1.2 Stock information and measured data

The quality of stock information about the building is very high due to its recent construction. High quality as-built drawings and detailed information on materials and constructions are available. In addition, Operation and Maintenance (O&M) information and detailed design criteria is available for all the HVAC equipment. The existing Building Management System (BMS) monitors:

- Space temperature (ºC);
- Space CO_2 levels (ppm);
- Electrical Energy Consumption (kWh);
- Heat Energy Consumption (kWh);

The electrical layout also explicitly separates electricity consumption by end-use, such as lighting, plug loads and HVAC systems.

4.1.2 BMS SWOT

The BMS at the Nursing Library in the National University of Ireland, Galway is a Cylon Building Management System with UnitronUC32 controllers. The BMS comprises an onsite PC with the BMS graphical user interface and OPC server for modifying and visualising set points, systems status and short-term logging of monitored variables. Data for Figure 4-2 was gathered from Operation and Maintenance Manuals of the Nursing Library and on-site visits (Appendix C).

From Figure 4-2, it is clear that the BMS characteristics fall into an age 2 BMS. Table 4-2 replicates Table 4-1 highlighting the age 2 for BMS and the KET used for or this case study. According to Table 4-2, two SAB characteristics can be carried out. For this case study it was decided to exploit the characteristic related to predicts, tracking and monitoring building's performance. The reason for this choice lies in the fact that this is a natural ventilated building and the energy consumption has a high dependency on user's choices (e.g. opening radiator valves, opening windows) rather than in scheduling of energy services such as air handling units, water heating, etc. For the studied SAB characteristic, the main technical developments are those provided by simulation models. In this regard, the rest of the section discusses different approaches for such modelling.

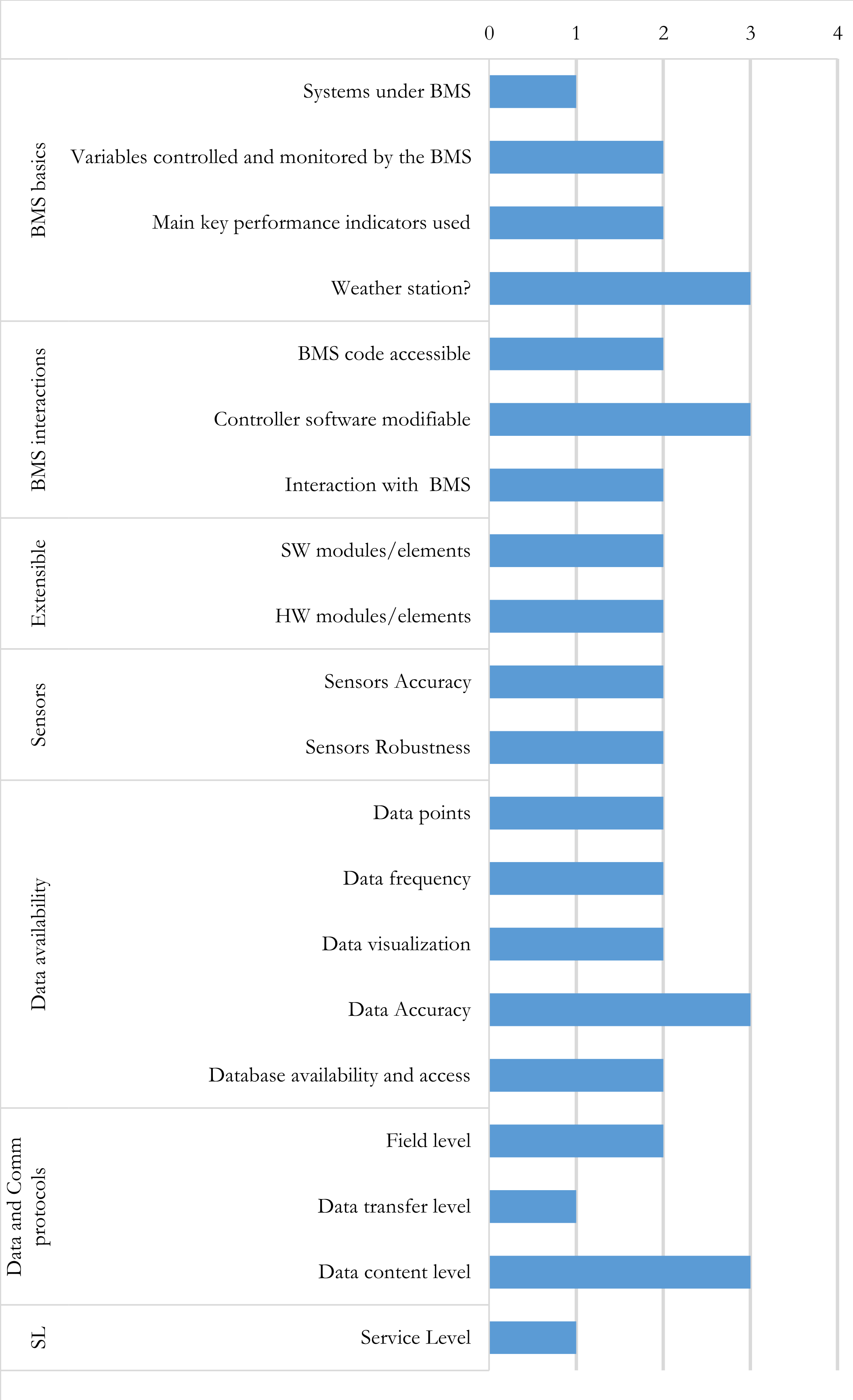


Figure 4-2. Strengths and weaknesses of BMS at the Nursing Library.

Table 4-2. BMS age vs. modelling and SAB characteristic selected for the case study of the Nursing Library.

Age	**1**	**2**	**3**	**4**
SAB Characteristics	None	**Predicts, keeps track and monitors building's performance.** Controls and adapts building's actions to the monitored/predicted performance.	Diagnoses root causes of building's performance reductions.	Supports building managers by providing information about building's operations in a way that matches their typical skill set.
What can be done?	Manual fault detection	Automated fault detection manual diagnosis	Automated fault detection and diagnosis	Automated fault detection, diagnosis and prognosis. Decision support systems
FDD&P Methodology Suggested	Limits and alarms	Statistical analysis, APAR rules, expert systems	Model based diagnosis, machine learning	Integration with BIM, ISO 50001 and alike standards
Modelling suggested	Expert knowledge	**First principles, simplified physics, black box**	First principles, detailed physics, black box, grey box	Same as age 3

4.1.3 Building performance simulation approaches

In order to monitor and predict building's performance, it is necessary to have an indication as per what such performance should be. This can be accomplished by the use of simulation models that provide a representation of the performance behaviour of the building. Furthermore, real data can be used to compare simulated and real performance and calibrate the simulation model to more accurately represent the behaviour of the building.

Different techniques can be found in literature that are applied to the problem of using modelling and simulation combined with real operation data to accurately represent the energy behaviour of the building, with applications that vary from small residential buildings to big office complexes. These techniques may be grouped into the following branches (Zhao & Magoulès, 2012a):

- Engineering models and methods;
- Black-box models;
- Grey-box models.

Simplified engineering methods and black-box models based on artificial intelligence offer the better trade-off between accuracy and model simplicity of the model while grey-box models can combine these two and leverage on the advantages of each to further improve accuracy (Zhao & Magoulès, 2012a). This section presents an approach for integrating a detailed engineering model (engineering method) with an artificial neural network (ANN) model (black-box method) to represent the energy behaviour of a naturally ventilated building based on the NUI Galway campus. The reason behind this approach is to reduce the development time of an accurate model (ANN + EnergyPlus) while still allowing the extraction of relevant information and data from the engineering model. Another advantage of the approach is the possibility of automating the learning process associated with ANN such that the most recent data may be incorporated. By presenting a case study using real data, the efficacy of the approach can be assessed based on two standard metrics used for evaluating the goodness of building energy simulation for measuring energy demand and savings (ASHRAE, 2002). These metrics are the coefficient of variation of the root mean square error (CV-RMSE) and the normalised mean square error (NMBSE) both comparing simulated with real measured data.

4.1.4 Building performance simulation calibration

Building Energy Simulation (BES) models are commonly used in building design to represent physical building operation through discrete time-step heat and energy-balance equations. These types of equation-based models are referred to as 'engineering methods' or models. Due to the complex nature of these models, they require detailed levels of inputs in order to produce accurate results. Even with detailed level inputs, attaining a detailed and accurate building energy simulation requires performing a calibration process that requires a modelling expert and the task itself is both, time consuming and computationally expensive given that the calibration problem is over-parameterised and under-determined thus leading to multiple suboptimal solutions (Coakley et al., 2011).

While traditional engineering-based building energy models are complex to develop, they also provide the important advantage of providing a realistic representation of building operation based on physical, environmental and operational data. This makes these models extremely useful for assessing design changes and energy efficiency interventions.

For the last two decades or so, black-box models, especially those based on machine learning, have received an increasing attention from the building energy simulation community (Zhao & Magoulès, 2012a). This approach for modelling makes use of already existing operation data to "learn" the expected behaviour of the energy consumption in the building. Black-box models produce estimates with sufficient accuracy to match those demanded by standards (e.g. <30% in hourly energy consumption (Ohlsson et al., 1993; ASHRAE, 2002)). On the down side, a point to consider with black-box models is that they are highly dependent on the parameters used for training and the quality of the data available for training. In the case of artificial neural networks, it has been proven that they can produce very good results while requiring considerably less time and computational resources than engineering methods (Zhao & Magoulès, 2012a). One important advantage of artificial neural networks over engineering modelling is the possibility to automatically update and retrain the model to adapt to changes in the modelled system (Yang et al., 2005). This procedure in engineering models may require the calibration process to be performed again, at least to some degree. This is because uncertainties in the calibrated model may be distributed and compensated across a broad range of calibration parameters (Coakley, 2013).

Based on the previous observations, this section proposes a grey-box methodology, combining traditional engineering building energy models with artificial neural networks. This approach will improve the accuracy of the engineering model by exploiting the learning capabilities of the artificial neural network. The methodology also has the advantage of easing the training burden of the ANN and still being able to extract relevant information from the BES model, particularly in qualitative terms of the form of trends resulting from any refurbishment or other changes in the facility.

In Figure 4-3, a graphical representation of the proposed methodology is shown by which a neural network is used to *correct* the errors of the engineering model related to the accurate representation of the electrical consumption of the building based on past consumption, weather conditions and calendar data (day/time).

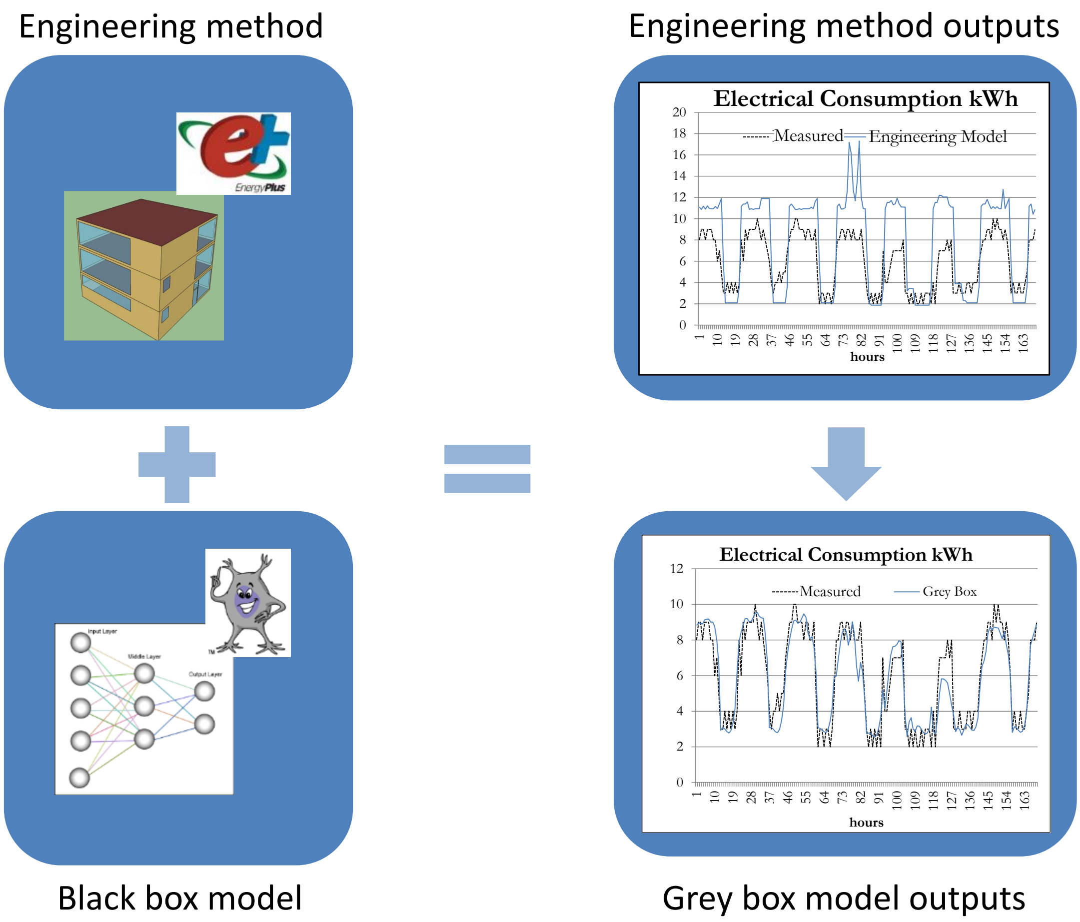


Figure 4-3. Using ANN to correct building simulation errors.

4.1.5 Approach

The approach of this case study consists in comparing the three tiers identified for developing simulation models of the building and also provide a methodology for developing short-term energy consumption prediction models. In this collaborative work, engineering models were kindly shared by Dr. Daniel Coakley (senior research at IRUSE) from his PhD Thesis (Coakley, 2013) while black- and grey-box models were fully developed by the author of this research thesis work.

4.1.5.1 Engineering model and simulation: EnergyPlus

The BES model was developed using the evidence-based methodology proposed by Coakley (Coakley et al., 2012, 2011). This methodology follows a four-step model development and calibration process: (1) Data gathering / building audit. (2) Evidence-based BES model development, (3) Iterative model improvement, (4) Bounded grid search.

- **Data gathering / building audit***:* The first step was to obtain comprehensive data pertaining to the building, its systems and environment. This information was sourced from:
    - As-built drawings;
    - Operation & Maintenance (O&M) manuals;
    - Building audits and surveys;
    - Building Management System (BMS);
    - Local weather station;
    - Interviews with facilities manager;
- **Evidence-based BES model development***:* Information collected from a building survey was used to construct an initial building energy simulation (BES) model using the OpenStudio plug-in for Google SketchUp. Zone information and HVAC details are added to the model using the tool HVAC Generator (Raftery et al., 2012). This tool is primary an excel workbook that describes all the components within a building or zone and their associated (EnergyPlus) parameters. Once all the information has been input into the worksheet, a VBA macro outputs macro-format simulation files compatible with EnergyPlus V7.0 In Figure 4-4 it is shown how the model of the Nursing Library looks in Google SketchUp.

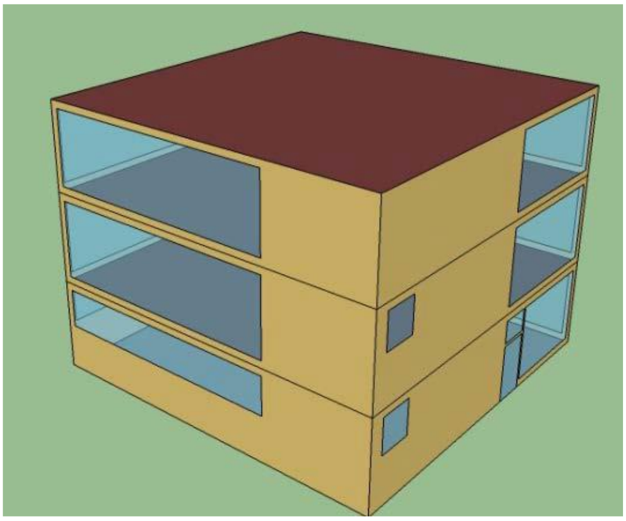


Figure 4-4. SketchUp model of the Nursing Library.

- **Iterative model improvement***:* The BES model is then iteratively updated to reflect new information collected during continuous auditing and data gathering. Each revision is tracked and linked to source information using version control software (e.g. Tortoise SVN).

- **Bounded grid search**: Each class of source evidence outlined above has an associated ranking and range of variation (ROV, %). This ROV represents the total heuristically estimated deviation from the mean value of the specified parameters.

  Using the ranges of variation shown in Table 4-3, probability density functions (PDFs) were developed, based on normal distribution $N(0, \sigma^2)$, for each of our continuous input parameters. For example, the probability density function for insulation conductivity (Figure 4-5) was calculated as follows:

$$\sigma = \frac{u * ROV}{3}$$

Where:

σ, Standard Deviation;

u, Initial Value;

ROV, Range of Variation;

Table 4-3. Hierarchy of Source Evidence.

SOURCE	CLASS	ROV (%)
BMS Data	1	0
Sensor Data	1	0
Spot-Measured Data	2	5
Physically Verified Data	2	5
As-Built Drawings	3	10
O&M Manuals	3	10
Commissioning Documents	3	10
Design Documents	4	15
Guides & Standards	5	30
Default Values	6	40
No Available Information	7	50

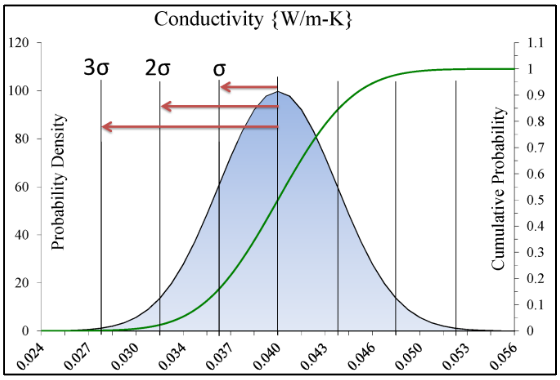


Figure 4-5. PDF for insulation conductivity value.

Using the mean values for each parameter and assigned ranges of variation, a sample input matrix is generated. This step results in the creation of a job matrix in the form:

$$M = \begin{bmatrix} z_1^{(1)} & z_2^{(1)} & \cdots & z_r^{(1)} \\ z_1^{(2)} & z_2^{(2)} & \cdots & z_r^{(2)} \\ \cdots & \cdots & \cdots & \cdots \\ z_1^{(N-1)} & z_2^{(N-1)} & \cdots & z_r^{(N-1)} \\ z_1^{(N)} & z_2^{(N)} & \cdots & z_r^{(N)} \end{bmatrix}$$

Where; z represents the input variables; N the sample size and M the corresponding vector input matrix.

The sampled job file is then processed using a batch simulation tool, jEPlus (Yi Zhang et al., 2012). Finally results are ranked according to their fit to the measured building data, according to defined Goodness-of-Fit (GOF) indices, calculated based on a combination of NMBE and CVRMSE error values (Coakley, 2013).

4.1.5.2 Black-box model and simulation: Artificial neural networks

An electricity consumption model based on a non-linear autoregressive neural network (NARX) was developed as a learning-based energy consumption model. For the neural network architecture, the multilayer perceptron (MLP) with one hidden layer was selected based on the simplicity of its application and the lower computational cost for training. Data available for training corresponds to one-year (May 2011 – April 2012) real, hourly measurement data of temperature and the whole building electrical consumption. Furthermore, in this research work, date, time and facility schedule information was also included as training data for more accurate results. These variables were normalized to avoid prevalence of one input over other due to different ranges (Prechelt, 1994). In addition, normalization helps to reduce the range in which the artificial neural network must learn thus facilitating the learning process. The normalization was made between values of 0.1 and 0.9 to avoid any absolute value (Yang et al., 2003). During normalisation, maxima/minima where incremented/decremented by 20% to account for possible values outside the training range (Coakley et al., 2012). The chosen development tool for the artificial neural network was the Encog Java Library developed by Heaton Research (Heaton, 2010). Encog uses the Resilient Backpropagation (Rprop) algorithm as the predefined and commonly faster training algorithm. The Rprop algorithm is a heuristic supervised method with several variants meant to improve the efficiency of the training.

It is well known that when training neural networks for representing energy consumption in buildings, different input variables have different impact on the predicted energy consumption of the building. Although selection of the most relevant variables is an open research area and studies propose different approaches (e.g. (Karatasou et al., 2006)), the overall process is still largely done empirically (Kalogirou, 2006). For the purposes of this work, the selected approach for input variable selection is an empirical one based on how well the network is able to learn the desired behaviour after a reduced number of training iterations for each possible set of inputs. Figure 4-6 illustrates the whole process for training the ANN.

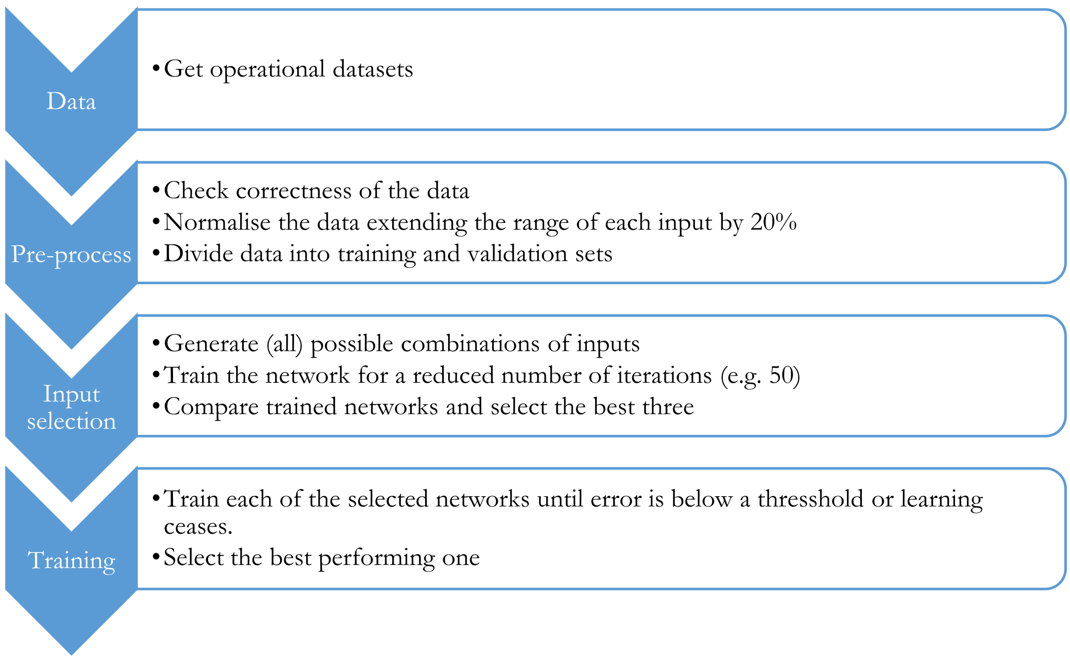


Figure 4-6. ANN training flow chart.

4.1.5.3 Grey-box model and simulation: ANN + EnergyPlus

The proposed grey-box model integrates a traditional engineering simulation model in EnergyPlus with an artificial neural network to adjust the results outputted by EnergyPlus to match actual measured data. First, a building energy model is constructed using information available from the facility such as drawings, materials, schedules, installed systems, etc., to provide a first approximation to building energy consumption. The energy estimation of the building energy model will differ from real measurements for a variety of reasons such as inaccuracies in materials and geometry data, modeller assumptions when data is missing for some model parameter, age of the building, etc. In addressing all of the above issues a large amount of time and personnel resources are required to provide fully calibrated model. However, if real operation data is available, it is still possible to provide a good accuracy if this real operation data is used to train a neural network to bridge the gap between simulation outputs and real data. This process is presented in the flow chart in Figure 4-7.

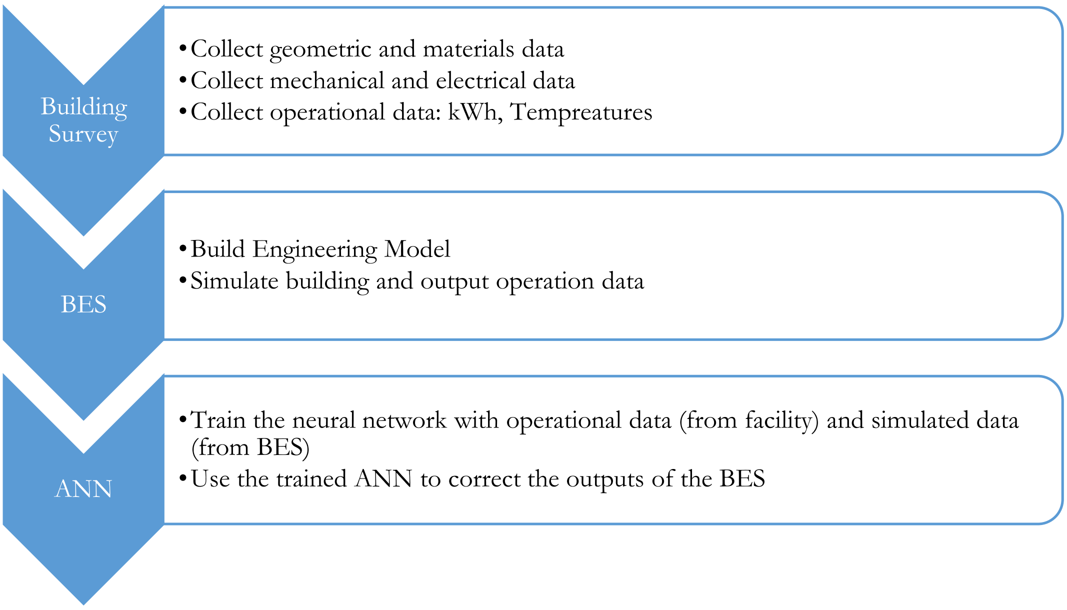


Figure 4-7. Grey model flow chart.

Note that the training of the neural network is similar to the implementation of the pure ANN model; the main difference is the adding of an input corresponding to the output of the EnergyPlus model.

4.1.5.4 Black-box energy prediction model

Prediction of performance is a form simulation where artificial intelligence techniques have shown great potential. In particular prediction of energy consumption is of fundamental importance for the future application of energy management strategies able to fully leverage the potential of energy production and storage. In fact only through a reliable knowledge of what will be the upcoming energy behaviour of a building it will be possible to make effective decisions on the approach for producing, storing, selling and buying energy (electric and thermal). This section aims at showing how a specific learning-based approach has been developed to perform real-time predictions of energy consumptions in buildings.

Two electricity consumption predictors, one hour ahead and 24 hours ahead, based on a non-linear autoregressive neural network (NARX) were developed as a learning-based predictive energy use model. For the neural network architecture the multilayer perceptron (MLP) with one hidden layer was selected based on the simplicity of its application, the lower computational cost for training and the satisfactory accuracy of its results.

Delayed values of the inputs are also provided to the network giving the ANN the necessary "memory" capability for effectively recognising sequences when dealing with time series data and produce a predicted output based on present and past inputs.

The process for developing the models is the same as shown in section 4.1.5.2 and results are presented in section 4.1.6.

4.1.6 Results

For the purposes of this section, whole-building electrical consumption estimation is used compare and analyse the advantages and disadvantages of different methodologies for simulating energy consumption in a building. Accuracy is measured using metrics suggested in literature (ASHRAE, 2002); the coefficient of variation of the root mean square error (CVRMSE) and the normalised mean bias error (NMBE) as follows in equations 1 and 2 respectively:

$$\text{CVRMSE}\ (\%) = \frac{\sqrt{\sum_{i=1}^{n}\left(y_{pred,i} - y_{data,i}\right)^2 \Big/ (n-p-1)}}{\overline{y_{data}}} \times 100 \tag{1}$$

$$\text{NMBE}\ (\%) = \frac{\sum_{i=1}^{n}\left(y_{pred,i} - y_{data,i}\right)}{(n-p)\cdot \overline{y_{data}}} \times 100 \tag{2}$$

Where, n is the number of data points, p is the number of predictor variables (only one in this case study), $y_{pred,i}$ is the predicted output for input *i* and $y_{data,i}$ is the real measurement for point *i*, and $\overline{y_{data}}$ represents the average.

Indicative values for these metrics are given in (ASHRAE, 2002) suggesting that a calibrated computer simulation model should be accurate to within 10% for the NMBE and 30% for CVRMSE relative to hourly measured data. While the NMBE gives a measure as per how much the model outputs will deviate, on average, from the expected values; the CVRMSE measures how much the model outputs can deviate from expected values at any given time.

4.1.6.1 Engineering model and simulation: EnergyPlus

Results of the CVRMSE and NMBE parameters obtained for this model are shown in Table 4-4. Figure 4-8 shows for comparison one week of output of the model against the measured values of electrical consumption.

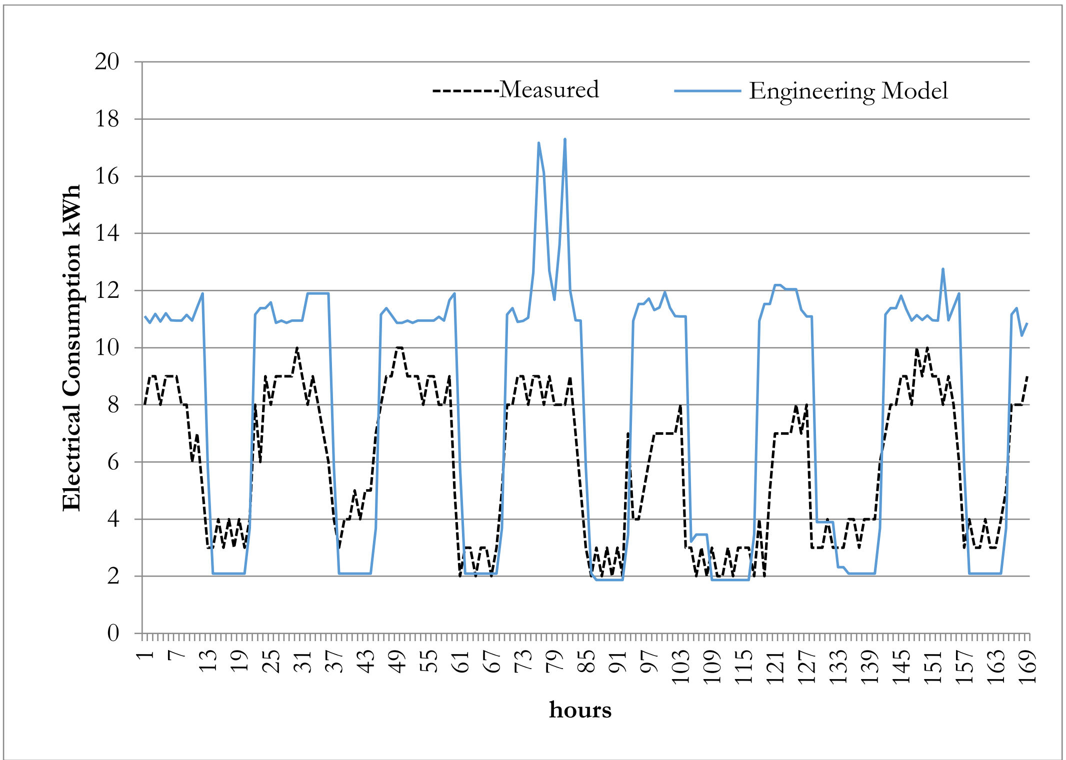


Figure 4-8. One week measured (ideal) whole-building electrical consumption vs. engineering model output.

In Figure 4-8, it can be seen how the model can predict the lower electrical consumption while it is unable to give an accurate prediction when consumption is high (e.g. during occupied hours).

4.1.6.2 Black-box model: Artificial neural networks

Best results of CVRMSE and NMBE obtained for this model are presented in Table 4-4. Figure 4-9 shows for comparison one week output of the model against the measured values of electrical consumption.

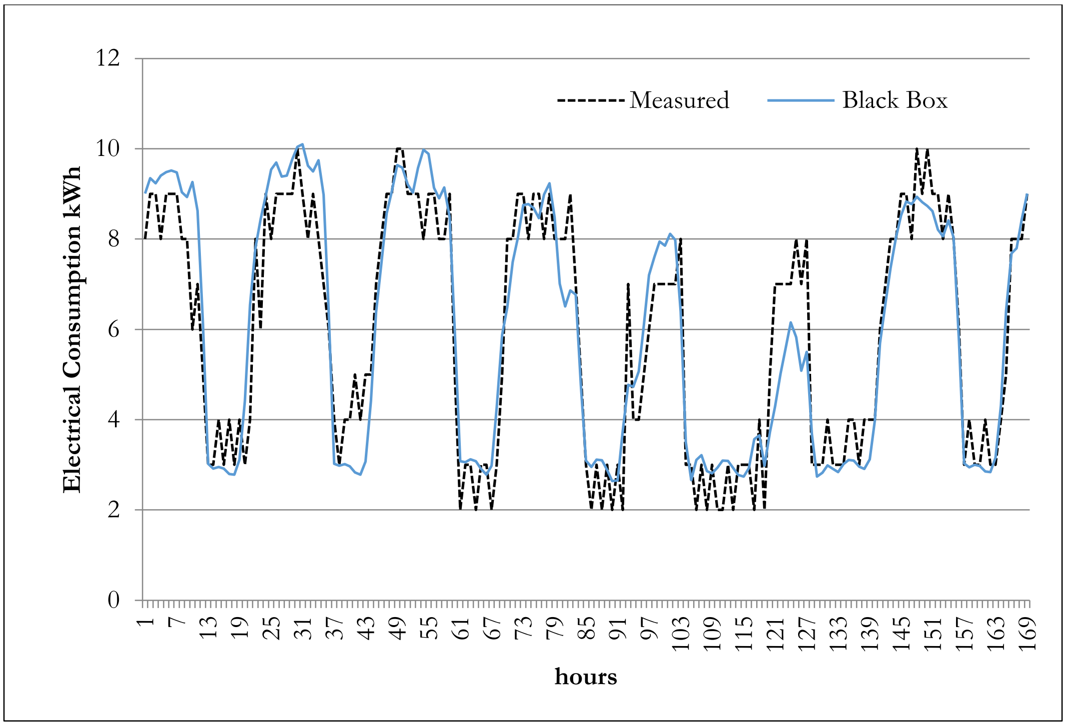


Figure 4-9. One week measured (ideal) whole-building electrical consumption vs. black-box model output.-

As expected, the result form the black-box model (Figure 4-9) accurately represents the energy consumption in the building.

4.1.6.3 Correction of EnergyPlus non-calibrated model residual error by means of ANN

Another way to tackle the accuracy issues of the engineering models in a timely manner is to exploit as much as possible the advantages of two modelling methodologies, engineering and black-box, and combine them in a grey-box model. This model will still have at the core an engineering EnergyPlus model but the errors between the EnergyPlus model and the measured data corrected using an artificial neural network. In this way relevant information can still be extracted from the EnergyPlus model (e.g. qualitative information as per effect of refurbishments and changes in schedules) and energy consumption results are accurate thanks to the neural network correction. The engineering EnergyPlus model used is the same presented before and the artificial neural network has structure and pre-processing of the data similar to the one explained for the black-box model but instead of learning the measured electrical consumption of the building it learns the difference between that and the output from the EnergyPlus model. The use of the EnergyPlus model has the advantage of providing an already pre-calibrated model (it includes correct dimensions and materials) which reduces the training effort for the neural network and allows for a dual use of the model: energy consumption prediction and test-bed for qualitative analysis prior retrofitting.

As with the black-box model a different ANN with different combination of inputs were trained. Best results of CVRMSE and NMBE obtained for this model are presented on Table 4-4. Figure 4-10 shows for comparison one week output of the model against the measured values of electrical consumption.

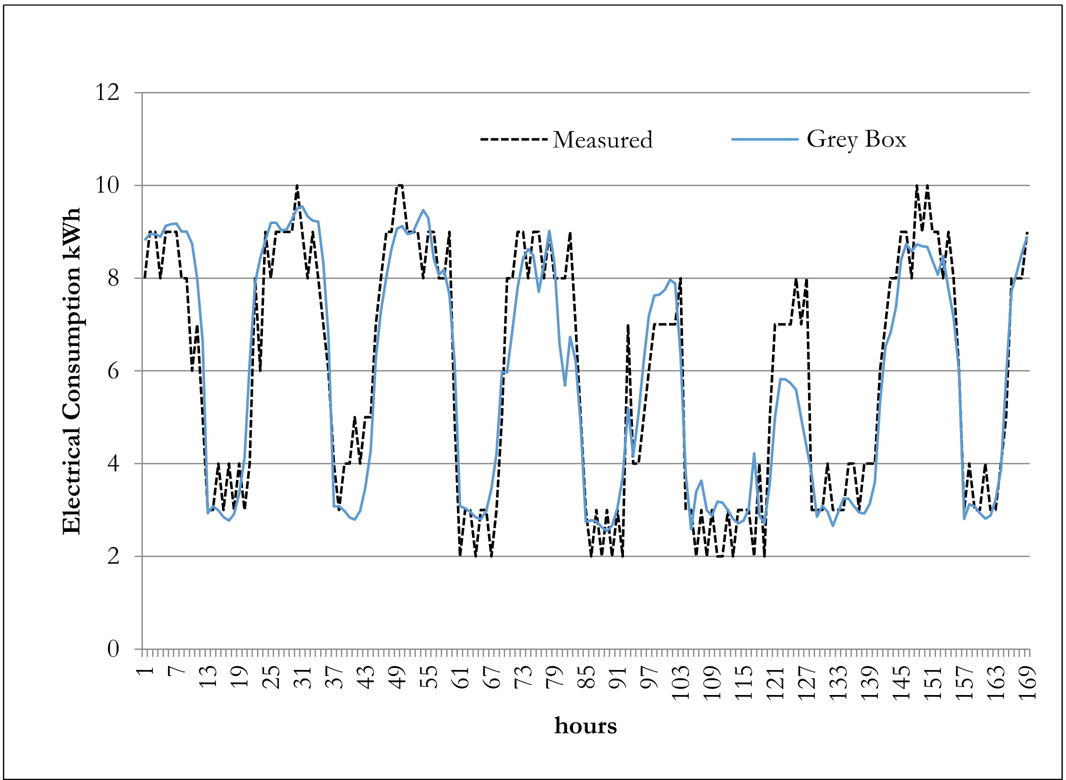


Figure 4-10. One week measured whole-building electrical consumption vs. grey-box model output.

When compared with Figure 4-8, it can be seen in Figure 4-10 that the artificial neural network is capable of correcting the deviation in the original model thus providing a much more accurate estimate of the electrical consumption.

Table 4-4 CVRMSE and NMBE for different simulation models.

Modelling Type	Modelling Tool	Calibration Effort	CV-RMSE	NMBE
Engineering Modelling	Energy Plus	High	58.89	29.30
Black-box	Encog AI library	Low	18.43	0.17
Grey-box	EnergyPlus + Encog AI Library	Medium	18.77	0.13

4.1.6.4 Black-box energy prediction model

Initial development and validation of the energy prediction model was done using the PROBEN1: A set of Neural Network Benchmark Problems and Benchmarking Rules (Prechelt, 1994). PROBEN1 provides real, hourly measured data for a commercial building over a period of six months. For the purpose of comparison with other models found in literature the database was split in two parts, one corresponding to the first four months that is used for training and the second comprising the last two months used for validation purposes.

The information contained in PROBEN1/building is the following: month, day, year, hour, outdoor temperature, outdoor humidity, solar radiation, wind speed, whole building energy consumption, whole building cool water consumption load and whole building hot water consumption, electrical consumption, cold water consumption and hot water consumption.

The following variables and considerations were used to train the ANN:

- Electrical Consumption
- Week/Weekend flag; (only relevant date information)
- Temperature
- sin(2.π.hour/24); (often used in literature)
- cos(2.π.hour/24); (often used in literature)

Results were compared with those of the ANN competition "The Great energy Predictor Shootout" organized by ASHRAE during the 1990s from which the PROBEN1 database evolved and became a benchmark problem for testing ANN algorithms. Results were evaluated using the same metrics (performance indicators) listed above which are those from the competition: coefficient of variation of the root-mean-square error and the mean bias error in case of a tie. The results of the competition, the predictor, and a recent publication found in the literature are shown in Table 4-5.

The prediction is not perfect but is placed (from many entries) near the top of the field from the competition. Factors affecting accuracy:

- The amount of data for training is 4 months;
- The training period is September-December and the predictions are made during January-February and no seasonal correction factor is applied.

Table 4-5. Consumption prediction comparison of authors. Modified from (González & Zamarreño, 2005).

Author	**CV-RMSE**	**MBE**	**Comments**
(González & Zamarreño, 2005)	1.4423	0.0033	Feed-back neural network
This case study's predictor 1	2.8554	0.6954	25 neurons hidden layer 10 time step delay Resilient Backpropagation training algorithm
Proben1 1º Place	2.9032	-0.0907	25 neurons 2 hidden layers No delay
Proben1 2º Place	3.1205	0.2722	Non-lineal Bayesian regression training algorithm
This case study's predictor 2	5.7240	0.4811	8 neurons in hidden layer 1 time step delay Resilient Backpropagation training algorithm
Proben1 3º Place	8.6475	-6.5550	Regression models
Proben1 4º Place	13.212	-1.805	Auto associative feed forward neural network.

After benchmarking the prediction technique using PROBEN1 data, the procedure was applied to pilot data from the Energy Warden FP7 project (Kouveletsou et al., 2012). Data comprised 1 year hourly energy consumption measurements. Two predictors were developed, one for one-hour ahead and one for 24-hour ahead predictions.

Table 4-6 shows the average results that were achieved with the different configurations of the neural network and window's size. In order to have statistical relevance of the results, each network configuration was trained 10 different times with different initialization values. Training time was calculated in a computer with the following specifications: an Intel Core i5 processor at 2.67GHz with 8GB of RAM memory and under Windows 7 x64 OS.

Table 4-6. One hour prediction results.

Neurons in hidden layer	**Past window size (hours)**	**Training MSE (%)**	**Validation RMSE (%)**	**Validation CV**	**Validation MBE**	**Training time**
1	1	0.0174	1.4854	2.5268	-0.8131	< 5 s
1	5	0.0125	1.3595	2.3122	-0.9193	< 15 s
5	1	0.0170	1.4434	2.4554	-0.8188	< 10 s
5	**5**	**0.0107**	**1.2137**	**2.0642**	**-0.8406**	**< 20 s**
5	10	0.0118	1.2943	2.2008	-0.9036	< 30 s
10	10	0.0109	1.2520	2.1288	-0.8215	~ 30 s

A 24 hours predictor was also developed and training results for different configurations of the network can be seen on Table 4-7.

Table 4-7. 24 hours prediction results.

Neurons in hidden layer	**Past window size (hours)**	**Training MSE (%)**	**Validation CV**	**Validation MBE**	**Validation RMSE (%)**	**Training time**
1	1	0.3046	5.3285	9.0612	-3.6460	< 15 s
1	5	0.2933	5.4461	9.2591	-4.1274	< 25 s
5	10	0.1632	4.5791	7.7830	-2.6046	< 90 s
5	**24**	**0.1456**	**4.2104**	**7.1516**	**-1.6230**	**< 150 s**
10	24	0.1280	4.3833	7.4453	-1.6906	< 205 s

Depending on the accuracy needed and the computational capabilities available for the implementation, different solutions with different levels of complexity and accuracies can be studied and applied. Also it was noticed that there is a trade-off between accuracy and complexity of the network since not necessarily complex networks produce better results as highlighted in the tables above.

4.1.7 Technical discussion

4.1.7.1 Accuracy

After performing the experiments and comparing with previous research work carried out, it was noticed how the accuracy of the black-box and grey-box models is highly dependent on the accuracy of the real measured data. In this research work the whole building electrical consumption measurement for the Nursing Library was unitary (resolution of 1kWh) with values ranging from 0 kWh to 13 kWh. This low resolution poses a difficulty to the learning of the artificial neural network since the low granularity produces several combination of input values to have the same output value. Higher consumption values and/or a more accurate measurements shall improve the artificial neural network training results as shown by the results presented by the energy predictor using PROBEN1 data and Energy Warden Data. Evolving the BMS to an age 3 BMS, at least on the aspects relating to data, would provide the necessary resolution for improving the accuracy of the black- and grey-box implementations.

It was noticed that outside temperature, although commonly used for this type of artificial neural network models, has little effect on the building electrical consumption for the particular case of the nursing library, this can be explained by the fact that electrical energy is mainly used for illumination and plugs and very little is used for air conditioning being the Nursing Library a naturally ventilated building.

Results presented in Table 4-4, show how black and grey-box models can greatly improve over engineering methods with a considerable less effort. They have also the advantage of being able to consider and adapt itself to stochastic variables such as occupancy and aging of the building simply by retraining the neural network with the latest data. Furthermore, in the case of grey-box models, as long as the changes to the building are reflected in the model (e.g. materials, geometry, etc.) and the tendency of the error between the model and measured data remains constant, the overall grey-box model is still valid without need for retraining. If such changes in the physical building are not reflected in the engineering model, a need for recalibration of the artificial neural network would arise. If non-physical changes such as zone use or set points occur in the building, there would also be a need for retraining.

An interesting result from this research work is the similarity between the accuracies of the grey-box and black-box models which leads to having two different approaches for modelling to choose from according with the necessities. For very fast development and where little extra information apart from the one being used for training is needed the black-box models are recommended. On the other hand, grey-box models are still rich in information and may become useful for many applications like decision support systems.

On the prediction side, although the one-hour predictor is much more accurate than the 24-hours one, the use of 24 one-hour predictors should not be used to obtain a 24-hours prediction since errors in the first will accumulate with each iteration and the results might prove to be less accurate that the 24-hours predictor itself.

4.1.7.2 Applicability

In terms of applicability, the engineering models have a clear advantage since they can cover a broader range of stages in the building's life-cycle. Engineering models can be used in both the design phase and the operation phase. Black and grey-box models are more suited to the operational phase where data is already available for training the models. In order to use artificial neural networks during the design phase, data from many other buildings in similar conditions would be needed to be able to perform accurate training of the network. The use of the engineering models within the grey-box implementation has the advantage of providing a pre-calibrated model that not only reduces the training effort of the neural network but also serves as a test-bed for qualitative analysis of further energy conservation measures.

4.1.7.3 Data requirements

This is an important aspect of the modelling and simulation area to be studied. It is actually one open question in the artificial intelligence community. The amount of data needed for training and calibration purposes is established in a case-to-case basis since it is dependent on factors normally outside the control of the modeller (e.g. quality of the data, building's usage patterns, weather conditions, etc.). In general, black-box models would require less data to calibrate as they can be programmed to continuously retrain themselves with new data. However, they are also more purpose focused and less generic (e.g. energy consumption). Engineering models cover a broader range of the building's aspects but detailed calibration to measured data is very difficult due to the over-specified and under-determined nature of the problem. Grey-box models merge the advantages of both, they retain a good degree of generalisation but they can be more easily calibrated to represent one aspect of interest. It is even possible to incorporate several artificial neural networks in the engineering model, each neural network adjusting the engineering model to a different building aspect. Furthermore, the possibility of automatic retraining and recalibration as new data is made available, is one advantage shared by the black and grey-box over the engineering models.

The minimum data set for considering the models fully applicable to the building, needs to cover the full range of seasonal changes for that building (e.g. one year in places with four distinguished seasons). The optimal amount of operational data would be three data sets (training, validation and testing) covering the full range of seasonal changes as this would allow for more averaged conditions. This minimum data set must also represent complete and reliable data and therefore, appropriate measures must be taken to ensure data quality.

In order to provide a good balance between the size of the training database, the accuracy and the training times, the implementation of the continuous learning algorithm is such that it will keep the size of the training database constant by implementing a sliding window of training. This means the neural network will always be trained with the most recent data up to a predefined time in the past. The sliding window includes the most recent data in the database while discarding the oldest.

4.1.8 Section summary

In this section a case study showing the SAB characteristic "*Predicts, keeps track and monitors building's performance*" was presented for the prediction of the energy consumption of a naturally ventilated building in NUI Galway campus. Different modelling and simulation techniques were studied to show advantages and disadvantages of each one and to demonstrate the independence the SAB characteristic has from tool choice. It was obvious how traditional engineering methods have the main disadvantage of requiring a large effort to reduce the gap between simulated and measured energy consumption due to the large amount of assumptions made during modelling. On the other hand, methods based on artificial intelligence by their very nature are much more accurate once trained but lack the capacity to represent different scenarios (e.g. change of materials, change of schedules). The combination of both techniques provides a KET that, while being easily calibrated, can be used for more than energy prediction under similar conditions.

Finally, by using artificial intelligence “memory” is added to the system as a bridging capacity whereby the building manager no longer needs to remember past building behaviour to predict future behaviour but instead such knowledge is already incorporated in the system.

4.2 AGE 2 BMS: CONTROLS AND ADAPTS BUILDING'S ACTIONS TO THE MONITORED/PREDICTED PERFORMANCE

This section presents a case study focussed on the SAB characteristic: "*Controls and adapts building's actions to the monitored/predicted performance*". It can be seen as a step forward from section 4.1 where some action is taken based on the simulated, monitored or predicted performance. In this regard, BMS with ICT systems falling in age 2 provide the necessary data and capabilities to accomplish this SAB characteristic in a basic form, that of basic schedule control. For predictive control and more advanced techniques, a BMS with ICT at least in age 3 is needed since direct modification of controlled variables is needed. The methodology and results presented in this section have been published in (Sterling et al., 2012b).

4.2.1 The facility

Within the building sector, up to 10% of the overall energy consumption is corresponds to sport and leisure facilities, as shown in Figure 4-11 (ENERinTOWN Project Consortium, 2008), where a dynamic adjustment of the operational behaviour of the HVAC systems serving these facilities is expected to result in significant energy savings (SportE2 Project Consortium, 2011). Swimming pools in particular are large energy consumers and controlling air temperature and humidity to minimise evaporation is an important energy savings strategy.

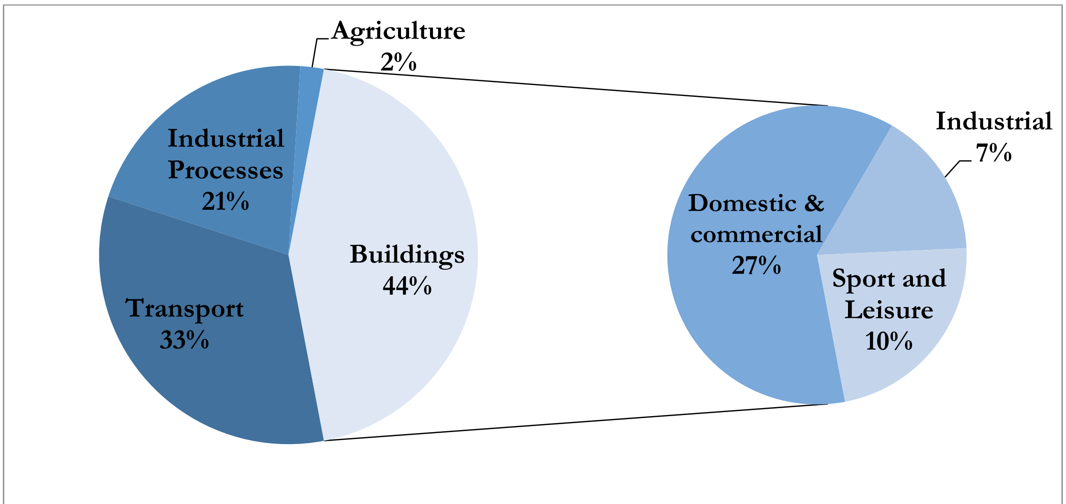


Figure 4-11. Share of EU energy consumption. Source: (European Commission, 2010).

The case study used for this research corresponds to the swimming pool hall of the sport facility located at the National University of Ireland, Galway (NUIG) which is owned by the university and run by a private company specialising in sport facilities management (Kingfisher Club Ltd.). The swimming pool hall has a floor plan area of 700 m^2 with a 25 m swimming pool maintained at 29ºC. This is served by two identical Air Handling Units (AHUs) which maintain a constant air temperature of 30ºC in the swimming pool hall. Each AHU consists of supply and return fan (6.6 m^3/s), water-to-air heat exchanger frost coil of 73 kW (preHC), an air-to-air cross flow without mixing heat recovery unit (HX) and a water-to-air heat exchanger heating coil of 250 kW (HC).

Figure 4-12 depicts the swimming pool facility and a Google SketchUp model of the swimming pool environment.

Figure 4-12. Swimming pool hall picture and model.

Figure 4-13 provides a schematic of these systems. The sport centre is open daily with week/weekend schedule and its occupancy is constantly monitored through the use of an access control.

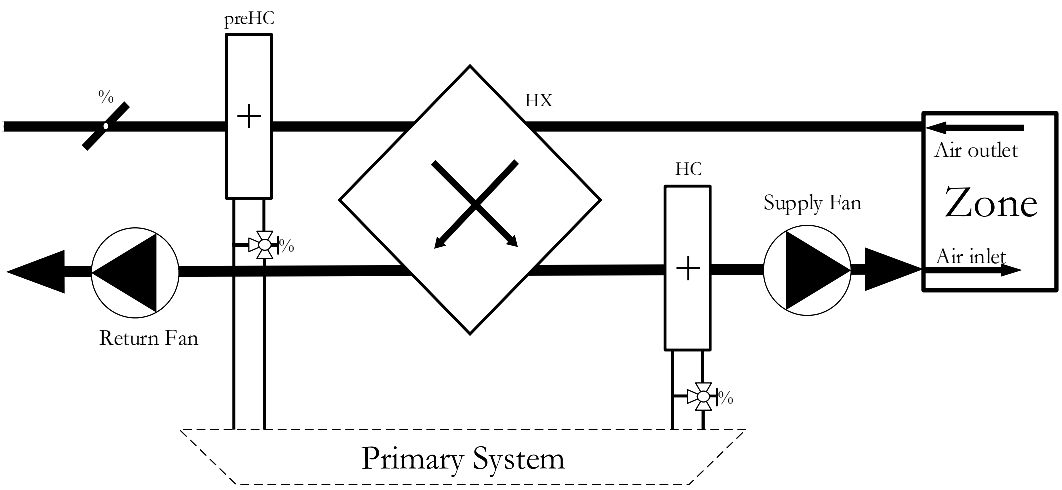


Figure 4-13. Air Handling Unit schematic.

4.2.2 BMS SWOT

The BMS at the Kingfisher Sport Club at the National University of Ireland, Galway is based on Cylon Building Management System with UnitronUC32 controllers. The BMS comprises an onsite PC with the BMS graphical user interface and OPC server for modifying and visualising set points, systems status and short-term logging of monitored variables. Data for Figure 4-14 was gathered from Operation and Maintenance Manuals of the Kingfisher Sport Club and on-site visits.

Table 4-8 replicates Table 4-1 highlighting the age 2 for BMS and the KET used for or this case study. According to the table, two SAB characteristics can be carried out. For this case study it was decided to exploit the characteristic related to controlling and adapting building's actions to the monitored/predicted performance. The reason for this choice lies in the fact that this is a highly controlled indoor swimming pool environment where users have little impact on performance and scheduling of energy services such as air handling units, water heating, etc. Thus, it becomes a high-impact measure. For the studied SAB characteristic, the main technical developments are those provided by automating a variable schedule. In this regard, the rest of the section discusses different approaches for such automated scheduling.

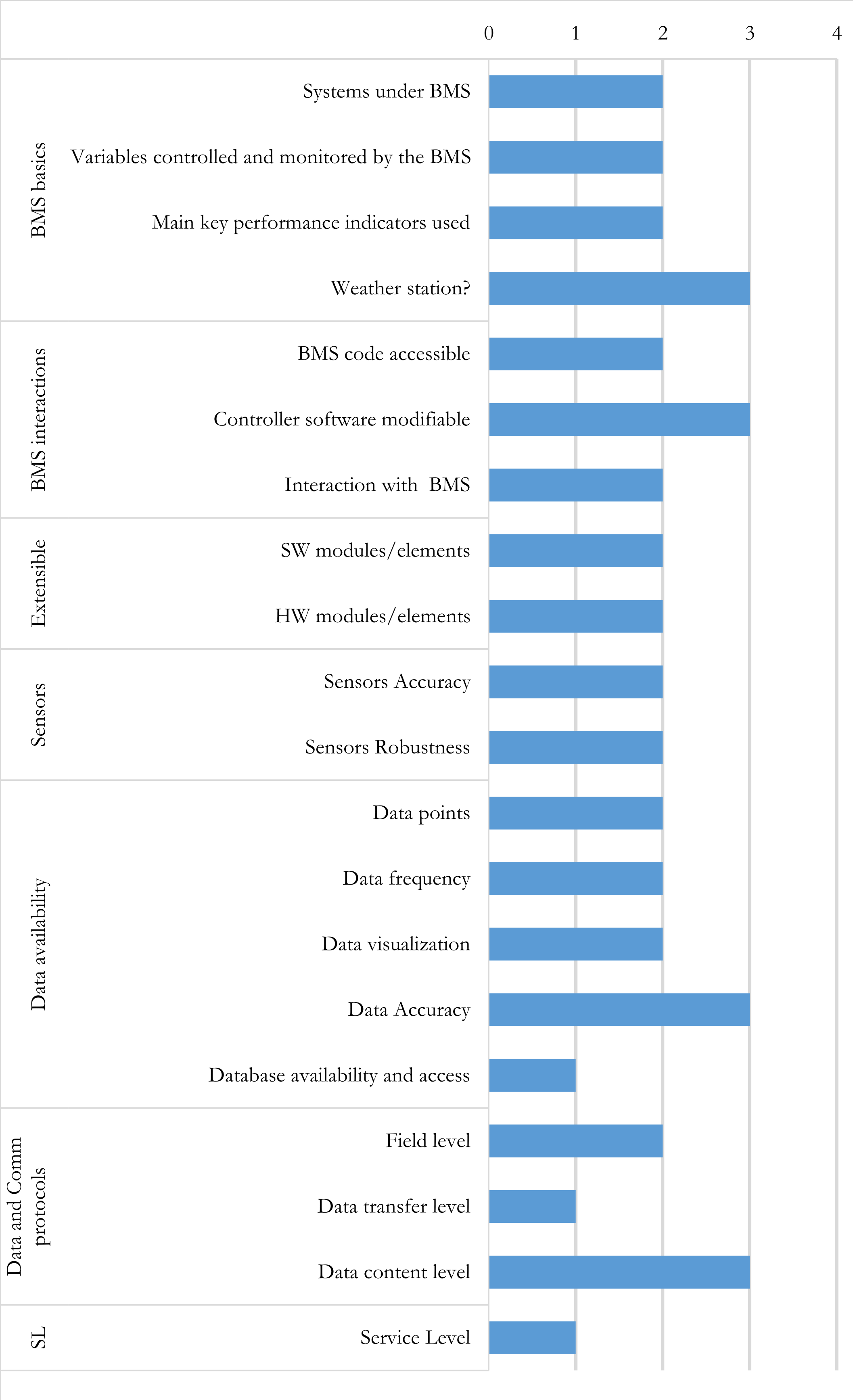


Figure 4-14. Strengths and weaknesses of BMS at the Kingfisher Club Gym.

Table 4-8. BMS age vs. modelling and SAB characteristic selected for the case study of the Kingfisher Sports Centre at NUI Galway.

Age	**1**	**2**	**3**	**4**
SAB Characteristics	None	Predicts, keeps track and monitors building's performance. **Controls and adapts building's actions to the monitored/predicted performance.**	Diagnoses root causes of building's performance reductions.	Supports building managers by providing information about building's operations in a way that matches their typical skill set.
What can be done?	Manual fault detection	Automated fault detection manual diagnosis	Automated fault detection and diagnosis	Automated fault detection, diagnosis and prognosis. Decision support systems
FDD&P Methodology Suggested	Limits and alarms	Statistical analysis, APAR rules, expert systems	Model based diagnosis, machine learning	Integration with BIM, ISO 50001 and alike standards
Modelling suggested	Expert knowledge	**First principles, simplified physics, black box**	First principles, detailed physics, black box, grey box	Same as age 3

4.2.3 Approach

Modelling and simulation of a swimming pool environment is a complex task due to the strong coupling between water, air temperature and relative humidity. Simulation tools that approach swimming pools are scarce and many of them have limitations. TRNSYS simulation software includes models for swimming pools (Auer, 1996). Ribeiro et al. (Ribeiro et al., 2011) describe a procedure to model swimming pools in ESP-r. However, both approaches are bounded by the inherent assumptions of each tool (ESP-r and TRNSYS). Traditionally, energy simulation tools provide accurate solutions for part of the building (e.g. building geometry) while making significant assumptions on other areas (e.g. HVAC controls). To address this problem, a 'divide and conquer' approach was taken whereby the modelling was divided in different tools to exploit the advantages of each one individually and then combined in a co-simulation tool named Building Controls Virtual Test Bed (BCVTB) (Lawrence Berkeley National Laboratory, 2011). Matlab/Simulink was used for simulation of time dynamics of both the, water and air handling side of a swimming pool hall's HVAC, while the hall's zone model (building envelope, materials, internal loads and weather) was developed and simulated using EnergyPlus. Energy flows between the pool water and the hall air were implemented inside the BCVTB. Both, Matlab/Simulink and EnergyPlus are simulation tools widely used in industry and academia for modelling and simulation of complex systems and energy flows in buildings respectively. Automated scheduling is performed by a prediction of the optimal starting time for the systems in order to reach comfort conditions at opening times (End of Set-Back). Prediction is one of the main applications of artificial neural networks in energy efficiency in buildings and in particular, the work carried out by Yang (Yang et al., 2003), provides a basis for the application of neural networks to predict optimal End of Setback (EoS) of a HVAC system.

The coupled model in BCVTB is used to provide data for training an ANN scheduler. Once trained, the scheduler decides the best time for starting the AHU to ensure the appropriate indoor conditions are met at opening time.

In this collaborative work, zone models were developed by Dr. Andrea Costa (senior researcher IRUSE group) while the rest of the work was fully developed by the author of this thesis.

4.2.3.1 AHU first principle models

As can be deduced from the description of the AHUs, there are three components that are used to control the temperature of the air. As such, the AHUs can be modelled as three heat exchangers in series with the first and last heat exchangers corresponding to water-to-air frost coil and heating coil and the middle one to an air-to-air heat recovery coil. For the purposes of this work, filters, fans and duct-work effects on the air temperature are not considered. Filters have little effect over temperature changes in the air. Effects of duct-work on temperature should be considered for systems with a long network of ducts which is not the case for the presented case study and fans present a predictable temperature raise that is outside the scope of this research work.

Underwood (Underwood, 1990) presented a set of ordinary differential equations (ODE) for the reduced order modelling of the heat transfer between the hot and cold fluid in a heating coil. Assuming that no condensation occurs in the heat exchangers since, for the purposes of this work, the operation mode considered is such that only sensible load is added to the air, the equations that represent the system are:

$$\dot{m}_{hf}(t) \cdot C_{phf} \cdot [T_{hfi}(t) - T_{hfo}(t)] + \ UA \cdot [T_{cfi}(t) - \overline{T_{hf}}(t)] = C_{hf} \cdot \frac{dT_{hfo}(t)}{dt} \tag{1}$$

$$\dot{m}_{cf}(t) \cdot C_{pcf} \cdot [T_{cfi}(t) - T_{cfo}(t)] + UA \cdot [\overline{T_{hf}}(t) - T_{cfi}(t)] = C_{cf} \cdot \frac{dT_{cfo}(t)}{dt} \tag{2}$$

In the above, equation (1) represents the heat transfer for the hot fluid and equation (2) for the cold fluid.

A proper implementation of the model requires the calculation of the parameters UA, C_{hf} and C_{cf}. These parameters are dependent on the geometrical and physical characteristics of the coil and fluids. In this study, the calculation of UA at the operation point was done using the ε-NTU method (ASHRAE 2009). Once the base calculation was done, the UA parameter was programmed to be automatically updated at every time step based on methodology presented in (Wetter, 1999). The calculation of C_{hf} and C_{cf} is done following the methodology suggested by Sørensen (Sørensen & Novakovic, 1995) where the calculation follows equation (3)

$$C_{xf} = m_c \cdot C_{pc} + m_x \cdot C_{pxf} \tag{3}$$

Equations and calculation steps to update parameters of the heat exchangers at every time-step were developed using Matlab/Simulink. In particular, a user interface was designed so that the actual user would only need to input a set of design data from the heat exchanger such as duty, fluids flow rates, fluids temperature, type of heat exchanger (counter flow, cross flow, etc.) specific heat of the fluids, coil material specific heat and coil weight.

4.2.3.2 Swimming pool loads calculation

The key point in calculating the load added to the zone by the swimming pool is to be able to split the load calculation into the sensible and latent components. The evaporation related latent load of the pool and the AHU are being modelled outside of EnergyPlus. The water evaporation calculation is carried out in the BCVTB and the

AHU model is divided between Matlab/Simulink and the BCVTB. The resulting loads are then added into the zone model developed in EnergyPlus.

Based on the previous work (Costa et al., 2011), the heat exchange between the water in the pool and the air in the hall is modelled by the means of the calculation of the sensible and latent loads respectively. Sensible load has been modelled as a surface at the constant water temperature. Latent load is calculated using the following equation:

$$\dot{Q}_l = \dot{m}_{water} \cdot L_{evap} \cdot A_{pool} \tag{4}$$

In equation (4) the water evaporation rate is calculated as a function of the water temperature, air temperature and relative humidity, area of the pool and pool type. The calculation uses the analytical formulas published in (ASHRAE, 2007) on its section dedicated to natatoriums and applying the necessary corrective factors in agreement with the type of activity performed in the pool. The water latent heat of vaporization is calculated using Watson's equation (Vidal, 2003) that accounts only for water temperature and other physical properties of the water; since the water temperature is assumed constant, the water latent heat of vaporization is also a constant.

4.2.3.3 AHU loads calculation

The AHU is modelled to control the supply air temperature in order to maintain air temperature in the zone close to the heating set point in the zone. The AHU model in Matlab Simulink calculates the supply air temperature into the zone. Given the supply air temperature (from Matlab/Simulink Model), the return air temperature and humidity ratio from the zone (from the Energy Plus model) and the outdoor air humidity ratio (given by the weather file used in EnergyPlus), it is possible (in the BCVTB) to determine specific enthalpy (ASHRAE, 2009) and the difference between return air and supply air. The enthalpy difference (h_2-h_1) together with the mass flow rate of the AHU determines both the resulting sensible (h_0-h_1) and latent (h_2-h_0) load associated with the AHU effect on the zone air conditions (temperature and humidity)(Figure 4-15).

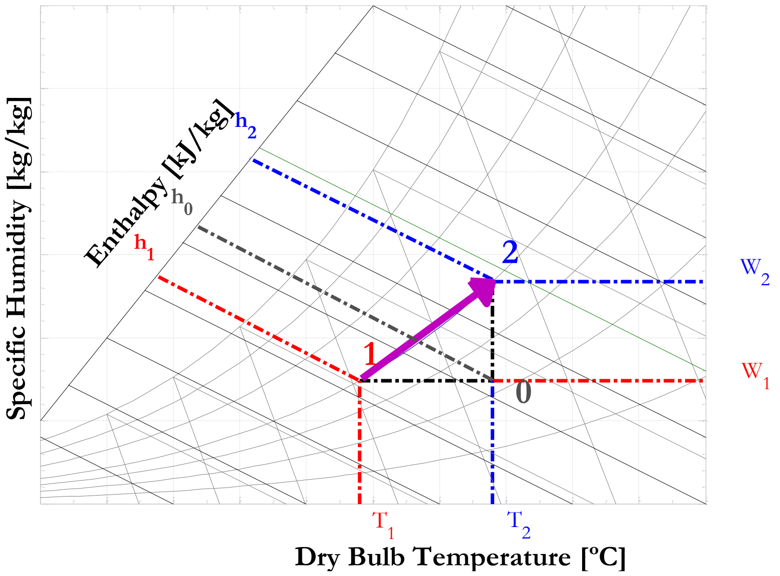


Figure 4-15. Simplified psychrometric chart.

4.2.3.4 BCVTB integration

The HVAC model developed in Matlab/Simulink was integrated with the swimming pool hall model developed in EnergyPlus by the means of the BCVTB which provides basic information as set-points, schedule of the facility for the night set-back, etc. The BCVTB serves as bridge for the data flow between EnergyPlus and Matlab. HVAC model and control were developed in Simulink and an interface between the BCVTB and Simulink was developed in Matlab as explained in (Sterling, et al. 2012), to overcome issues arising in the Simulink solver due to the necessity of using a fixed time-step imposed by the BCVTB. Figure 4-17 shows the data flow diagram of the BCVTB integration showing the variables that are interchanged between the different programs. As explained in a previous section, the calculation of the latent and sensible loads due to the energy exchange between the water in the swimming pool and the air in the hall are done within the BCVTB. Also within the BCVTB the heat exchange between the supply air coming from both AHUs and the swimming pool hall air is split into sensible and latent before being sent as input to EnergyPlus Figure 4-16. An operational scheduler was developed using the internal BCVTB tools to allow for rapid developing and testing of different operation scenarios.

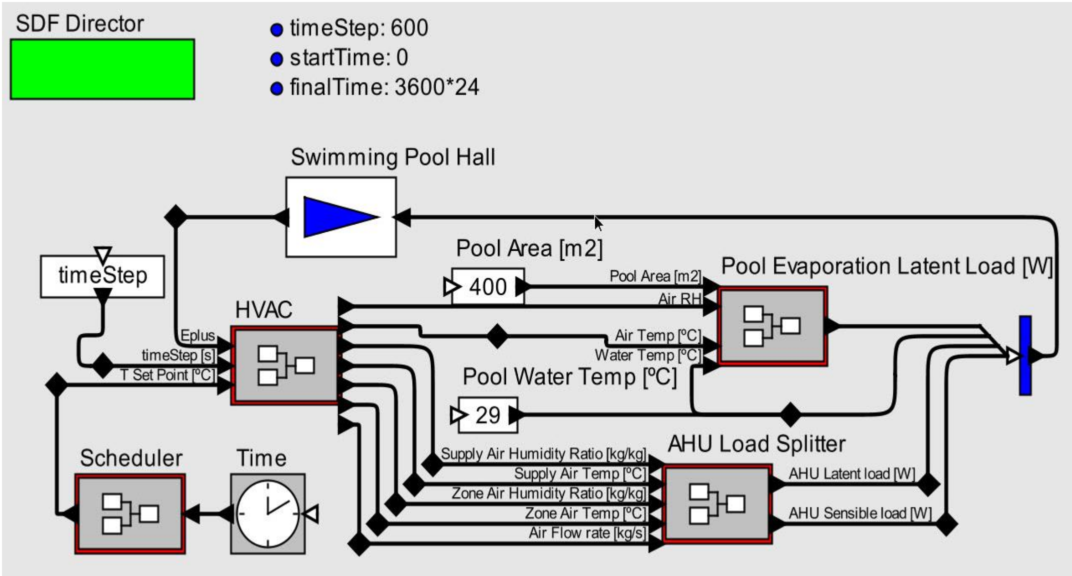


Figure 4-16. BCVTB screenshot.

The BCVTB acts as a central hub of communications between the programs providing a framework for the exchange of variables between the different models. In particular it synchronizes the bi-directional data flow between Matlab and EnergyPlus while adding the latent and sensible load values to the data exchange.

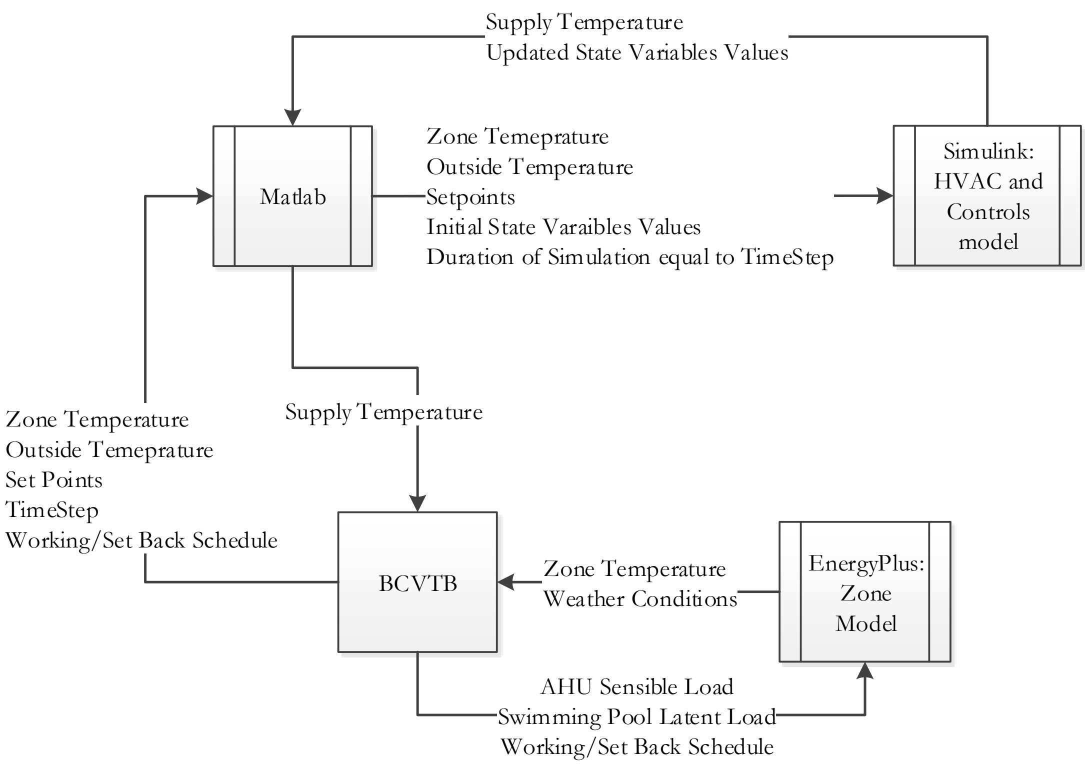


Figure 4-17. BCVTB operation data flow.

4.2.4 Results

4.2.4.1 BCVTB set-up

On Figure 4-16, it is shown the integration in the BCVTB environment where the four main actors can be clearly identified. The "HVAC" actor contains all the necessary information to run the Matlab/Simulink simulation, the "Scheduler" actor allows dynamic modification of the set points depending on the time and the type of day (week, weekend). The "Pool Evaporation Latent Load [W]" actor calculates the latent load due to evaporation of the water from the swimming pool. The "AHU Load Splitter" returns the separated latent and sensible loads due to the supply air. Finally the "Swimming Pool Hall" is the actor in charge of running the EnergyPlus simulation consisting of the hall's zone model.

In this research work, the main objective with the use of the BCVTB is the possibility to model and test different operational scenarios for energy efficiency in existing buildings with a focus on sport facilities. The idea is to provide a framework for rapid modelling of the facility and reliable results of different operational scenarios. The operational scenario tested was that of the set-back operation during non-occupied hours of the facility. This is common practice for energy efficiency and previous studies performed in EnergyPlus (Costa et al., 2011) have shown a reduction of up to 30% of energy consumption if the temperature set point of the swimming pool hall is reduced during night. However restrictions in the operational schedules of the EnergyPlus model limited the reach of the study to fixed times for the setback and EoS of the system as opposed to the dynamic EoS presented in this section. With the use of the BCVTB a dynamic schedule of the facility was implemented allowing for a further study of the feasibility of establishing a dynamic EoS algorithm based on ANN.

4.2.4.2 Simulations

A simulation time-step of 1 minute was chosen to account for the thermal dynamics of the system when the set-point is modified. The first implementation used a week / weekend schedule that switched the system to set back set-point at 21.00h during week days and at 20.00h during weekends. The schedule for bringing back the system to normal operation set-point is established at 7.00h during weekdays and 9.00h during weekends. In Figure 4-18 the behaviour of the system under the above mentioned schedule and for one week of operation can be observed.

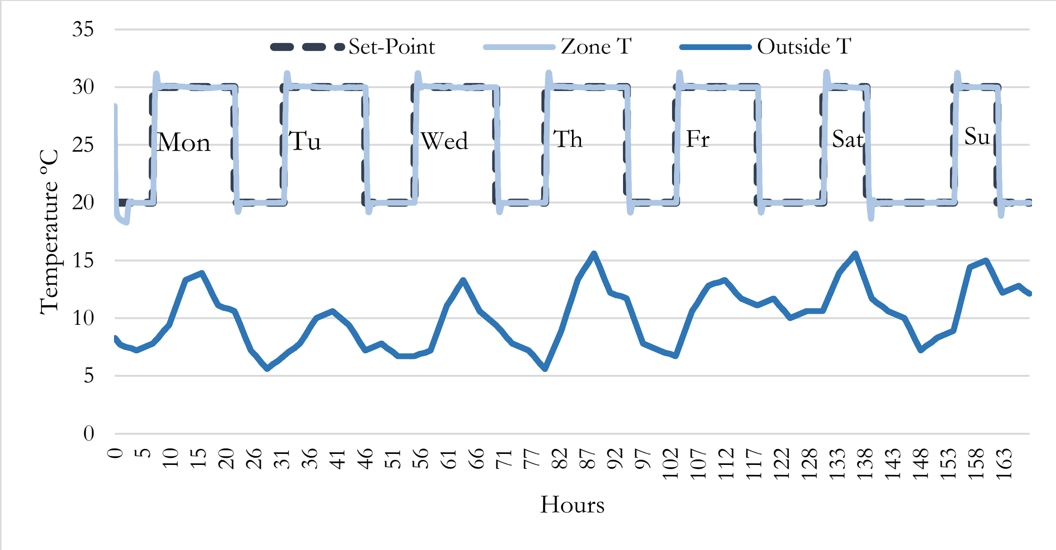


Figure 4-18. One week simulation with BCVTB.

4.2.4.3 Artificial neural network implementation

Simulation results were used to train an artificial neural network (ANN) to determine the optimal end of set back of the system so it will reach comfort conditions at the opening time. Given the discrete nature of the model, instead of predicting the actual opening time, the focus was on learning the number of time steps the system would take to reach comfort conditions. A simple algorithm was then developed to translate the ANN prediction into a signal for the EoS. The optimisation algorithm takes as input the actual time, the opening time and the output from the ANN and produces a signal for changing from set-back set-point to normal operation set-point Figure 4-19.

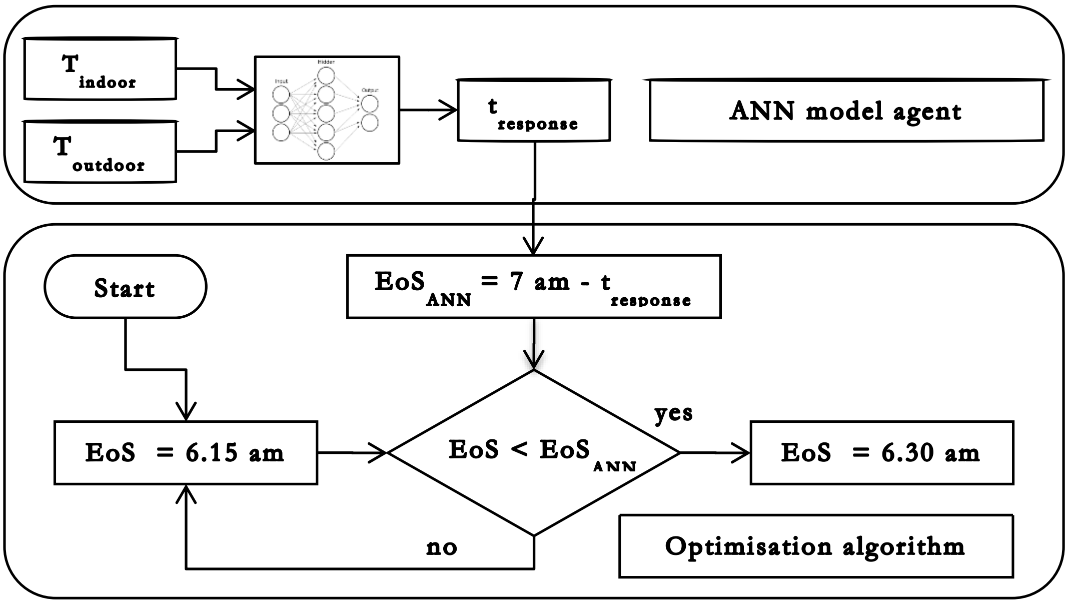


Figure 4-19. ANN EoS prediction.

The ANN developed has 2 inputs corresponding to outdoor and indoor temperature, 25 neurons in the hidden layer with sigmoid transfer function and one output with linear transfer function corresponding to the number of time steps it would take to reach the comfort conditions if the system was brought back to normal operation. Inputs and outputs were normalized to prevent prevalence of one variable over other. The training dataset was originated by simulating the system over one month. Training was done using the levenberg-marquardt backpropagation algorithm (Levenberg, 1944; Marquardt, 1963). To test the efficiency of the approach the ANN and the algorithm to translate the results of the ANN were used to substitute the scheduler. This new system was simulated over one week during the next month. Results showed that the ANN was able to accurately predict the optimal EoS for the system such that comfort conditions were reached by the opening time of the facility.

4.2.5 Technical discussion

This section presented the results obtained from the integration of Matlab/Simulink and EnergyPlus by means of the BCVTB applied to the Kingfisher swimming pool hall at the National University of Ireland, Galway.

In this case study the use of a simulation model allowed for the study and development of the automated EoS scheduler without the need to intervene in the actual BMS and thus not disrupting the normal operation of the facility. Such use of simulation models saves time and operational costs since on the one hand, no experiments need to be carried out in the facility and on the other hand, results from simulations models are obtained more quickly than using the real facility. One of the main advantages found in the use of the BCVTB is the possibility to easily implement different operational scenarios that otherwise would require separate simulations such as the modelling and simulation of different operational scenarios where faults occur and the particular response of the system to each individual fault. As well, for the case where different EoS times can be implemented, the BCVTB offers an intuitive and straight forward approach for the modelling and simulation of operational scenarios without requiring advance language scripting or adding new objects like in EnergyPlus (Basarkar et al., 2011).

In the implementation and methodology developed and presented in this section, no particular knowledge about the HVAC controls was assumed. Therefore, it is left to the user to specify and implement the type of controller that better fits the needs. For the swimming pool at the NUI Galway, two PID (proportional, integral and derivative) controllers were implemented. One PID controls the frost coil and ensures that the temperature of the air leaving the coils is never below a 5ºC. The other PID controls the heating coil to maintain the swimming pool hall temperature at the set-point temperature.

Of special interest is the use of Matlab as an extra interface to connect the BCVTB with Simulink in the presented case study. As shown in Figure 4-17, at every time-step Matlab sends to Simulink the present values of the variables needed to perform the calculation of the interactions in the HVAC unit while Simulink returns the updated supply temperature and a set of state variables that are needed for initialization of the values of the variables inside the AHU for the next time-step. This procedure allows for the implementation of different time-steps in the BCVTB without the need to fix a time-step in Simulink. Such is achieved by running, at every time-step, the Simulink model for a period of time equal to the time-step while leaving Simulink to decide the best time-step.

With the ANN approach, it was possible to predict the optimal EoS time for the simulated system and through the use of the BCVTB a dynamic schedule could also be implemented. Simulation results obtained with the use of the ANN-based dynamic EoS showed a reduction of energy consumption by 1% over the case with a fixed scheduled EoS that ensures no discomfort and provides 30% energy savings when compared with the case where no set-back is in operation.

Even though the controlled conditions of the experiment left little room for the possible improvement of the EoS using the ANN approach, in the case of variable zonal loads, the potential of the ANN provides much more scope for exploitation. Otherwise, a fixed EoS is suggested.

Simulation time is the biggest drawback of the developed integration. The cascade processing of information seemed to have slowed down simulations to the point where a week's simulation would take around 20 minutes to be processed on an Intel Core i5 processor at 2.67GHz with 8GB of RAM memory and under Windows 7 operating system.

4.2.6 Section summary

In this section a case study showing the SAB characteristic "*Controls and adapts building's actions to the monitored/predicted performance*" was presented for the automated end of setback of the HVAC systems in the swimming pool of the Kingfisher Sports Centre in NUI Galway campus. It was shown how, through the use of co-simulation, several tools can be brought together to exploit the strengths of each one while avoiding the drawbacks. This case study, thanks to the co-simulation approach reinforces the tool independence of the SAB concept whereby each characteristic can be implemented with one or more tools independent from each other. Since the ANN scheduler is developed to be automated and act directly on the system, it does embed knowledge (prediction of start time) and capacity (controlling set-back) to the facility. This case study also served to demonstrate how there is no need to for fixed schedules in the facilities as they are not flexible enough to cope with atypical days and thus resulting in either energy waste or discomfort.

4.2.7 Nomenclature

Variables		**Subscripts**	
$\dot{m}_{xf}$	mass flow rate of the fluid 'x' (kg/s)	c	coil
C_{pxf}	specific heat of flow 'x' (kJ/kg·ºC)	x	hot or cold fluid
T_{xfi}	input temperature of fluid 'x' (ºC)	f	fluid
T_{xfo}	output temperature of fluid 'x' (ºC)	i	input
UA	overall heat transfer coefficient of the coil (kW/ºC)	o	output
C_{xf}	total heat capacity of the coil for the fluid 'x' (kJ/ºC)		

4.3 Age 3 BMS: Diagnoses root causes of building's performance reductions

This section presents a case study focussed on the SAB characteristic: "*Diagnoses root causes of building's performance reductions*". In this regard, a BMS with ICT systems falling in age 3, especially in relation to extensibility, sensors and data availability, is needed to provide the necessary data and capabilities to accomplish this SAB characteristic. The methodology, application, deployment and results presented in this section have been published in (Sterling et al., 2014c). This case study was developed under the umbrella of the International Energy Agency EMWiNS project.

4.3.1 The facility

This case study comprises a constant air volume AHU which schematic is shown in Figure 4-20. The AHU serves a facility consisting of an audio laboratory of around 50 m^2. In this audio laboratory, strict conditions of temperature and humidity should be maintained due to the presence of highly sensitive music instruments (e.g. Steinway grand pianos). The building of the Cork School of Music is located in Cork city in the Republic of Ireland.

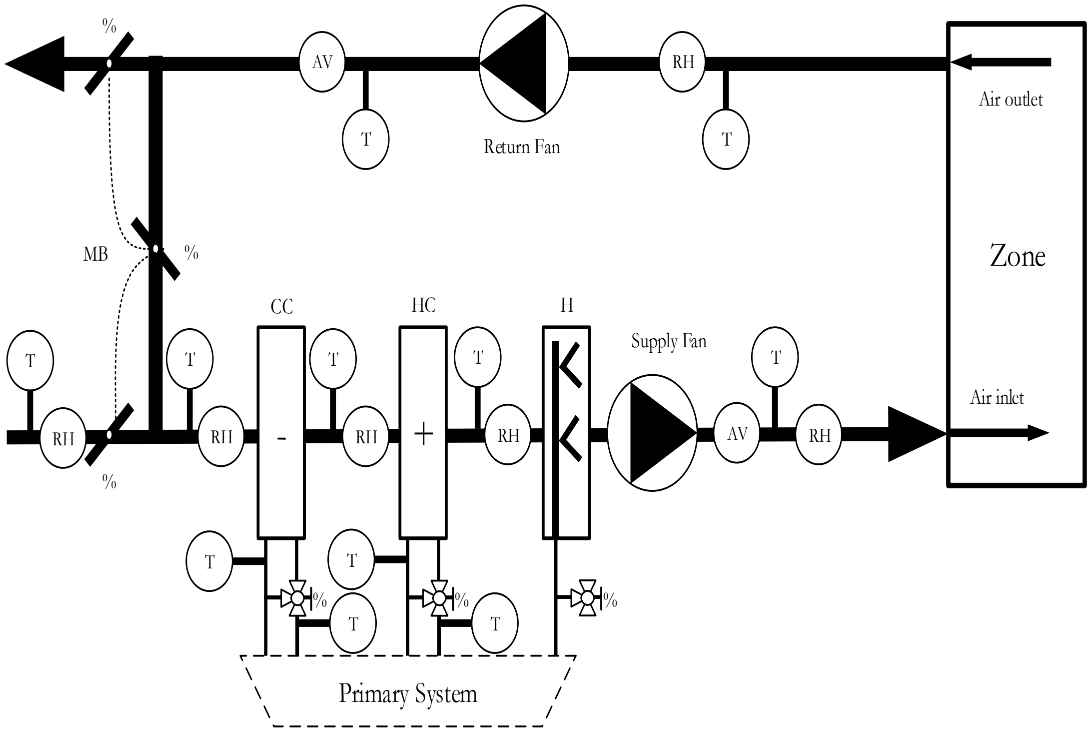


Figure 4-20. Air handling unit schematic.

The AHU presented in Figure 4-20 comprises the following components:

- Mixing Box (MB): serves to recover heat from exhaust air by mixing a fraction of it with fresh air from outside;
- Cooling Coil (CC): is used to control both temperature and humidity by cooling and dehumidifying the air;
- Heat Coil (HC): is used to control temperature by heating the air;
- Humidifier (H): serves to control humidity by adding water vapour to the air.

Coils and humidifier are operated by controlling the respective valves that increase, decrease, or block the flow of hot or cold water through them. The mixing box is operated by means of dampers that regulate the mixture between outdoor fresh air and recirculation air that passes though the unit.

The unit under study is a reasonably well instrumented AHU making it suitable for research purposes. The available sensors can be seen in Figure 4-20, where 'T' stands for temperature (ºC) sensor, 'RH' for relative humidity (%) sensor, 'AV' for air volumetric flow rate (m^3/s) sensor and '%' represents the opening of valves and dampers. The signals and sensors data is recorded with a frequency of one minute. The current application exploits only the control signals and the data from the temperature sensors. Technical manufacturer data for each of the components of the unit is available.

4.3.2 BMS SWOT

The BMS at the Cork School of Music, is a Trend Building Management System, provided with Trend 963 Graphics Software Package, Trend IQ3Cxite controllers, LAN communications and web access. Data for Figure 4-21 was gathered from Operation and Maintenance Manuals of the Cork School of Music and on-site visits. This facility was upgraded from age 2 to age 3 which is reflected in Figure 4-21. The improvements made to the facility consisted in increasing and harmonising the frequency for data collection, increasing the number of sensors to those shown in Figure 4-20, the setup of a database with external access for data transfer capabilities and the implementation of platform that allowed for the development and deployment of innovative software and hardware modules feeding from the data and providing advanced visualisation and FDD capabilities.

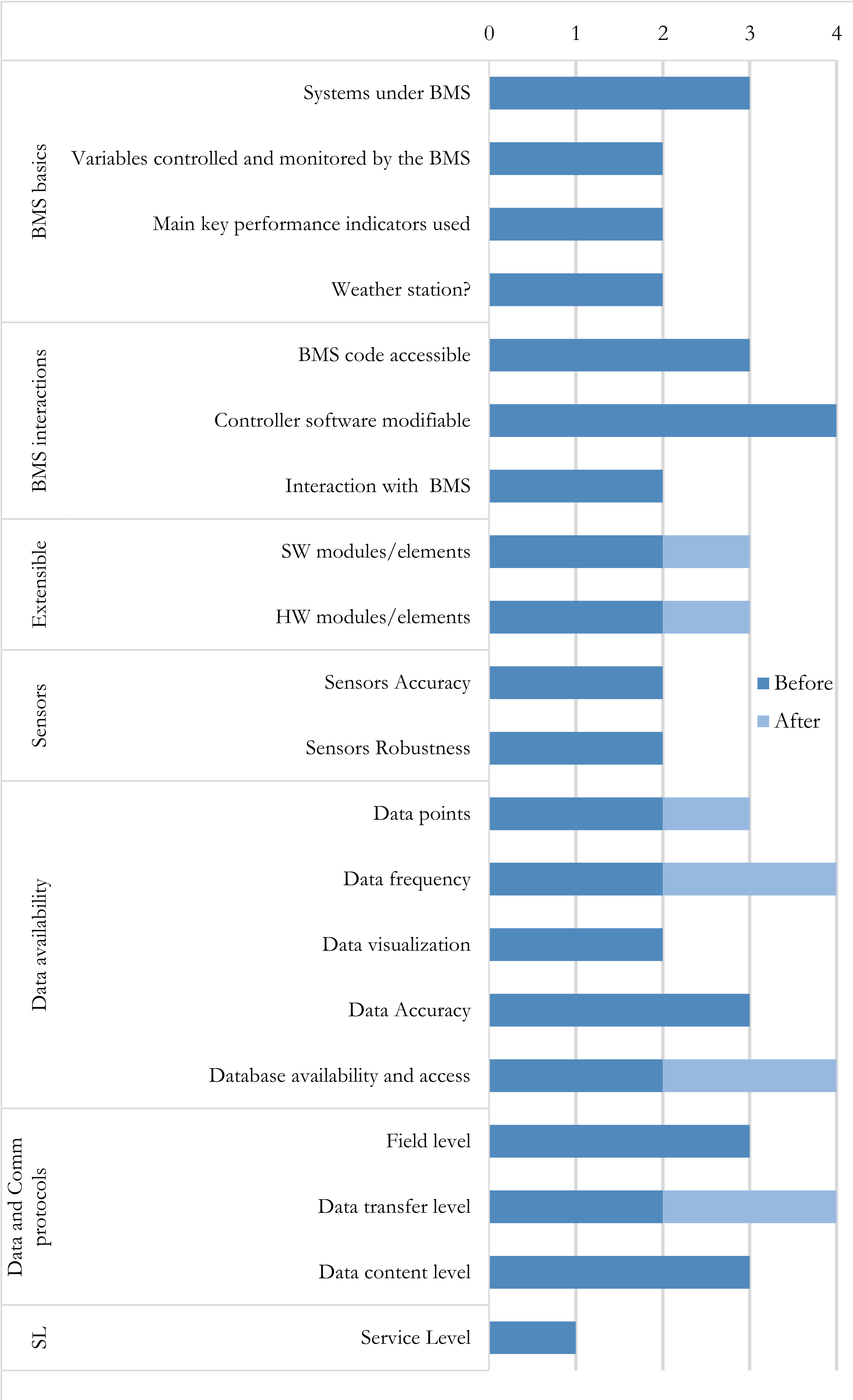


Figure 4-21. Strengths and weaknesses of the Cork School of Music.

Table 4-9 replicates Table 4-1 highlighting the age 3 for BMS and the KETs used for this case study. According to the table, three SAB characteristics can be carried out (characteristics from previous ages can be implemented). For this case study it was decided to exploit the characteristic related to diagnosing root causes of building performance reductions. The reason for this choice lies in the fact that the level of instrumentation of the facility was very apt for the study and comparison of different FDD approaches. For the studied SAB characteristic, the main technical developments are those provided by mode-based diagnosis models. In this regard, the rest of the section discusses different approaches for such diagnosis.

Table 4-9. BMS age vs. modelling and SAB characteristic for the case study of the Cork School of Music.

Age	**1**	**2**	**3**	**4**
SAB Characteristics	None	Predicts, keeps track and monitors building's performance. Controls and adapts building's actions to the monitored/predicted performance.	**Diagnoses root causes of building's performance reductions.**	Supports building managers by providing information about building's operations in a way that matches their typical skill set.
What can be done?	Manual fault detection	Automated fault detection manual diagnosis	**Automated fault detection and diagnosis**	Automated fault detection, diagnosis and prognosis. Decision support systems
FDD&P Methodology Suggested	Limits and alarms	Statistical analysis, APAR rules, expert systems	**Model based diagnosis,** machine learning	Integration with BIM, ISO 50001 and alike standards
Modelling suggested	Expert knowledge	First principles, simplified physics, black box	**First principles,** detailed physics, black box, grey box	Same as age 3

4.3.3 Fault detection and diagnosis in building systems

Heating Ventilation and Air Conditioning (HVAC) systems are known for being very inefficient for reasons such as the presence of undetected failures in one or more of its components. Faults can remain unnoticed for long periods due to different factors ranging from compensations made by the control algorithm to the lack of proper maintenance and improper commissioning. Even when systems are known to operate at reduced performance, which undoubtedly leads to energy waste, the presence of faults may be very difficult to localize and identify. This makes fault localisation and identification a costly task for human operators who commonly only act when indoor environmental conditions are not met. The lack of timely intervention leads to increased operational costs and raises the need for developing fault detection and diagnosis methods and technologies that automate or support the identification and localisation of all the issues in the HVAC system.

Different fault detection and diagnosis (FDD) methodologies have been developed for HVAC systems, mostly based on expert knowledge to help identifying the faulty condition and its source (Katipamula & Brambley, 2005b). However, a new trend in FDD is that of using models of the HVAC systems that provide a base line for optimal operation, and supports the detection of deviation from this optimum (Isermann, 2005). Model-based methods offer the advantage of an increased flexibility to adapt to different and innovative HVAC systems.

The focus of this section is on a model-based diagnostic solution that uses a qualitative model for the part of the HVAC system corresponding to the Air Handling Unit (AHU). This solution is based on generic compositional first-principle models and exploits a general diagnosis algorithm that isolates and identifies faults that occur frequently and can cause significant loss of system performance in AHUs: passing heating- and cooling-coil valves, and stuck dampers.

4.3.4 Approach

The approach of this case study is shown in Figure 4-22. System specific information was gathered from the facility's maintenance and operation manuals. Domain specific information corresponds to model developed in Modelica modelling language (Elmqvist, 1978) and representing first-principles of energy and mass transfer between the components of the AHU. Finally the task specific information is provided by OCC'M Raz'r diagnosis engine (OCC'M, 2014).

In this case study, model development, calibration and validation was a collaborative work with Mr. Jesús Febres (PhD candidate at IRUSE) and the author of this thesis while the diagnosis tasks were developed in collaboration between the author of this work and Dr. Peter Struss (Technical University of Munich). The theory behind consistency-based diagnosis was provided by Dr. Peter Struss.

4.3.4.1 Model-based diagnosis

In current practice, diagnostics systems are usually programmed by experts for each specific plant exploiting knowledge about the structure of the plant and the behaviours of its components including nominal (ideal) and if necessary faulty conditions. These programs, traditionally called "expert systems", are sometimes structured as a set of rules that link potential symptoms and the faults possibly causing them, and an algorithm that applies the rules to given observations about the system's behaviour. The problem with this approach is not so much a technical one, but lies in the inevitably high efforts required to adapt or re-write the diagnostic program for a new plant or to reflect changes in an existing plant. The code (or the set of rules) has to be inspected in order to determine which part still applies and what has to be modified or produced afresh. The reason why these, often prohibitive, efforts are inevitable is that such programs capture the application of expert knowledge to a specific plant and, hence, leave both the structure of the plant and the knowledge about the physics of its components implicit in the code. A further drawback is that the set of rules is limited to symptoms and faults that have been experienced previously.

Model-based diagnosis overcomes these limitations by using models that provide an explicit representation of the knowledge about the components and the information about the plant structure, which determines how the components interact with each other (see Figure 4-22). Based on a library of generic component models and the representation of the HVAC system topology, a system model (possibly covering both the nominal and faulty behaviours) is obtained. The context-free component models allow for their re-use, the automated generation of system models, and, hence, cost-effective creation of new applications and easy adaptation to variants and modifications. This model is then exploited by a generic diagnosis algorithm, which is not plant-specific and even not domain-specific. This way, diagnostics tailored to a specific plant require only the specification of the plant structure; they are generated instead of being programmed.

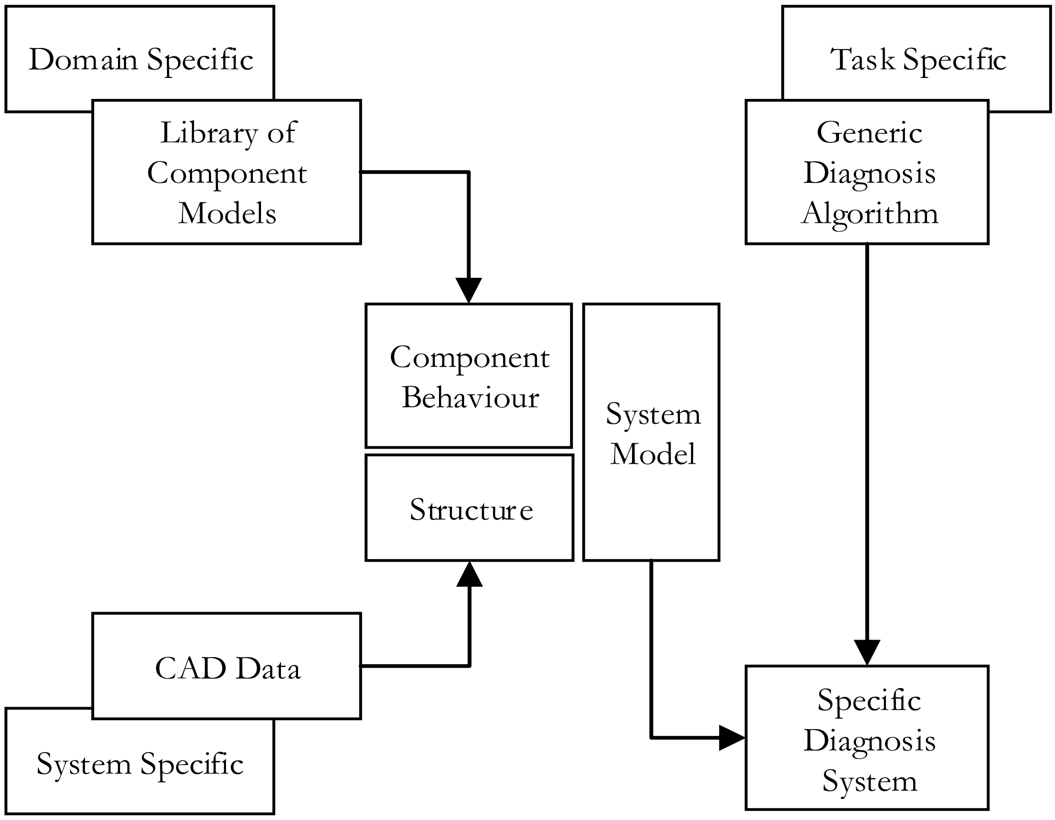


Figure 4-22. Generating diagnostic systems.

The existence of a generic model-based diagnosis algorithm is crucial to this approach and the following sub-section presents the key ideas behind such an algorithm.

4.3.4.2 Consistency-based diagnosis

For model-based diagnosis, the system's structure and behaviour need to be represented in a model which allow automation of the location of causes of misbehaviour within the system. A model-based diagnosis algorithm compares the model's predicted behaviour with the observed behaviour of the real world system. The core step is to check whether or not the observed behaviour contradicts the model (hence, consistency-based diagnosis). Consistency-based diagnosis is able to perform fault localization based solely on a model of the system's correct behaviour ($MODEL_{OK}$), but it might be supplemented by failure models for fault identification.

AHU plants contain a fixed set of components (mixing box, coils, fans, etc.) which interact in a fixed system structure. This set of components is denoted as COMPS. It is assumed that:

- the system is well-designed, i.e. it behaves and performs as intended if all components behave correctly;
- A disturbance of the entire system can be caused by a single faulty component or a set of faulty components.

The diagnosis task is then to decide whether there are components that are not behaving as intended, i.e. are showing faulty behaviour (fault detection). Furthermore, it can determine which components are operating in a fault mode (fault localization) and in which fault modes they operate (fault identification).

4.3.4.2.1 Performing fault detection

Each component C_i of the diagnosed system, will have assigned, within the diagnostics model, a set of behaviour modes $(C_i) = \{mode_j(C_i)\}$, where the mode $ok(C_i)$, represents the intended, normal behaviour of C_i and is always included in modes (C_i). As an example $\neg ok(C_i)$ would represent model behaviour not normal or intended thus faulty behaviour although it doesn't specify the type of fault just yet.

During diagnostics, out of these behaviour modes (e.g. $ok(C_i)$, $\neg ok(C_i)$, etc.), one mode is assigned to each component. The assignment of one behaviour mode to each component contained in COMPS or a subset of it, is referred to as mode assignment and denoted by MA. MA is called complete if modes are assigned to all components in COMPS.

If we denote the model library (i.e. the representation of the knowledge about the components) as LIB, the information about the plant structure as STRUCT, and a set of observations of the real system behaviour by OBS, then a complete mode assignment MA that is consistent with LIB, STRUCT and OBS, is a consistency-based diagnosis. In a logical notation (equation (5)), we state as a criterion that a mode assignment MA together with the library LIB, the structure STRUCT and the observations OBS should not be contradictory, i.e. does not entail (denoted by $\nvDash$) an inconsistency (denoted by $\perp$):

$$LIB \cup STRUCT \cup \{MA\} \cup OBS \nvDash \perp \qquad (5)$$

For detecting faults, the system starts with the assumption that all components operate correctly (i.e. ok modes are assigned to all components), and, hence, the system behaves as intended. This means that for every component Ci only mode ok(C_i) is assigned thus a correctly working system must comply with equation (6):

$$LIB \cup STRUCT \cup \{MA_{OK}\} \cup OBS \not\models \perp \quad (6)$$

Then, the system checks whether the model of the correctly behaving system ($MODEL_{OK}$) is **inconsistent** with the observations:

$$MODEL_{OK} \cup OBS \models \perp. \quad (7)$$

Shall formula (7) be true for the current observation, then a fault has been detected.

4.3.4.2.2 Performing fault localisation

If faulty components are to be localized, i.e. separating correctly operating components from broken ones, this means searching for consistent mode assignments containing the modes ok(C_i) (correct operation) and ¬ok(C_i) (any arbitrary kind of deviating behaviour). In particular, minimal fault localizations are of practical interest (i.e. a minimal set of broken components which suffices to explain a symptom), since there is no need to assume additional components to be broken. The diagnosis algorithm in generates such mode assignments from detected inconsistent partial mode assignments (so-called conflicts) {ok(C_i)}. A conflict means that at least one of the mentioned components is not ok, and, therefore, a diagnosis has to include a component from each conflict. This means that the use of a model of the nominal behaviour suffices to generate diagnostic hypotheses, and, therefore, also unknown faults can be diagnosed (Struss, 2008). Also there is no problem to localise multiple faults.

4.3.4.2.3 Performing fault identification

To refine fault localization, specific faults (such as valves being stuck open or closed) can be defined as additional behaviour modes of components to identify particular component faults that caused disturbed system behaviour. This can also be used to exonerate components, based on the above consistency check: if, in a particular context, none of the possible fault models of a component is consistent with the observed behaviour, then it must be considered OK in this context (or the context itself is inconsistent). Of course, explicit fault models that cover all possible ways of misbehaviour enlarge the space of models. The larger the space of models, the more mode assignments need to be checked for consistency with the observations and hence, the space of conflicts also grows. Fortunately, most of the possible mode assignments are not interesting from the application perspective and, therefore, many of the conflicts need not to be discovered. For more detailed information about model-based problem solving and especially consistency-based diagnosis, we refer the reader to reference (Struss, 2008).

4.3.4.3 From model development to fault diagnosis

In this section, we present a complete workflow and system modules required to build a diagnostic solution for a class of plants (e.g. HVAC systems), deploy it for a single plant and run it on-line (see Figure 4-23). This process is referred to as qualitative model-based diagnosis. Here, we give only an overview of the steps and modules, the most relevant ones being discussed in more detail in the following sections.

Producing the general solution (top row) involves:

- The production of a library of models of the OK modes of the components and;
- Its transformation into a diagnostic model library (LIB).
- Producing an application system (middle-row), based on the general solution, requires:
- The configuration and calibration of the Modelica models of the correct behaviour and;
- The composition of the diagnostic model based on the diagnostic library and the topology of the plant, which can be extracted from the Modelica system model.
- For on-line diagnosis (bottom row):
- Deviations are generated by computing the difference between the real data and the predictions generated by the Modelica OK model of the plant, and comparing the difference with given thresholds. The resulting deviations of variables form the set of observations OBS, which are processed by;
- The runtime diagnosis engine, Raz'r (OCC'M, 2014), which is an implementation of consistency-based diagnosis as described in section 4.3.4.2. For on-line diagnosis, the qualitative model-based diagnosis algorithm and the diagnostic plant model can be compiled into very compact C-code. The output is the set of all mode assignments containing minimal combinations of component faults that are consistent with the abstract observations.

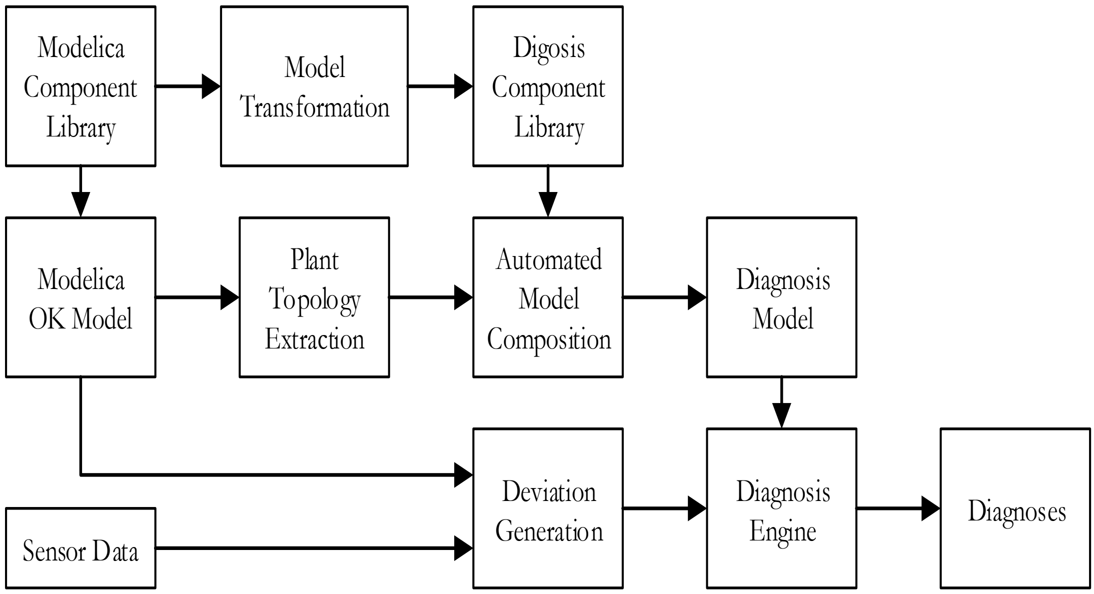


Figure 4-23. From model to diagnosis, the QMBD chain.

4.3.4.3.1 First principle models for model-based diagnosis

First principle models are meant to capture the objective physical laws behind the behaviour of systems and components as opposed to representations that collect simply empirical associations, encountered in diagnostic settings. Energy models have traditionally been defined to describe the nominal behaviour only, which, can be used to predict system behaviour over time and can also be used for fault detection when observed behaviour deviates from the nominal one as previously explained.

In order to support QMBD, numerical models used to generate diagnostics model have to satisfy particular requirements:

- The modelling approach needs to be strictly component-oriented: the library has to be organized around the component types (with models that can be parameterized) that constitute the plant and that are units subject to diagnosis, e.g. heat exchangers (coils), mass exchanger (humidifier, mixing box), mass movers (fans), etc.;
- For fault identification, fault models must be represented (perhaps with a parameter characterizing the fault, such as the opening of a passing valve);
- The plant model has to be configured strictly according to the real physical interconnections in the plant. It must not include computational artifacts that link certain variables that are not really interacting directly via a physical connection;
- The models in the library have to be formulated in a context-independent manner and must not rely on implicit assumptions about a specific control regime, operation mode, or the presence and correct functioning of other components, even though

they may exist in most standard configurations. This is relevant for two reasons: it enables the re-use of the component models for different plants, and it is a precondition for the adequacy of the models in fault situations.

The AHU under study (Figure 4-20), comprises the following components: dampers/mixing box, cooling and dehumidification coil, heating coil, humidifier, ducts, filters, and fans. In this work, the focus is on the so-called active elements that are used for changing air temperature and humidity (and thus enthalpy) to match the setting for the space being served. To this end, it is assumed that ducts and filters have negligible effects on air temperature and the fans just cause an air temperature increase and has no effect on the air humidity content. In addition, steady state conditions and no frictional losses are also assumed since it suffices for the application at hand. The models developed are: mixing box, heating- and cooling-coils and humidifier.

Model development was driven by the specific application needs which encompass, apart from what has been previously stated, best use of component manufacturer's data for setting up models and ease of use. These last two criteria are closely related, since the manufacturer's data is the first source of information a model developer will have at hand. This information is often provided as a set of values for interacting variables for one operation scenario of the component. The models developed are such that manufacturer's data is used as input parameters when setting up the models. By using the component manufacturer's data as parameters we ensure a first calibration of the model under manufacturer's nominal conditions. Table 4-10 shows the parameters, from the manufacturer's data, to be provided to each component model.

Models were developed using the Modelica modelling language (Elmqvist, 1978). An example using the heating coil model and its calibration is presented for illustrative purposes. Full model development and calibration can be found in (Febres et al., 2013).

The heating coil model calculates the outlet steady-state conditions for both, water and air, using equations derived from the conservation of energy principles and the definition of effectiveness in the classical eff-NTU method given by equations (8), (9) and (10) (ASHRAE, 2009):

Table 4-10. Manufacturer's datasheet operation point values needed as parameters for model setup.

Component	**Parameter**	**Component**	**Parameter**
Mixing Box	No data required	Humidifier	Maximum steam mass flow rate, Steam temperature
Heating Coil	air input temperature air output temperature air mass flow rate water input temperature water output temperature water mass flow rate	Cooling Coil	air input temperature air input relative humidity air output temperature air output relative humidity air mass flow rate water input temperature water output temperature water mass flow rate

$$Q = C_a*(T_{aO}-T_{aI}) \quad (8)$$

$$Q = C_w*(T_{wI}-T_{wO}) \quad (9)$$

$$Q = eff*\min(C_a, C_w)*(T_{wI}-T_{aI}) \quad (10)$$

The effectiveness 'eff', depends on the coil configuration (parallel flow, counter flow, or cross flow with both streams unmixed) (Wetter, 1999).

For the heating-coil component, there are inputs and outputs for flow of air through the ducting, and flow of hot water through the heating coil. Hence, mass- and energy-balance equations must be defined for the airflow and water-flow. The imposition of energy- and mass- balance provides the remainder of the Modelica model equations. The other models (cooling-coil, mixing box and humidifier) follow a similar modelling approach.

The calibration methodology for each component uses real operation data obtained from the facility's building management system (BMS). For this approach, instead of trying to adjust each of the component's parameters, an initial calibration is done by using the manufacturer's data sheets (Table 4-10) and a more accurate calibration is then carried out by focusing solely on the valve model (Figure 4-24). The reason behind the focus on the valve model, shown in Figure 4-24, is that inaccuracies introduced by using the manufacturer's datasheet can be offset by adjusting the parameters of the valve model. In this sense, it can be seen as if the parameters of this valve model lump those of the elements thus reducing the dimension of the problem.

The relationship between control signal and mass flow rate through real valves may present non-linear behaviour and even show hysteresis (Borden (ed.), 1998). To model the valve's hysteresis, several options can be followed depending on the valve type, e.g. using on-off hysteresis, linear hysteresis and non-linear hysteresis (Borden (ed.), 1998). For the purposes of this research work, a hysteresis as shown in Figure 4-24 was chosen since it produced a good trade-off between accuracy and simplicity and it was not linked to any valve type and thus improving generalisation.

The functioning of the valve model is as follows. When fully closed it is in point 'a', as controlSignal increases it moves along the 'a-b' line with near zero flow, when it reaches 'b', the flow suddenly increases and moves to the 'c-d' lines until it reaches point 'c' when fully open (controlSignal equal 1). While closing, flow is reduced following 'c-d' line until it reaches 'd' at which point the flow is suddenly cut to zero.

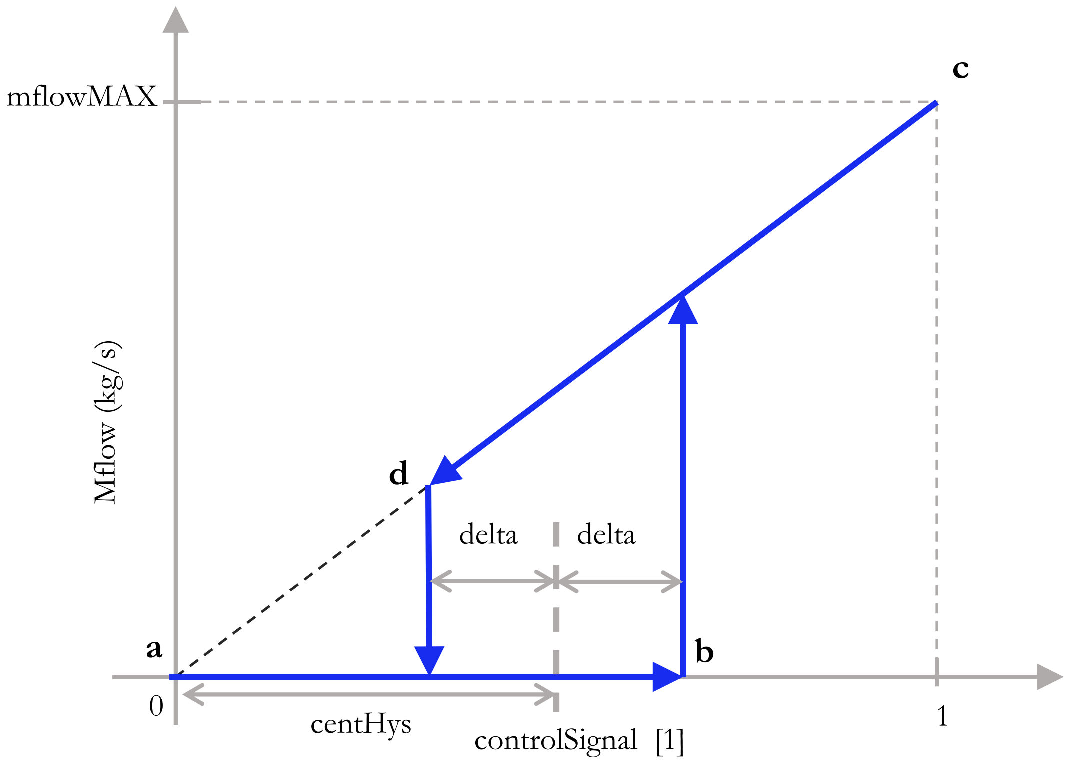


Figure 4-24. Valve model hysteresis function.

There are three parameters to calibrate. 'mflowMAX', 'cenHys' and 'delta. Parameter 'mflowMAX' is the water mass flow rate when the control signal is equal to its maximum possible opening position, 'centHys' and delta characterise the hysteresis' curve and the on/off points.

The real data has to be carefully observed to find maximum opening points, if present, and then the 'mflowMAX' value is fixed in such way as to decrease the difference between real data and model results of the controlled variable in those points.

To determine 'centHys' and 'delta', the employed strategy was to find sharp changes in controlled variable (output air temperature). When the controlled variable has a steep rise (point 'b' in Figure 4-25), the control signal coincides with a value equal to 'centHys' plus 'delta'; if the controlled variable has a sharp decrease (point 'd' in Figure 4-25), the control signal coincides with the value equal to 'centHys' minus 'delta'. This process is shown in a very simplified form in Figure 4-25.

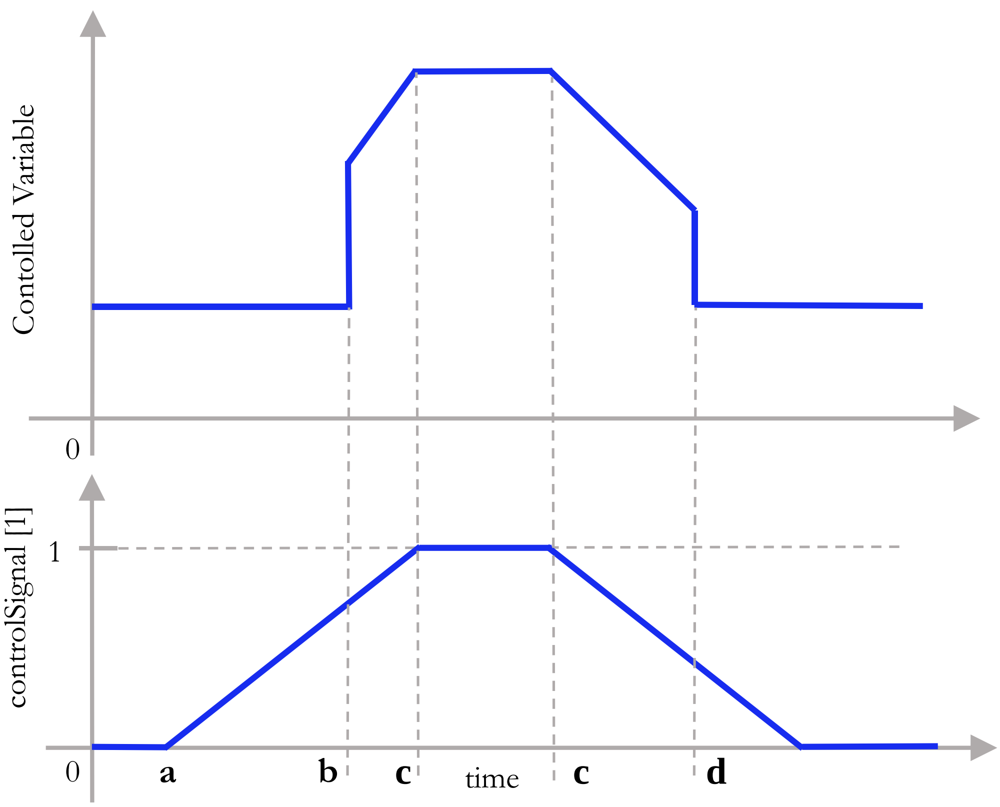


Figure 4-25. Identifying sharp changes in controlled variable.

Once each component model was calibrated (calibration results are shown in Table 4-11), the whole AHU model was assembled and simulated. Simulation results for the output air temperature for the whole AHU are presented in Figure 4-26 and in Figure

4-27. Figure 4-26, shows the AHU model simulation output before calibration and Figure 4-27 shows simulation results after calibration. Figures also show the difference between measured temperature and simulation results.

Table 4-11. Calibration parameters.

Calibration Parameter	**Mixing Box**	**Heating Coil**	**Cooling Coil**	**Humidifier**
mflowMAX	-	0.47	1.31	0.0077
centHys	0.55	0.25	0.13	0.0
delta	0.15	0.025	0.07	0.0
Air temperature change by fan (°C)	-	-	-	1.5

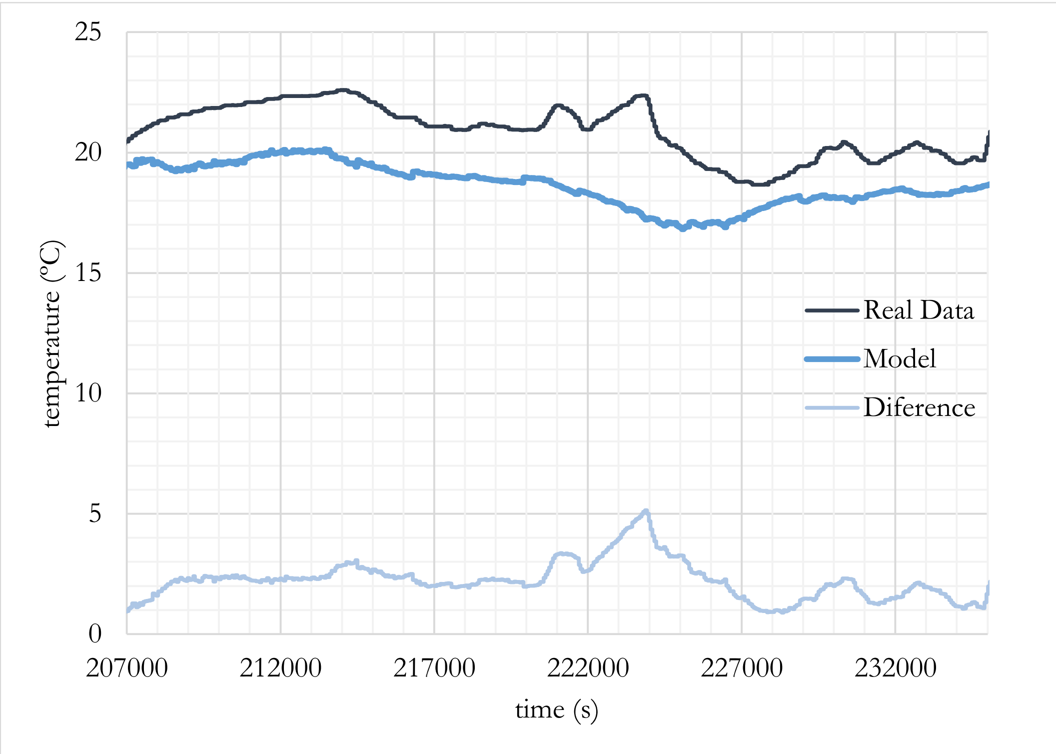


Figure 4-26. Simulated (model) vs. measured (real) supply air temperature for the whole AHU model before calibration.

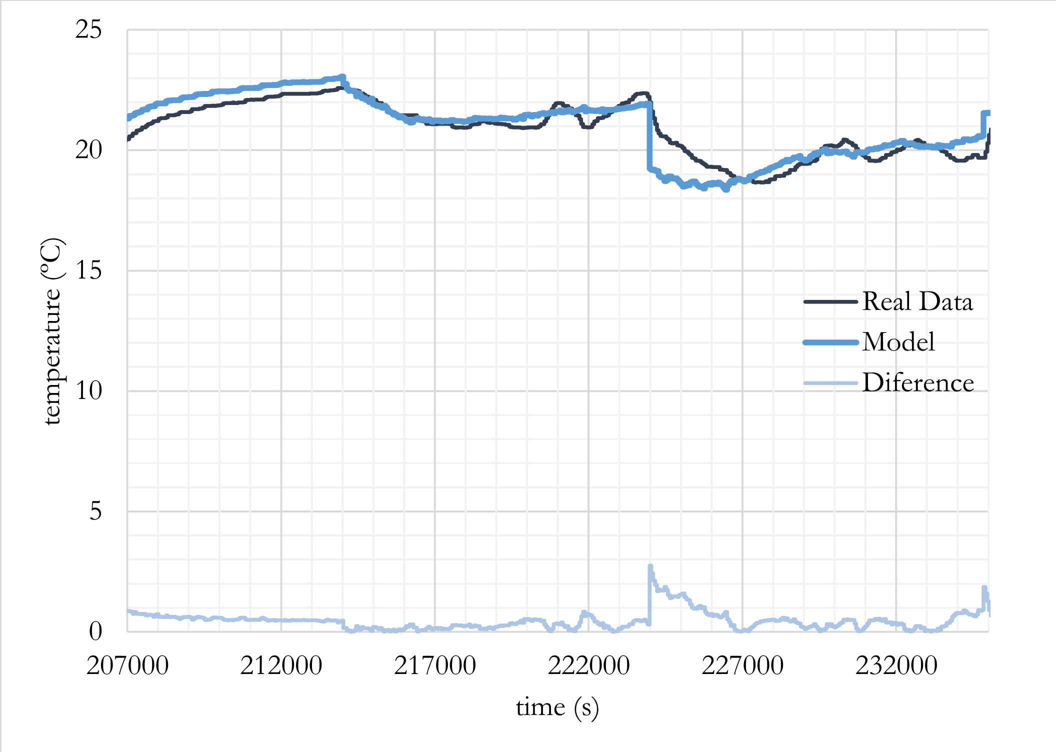


Figure 4-27. Simulated (model) vs. measured (real) supply air temperature for the whole AHU model after calibration.

Figure 4-27 shows the significant improvement achieved through the calibration process. Furthermore, a substantial reduction in the absolute error can be perceived in almost all the points. However, at about 24.000 seconds of simulation, the error value peaks shortly at just over 3 °C. This peak is due to the simple linearization of the valve model (Febres et al., 2013). To obtain a smoother curve, the valve model could have been approximated to a higher order, but this would have to be done at the expense of increasing the computational effort.

In order to provide a measure of the quality of the calibration, the error metrics corresponding to the root mean square error (RMSE) and the mean bias error (MBE) where used. The resulting values for these metrics can be seen on Table 4-12.

In Table 4-12, it is shown the improvement achieved by the calibrated model in temperature and humidity, which means a substantial decrease in the expected deviation of the simulation outputs from measured data.

Table 4-12. RMSE and MBE pre and post calibration for each AHU component and for the full unit.

Component			**Mixing Box**	**Heating Coil**	**Cooling Coil**	**Humidifier**		**AHU**	
Variable			**T**	**T**	**T**	**T**	**W**	**T**	**W**
ERROR	**RMSE**	**Pre-calibration**	2.01	0.68	0.80	1.16	0.0010	2.76	0.0011
		Post-calibration	0.83	0.41	0.48	0.61	0.0009	0.98	0.0007
	MBE	**Pre-calibration**	1.78	-0.05	-0.34	1.07	0.0004	2.21	0.0006
		Post-calibration	0.34	0.05	-0.12	-0.44	0.0002	-0.23	-0.005

T: Temperature; W: Moisture content

A second model of the AHU was developed using the Modelica Buildings Library (Wetter et al., 2014). The purpose for using this library is to prove the applicability of the calibration methodology in different libraries and to validate the results from the first principles model. In Table 4-13 it is shown the calibration parameters for the case of the AHU model using the Modelica Buildings while Table 4-14 shows the calibration results using the same.

Table 4-13. Calibration parameters using Modelica Buildings Library.

Calibration Parameter	**Mixing Box**	**Heating Coil**	**Cooling Coil**	**Humidifier**
mflowMAX	-	0.30	0.63	0.0063
centHys	0.55	0.25	0.13	0.0
delta	0.15	0.025	0.07	0.0
Air temperature change by fan (ºC)	-	-	-	1.5

Models developed with the Modelica Buildings Library show better accuracy than those developed using first principles. However, the former also have higher computational cost which leads to simulation times up to 19 times slower. This difference in simulation time reduces the scalability of the solution when approaching multiple AHUs at the same time.

Table 4-14. RMSE and MBE pre and post calibration for each AHU component and for the full unit modelled using the Modelica Buildings Library.

Component			**Mixing Box**	**Heating Coil**	**Cooling Coil**	**Humidifier**		**AHU**	
Variable			**T**	**T**	**T**	**T**	**W**	**T**	**W**
ERROR	**RMSE**	**Pre-calibration**	1.67	0.98	0.90	0.57	0.0010	2.04	0.0009
		Post-calibration	0.74	0.46	0.35	0.56	0.0009	0.99	0.0005
	MBE	**Pre-calibration**	1.42	-0.33	0.39	-0.33	-0.00001	0.80	0.0005
		Post-calibration	0.30	0.05	-0.08	-0.31	-0,00042	-0.17	-0.0003

T: Temperature; W: Moisture content

4.3.4.4 Qualitative diagnostic models

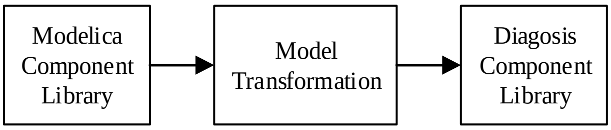


Figure 4-28. From numerical model to diagnosis models

Qualitative model-based diagnosis (QMBD) applies consistency-based diagnosis with fault models based on a transformation of first-principle models into a qualitative representation of the components behaviour.

To illustrate the QMBD process (described in Figure 4-23), the theoretical explanation will be supported with an example based on the diagnosis model of the heating coil component. The rest of the component models follow a similar approach and the final diagnosis model for the AHU is a composition of the individual component models.

The models used in the diagnostic approach are stated in relative, rather than absolute terms: they capture the deviation of measured values from the respective simulated values under nominal behaviour.

Following (Struss & Fraracci, 2012), the qualitative deviation of a variable x is defined as:

$$\Delta x := \text{sign}(x_{act} - x_{nom}) \tag{11}$$

Equation (11), captures whether an actual (observed, assumed, or inferred) value is (significantly) greater, less or equal to the nominal value. The latter is the value to be expected under nominal behaviour, technically, the value implied by the model in which all components are in OK mode.

Qualitative deviation models can be obtained from standard models stated in terms of (differential) equations by canonical transformations, such as equations (12) and (13).

$$a + b = c \Rightarrow \Delta a \oplus \Delta b = \Delta c \tag{12}$$

$$a * b = c \Rightarrow (a_{act} \otimes \Delta b) \oplus (b_{act} \otimes \Delta a) \ominus (\Delta a \otimes \Delta b) = \Delta c \tag{13}$$

Here, $\oplus$, $\otimes$, $\ominus$ are addition, multiplication, and subtraction operators of interval arithmetic.

It is important to note that these equations do not contain nor require values for the reference values x_{nom} and, hence, can be applied to several plants and with different parameters and under distinct operating modes. The qualitative deviation models, obtained from the Modelica models, reflect current modelling assumptions, (steady state, and no deviation in airflow) and become very compact due to their qualitative nature and because constants can be dropped and just replaced by their signs. Internally, this model is automatically transformed into an efficient data structure representing finite relations.

In the following, we illustrate how this transformation can be done by manipulating the equations using the heating coil component as an example. According to energy balance equations (8), (9) and, (10), and assuming no losses, the energy balance in equation (14) can be reformulated in terms of deviations (Δ) as in equation (15).

Assuming that the air flow and the water temperature (drop) are positive and not deviating and replacing the capacity flow by the mass flow $mflow_w$ (which differ only by a constant factor), we obtain equation (16) which applies to all modes of the coil.

$$0 = C_a*(T_{aO}-T_{aI}) - C_w*(T_{wI}-T_{wO}) \tag{14}$$

$$0 = \Delta\ (C_a*(T_{aI}-T_{aO}))\oplus\Delta\ (C_w*(T_{wI}-T_{wO})) \quad (15)$$

$$0 = \Delta T_{aI} \ominus \Delta T_{aO} \oplus \Delta mflow_w \quad (16)$$

Following equation (11), each of the variables used for diagnostics (equation (16)) can have a deviation of the measured value from the simulated one as follows:

- positively ('+'), when the actual (measured, predicted, or assumed) value is above the simulated plus a threshold;
- negatively ('-'),when the actual value is below the simulated minus a threshold;
- or not deviate ('0'), when the actual value is within the simulated value plus/minus the threshold.

Table 4-15 depicts the resulting relation on the three deviation variables, i.e. all solution tuples of equation (16). For instance, the first three rows of the table indicate the intuitive fact that, if the mass flow shows no deviation, a deviation of the incoming air temperature will simply be propagated to the output air temperature.

On the other hand, a positive deviation of the output air temperature in combination with no deviation in the input air temperature, is only consistent with a positive deviation in the mass flow rate of the water (last-but-one row). From the diagnostic perspective, this reveals a fault in the coil (e.g. a passing valve), because a correct coil will not produce a deviating water flow. Since QMBD uses the signal that controls the opening of the valve 'Cmd', it can reproduce proper diagnoses for the faults under study. A valve stuck closed may lead to a negative deviation "–", if the command Cmd to the valve is "open" (to some non-zero position, "+"). If the control commands the valve to be shut, anyway, a stuck-closed valve would cause no deviation in the water flow. This is captured by the model fragment in Table 4-18, which actually, is the complete fault model. Table 4-16 and Table 4-17 show the models of the OK mode and the stuck valve, respectively.

With respect to their use for diagnosis, Table 4-16, Table 4-17 and Table 4-18 jointly with Table 4-15, capture which tuples of temperature and water flow deviations are consistent with which behaviour modes.

Table 4-15. Relation on temperature deviations and water flow deviation.

$\Delta mflow_w$	**ΔT_{aI}**	**ΔT_{aO}**
0	-	-
0	0	0
0	+	+
-	-	-
-	0	-
-	+	*
+	-	*
+	0	+
+	+	+

Table 4-16. Qualitative representation of the OK mode.

Cmd	**$\Delta mflow_w$**
0	0
+	0

Table 4-17. Qualitative representation of the stuck closed valve mode.

Cmd	**$\Delta mflow_w$**
0	0
+	-

Table 4-18. Qualitative representation of the passing valve mode

Cmd	**$\Delta mflow_w$**
0	+
+	0
+	+

Note that the qualitative behaviour relations of different modes are not necessarily disjoint, i.e. a certain tuple of variable values may be consistent with several modes.

The rest of the components of the air handling unit follow a similar approach to generate the qualitative representation.

4.3.4.5 Runtime deviation generation

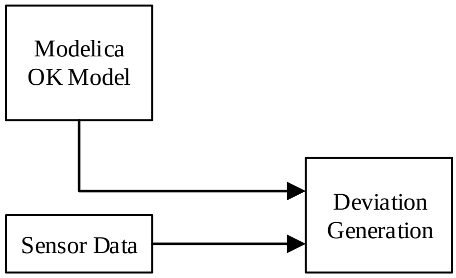


Figure 4-29. Generating deviations

At runtime, the system will calculate deviations (Figure 4-29) by following the steps:

- Read each data vector corresponding to the sensor and actuator signals;
- Extract the exogenous variables: external temperature, damper and valve commands;
- Provide the exogenous variable values to the Modelica model of nominal behaviour;
- Compare the values predicted by this model with the actual sensor data, and;
- Compute the deviations. In the current solution, this is simply done by using a threshold (defined by the modelling expert and which can be different for different variables).

For the example with the heating coil documented here, a threshold of 2°C was chosen in order to produce deviations in the domain of signs (‘+’,’-‘,’0’). This threshold ensured that the resulting deviation was not a product of the sensor or model accuracy. In future solutions, different orders of magnitudes of the deviations could be generated by the abstraction module, which can take arbitrary sets of interval boundaries as an input.

For the example with the heating coil, Table 4-19 shows both the sensor data and the predicted values, highlighting the temperature before and after the heating coil. Using the 2°C threshold, the inflow air temperature is determined as nominal, while the outflow air temperature is higher than expected. This triggers a diagnosis event.

Table 4-19. Deviations between sensor data and model data.

	T_{aI} (ºC)	T_{aO} (ºC)
Sensor Data	18.32	20.87
Model Prediction	18.44	18.44
Resulting Deviation	0	+

4.3.4.6 Diagnosis inference

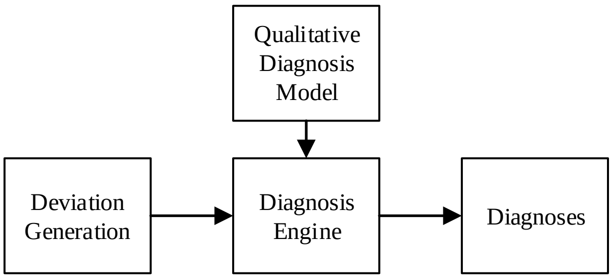


Figure 4-30. From deviations and qualitative model to diagnosis

The computed deviations (with a zero deviation of exogenous variables -input temperature, and valve commands-) form the input to the diagnosis runtime system (Figure 4-30). The deviation patterns will be checked for consistency with the possible models. In the trivial example restricted to one component presented in Table 4-19, the input/output temperature deviations (0, +) match with only one row in Table 4-15 that holds for all behaviour modes, which fixes $mflow_w$ to be positively deviating. This positive deviation is consistent with the valve passing mode (Table 4-18), but neither with the OK mode nor the stuck closed mode. Note, that this result can actually be concluded without information about the command to the valve.

What is illustrated here for a single component is actually applied to the full AHU model, which may yield alternative diagnosis hypotheses, possibly including some that correspond to multiple component faults.

4.3.5 Results

In this section, we present the results of testing the developed qualitative fault detection and diagnosis methodology in a real facility. First, we will introduce the different experiments carried out, followed by a comparison of the results against the traditional AHU Performance Assessment Rules (APAR) approach (House et al., 2001)

4.3.5.1 Experiments description

A number of experiments were conducted in a systematic manner with faults introduced to the system by modifying a single component and observing the reaction. This procedure ensured that the best possible data was captured. The initial experiments only included temperature as the variable under study.

In the experiments, while one of the components is being tested, the rest of the system is left to operate normally (e.g. control will compensate for any disturbance in order to maintain set point conditions in the zone). To simulate a passing valve in one of the coils, the valve is initially set at the minimum position (0%) and the reaction of the system is then observed for ten minutes which allowed the system to stabilise. The valve position is then opened by 10% of the maximum opening and again the system is left to settle for a period of ten minutes. This step is performed incrementally with ten-minute settling periods until a valve position of 100% is achieved. The procedure is then reversed going from 100% back to the minimum position in steps of 10% with a 10-minute settling period between changes as it is known to be enough time for the system dynamics to settle. The whole procedure is then repeated a second time giving two sweeps through the applicable valve positions to give sufficient data to enable the model calibration and diagnostics analysis on the components of the AHU. During the diagnosis process, the value of the command presented as input to QMBD is 0%. Table 4-20 below outlines the details of the experiments undertaken on the AHU.

Table 4-20. Experiments carried out in the air handling unit.

Experiment Description	**Actuator Position**		
	Damper	Heating Coil Valve	Cooling Coil Valve
Nominal	[0.3, 1.0]	[0.0, 1.0]	[0.0, 1.0]
Mixing Box Stuck Dampers	Sweep in steps of 0.10 from 0.3 to 1.0	[0.0, 1.0]	[0.0, 1.0]
Cooling Coil Passing Valve	[0.3, 1.0]	[0.0, 1.0]	Sweep in steps of 0.10 from 0.0 to 1.0
Heating Coil Passing Valve	[0.3, 1.0]	Sweep in steps of 0.10 from 0.0 to 1.0	[0.0, 1.0]

The notation [0.0, 1.0] in Table 4-20, means that the value can take any values between 0.0 and 1.0 according to the command signal from the BMS. In Figure 4-31 the behaviour of the command signal for a typical experiment is shown.

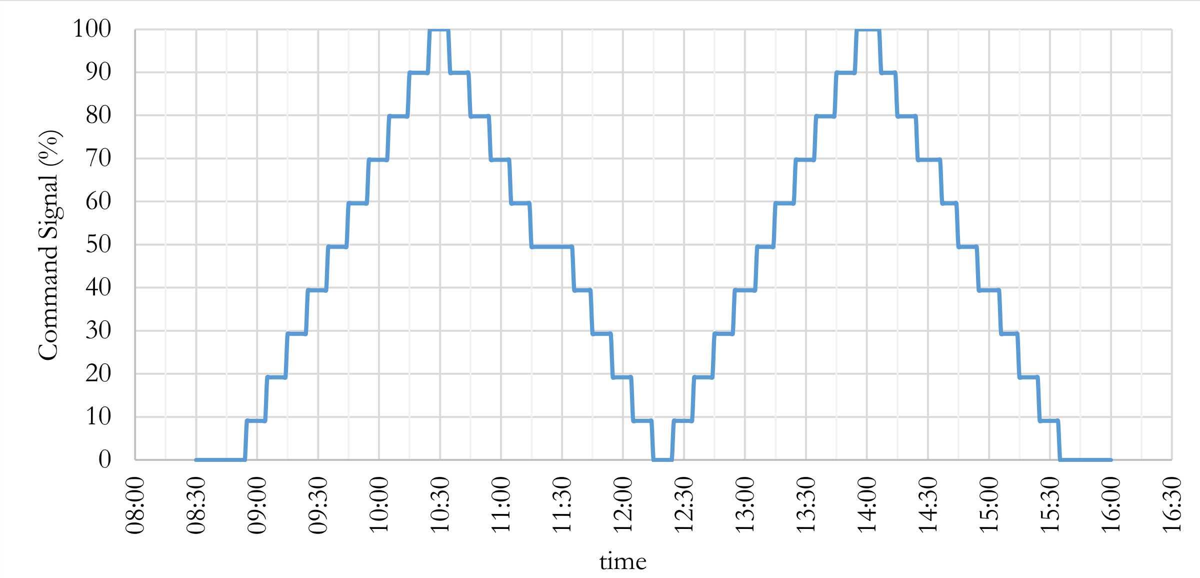


Figure 4-31. Typical command signal behaviour during experiments.

4.3.5.2 Results and comparison with APAR

As a result of the experiments, four 24-hour data sets were compiled from real AHU data, including each one of the experiment scenarios described in Table 4-20. In order to provide a baseline on diagnostics accuracy, the traditional APAR rule set was also applied to the data and results were used for comparison with QMBD.

In the first experiment, the nominal one, each of the approaches reports that no fault has been identified as expected.

In the second experiment, the mixing box stuck dampers, both approaches identify a fault with the mixing section of the unit as shown in Figure 4-32.

In the third experiment, the cooling coil passing valve, QMBD identifies an issue with the cooling coil. However, the APAR approach does not identify any faults. APAR fails to identify the existing fault because the cooling-coil valve command signal set to 0% makes the rule-set decide that the unit was not on cooling mode and, therefore, rules pertaining to the cooling coil were not applied. This is a shortcoming of the APAR rule-set where operation modes and control influence diagnostic results. These result can be seen in Figure 4-33.

In the last scenario, shown in Figure 4-34 and referring to the heating coil passing valve, each of the approaches identifies an issue with the heating coil. However, QMBD also determined that there is a fault in the mixing section of the AHU. The mixing fault was occurring as a result of broken actuator arm connecting the control valve to the recirculating damper and so QMBD identified simultaneous faults when APAR did not.

Finally, Table 4-21 summarises the experiments' results.

Table 4-21. Diagnosis results summary.

Experiment	APAR	QMBD	Comments
Nominal	No fault identified	No fault identified	No fault identified by each of the three approaches.
Passing Cooling Coil	No fault identified	2 possible faults identified during 5 separate time periods	No fault identified by APAR as the cooling coil being 0% made the engine think that the unit was in heating mode and therefore rules pertaining to the cooling coil were not applied. QMBD both correctly identified an issue with the cooling coil.
Passing Heating Coil	6 possible faults identified during 3 separate time periods	4 possible faults identified during 3 separate time periods	APAR identified a number of possible faults including an issue with the heating coil. QMBD correctly identified a fault on the heating coil and also correctly identified a fault in the mixing section of the AHU.
Stuck Mixing Damper	4 possible faults identified during 5 separate time periods	2 possible faults identified during 6 separate time periods	APAR identified a number of possible faults including an issue with the mixing dampers. QMBD correctly identified a fault on the mixing dampers.

It should be noted that for the APAR approach, a number of possible different faults are identified for any given scenario of which one or two are related to the component in question. However, it does also give a number of other possible causes for the fault and so an amount of user knowledge is required to investigate the fault further before an accurate determination of the issue can be made. In QMBD the fault messages are targeted at specific components and therefore give superior resolution to fault diagnosis when compared to APAR.

Time		8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18
Fault Occurrence											
Methods	**Diagnosis Possibilities**	Diagnosis									
APAR	Leaking Cooling Coil Valve										
	Stuck Cooling Coil Valve										
	Leaking Heating Coil Valve										
	Stuck Heating Coil Valve										
	Leaking Pre-heating Coil Valve										
	Stuck Pre-heating Coil Valve										
	Leaking Mixing Box Dampers										
	Stuck Mixing Box Dampers										
QMBD	Leaking Cooling Coil Valve										
	Stuck Cooling Coil Valve										
	Leaking Heating Coil Valve										
	Stuck Heating Coil Valve										
	Leaking Pre-heating Coil Valve										
	Stuck Pre-heating Coil Valve										
	Leaking Mixing Box Dampers										
	Stuck Mixing Box Dampers										

Figure 4-32. Mixing box stuck damper experiment.

Time		9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18
Fault Occurrence										
Methods	**Diagnosis Possibilities**	**Diagnosis**								
APAR	Leaking Cooling Coil Valve									
	Stuck Cooling Coil Valve									
	Leaking Heating Coil Valve									
	Stuck Heating Coil Valve									
	Leaking Pre-heating Coil Valve									
	Stuck Pre-heating Coil Valve									
	Leaking Mixing Box Dampers									
	Stuck Mixing Box Dampers									
QMBD	Leaking Cooling Coil Valve									
	Stuck Cooling Coil Valve									
	Leaking Heating Coil Valve									
	Stuck Heating Coil Valve									
	Leaking Pre-heating Coil Valve									
	Stuck Pre-heating Coil Valve									
	Leaking Mixing Box Dampers									
	Stuck Mixing Box Dampers									

Figure 4-33. Cooling coil passing valve experiment.

Time		**8-9**	**9-10**	**10-11**	**11-12**	**12-13**	**13-14**	**14-15**	**15-16**	**16-17**
Fault Occurrence										
Methods	**Diagnosis Possibilities**	**Diagnosis**								
APAR	Leaking Cooling Coil Valve									
	Stuck Cooling Coil Valve									
	Leaking Heating Coil Valve									
	Stuck Heating Coil Valve									
	Leaking Pre-heating Coil Valve									
	Stuck Pre-heating Coil Valve									
	Leaking Mixing Box Dampers									
	Stuck Mixing Box Dampers									
QMBD	Leaking Cooling Coil Valve									
	Stuck Cooling Coil Valve									
	Leaking Heating Coil Valve									
	Stuck Heating Coil Valve									
	Leaking Pre-heating Coil Valve									
	Stuck Pre-heating Coil Valve									
	Leaking Mixing Box Dampers									
	Stuck Mixing Box Dampers									

Figure 4-34. Heating coil passing valve experiment.

4.3.6 Technical discussion

In this section, QMBD, a tool chain from model development to fault detection and diagnosis and its application to air handling units has been presented and discussed. As modelling language, Modelica was chosen, since it provides all the necessary tools to comply with model requirement for model-based fault detection as shown in section 4.3.4.2.

One of the main advantages of QMBD is the adaptability to different plants and to changes in the same plant. This inherent adaptability makes model-based diagnosis a viable approach to fault detection and diagnosis in air handling units. A brief description of the steps involved in adapting the qualitative model-based diagnosis is presented below.

- **Structural changes**: By structural changes it is intended the addition or removal of components or component connections. These changes will have to be reproduced in the model, which would need to be compiled and recalibrated. The diagnosis model structure is a one-to-one mapping of the model and as such only minor adaptation is needed. If the change involves different observations to be considered for diagnosis, the variable mapping between the model and sensor values has to be modified and tested with new data sets. For new components, model needs to be compiled and calibrated.
- **Parameter changes**: recalibration of the models is in principle the only requirement when a parameter is changed (e.g. because a component was changed). In the case these parameters changes have an impact in the accuracy of the model, the tolerances of the diagnosis framework might have to be adjusted.
- **Sensor changes**: similar consideration to the case of structural changes should be taken in the case of adding new sensors, removing existing sensor, or modifying position of existing ones. In the case that existing sensors are to be replaced with new ones with different precision, the steps described in the parameter changes are to be followed.
- **Changes in control**: the plant model and diagnosis framework are not at all affected by changes in the control strategy since they use the control commands as exogenous variables and the model captures the response of the physical system to any kind of input.

This adaptability makes model-based diagnosis a viable approach to fault detection and diagnosis in air handling units.

Finally, this research work presented the implementation of QMBD using first principle models. However, QMBD can work with any model accurately representing the input-output relationships of HVAC system components as the qualitative models can be generated by simulated the models with different combinations of inputs.

4.3.7 Section summary

In this section a case study showing the SAB characteristic "*Diagnoses root causes of building's performance reductions*" was presented for the diagnosis of faults in the valves and dampers in a typical air handling unit serving a dedicated room in the Cork School of Music in Ireland. The reader will note that, albeit the modelled unit was similar to that of section 4.2, the modelling tool selected was different. The reasons for the choice of Modelica as the modelling tools lies in the recent setup, by the time of starting this case study, of the IEA EBC Annex 60 (Wetter et al., 2013) and the participation of IRUSE in the Annex 60 project. The "Annex 60 will develop and demonstrate new generation computational tools for building and community energy systems based on the non-proprietary Modelica modelling language and Functional Mock-up Interface (FMI) standards" (Wetter et al., 2013). It is clear how the building simulation community is moving towards a standardised use of Modelica for modelling and simulation of buildings and building systems and this imposes a drive towards the use of such tool for the activities related to this case study.

As with the previous case studies, the choice of tool is irrelevant from a SAB point of view as long as the desired characteristics can be implemented effectively. For this case study, Modelica allowed a rapid development and implementation of a model-based diagnosis system. This case study served SAB by embedding knowledge (models and diagnosis capacity) into the system thus reducing the technical knowledge required by the building manager to address issues relating to faults in the air handling unit.

The case study also serves to demonstrate the feasibility of the implementation of fault detection and diagnosis techniques in building systems and how these contribute to the reduction of energy consumption. Furthermore, the case study expects to encourage the implementation of more stringent building energy regulations whereby an automated FDD systems must be incorporated in BMS to avoid unnecessary energy waste.

Use of detailed simulation and the incorporation of inference systems and FDD constitute the main KETs of this case study. In particular for FDD, a model-based approach (age 3) and a rule-based approach (age 2) where developed, implemented, compared and discussed to understand the advantages and disadvantages of each one.

4.3.8 Nomenclature

Variables		**Subscripts**	
eff	effectiveness [1]	*a*	air
Q	heat transfer [W]	*I*	input
c	specific heat capacity [J/kg·K]	*O*	output
C	capacity flow [W/K]	*w*	water
n	saturation efficiency [1]	**Functions**	
mflow	mass flow rate [kg/s]	max(·, ·)	largest value between arguments
T	temperature [°C]	min(·, ·)	smallest value between arguments

4.4 Age 4 BMS: Supports building managers by providing information about building's operations in a way that matches their typical skill set

This section presents a case study focussed on the SAB characteristic: "S*upports building managers by providing information about building's operations in a way that matches their typical skill set"*. In this regard, a BMS with ICT systems falling in age 4 is needed to provide the necessary data and capabilities to accomplish this SAB characteristic. In particular, the incorporation of energy management in the overall management of the facility is a key aspect of this SAB characteristic.

The aim in presenting this case study is to illustrate the main limitations of BMS and the way this can be overcome to provide methodologies and tools to support efficient building operations in a manner suitable to the skill set of the typical facility manager. This case study results show that upgrading a facility to age 4 is suitable and in many cases cost-effective. However, being this case study part of an ongoing project, the actual, long-term impact of such measures and improvements is yet to be measured.

Next it is presented an overview of the necessary steps to be taken to improve an existing facility to match the capabilities of an age 4 BMS and thus provide the necessary level of information to support optimised facility operations while matching average facility manager or operator skill set. In order to achieve this, the data needs to be pre-processed and technologies such as automated FDD, ontologies and software-based energy management standard implementation are to be integrated as explained in the following paragraphs.

4.4.1 The facility

The case study selected to demonstrate the process of upgrading an existing BMS to match age 4 requirements is the Satellite A Building of the Malpensa Airport in Milan, Italy. The location of Satellite A within the Airport Layout is shown in Figure 4-35. An aerial view of Satellite A can be seen in Figure 4-36. As can be seen from Figure 4-36, Satellite A is a separated segment of the airport terminal linked to the main concourse by a long, two stories corridor. This facility is managed by the company *Società per Azioni Esercizi Aeroportuali S.p.A* (SEA). SEA is controlled by the municipality of Milan and is responsible for the planning, construction, maintenance of airport infrastructures including their compliance with regulations.

Satellite A facility systems include four Variable Air Volume (VAV), dual-duct AHUs which service an area of 10,700 m^2. The AHUs, which schematics are shown in Figure 4-37, provide the required environmental demands for the main space of Satellite A (not including connecting corridor and boarding bridges). The AHUs comprise the following components:

- Dampers (D): serves to regulate the fractions of air through them;
- Cooling Coil (CC): used to control both temperature and humidity by cooling the air;
- Heating Coils (preHC and HC): used to control temperature by heating the air;
- Heat Exchanger (HX): used to recover heat from exhaust air;
- Humidifier (H): serves to control humidity by adding water vapour to the air;
- Variable Air Volume Boxes (VAV): mix hot and cold air streams to provide the required heat to the zone and also regulates the flow of air to the zone.

Prior upgrades, Satellite A incorporated the temperature (T) and relative humidity (RH) sensors shown in Figure 4-37. After the upgrade the minimal data set as shown in Appendix B was added to the systems.

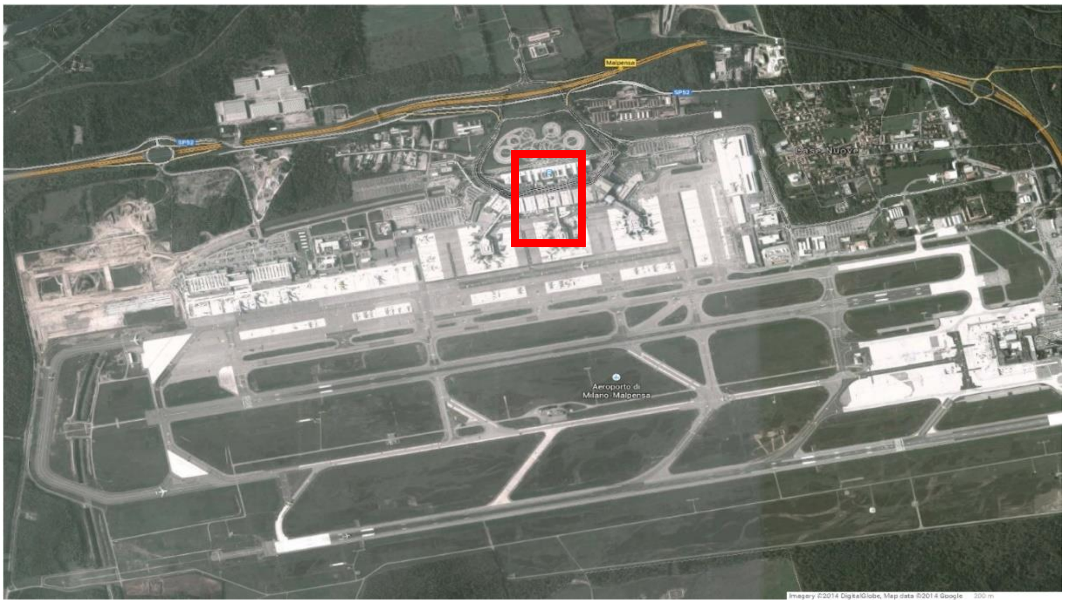


Figure 4-35. Malpensa Airport layout and Satellite A location.

Figure 4-36. Malpensa Airport Satellite A terminal aerial view. Source: (Blanes et al., 2013a).

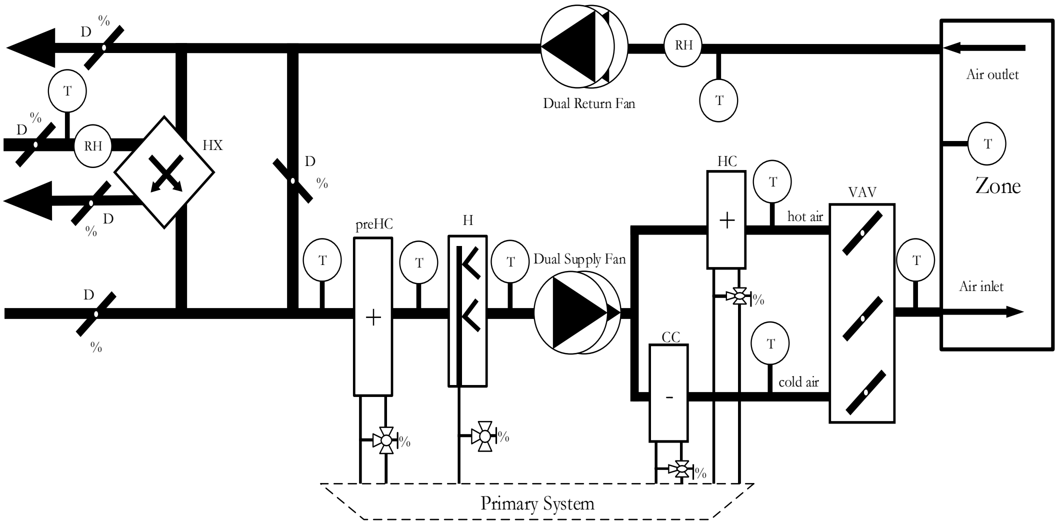


Figure 4-37. Dual duct AHU Malpensa Satellite A schematic.

4.4.2 BMS SWOT

The BMS at the Satellite A of Malpensa Airport is a DESIGO system (by Siemens). The DESIGO BMS is responsible for the supervision of HVAC systems and hot and cool water loops. The DESIGO BMS is based on BACnet protocols for the automation and management levels and LonWorks for the room automation and secondary processes. The DESIGO BMS system topology in Satellite A of Malpensa Airport is shown in Figure 4-38 and can be divided in two levels: a management level and an automation level. The primary components of the BMS are (CASCADE Consortium, 2012a):

- DESIGO INSIGHT management station for higher-level operation and monitoring, graphics-based display of the process, automatic alarm distribution and a wide range of different data analysis options using standardized protocols;

- DESIGO PX automation system for control and for operation and monitoring of primary plants. By use of PX-WEB, the automation system can be operated via a Web client;
- DESIGO TX-I/O modules, which provide the interface to the devices at the field level, the sensors and actuators;
- DESIGO RX room automation system for control of comfort conditions in individual rooms, and for operation of lighting and blinds;
- DESIGO OPEN for the integration of a wide variety of plants and protocols at all levels of the system;
- DESIGO S7 expands the DESIGO product portfolio using SIMATIC S7 automation stations for industrial and infrastructure related applications through the consistent use of BACnet/IP communications.

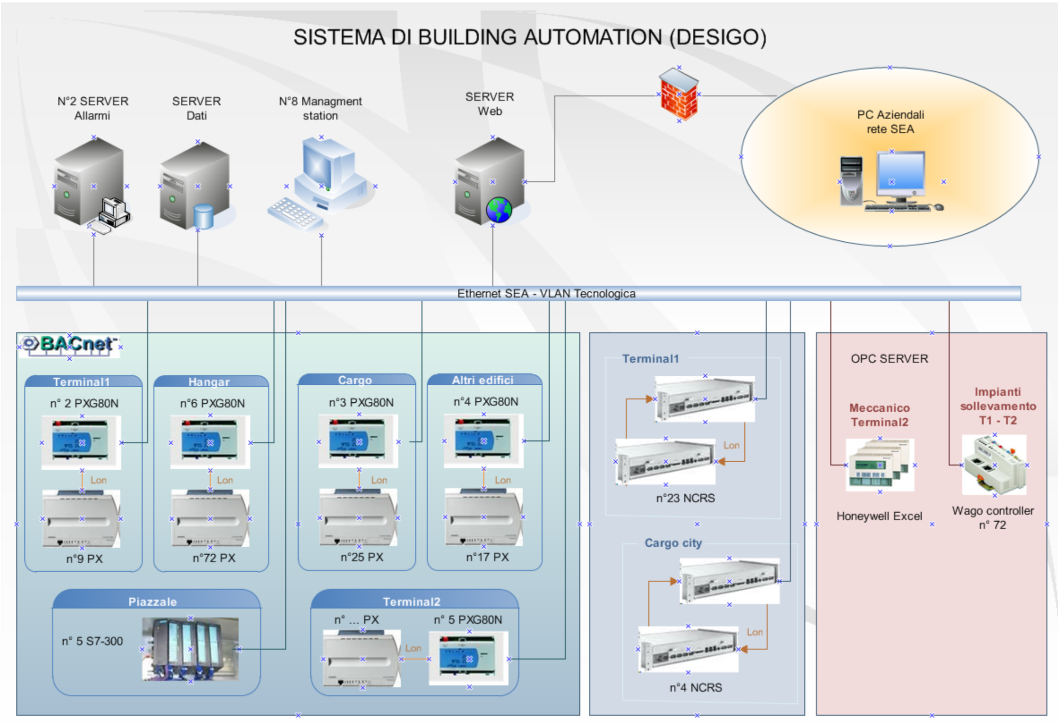


Figure 4-38. DESIGO BMS topology at Satellite A of Malpensa Airport.

In Figure 4-39, it is shown the strengths and weaknesses of the SWOT analysis of the DESIGO BMS. Data for Figure 4-39 was gathered from the Operation and Maintenance Manuals of the facility, interviews with facility manager and on-site visits. This facility was upgraded from age 3 to age 4 as can be seen in Figure 4-39.

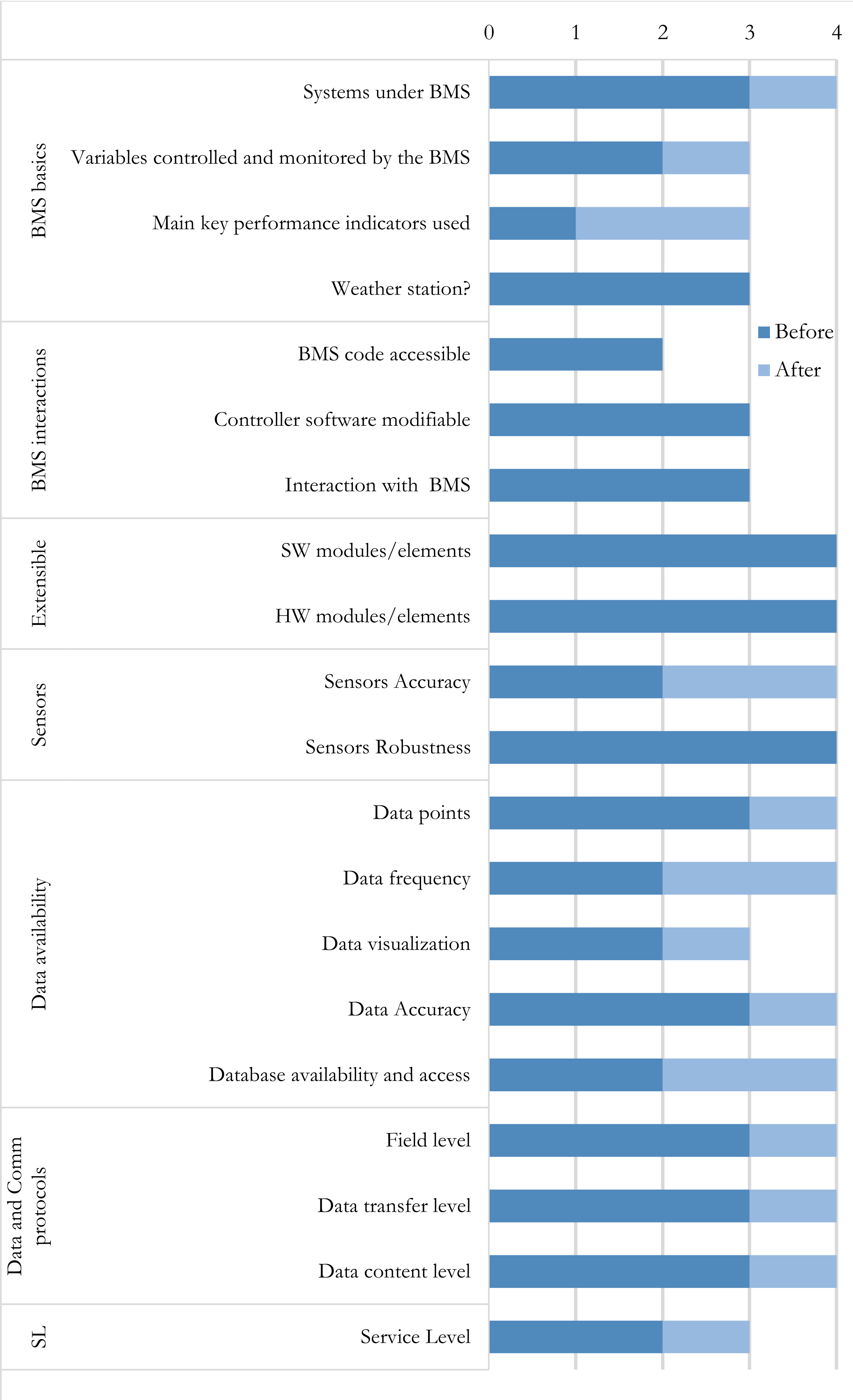


Figure 4-39. Strengths and weaknesses of the Satellite A at Malpensa Airport.

Table 4-22 replicates Table 4-1 highlighting the age 4 for BMS and the KET used for this case study. According to the table, four SAB characteristics can be carried out (characteristics from previous ages can be implemented). This case study develops the characteristics related to diagnosing root causes of building performance reductions and supporting facility managers by providing information in a way that matches their typical skill set. For the studied SAB characteristic, the main technical developments are those provided by model-based diagnosis models and ISO 50001 energy management systems. In this regard, the rest of the section discusses different approaches for such developments.

Table 4-22. BMS age vs. modelling and SAB characteristic selected for the case study of the Malpensa Airport.

Age	**1**	**2**	**3**	**4**
SAB Characteristics	None	Predicts, keeps track and monitors building's performance. Controls and adapts building's actions to the monitored/predicted performance.	**Diagnoses root causes of building's performance reductions.**	**Supports building managers by providing information about building's operations in a way that matches their typical skill set.**
What can be done?	Manual fault detection	Automated fault detection manual diagnosis	Automated fault detection and diagnosis	**Automated fault detection, diagnosis and prognosis. Decision support systems**
FDD&P Methodology Suggested	Limits and alarms	Statistical analysis, APAR rules, expert systems	Model based diagnosis, machine learning	Integration with BIM, **ISO 50001** and alike standards, **Model based diagnosis**
Modelling suggested	Expert knowledge	First principles, simplified physics, black box	First principles, detailed physics, black box, grey box	**First principles, detailed physics,** black box, grey box

4.4.3 Approach

This case study is immersed in the European FP7 project CASCADE (CASCADE Consortium, n.d.). The CASCADE project developed facility-specific measurement-based energy action plans underpinned by FDD and ISO 50001. In the CASCADE collaborative project, the author of this thesis developed the SWOT framework that is at the core of this thesis and the first commercialisation approach. Through the developments of this particular case study the author of this thesis participated in a supporting role, in particular in the development of the framework methodology for integrated customised ICT solution in BMS. The actual implementation of the methodology was performed by CASCADE consortium partners. All the information provided in this case study has been made publicly available in diverse CASCADE publications (CASCADE Consortium, 2012a, 2012c; Costa et al., 2013b; CASCADE Consortium, 2012b; Blanes et al., 2013b).

The CASCADE approach focuses on the actions which airports can take in order to address GHG sources within their control and influence, fully in the line with ACI guidelines and recommendations for the future strategic airport planning and management (Airports Council International, 2009).

A framework and methodology for building customised ICT solutions was developed in order to integrate with and on the basis of the existing ICT infrastructure and operational procedures. A measurement framework and minimal data set was incorporated to complement the existing framework and to control and benchmark the equipment performance, to optimise user behaviour, and to match client specifications.

To achieve its objectives, CASCADE developments are based on two main pillars: (i) the incorporation of automated FDD and, (ii) the integration and automation of the ISO 50001 energy management standard. The architecture of the final CASCADE solution is presented in Figure 4-40.

Automated FDD enables identification of problems in system design, equipment efficiency, and operational settings. CASCADE aims at turning FDD into the actionable information by developing an energy action plan that links Actions-Actors-ISO Standards (ISO, 2010) through a web-based management portal underpinned by an ontology engine that attaches additional/complementary meaning to the data.

Furthermore, the developed ICT solutions shall be able to integrate with existing systems to avoid unnecessary replacements.

Energy management actions in large organizations, such as airports, span across different management levels from the top level with the overall energy policy strategy and planning to the bottom with scheduled and emergency based operation and maintenance (included in the fourth SAB characteristic). In order to support top level energy management it is important to better understand the starting point of an airport in relation to its energy consumption and set reasonable targets. These reasons lead to the selection of an energy management standard such as ISO 50001 to support the overall energy management process from start to end.

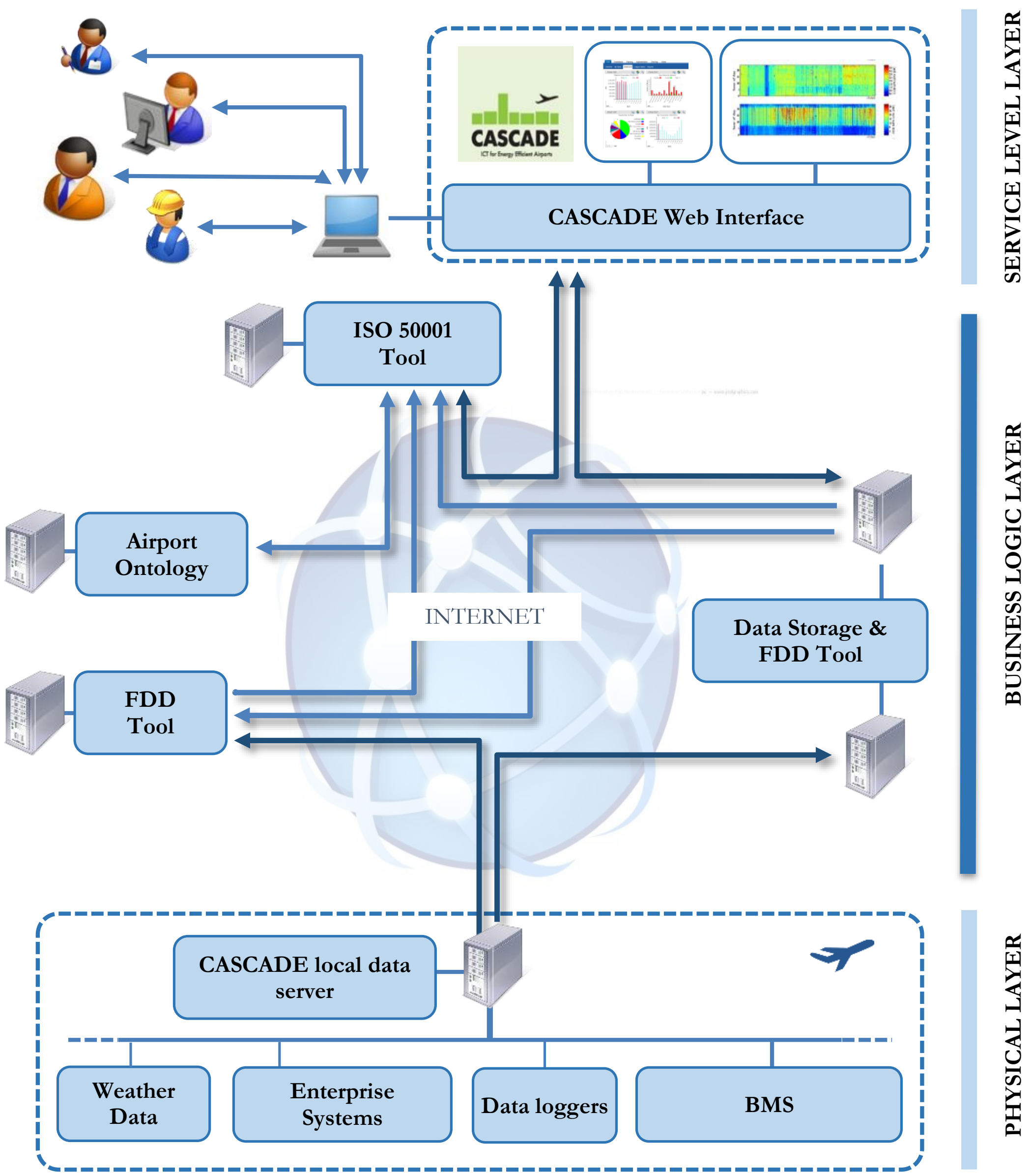


Figure 4-40. CASCADE solution overview. Source: (Costa et al., 2013b).

In Figure 4-40, three distinctive layers can be perceived:

- **Physical layer**: which concentrates the hardware and physical network used for gathering airport specific data, energy systems, environmental variables and enterprise related data. The data is concentrated in a local server in the facility which is then queried by the different tools.
- **Business logic layer**: this layer coordinates the different parts of the CASCADE solution. In this layer, raw data coming from the physical layers is transformed into actionable information to be provided to the service layer. Automated FDD (Data Storage and FDD tools) and ISO 50001 algorithms and services reside in this layer. Airport ontologies also are present in this layer. Ontologies serve to automate the transformation of data/information into knowledge by providing interpretation rules to the data that can be understood by automated algorithms.
- **Application layer**: this layer provides the final users with access and services targeted to efficient energy operation and management of the facility. This layer consists of a web-based graphical user interface that show information in a way that matches the skill set of different types of users from managers to technicians. The graphical user interface provides information ranging from simple actionable tasks to advanced visualisation of facility's performance.

Although the processes in the business logic and application layers can be standardised, it is not possible to do so for the physical layer where the data extraction from the facility and its transformation into suitable forms takes place. The reasons for the above is the diversity of systems, components, manufacturers, protocols and other data sources that are found in buildings.

To overcome these issues relating to data sources and sufficiency, within the CASCADE project a series of steps where developed to ensure the necessary data was provided in the right from to the FDD and ISO 50001 tools and algorithms. The steps are mentioned next and there are discussed in section 4.4.4:

1. Definition of a minimal data-set and data quality including the definition of KPIs;
2. Use of data points naming convention to translate the native data point names and tags into a format usable by FDD and ISO 50001 tools and algorithms;
3. Set-up an appropriate storage of the data;

4. Provision for secure and reliable data access.

Once the data is in a suitable format, the processes taking place in the business logic and application layer can be applied to the data. This process include:

- Automated FDD;
- Energy Management underpinned by ISO 50001;
- Advanced visualisation;
- Ontologies definition.

Finally, all the information generated in the business and application layer is presented to the user in the web interface. Information is visualised in different ways to users to ensure the information presented matches the needs and technical skills of the different users.

4.4.4 Results

This section explains the resulting implementation of the different aspects of the CASCADE approach that made the BMS an age 4 BMS. The aspects presented below are the ones that support the SAB characteristic: S*upports building managers by providing information about building's operations in a way that matches their typical skill set*. These aspects transform diverse data streams into knowledge representation that can be understood by humans and machines alike.

4.4.4.1 Minimal data sets

Typically, the instrumentation level of the energy systems in buildings is designed with the minimum set of sensors to allow control of the facility's environmental conditions but not enough to support optimal operation and tasks such as energy management and FDD. The Fraunhofer Institute for Solar Energy has developed a list of minimal building data-points necessary to construct KPIs and collect relevant data for FDD and energy management. This list can be found in Appendix B. The minimum data-set also includes the necessary time resolution for the data-points to ensure the collection of data captures the actual physical characteristics and dynamics of the variables being measured. The necessary sensors to achieve this minimal data set were incorporated in Satellite A of Malpensa Airport bringing to age 4 the *Data Points* characteristic as shown on Figure 4-39.

Apart from the information provided directly by the sensors and control signals, KPIs are being used in Malpensa to provide valuable information such as energy consumption, CO_2 emissions, behaviour of different devices, among others. In Table 4-23 it is shown the list of KPIs used in the Satellite A of Malpensa Airport.

Table 4-23. KPIs used in Malpensa airport. Sources: (CASCADE Consortium, 2012b, 2012c)

KPI	Units	Remarks	Frequency
Primary energy consumption	kWh / MWh / GWh	Total energy consumption at a given facility, defined as the energy that has not been subjected to any conversion or transformation process. Energy Consumption should refer to building related uses, thus not including oil consumption for ground transportation, auxiliary power units, and/or other non-building-related energy uses.	Annual Monthly Daily
CO_2 emissions	tCO_2	Direct and indirect CO_2 emissions from sources controlled by the facility.	Annual Monthly Daily
Electricity consumption	kWh / MWh / GWh	Electricity end-use consumption	Annual Monthly Daily
Gas consumption	kWh / MWh / GWh	Gas direct end-use consumption	Annual Monthly Daily
Energy consumption per passenger	kWh / PAX	Ration of primary energy consumption to annual number of passengers	Annual Monthly Daily
Delivered heating energy	kWh / MWh / GWh	Heat energy consumption by heat generators, water transport for heating duty and air transport for heating duty	Annual Monthly Daily
Delivered electrical energy	kWh / MWh / GWh	Electrical energy consumption	Annual Monthly Daily
Delivered cooling energy	kWh / MWh / GWh	Cooling energy consumption by equipment of cool generation and heat rejection, for water transport for cooling duty and air transport for cooling duty	Annual Monthly Daily

KPI	Units	Remarks	Frequency
Delivered ventilation energy	kWh / MWh / GWh	Energy consumption for ventilation and extraction only when ventilation/extraction modes are in operation	Annual Monthly Daily
Cogeneration electrical efficiency	%	Ratio of electrical energy produced per unit of gas consumption.	Annual Monthly Daily
Cogeneration thermal efficiency	%	Ratio of heat produced per unit of gas consumption	Annual Monthly Daily
Energy efficiency ratio	-	Ideal energy demand by consumed energy	Annual Monthly Daily
Solar thermal efficiency	%	Ratio of thermal energy produced by the solar thermal plant to the demand for hot water	Annual Real time
Chilled water loop temperature differential	K	Difference between the chilled water return and supply temperatures	Real time
Hot water loop temperature differential	K	difference between the hot water supply and return temperatures	Real time
Coefficient of performance	-	Equipment energy input to energy output ratio	Annual Monthly Daily
Heating coil efficiency	%	Ratio of energy consumption to thermal energy delivered by the heating coil.	Annual Monthly Daily
Cooling coil efficiency	%	Ratio of energy consumption to thermal energy delivered by the cooling coil.	Annual Monthly Daily
Humidifiers efficiency	%	Energy consumed by an humidifier in order to produce steam	Real time

The selection of the KPIs was done by applying a cost-benefit analysis between the impact of any proposed KPIs and the cost in hardware, personnel and time required to implement such KPI.

4.4.4.2 Data points naming convention

The second step that was undertaken in the case study, after ensuring all the points of the minimal data-set were being recorded, was to translate the native data-point naming used by the BMS to the standardised convention shown in Table 2-10. This process was performed by means of a spreadsheet that requires the existing naming convention as inputs and produced the standardised naming convention as outputs. Even if this process needs to be repeated for each facility, it is a fundamental one as it allows the automation of all the other tasks such as FDD and energy management. Implementing a standard naming convention prevents the need to hardcode the data-point naming of each facility in the algorithms. In the case of Malpensa airport, a series of transformation rules were applied to the data when extracting it from the BMS and storing it in the data base described in section 4.4.4.3.

4.4.4.3 Data storage and access

Sources of operational data from Malpensa airport are: BMS and data from additional sensors. All retrieved data is stored, previous pre-processing to ensure appropriate naming convention, frequency and quality, in a SQL data base installed in a server in the facility.

In Figure 4-41 it is shown the architecture for data storage and access implemented by the CASCADE project in Malpensa Airport. As can be seen from Figure 4-41, data transfer inside the facility happens over a Modbus TCP network which provide robustness, flexibility and ease of access to each data point.

For external access, in the particular case of the airport and due to security reasons, direct access to the data base and the server is given to only two entities. These entities then retrieve the data through a secure VPN connection and stores it in their own servers using HFD5-Fileformat. The data in HFD5-Fileformat may then be accessed through a web access platform via https connection.

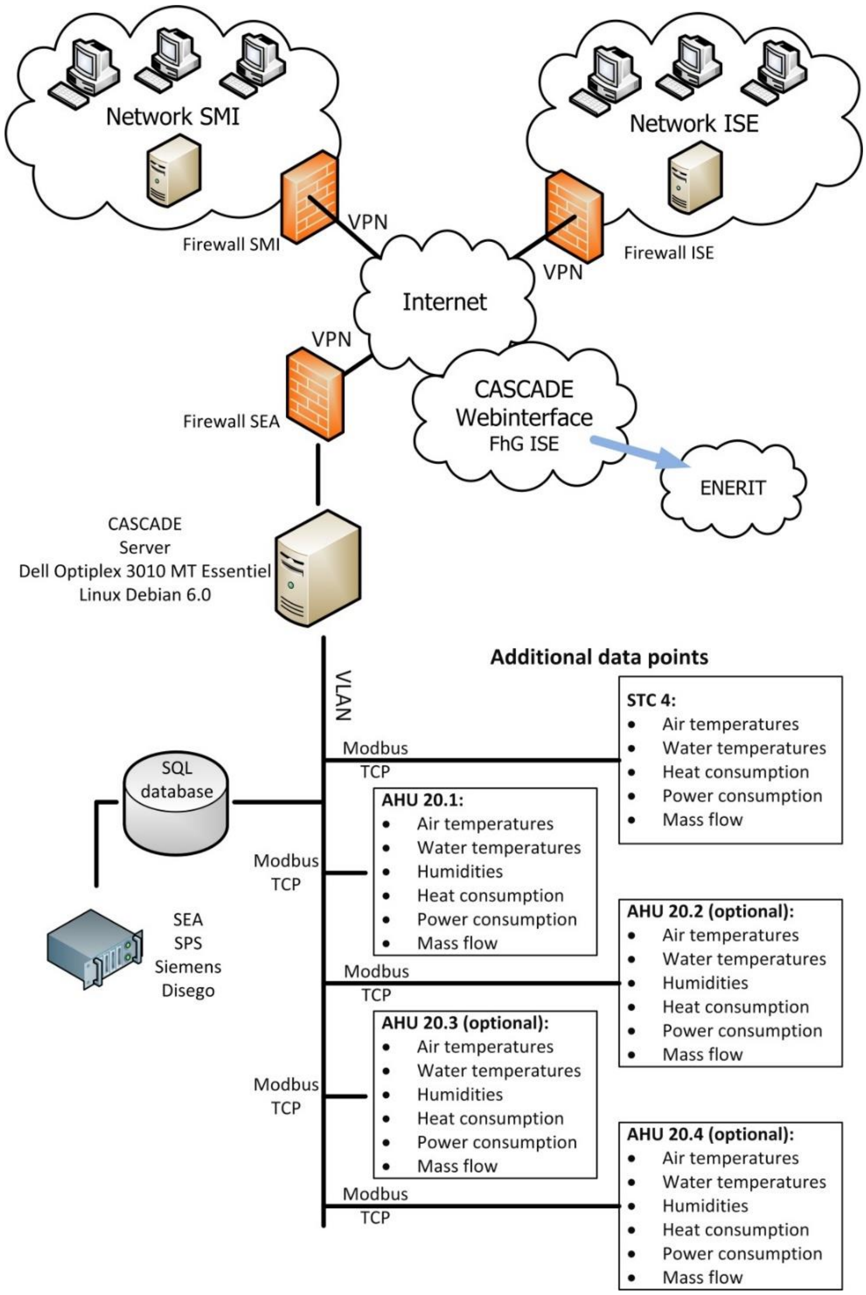


Figure 4-41. Data storage and access solution for Malpensa Airport. Source: (CASCADE Consortium, 2012c).

4.4.4.4 Automated FDD

Once data has been retrieved and stored in an appropriate format, other tasks such as FDD can be performed. Within the CASCADE project, and specifically in Malpensa Airport, a number of different methodologies for automated FDD are being tested. The methodologies are described in simple terms in the following paragraphs, for a more detailed description please refer to (CASCADE Consortium, 2012b):

- **Sensor fault detection**: used to identify sensor issues that lead to incorrect measurement that translate into incorrect data analysis. To perform sensor fault detection, a classifier is previously trained with normal and faulty data and then used to recognise the patterns in the real data coming from the sensors. Sensor fault detection ensures a high quality of data is being used for the rest of the FDD and energy management processes.
- **Rule-based fault detection**: aimed at detecting faults at system level such as AHU, Heating, Cooling, among others. For AHUs, the rule-based method is based on the APAR rule set (House et al., 2001). However, before applying the rule-set, the data is run though a pre-classifier routine based of Mollier enthalpy diagrams of moist air. The pre-classifier is used to identify the state in which the AHU is operating (humidification, heating, cooling, fresh air and combination of these) and to detect faults of the type of simultaneous heating and cooling.
- **Model-based fault detection and diagnosis**: two model-based FDD techniques are implemented, the first one using a trained regression model to detect pattern deviations at systems level such as excessive daily consumption, and a second method based on a qualitative model that identifies if the sequence of states any element has undertaken corresponds to a normal operation mode or a faulty one..

The implementation of the three methodologies ensures that faults are detected from sensor level to systems level and also increases the robustness of the implementation by reducing the possibility of providing false positives.

4.4.4.5 Advanced visualisation

The CASCADE solution improves on existing data visualisation capabilities of the BMS and allows to perform four types of visualisations:

- **Time series plots:** that show values in a chronological sequence;
- **Scatter plots (XY plots):** to show the dependencies between two variables;
- **Carpet plots:** carpet plots are basically colour maps displaying long time series of a single variable. It is used to identify patterns in the behaviour of the variable;
- **Box plots:** used to show the variation of a variable through time by grouping the information in days or months.

The advanced visualisation capabilities are very useful for the expert in building operations. However, the average facility manager needs special training to interpret the information provided by the visualisation techniques alone. To overcome this, an ontology is used to add meaning to the data as explained in section 4.4.4.6.

4.4.4.6 Ontologies

The development of a facility specific ontology, an airport in this case study, is one of the key aspect of the development of CASCADE that make the facility comply with the SAB characteristic under study. The ontology provides a framework for data classification whereby data is extended with meaning based on a-priori knowledge of the systems entities, interactions, actors and concepts (Tomašević et al., 2013). The main advantage of using ontologies is the ability to attach knowledge to the data in a way that can be understood by humans but also, used by computer programs to create inferences. In practical terms, the ontology allows a data point to be linked with its location, equipment, use and significance. This is done by developing the ontology in a way that models the building domain, provides a technical characterisation, creates a semantic representation of the data and incorporates a topological profile of the facility (CASCADE Consortium, 2012b).

4.4.4.7 Energy management: ISO 50001

The ISO 50001 Energy Management Standard provides organisations with the necessary tools and processes to improve energy performance of their facilities, regardless of the size and use. Implementation of the standard requires that an energy policy is developed and implemented by the organisation via a series of actions, objectives and targets. The energy policy takes into account not only the energy needs but also legal, managerial, technical and organisational aspects related to energy efficiency. Furthermore, the standard provides means for measuring and documenting actions and results. The standard, bases its methodology on the plan-do-check-act (PDCA) continuous improvement framework aiming and incorporating energy management into the everyday organisational aspects of the facility. Figure 4-42 provides an overview of the PDCA approach for ISO 50001.

In CASCADE, ISO 50001 standard has been implemented by means of the Enerit Energy Management Tool (Enerit, 2010). This software tool automatically manages all the aspects of the ISO 50001 and provides a consistent organisation of the actions and automatically monitors the whole process from creation of the action to closure of the same by the energy manager. This is a core development as it relieves the energy manager from many organisational aspects allowing him/her to concentrate on actual optimisation of the energy consumption in the facility.

In CASCADE, the Enerit Energy Management Tool has been extended to include information provided by the FDD tools, incorporate advanced visualisation and, the airport ontology. This combination allows this case study to provide information with different levels, each one matching the specific skills of the particular user, from the operators or technicians to the facility and energy managers.

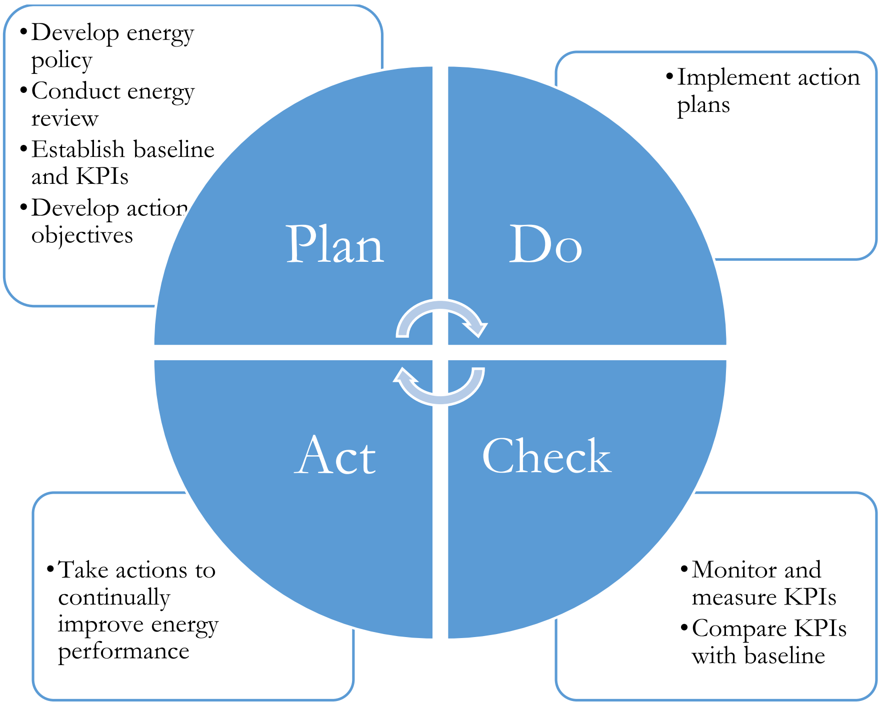


Figure 4-42. PDCA in ISO 50001.

4.4.5 Technical discussion

In this section it has been shown the necessary steps to be taken to achieve the SAB characteristic whereby a building provides information in a manner suitable to the skill set of the user. Buildings nowadays produce vast amounts of data but little of it is actually used in any further operational optimisation action. This information is provided by an instrumentation that in most cases is insufficient to support energy efficiency actions. One of the key aspect of a SAB is to provide useful information to the users, the first step to achieve this is to implement a minimal data set, normally greater than the instrumentation of a typical facility, so enough data is collected to support energy efficiency measures. Subsequently, this data needs to be pre-processed to ensure consistency and quality. The use of a standardised data-point naming convention allows for the standardisation of processes such as data quality control, FDD and visualisation of data, greatly reducing the implementation cost of these technologies. After pre-processing, the data is stored in a data base for further analysis. Up to this point the process has focused in transforming the data into a suitable format for further analysis. The following steps, automated FDD, advanced visualisation, ontologies and, energy management, can be implemented independently depending on the real needs of the facility. However, it is the combination of all of them that can automatically provide information in a way matching the skill set of the user.

Advanced visualisation can provide the necessary information to an expert but, it might not be easy to interpret by the typical facility manager. On the other hand the combination of a simplified visualisation with extra information, automatically generated, such as fault reports, expected behaviour according to benchmarks, indications of the type of data and the location of the sensor might be more helpful to the operators or technicians.

4.4.6 Section summary

In this section a case study showing the SAB characteristic "S*upports building managers by providing information about building's operations in a way that matches their typical skill set*" was presented. Being this case study one pilot case of an FP7 EU project shows how the EU community is driving research towards the implementation of high-impact measures for the reduction of emissions in buildings, particularly in public spaces.

This case study shows how even old facilities can be made fully SAB by the use of the KETs identified in this research work.

Contrary to the other case studies, the modelling involved for this case study[30] was not reviewed in depth. Instead, of more interest to the SAB characteristic under review, it was presented the implementation of automated energy management based on ISO 50001 standard and the incorporation of ontologies to attach meaning to the data. These were the main KETs bridging the knowledge gap between facility managers and building systems.

[30] The CASCADE Project involved several modelling activities but for the purpose of this case study, and to avoid unnecessary repetition, they were not included.

Standardisation in data is the key to unlock the full potential of innovative KET for buildings systems and the results of this case study aim at encouraging policy to foster a broader standardisation in the different aspect of building operations.

In Chapter 3, it was discussed how facility managers are still sceptical about the real value of automated FDD as it was perceived as an extension of the alarm functions already incorporated into BMS. This perception may be changed if fault notifications are complemented with specific corrective actions to be automatically created, assigned and tracked. This is achieved in this case study by integration of automated FDD in the ISO 50001 energy management implementation that does the process of automatically creating, assigning and tracking the actions until their completion. Furthermore, with the use of ontologies, such actions could be complemented with much richer information reducing the users' need of interpretation and post-processing of data.

4.5 CHAPTER SUMMARY

In this chapter, different case studies dealing with the four different aspects of SAB were presented. Table 4-24 provides an overview of the different policy, socio-human, market and SAB aspects addressed each case study. In particular, the case studies results were used to:

- Demonstrate the use of the combination of SWOT analysis (section 3.5) to identify building's age as an standardised assessment tool for evaluating building systems (section 2.1.5 and point 'h' of section 2.2.4);
- Demonstrate the utility of Table 3-5 in in combination with the SWOT results (section 3.6) in implementing SAB characteristics in buildings depending on their identified age (section 3.4);
- The combination of the two previous points in informing decision makers on the possibilities BMS have for the implementation of technologies aiming at improving energy efficiency in buildings (section 2.1.5 and point 'g' of section 2.2.4);
- Demonstrate repeatability of the combination of SAB concept, SWOT analysis and Table 3-5 (point 'f' of section 2.2.4);

- Show how technologies aimed at bridging the knowledge gap between facility mangers and building systems can be applied in real facilities.
- Sections 4.1 and 4.2 show the possible approaches to utilise the information provided by different types of building management systems prior any upgrade;
- Sections 4.3 and 4.4 demonstrate the support the SWOT analysis (section 3.5) and Table 3-5 provide in the upgrade process in face of integrating technologies aiming at both, implementing energy efficiency measures and reducing the knowledge gap between facility managers and building systems (section 2.2.2);
- Aggregate different technologies in delivering energy efficiency (section 2.3);

For technical conclusions on each case study please refer to Chapter 5.

Table 4-24. Linking case studies with findings from literature review.

Case Study	SAB Characteristic	Main bridging capacity embedded	Main technologies used for implementing SAB characteristics	How is policy-making being supported?	What socio-human barrier is addressed?	What market barrier is addressed?
Nursing Library	Predicts, keeps track, and monitors building's performance.	Memory incorporated into the system.	Artificial Intelligence: Artificial Neural Networks.	Demonstration of the difference between the energy consumed and the energy predicted.	High visibility of energy gap can be linked to production to show the importance of energy management.	Repeatability of the measures by the implementation of a methodology to evaluate the systems, decide the technologies and implement the solutions.
Kingfisher Swimming Pool	Controls and adapts building's actions to the monitored/predicted performance.	Embeds knowledge and acting capacity in the facility.	Artificial Intelligence: Artificial Neural Networks; Building Performance Simulation.	Demonstration of how automation reduces energy consumption.	Automated optimisation reduces the need for high expertise by the building manager to decide on control actions.	
Cork School of Music	Diagnoses root causes of building's performance reductions.	Embeds knowledge and self-diagnosing capabilities.	Detailed Simulation; Artificial Intelligence: Propositional Logic and Inference Systems.	More stringent regulations can be put in place that demand optimal system's operation at all times; Actual performance can be evaluated.	Enables the possibility to automate most steps and thus reduce the knowledge needed by the person performing the SAB characteristic; Information is processed and delivered as knowledge to the manager so action can be taken.	
Malpensa Airport	Supports building managers by providing information about building's operations in a way that matches their typical skill set.	Information is linked to meaning enabling automated analysis.	Ontologies; ISO 50001; FDD; Performance Simulation; Advanced Visualisation.	Demonstration and methodology to implement energy management in existing buildings; Policy can now be addressed to existing and even old facilities	Most of the energy management actions are automated so the capacity gap is bridged to the maximum extend the technology allows; Energy Management ensures efficient building operations and maintenance is carried out.	

CHAPTER 5

CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

This chapter presents the main conclusions from this thesis work. Concluding remarks are presented regarding the policy, socioeconomic and technological aspects that could drive energy efficiency in future building operations. The chapter continues with remarks relating to the requirements for Building Management Systems (BMS) in actually supporting optimised energy efficiency and implementing the Self-Aware Building (SAB) concept. Conclusions based on the implementation of the different SAB characteristics in the case studies are also presented.

The chapter concludes by providing recommendations and future work based on the results of this thesis.

5.1 CONCLUSIONS

The main conclusions from each section of the thesis are summarised in the following bullets points:

- Outcome-based building energy regulation approaches are needed to overcome the market distortion of current approaches that encourage retrofitting actions regarding installed equipment and materials rather than continuous optimisation of operations;
- The impact of the end-user in energy consumption in buildings is underestimated by policy expecting reasoned rather than idiosyncratic behaviour. The reality is that energy efficiency is underrepresented in

educational programmes worldwide and therefore users are not prepared to make energy efficient decisions;

- Although educations and training is needed to increase the favourable impact of users in building's operations, it has been recognised that it is unrealistic to expect a major future increase in the typical building manager skillset. In this regard, a capacity gap existing between buildings systems and users' needs to be filled by technology embedded in the systems themselves;

- To increase the penetration of technologies supporting energy efficient building operations, standardisation at different levels of building operations is needed, in particular in data management but also in the approach to evaluate building before implementing technologies;

- The SAB concept and associated framework deliver the necessary standardisation to enable energy efficient building operations through integrated key enabling technologies;

- Fully achieving SAB means a conceptual change whereby energy is managed and optimised as an asset rather than utilised as a utility. In this sense, a SAB is not necessarily a fully automated building but a building that incorporates the necessary characteristics to continuously operate optimally and efficiently support users in the application of energy conservation measures;

- A SAB is a building that: (i) predicts, keeps track and monitors building's performance; (ii) acts in consequence of the monitored performance; (iii) automatically diagnoses root causes of performance reductions and; (iv) supports building operations by providing information in a suitable manner depending on the specific skillset of the particular user

- The implementation of the four SAB characteristics in the respective case studies produced the following main technical conclusions:

    - Accurate models can still be developed, even when few measured variables, through machine learning techniques to provide prediction and automated monitoring capabilities to facilities systems;

- A combination between simulation models and machine learning techniques allows for the successful integration of knowledge and acting capacity in facilities that results in energy savings;
- Model-based diagnosis can provide more robust and accurate diagnosis capabilities than rule-based methodologies;
- Once data streams are standardised, it is possible to effectively integrate energy management with fault detection and diagnosis and ontologies in a broader range of facilities, in order to enable continuous and automated energy optimisation of buildings.

Subsequently, full concluding remarks per each section of this thesis will be presented.

5.1.1 Policy drivers

The building sector is diverse. Within this diversity lies a fragmentation of work practices; management and monitoring tools for energy efficient operations and; metrics, regulations and standards needed to evaluate buildings based on real energy consumption. In section 2.1.1, it was established that international organisations such as the European Commission, the International Energy Agency or the United Nations, recognise the issues arising from the lack of standardisation and agree that the correct combination of policy, technology and behavioural change is needed to bring about demanding energy efficiency targets. However, this combination is yet to be realised as even these international organisations don't agree on the paths to be taken aimed at improving building operations. Nonetheless, a convergence on the need for a combination of outcome-based policies (e.g. regulations, white certificates) appears to be gaining ground as the most efficient way to ensure optimal building operations.

To ease the path towards the paradigm shift that represents outcome-based building operations, a combination of direct and indirect policy mechanisms is needed (sections 2.1.2 and 2.1.3). Direct mechanisms seem more suitable for targeting the physical aspects of buildings (e.g. geometry, materials and technologies) while indirect mechanisms appear to be suitable for influencing the behavioural change by creating the awareness and public engagement needed to finally achieve energy efficiency targets.

Today's policy on building energy efficiency varies from different types of constructions and from country to country. This is a result of the diverse realities. For example, Europe will see little future floor-space growth when compared to Brazil, China and

India who will represent the bulk of floor-space growth worldwide up to 2050 (section 2.1.5). However, in the EU, policy focuses mainly on new constructions and large renovations, while not enough attention is paid to the efficiency of those existing buildings not undergoing renovations.

In the EU, policy demands that all buildings must be assessed and certified as a way to encourage more efficient operations (section 2.1.4). However, many opportunities might be missed by current assessment procedures. This is as a result of assumptions made when assessing a particular dwelling since a proper case-by-case assessment is not carried out (Kelly et al., 2012). Furthermore, current EU policy seems to be creating a market distortion where the regulations encourage refurbishment actions regarding installed equipment and materials substitution, rather than continuous optimisation of equipment operations. This may result in even higher energy consumption and associated GHG emissions in the building's life-cycle (García Casals, 2006). The only difference is that the GHG emissions resulting from the refurbishment are released in the third-party countries that produce the materials for such renovations (e.g. a refurbishment in an EU country might result in elevated emissions in some Asian country where the materials are manufactured). However, from a global point of view, the impact of the benefits from the renovations is reduced. If policies broaden their scope and account for building's life-cycle, it will become clear that optimisation of operations should be the first step of any retrofitting scheme.

An approach to correct this situation is to develop policy measures that incentivize optimal operations of building systems before retrofitting or equipment change. Currently, as stated by Prill (Prill et al., 2009), operation and maintenance of systems is largely prescriptive and in most cases there is no assessment after commissioning. Policy must strive to improve operations and, in this sense, Prill proposes a labelling for rooftop air conditioning units that assess energy efficiency of the units under operation and has a short period of validity to encourage a continuous monitoring of the facilities.

Eventually, developed countries will have to shift to an outcome-based regulatory framework for building operations in order to meet stringent global environmental concerns. Developing countries will follow by adjusting the policies of developed countries to their particular needs. However, these countries are more in need of better building energy policy. For developing countries, where the floor area will dramatically increase in the years to come, regulations promoting a prescriptive approach combined with the outcome-based approach for building operations could have the necessary impact.

Regulations that either directly or indirectly target the engagement of the end-user in energy efficiency measures, have been shown to be successful in delivering results beyond expectations in the countries where such policy measures have been applied (section 2.1.3). These results are achieved because users have the biggest impact on energy consumption. In this regard, it follows that information and education campaigns and policy measures aiming at behavioural changes may have great impacts.

The implementation of government-led programs in large buildings of public use (Yan-ping et al., 2009), particularly those buildings owned and/or managed by the State, is encouraged as a starting point serving a double purpose: testing the applicability of energy efficiency measures (political, social or technological) and educating the population in relation to energy efficiency in buildings issues. This holds for developed and developing countries alike. As a result, public-use buildings will serve as demonstrators to provide a greater understanding of the user's influence and reaction to the measures.

Finally, on a technical note, it is known that the biggest share of energy consumption comes from office and commercial spaces (Iwaro & Mwasha, 2010), all which have some form of HVAC system in place. Many of these HVAC systems operate far from optimal conditions. Public-use buildings normally incorporate HVAC systems reinforcing their suitability as a test bed for the implementation of energy efficiency measures. HVAC systems and buildings of public-use were used as main demonstrators for the SAB concept.

5.1.2 Socio-human and market drivers

In section 2.2, it has been discussed that, contrary to what policy expects, many of people's decisions on building operations follow idiosyncratic rather than reasoned and predictable behaviour. People's decisions on building operations are based on the cultural and educational background and the actions believed to bring an increased comfort in the short term (e.g. opening a window to reduce overheating rather than reducing the thermostat's set point, with the added advantage that the building is being aired). As a consequence of the approach taken by current policy when dealing with people's behaviour, the actual impact of building users on the built environment, although known to be high, is poorly understood and often overlooked (Janda, 2011). In this regard, Harrigan (Harrigan & Curley, 2010) shows that energy efficiency is under-represented in national and international environmental education programmes, so policy assumptions on people's readiness to make energy-efficiency decisions are unrealistic.

The first barrier to be tackled for improved building operations is to really understand how energy is used, not only by equipment but also the impact users' decisions have on building energy consumption. Another barrier, which may also have its root cause in peoples' idiosyncratic approach to building operations, is the fact that energy is still seen as a utility and not as an asset. This results in energy being used (and many times wasted) and not managed (and optimised) as discussed in section 2.2.1.

Integrating energy management in building operations, in particular in buildings of public use and those incorporating HVAC systems, requires a combination of high technical skills and deep knowledge of the building from the person responsible for building operations (e.g. facility manager). He/she is the key person and decision maker in building operations and his/her actions have a deep impact on energy consumption. However, the truth remains that most facility managers do not have the required educational and technical skills to effectively optimise building operations with current tools. Furthermore, this lack of skills makes facility managers more prone to make decisions on energy matters based on their idiosyncratic and cultural background rather than in proven good-practices.

Two problems need to be addressed before energy management can be successfully incorporated in building operations: (i) building management tools need to provide the proper information for optimised building operations and (ii) the gap between the facility manager's skill set and the skill set required to manage the building optimally. In the current socio-economic-technological state of facilities management, it is unrealistic to expect a future increase in the skill set of the typical facility manager. This is a consequence of the diversity of the building sector, the wide range of technologies used, the typical workload of facility managers and the resources typically allocated for facility management (sections 2.2.2 and 3.3.1). The solution then lies in embedding the knowledge needed in the building systems themselves so the information provided by them doesn't really need interpretation and can be translated into actionable tasks for the facility manager to carry out. This approach, incorporated in the SAB concept, solves the two problems afore mentioned.

The benefits of energy efficiency in building operations are not only environmental but in many cases also economic as shown in section 2.2.4. In the section it was shown how payback periods for many energy efficiency measures are short and that many measures require an optimisation of operations rather than any physical change in the building. It is important to stress that energy efficiency measures need continuity for them to be really effective and provide long-term impacts.

Finally, there is a market to be exploited in optimised building operations in the form of building performance services (commissioning, re-commissioning, continuous commissioning, fault detection and diagnosis, improved monitoring, performance prediction, etc.) and a combination of political with technological and standardisation measures are needed to fully develop this market.

5.1.3 Technology

Although technology exists for delivering improved building operations and even for effectively integrating intelligence in building operations, the truth remains that many factors are still preventing an appropriate implementation of innovative technologies for energy optimisation of buildings. On the one hand, there is the lack of the appropriate infrastructure, such as non-standard/proprietary communication networks and poor data access and management capabilities of existing BMS (sections 2.2.1 and 3.1). On the other hand, there is the organisational/managerial problem whereby the lack of an appropriate skill set of building operators translates into missed opportunities.

The realisation of such problems exist at stakeholder level and actions, although fragmented, are being taken to address the problems. The standard EN15232 provides a starting point and can be used directly as a tool to qualify the energy efficiency of building automation and control. However it does not account for improved building's intelligence. Such a tool for demonstrating the impact of embedding intelligence in building operations is missing. In fact, standards on building automation are focusing on the advantages of increased automation but not demonstrate how to turn that automation into improved building operations and even less into intelligent operations. In this sense, as was stated, a building conforming to standards may be highly automated but not intelligent nor energy efficient.

Standardisation in data management (including data point naming, data protocols, etc.) is a cornerstone for improved building operations. It will allow standard methodologies and tools to be developed in a more general fashion rather than in the case-to-case basis as today. Wireless technologies, Semantic Data, Ambient Intelligence and the concept of the Internet of Things (Atzori et al., 2010) will help in this regard by increasing the amount of useful information that can be transformed into knowledge and by providing the basis for automatically transforming data into knowledge.

The main advantages of artificial intelligence (AI) over traditional monitoring and control techniques include memory, learning, reasoning, optimisation capacities, possibility to deal with poor and fragmented data, etc.

Methodologies such as intelligent and automated facility and systems scheduling, performance prediction and fault detection and diagnosis can readily deliver impacts on building's energy consumption at reduced costs. However their broad industrial uptake is yet to be seen. Reasons for this lack of industrial uptake point towards a resistance on the side of the decision makers to adopt these technologies as they are wrongly seen as overlapping in functionality with those already incorporated in BMS. Once these key technologies have been accepted and broadly incorporated in building operations, a step forward can be taken by developing 'intelligent' Decision Support Systems and Controls that act on the basis of the information provided by the afore mentioned key technologies.

Futuristic visions for intelligent control in building operations leverage the ever increasing pervasiveness of internet-enabled devices, including those forming part of the buildings and also those carried (and many times 'worn') by the users in a new paradigm concept called "Ambient Intelligence" (AmI) (Ducatel et al., 2003). AmI includes devices not actually forming part of the building standard systems (e.g. portable electronic devices). The concept behind AmI encompasses that of the Internet of Things and extends it by applying intelligent techniques to the data provided by the interconnected devices.

Finally, there is a need to fill the knowledge-gap between building operations and building operators and a step towards this realisation is the introduction of the SAB (section 2.3). Technologies are in place for achieving SAB but they still need to be incorporated in the building's infrastructure and brought to the attention of the relevant stakeholders.

5.1.4 Building management systems: past, present and future

BMS have the potential to greatly contribute to global energy efficiency and carbon reduction goals. All of the technologies needed for the implementation of the continuous monitoring and maintenance as envisioned for the future of BMS exist today and are available in the market with different levels of development. Wireless technologies and low-cost electronics are helping to reduce the cost associated with the installation and retrofitting of such systems. Manufacturers already have in place proprietary tools to enhance energy efficiency and promote them in the market.

However, different barriers are faced by products and tools when trying to be incorporated in building operations (section 3.2). Such barriers are largely managerial and organisational rather than technical, as incorporation of innovative tools is often omitted when the traditionally short-sighted cost-analysis is applied on the cost-driven building environment. In this regard, a regulatory framework establishing an outcome-based methodology for building energy rating, as opposed to the prescriptive-based framework in existence in most countries today, could be the solution to foster building energy optimisation (García Casals, 2006).

In fact, Pérez-Lombard (Pérez-Lombard et al., 2009) already proposes how an energy certification in buildings should be implemented. A seven-step approach is discussed by Pérez-Lombard, from the definition of adequate energy performance indicators to how the energy certificate should look like. However, this approach is still static and evaluates how energy efficient the building could be, assuming proper operations, as opposed to actual efficiency. Some policy instruments to reduce energy consumptions can be found in the report on buildings and climate change by the UNEP (United Nations Environment Programme, 2009) but, as it happens with the Energy Performance in Buildings Directive (*Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast)*), implementation details are left open for interpretation reducing the impact of the instruments.

Today we are at a cross-roads. Energy efficiency is very topical at all levels of society. However, the regulatory frameworks are somehow narrow, as they address the energy consumption problem from the energy supplier point of view, not from the building energy demand, operations and management point of view. To exemplify, a change in one component might reduce the energy consumption for a number of years, however, the mere fact of changing such component affects the cost of the building's life cycle because the new component needs to be manufactured and transported and the old one needs to be decommissioned and/or recycled. All of these activities are energy intensive and the gain in efficiency from the new component may be offset by the energy-intensive fabrication/transport processes involved. In many cases, a simple optimisation of the operation of the existing component or system will achieve a bigger impact. The cross-roads is deciding if the narrow vision and the prescriptive-based regulatory framework will continue to be enforced or if a shift towards outcome-based operations will be chosen.

The vision is that all, or at least most of the BMS will incorporate technologies that place them in age 4 (section 3.4) and deliver tangible energy reduction in the built environment. Age 4 means optimised operations and not necessarily the replacement of components. The process under which these future BMS will work was depicted in Figure 3-6. Although the technologies are mature enough, there are still a number of technical and non-technical barriers that must be overcome and in a cost-effective manner. Table 5-1 attempts to link the needs for achieving the desired age 4 with cost-effective actions or solution addressing (partly) these needs.

Table 5-1 is indicative to show that solutions that address the identified needs exist today or may become available soon if the actual need arises.

The SWOT analysis framework presented in section 3.5 is an attempt to characterise building information and communication systems and place them in the pre-established technology framework delimited by the building ages (section 3.2). The SWOT framework takes into account top-level information that, during the experience of the author of this thesis, is normally available in most facilities. The purpose of the SWOT framework is to serve as a basis to understand what innovative capabilities can be included in the building by means, for example, of Table 3-5 (section 3.5.3) in order to bring buildings at some standardised level that can be used not only to improve operations but also to compare different buildings.

It is of interest to note the close relationship between the SWOT analysis and the implementation of Energy Management such as the ISO 50001 tool. This relation can go two ways: the SWOT can be used, during the planning phase, to understand what is needed for the facility to implement an ISO 50001 energy management framework or, on the other hand, the ISO 50001 can be one of the goals to achieve an age 4 building under the SWOT analysis.

Table 5-1. BMS needs to support energy efficiency in buildings advances.

Needs	**Cost-effective solution**
More and better monitoring	Wireless sensor networks
Better integration	Open or standard communication protocols
Increased inter-operability	Standardisation of point naming conventions
Major acceptance	Incentives Regulatory outcome-based framework Improved training for building manager (at least in the transitional stage) Extensive field studies
Move from data-rich to information-rich environments	Better visualisation and reporting tools and capabilities Incorporation of energy management standards
Possibility to test energy efficiency measures before commissioning them	Integration of simulation capabilities in the BMS

5.1.5 Self-aware buildings characteristics implementation

Section 2.3 states that a SAB is a building that, without the need for high automation, has the following characteristics:

- Predicts, keeps track, monitors building's performance;
- Controls and adapts building's actions to the monitored/predicted performance;
- Diagnoses root causes of building's performance reductions;
- Supports building managers by providing information about building's operations in a way that matches their typical skill set.

In section 3.2, the evolution of building management systems was devised into four 'ages'. Each age corresponding with a technology leap from the previous one towards the realisation of the SAB concept. The ages indicate the readiness of a building to incorporate elements from the SAB concept.

According to the identified BMS age (section 3.2), Table 5-2 (recapitulating from section 3.5.3), shows technologies that provide the necessary support for SAB characteristics.

The rest of the section provides conclusions on the implementation, through case studies, of each SAB characteristic.

Table 5-2. BMS age vs. FDD&P approach, modelling and SAB characteristics.

Age	**1**	**2**	**3**	**4**
SAB Characteristics	None	Predicts, keeps track and monitors building's performance. Controls and adapts building's actions to the monitored/predicted performance.	Diagnoses root causes of building's performance reductions.	Supports building managers by providing information about building's operations in a way that matches their typical skill set.
What can be done?	Manual fault detection	Automated fault detection manual diagnosis	Automated fault detection and diagnosis	Automated fault detection, diagnosis and prognosis. Decision support systems
FDD Methodology Suggested	Limits and alarms	Statistical analysis, APAR rules, expert systems	Model based diagnosis, machine learning	Integration with BIM, ISO 50001 and alike standards
Modelling suggested	Expert knowledge	First principles, simplified physics, black box	First principles, detailed physics, black box, grey box	Integration with BIM, ISO 50001 and alike standards

5.1.5.1 Predicts, keeps track, monitors building's performance

In order to implement this SAB characteristic, a minimum level of instrumentation is needed as shown by the SWOT analysis in section 4.1.2. Computer simulation models are more suitable in implementing automated monitoring or prediction of the building's performance. The main technology presented in this research work for implementing the current SAB characteristic is the development of simulation models, either white, black or grey box, that accurately represent the behaviour of the desired building variables.

The models developed in the case study require very few measured variables to produce accurate results, especially the black box models. This fact makes black and grey box approaches appropriate for applications such as those were little data is available for learning. Nonetheless, the accuracy of the solution will always depend on the quality of the data provided to the models and that is why the SWOT analysis needs to be carried out in order to ensure the data quality is sufficient for developing accurate models.

Finally, the initial set-up of such models nowadays requires some expert to develop the model and link them to the facility. This results in added cost and less broad uptake of the technology. In the future, when the building sector is more standardised, and data-point naming conventions are the norm (section 3.5.2), models will be automatically developed and thus reducing time and cost of the implementation.

5.1.5.2 Controls and adapts building's actions to the monitored/predicted performance

In the case study presented in section 4.2, a methodology was described for the application of simulation techniques to a swimming pool environment aimed at its application in energy efficiency studies, specifically to automate the schedule of the facility based on predicted performance. The case study builds from the simple prediction or monitoring presented in the previous case study and adds the SAB capability of being able to automatically act on predicted behaviour.

The proposed methodology leverages the use of the Building Control Virtual Test Bed (BCVTB) to couple different simulation environments in order to integrate and complement the capabilities of the different tools and ultimately integrate and embed the knowledge from different experts into the facility. Results obtained from the simulation of the case study were used to train an artificial neural network (ANN) to predict the optimal end of setback of the swimming pool hall if the temperature set-point is reduced during unoccupied hours.

The BCVTB provides researchers with an innovative and powerful tool for the study of complex systems. The idea of 'divide and conquer' can be easily implemented by using the best modelling and simulation tool for each subsystem and then integrating them in the BCVTB to form the desired complex system. In the research work presented here, Matlab/Simulink was used for modelling and simulation of the HVAC system, EnergyPlus was selected to model the swimming pool hall and latent loads calculations were performed using tools provided by the BCVTB itself.

The capabilities of the BCVTB allow for rapid prototyping and testing of different operational scenarios and their impact over the systems under study. In this research work in particular, a better control over the operational schedules of the system was achieved as opposed to what was achieved with the sole use of EnergyPlus to model and simulate the whole system. Also, the BCVTB allows to interface with real BMS through the BACnet protocol.

Care should be taken when deciding on the modelling and simulation methodology to adopt since, depending on the application, less modelling and simulation effort might be achieved with the use of a single tool. However, the BCVTB has proven to be well-suited to approach problems where part of the model is already developed and new additions are to be made but the new modeller has little knowledge of the modelling tool previously used. Also the BCVTB is useful for cross-discipline cooperative work, allowing each expert to develop a model using his own tool and then integrating all the solutions into one. This last is often the case of the whole building energy modelling and simulation developments.

As with any model, the HVAC model developed in the research work is an approximation to the real functioning of the systems allowing for improvement in the accuracy of the simulations. Simulation results showed a good match between the monitored and the simulated thermal behaviour of the facility.

Real operation data will allow a fine tuning of the ANN and this is a necessary step to be taken to assess the real impact of the use of neural networks for optimising end of setback. Once linked with real data and utilising a continuous learning algorithm, the ANN approach allows the system to operate automatically and optimally without any human intervention.

The use of more advanced AI techniques should be also investigated. Even if ANN have demonstrated promising results, other techniques might improve on the computationally and data intensive task of training the ANN to learn the desired behaviour. One drawback of the approach taken in this case study is the need for supervised learning whereby the expected target is provided to the ANN. In this case study, this target needed to be calculated as the time the system will take to reach desired conditions. This can be avoided by the implementation of unsupervised learning such as reinforced learning where the network is not given the numerical value of the desired output but rather an indication of how good or bad any output is.

5.1.5.3 Diagnoses root causes of building's performance reductions

The task of detecting and diagnosing performance reduction in buildings is accomplished through fault detection and diagnosis (FDD) techniques discussed in section 4.3. The FDD approach discussed in this case study, the qualitative model-based diagnosis (QMBD), provides a clear advantage towards a SAB implementation, as it requires reduced instrumentation and little interpretation from the building operator because all the knowledge, both from building physics and from diagnostics theory, is already embedded in the tool.

When comparing with the traditional rule-based APAR approach, the QMBD provides the following advantages:

- For the APAR approach, a number of possible faults are identified for a given scenario of which one or two are related to the component in question. However, it also gives a number of other possible causes for the fault. In this regard, an amount of user knowledge is required to investigate the fault further before an accurate determination of the issue can be made. In QMBD, the fault messages are targeted at specific components and, therefore, they provide superior resolution to fault diagnosis when compared to APAR.
- Maintenance efforts are the key issue hampering the broad application of the APAR rule-set. The APAR rule-set was developed for single-duct, variable or constant volume systems, with heating and cooling coils and economizer capabilities. As such, the extension of the system and the inclusion of components (or operational modes such as humidity control) outside of this range would represent a significant challenge to implementation within the APAR framework. Similar reasoning could be applied to the changes in the sensor network and in the control strategy. For QMBD these problems don't exist, as previously discussed in section 4.3.6.

One important point of discussion is the time-lapse that must exist between fault detection and alarm triggering. Taking into account that HVAC systems are rarely critical systems, the benefits of FDD in the build environment are more economic and environmental rather than being a safety issue. Thus, hourly fault detection and diagnosis frequencies seem acceptable in building applications and there is little scope for extending the models to include dynamic behaviour at the moment.

Although in early stage, there exists a scope for Modelica models to become the de-facto standard in energy modelling of buildings and components, as shown by the recently established International Energy Agency Annex 60 (Wetter et al., 2013)[31]. Within this context, one of the key issues for model use during operations (e.g. Model-Based FDD, Model-Predictive Control, etc.) is the development of calibrated models that represent, in a cost-effective manner, the expected normal behaviour of the systems. Focused on air handling units' components, an approach to tackle such problem, which can be automated, has been discussed in this research work (section 4.1.7). The presented approach provides a trade-off between simplicity and accuracy necessary for FDD.

From an economic point of view, the availability of targeted diagnosis information reduces the time and associated cost a maintenance crew would have to invest in addressing any fault in the facility. Also, it will reduce the down time for the unit while the crew identifies the problem. Finally, crews could also be already equipped with the required replacement part thus avoiding the task of having to identify the faulty element and procure such element for replacement.

It was demonstrated how a BMS in age 3 can provide the necessary information for implementing the diagnosis capabilities of a SAB building. The diagnosis will directly impact energy efficiency as it will ensure that all components of the HVAC system are operating optimally. Finally, QMBD outputs need no interpretation from the building manager as results are presented as specific fault messages targeting specific systems that must be repaired.

5.1.5.4 Supports building managers by providing information about building's operations in a way that matches their typical skill set

In this case study, presented in section 4.4, the BMS in Satellite A of Malpensa Airport was upgraded to age 4 incorporating SAB characteristics for diagnosing the facility's

[31] In fact, Modelica is suitable for modelling large and complex systems including elements from different areas of knowledge.

own environmental and energy conditions and providing information in a manner suitable for the skill set of the average facility manager, operator and technician.

An age 4 BMS was shown to provide the necessary capabilities to fully support the Self-Aware Building concept. Within the CASCADE project, simulation models were developed to support automated FDD and to understand facilities operations. These models have the potential, once properly calibrated, to provide one of the missing SAB characteristics by supporting performance prediction. However, in order to adapt the facility's systems to the predicted performance more developments are necessary, such as the incorporation of automated scheduling and predictive controls, none of which was within the scope of the project.

In the case study it was recognised that different users have different information needs from the building management systems. In this regard the information presented by the tool is aimed at matching the particular skill set of each user. The key technology to accomplish this is the incorporation of ontologies that attach information to the data-streams in a way that is easily interpreted by humans and machines alike. The data is thus transformed into knowledge and actionable tasks not requiring interpretation for its understanding and that can be directly used to improve building operations.

The main problem that was overcome in this case study was the diversity of data sources existing in the building sector. This was accomplished through the development of a minimal data set, including quality and quantity of data, which supports all the technologies for energy efficiency in buildings applied to the facility and, not less important, the standardisation of a naming convention for the data-points of the facilities. A standard naming convention not only serves to avoid hard-coding data point names in the algorithms aimed at energy efficiency, but also allows an automated incorporation of further information to data streams for example, through ontologies, thus directly supporting the embedding of knowledge in the facility's systems.

Finally, the implementation of ISO 50001 demonstrated how energy management can be used to optimise building performance, not only from a technical point of view but also from a managerial point of view which is also part of the SAB concept.

5.2 Recommendations

It is clear that the problem of energy efficiency in building operations is not so much technical in nature but rather a combination of factors ranging from policies not delivering to expectations due to the lack people's ability to perform their activities in an energy efficient manner. With this idea in mind direct policy, especially in developed countries, should aggressively target existing constructions. With the focus on existing construction, it is important to aim at optimising operations and at the inclusion of renewable energy resources prior to recommending or demanding refurbishing. The goal is to reduce GHG worldwide and optimal operation of facilities contributes to that, while simple refurbishment might just shift the emissions from one world region to another.

On the technology side, the main need is the standardisation of the building sector, especially with regard to the recognition of data streams as part of the energy efficient philosophy. There is a need to standardise the data that is gathered from any facility in order to be able to develop and widely implement methods and technologies for energy efficiency operation of buildings. Once data streams are standardised, the next step is to attach meaning to such data in order to reduce the need to interpret raw data. The integration of modelling and simulation in different stages of the building's life-cycle is also instrumental not only for standardisation purposes but also for embedding the desired knowledge in system operations. In this sense, the building simulations community is moving towards a standardised use of Modelica as a modelling language with combined efforts such as those demonstrated by the IEA Annex 60 initiative. Annex 60 is developing and demonstrating new generation computational tools for building and community energy systems based on the non-proprietary Modelica modelling language and Functional Mock-up Interface (FMI) standards. The anticipated outcomes are open-source, freely available, documented, validated and verified computational tools that allow buildings, building systems and community energy grids to be designed and operated as integrated, robust, performance based systems with low energy use and low peak power demand.

The SAB concept is instrumental in identifying the real needs of the building sector in order to transform itself from an energy-as-utility consuming sector to an energy-as-asset managing sector. High automation does not imply energy efficiency but optimal operation does. Although standards such as the EN 15232 aim at highlighting the benefits of a higher building automation, its scope falls short by not identifying the actual implementation needs of each facility. The SWOT analysis presented in this research work targets this gap by matching building energy efficiency needs to the building's ICT infrastructure. The SWOT process, or a similar process, should be followed on each step of the building optimisation process in order to have an overview of the real capabilities of the facilities.

On the energy management side, the standard ISO 50001 is a first step towards enabling facilities to actually and effectively implement energy efficiency measures. It is still early to realise the broad impact of the implementation of ISO 50001, especially since it is dependent on the perseverance of the facilities in following the process of continuous monitoring and improvement. If the ISO 50001 remains as a manual process, it is most likely doomed to fail in the long-term due to the lack of human resources. The use of automated software that manages the energy management processes is recommended as this will be the real driver in its broad and continuous implementation.

Finally, technologies such as Ambient Intelligence can aggregate BMS data and other data and information streams from paradigms such as the Internet of Things, in order to accomplish the ideal future optimal building operations and more applied research should be encouraged in this area.

5.3 FUTURE WORK

In this thesis, the implementation of the concept of Self-Aware Building was implemented utilising different case studies, each targeting one particular SAB characteristic. The following step is the implementation of all of the characteristics into one facility and the measurement of the long-term impact that the application of the SAB concept. Developments within the CASCADE project (section 4.4) will allow for such an overall case study, once the project is finished and the results and data are made available to the public. Of particular interest for future work is the implementation of intelligent control techniques in an age 4 BMS and measuring the impact, not only in terms of optimal operations, but also in the effort required in the development of the controllers and control algorithms. Further work will seek to increment the automation level of the energy management implementation (based on ISO 50001) to include a multi-facility management and automated actions such as ordering broken/end-of-life elements or adjusting overall controls to minimise the impact of detected faults. In addition, future work will seek the incorporation within the SAB framework technologies and in particular of the SWOT analysis of means for auditing how uncertainty in measurement propagates through the system and how this affects the reliability of the implementation.

For the case study presented in section 4.1 relating to prediction of energy use in a natural ventilated building, future work relates to the implementation of the continuous learning algorithm. This continuous learning algorithm will be based on the sliding window technique and it is expected to reduce the amount of training data for the modelling the energy consumption and, at the same time, will introduce robustness to the system. In addition, the continuous learning algorithm ensures that the knowledge is embedded in the system rather than requiring the building manager to understand the machine learning and prediction techniques. Thus, complying with the SAB concept by bridging this particular knowledge gap.

The same approach for continuous learning applies to the case study aimed at controlling the re-start time of a swimming pool facility (section 4.2). For this case study, future work will also include the extension of the models to incorporate the dynamics of the swimming pool water and the automation of the set-back time (time to turn off the systems).

In the case of the implementation of automated FDD in HVAC systems (section 4.3), future work will seek to automate several steps in the development and calibration of the Modelica models in order to significantly speed up the initial configuration and calibration of the AHU. Also, research work needs to be undertaken to fully automate the tool chain commencing with model calibration and finishing with on-line diagnosis. Finally, humidity-related faults will be included in the tool.

The SWOT analysis presented in Chapter 3 needs to be refined, especially the questionnaire used to identify opportunities and threats in order to be able to extract more useful information, including economic information, from facility managers and include such information in the actions that can be taken once a facility's age is identified (Table 5-2). A future line of work in the improvement of the SWOT analysis is to relate potential costs and savings of the implementation of the SAB concept with the actual operating and maintenance costs of the facility. Such comparison must account for indirect costs such as personnel working efficiency, increased competitiveness provided by possibility to reduce price of products and services due to reduced operational costs and impact of increased corporate social responsibility.

Finally, further developments will seek to evaluate the impact of the application of the developments of this research work into other industrial sectors. In particular, in the water distribution and management sector. The SWOT methodology that evaluates an ICT infrastructure in face of implementing operational optimisation technologies such as FDD could be applied aimed at reducing the water consumption in the secondary systems. Finally, also in the water management sector, the implementation of methodologies based on the energy management standard ISO 50001 could be investigated to optimise and manage the water consumption at different levels, from the facility level to the municipality level.

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APPENDIX A

A NOTE ON FDD RESEARCH TOOL MARKETING

Although some commercial FDD tools exist on the market (Panoptix® Continuous Diagnostics Advisor of Johnson Controls, DABO™, SCIwatch by the Scienergy, among others), none of these technologies have achieved broad acceptance. Research has identified some reasons for this lack of market penetration including old buildings with very basic technologies, lack of standardisation and economic feasibility demonstration, lateness of the research and development (research not done on time to perform preventive actions rather than corrective actions), to name a few. Nevertheless, the literature review presented in Chapter 2 identified that research is mostly focused on fault detection and diagnosis with little development for automated prognosis, thus lacking an overall approach going from fault detection to performing corrective actions (Katipamula & Brambley, 2005b). In this niche lays the key for development and integration of new technologies that are cost-efficient enough for the cost sensitive building community to take on board.

Also, research and developments are in place in the areas of benchmarking, KPI monitoring and real field testing of FDD approaches, all of which can be incorporated into existing systems to provide an overall decision support system that will help facility managers in the task of becoming more energy efficient by optimised building operations (Maile et al., 2012; Escrivá-Escrivá et al., 2010; Pérez-Lombard et al., 2012a; Katipamula et al., 2003).

But even with a good deal of research in place, it is likely that little of it can reach the market, not only for the reasons named above, but also because traditionally there is a gap between research and commercialisation that prevents the marketing of an innovative product. Trying to bridge this gap, this research work proposes a generic marketing approach and exploitation strategy for FDD solutions based on the methodology developed by Maurya (Maurya, 2010). It is expected that this will provide researchers with a sort of template for identifying their key value proposition and commercialisation path in an optimal and cost efficient manner.

Before moving forward some definitions can be briefly introduced, although it is important to note that they will become clearer in the following sections:

- **Tool**: actual development, it includes the methodologies and technologies that represent the implemented outcome of the research.
- **Solution**: comprises the tool plus the minimum feature set to integrate the tool in the commercial product.
- **Product**: it includes the solution plus the exploitation strategy developed in the business model. What is marketed is the product as an overall combination of the solution to solve a problem by means of the tool and the associated side services provided.

In the case of FDD, the methodologies and technologies comprise the *tool*. The integration of the FDD into the facility is the *solution* and the *product* includes the solution, the customer relationships and channels, cost and revenue structures and any other service provided on the side of the FDD tool itself.

A.1. Exploitation strategy

One of the very first things to do when embarking on a commercialisation path is to start shaping the exploitation strategy. This is, the way(s) in which the developed technology, method or service is to be presented to the market and by whom. Often the developments do not pertain to a single item but are a combination of different technologies or methodologies with different levels of readiness, integration, interaction and are even being developed by different legal entities. The above can be seen as an obstacle but it is in fact an advantage to be profited since it may provide with different commercialisation paths, leading to different business models from which to exploit the research work.

Assuming that the development is an FDD tool that is to be integrated in the BMS/BAS of large facilities, some paths for exploitation, each constituting a possible product, may include, but are not restricted to:

- **Presenting the FDD tool as on-site solution**. In this case the solution *resides in the facility*. This can be accomplished both for the integrated solution and for single operational components as modules to be assembled. When the product is exploited as an on-site solution, some possible break-up could be as follows:
  - Deploy the tool in the facility, identify current faults and provide support for addressing them. After operation is optimised, there will be the option to leave the tool on site charging a license fee or to retire the solution. If the tool is to be left in the facility, the customer must be trained to use it and maintain it.
  - As a continuous service the FDD will be continuously monitoring the facility to identify new issues and also the algorithm will be adapted to changes in the facility. In this case the entity deploying the tool is in charge of managing the solution.
- **Delivering FDD as a cloud service to the client**. In this case, the products are the services related to monitoring and reporting of the facility, compliance with standards (e.g. ISO 50001) and providing continuous advice on energy conservation measures. The solution *resides in a server outside the facility* and the information of the facility is sent to the server for processing and FDD. Subsequently, the facility will receive a report on the outstanding energy conservation measures that need addressing. An important difference between exploiting the solution on-site or as cloud service relies in how the customer interacts with it. When is exploited as a product, the customer will be trained to use the tool and will be the main responsible for the operation of such (including maintaining the system up and running), while as a service the entity that is providing the solution will be responsible of the operation of the tool. The customer will only receive the results coming from the application of the tool to the specific facility. These first two options are strongly linked with how sensitive the facilities' data is and the security measures in place are. All of this can be identified with the SWOT analysis presented before.
- The last commercialisation path that will be discussed is that of **license the tool to third parties** or to other energy related companies for inclusion into their own business models and solutions. In this way the client is not the final user but some intermediate solution or service provider.

A.2. BUSINESS MODEL

Once the tool is developed and there is a good knowledge on how it can be exploited is time for defining the paths to marketing and the creation of the product as a whole. A business model is the way the tool or solution becomes a product and is brought to the market. The business model describes the rationale of how an organization creates, delivers, and captures value. A recognised and efficient way to develop a business model for technological developments is that of the *business model lean canvas* (Maurya, 2010). The canvas is a graphical representation that is easy to understand and straight forward to develop and to modify so it can adapt new ideas and iterations (see Figure A-1). During the following sections each canvas' section will be explained including examples of how the business model of a FDD solution might be represented using the sections of this canvas. One very important thing to remember is that neither the tool nor the solution are the product, rather the whole business model is the product that is being commercialised.

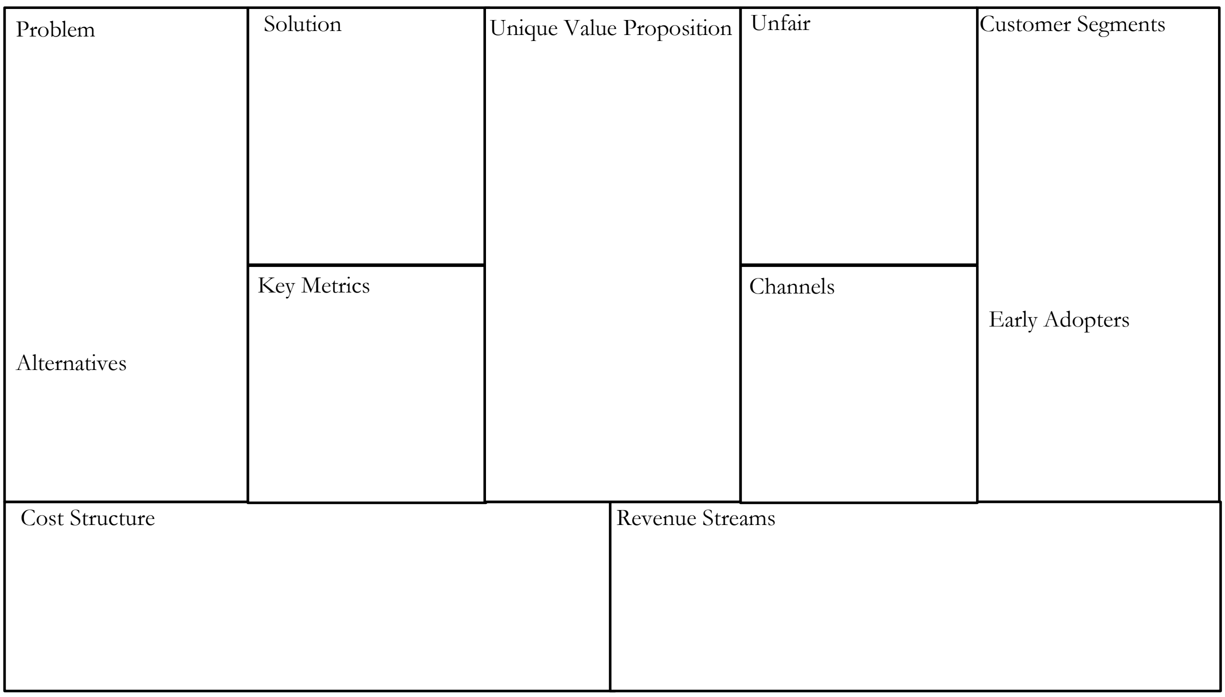

Figure A-1 Business model canvas. Source: (Maurya, 2010).

A.2.1. Problem

The *problem* is what the solution tries to address. Unless the solution has been developed within a possible customer, it is important to interview the targeted customer during tool development since the primary problems for the customer are not necessarily related to the most interesting research questions or features developed in the solution. If the latest is the case then simply addressing the customer's concern will present a valuable solution and the rest of the features will only add value to the solution and can even be sold as separate modules. The interviews with potential customers should be short and precise (a 10 minutes telephone call or 5-6 questions questionnaire) in order to ensure the highest number of responses and force the customer to be concise in the main problems that need to be addressed. Having identified the customer's problems makes much easier the development of the value proposition (see section A.1.2) and reduces the number of iteration the business model will have. Within the problem it is important to identify the existing alternatives as they represent the natural market competitors and because they might be solving partially or totally the customer's problem, so it is important to make an early identification of the alternatives and improve over them. For the example of the FDD tool, the main competitors might be ad-hoc FDD and solutions provided by the HVAC manufacturers and maintenance companies, so it is important to clearly state how the developed product makes the customer's life easier and cheaper, because only advertising technical improvement is often not enough to sell the solution.

A.2.2. Value propositions

"The Value Propositions Building Block describes the bundle of tools and services that create value for a specific Customer Segment" (Osterwalder et al., 2010). Simply put, a value proposition is why a customer will be interested in the solution offered over other existing solutions. The value propositions are intended to sell the product so it is not only about the advantages of the developed solution but also how customer interactions and even pricing options are offered.

Value propositions can be addressed in several categories:

- They can be specific to the application environment. For example, in an FDD tool for HVAC systems they can be a set of guidelines and best practises, KPI, prognosis actions, etc.;
- They can be specific to the methodologies developed. For example, applying the SWOT analysis presented in section 3.5 of this chapter can be a value proposition for a business mode where the offered solution is studying the readiness of a BMS for the integration of FDD technologies;

- They can also be specific to the technologies used for implementing the product. As examples can be mentioned standardisation of communication protocols, incorporation of data aggregation, data storage services, web services, visualisation tools, etc.;
- Value propositions can even be specific to a hardware implementation, as it can be a monitoring framework and data acquisition system;
- Finally, any combination of the above can also be a value proposition.

In general, value propositions are expressed as short paragraphs where the product is presented in a way that targets the most pressing concerns of the customers and differentiate the presented solution from possible competitors. As stated before, it is important to explicitly state how the customer will benefit from the product.

A.2.3. Solution

The *solution* should be represented by the minimum feature set needed for launching the product. It is closely related to who the early adopters could be and whether the customer will pay or not for the solution. It is very important to choose and target the early adopters as they shall become promoters of the product and, therefore, multiply the number of customers. A basic FDD tool will require, for example, a data acquisition, a FDD engine and results reporting with action suggestions as minimum features to become a solution. It is important to note that the solution shall contain the minimum features to comply with what the value proposition offers as a product.

A.2.4. Key metrics

Key metrics shall be able to show how the business is performing in (near) real time. This is not necessarily easy to spot but it is important in order to take correction actions on time. Key metrics could be related to technical issues that degrade the value proposition or business related metrics that endanger customer retention or increases operation costs. For the example of FDD tool, some key metrics might be: number of detected faults, actions taken on the faults, energy and monetary savings to date and projected for some future date, expenditure in maintenance, sensors reading reliability for FDD, etc. As can be seen, the key metrics are closely related to how much effort and resources are being expended in maintaining the value proposition. A good metric definition will help keep costs contained and might even open new revenue streams possibilities, for example, if some customer is not taking into consideration some fault, one can offer fixing it as long as the repair cost is below the potential earns and savings within a defined period of time.

A.2.5. Unfair advantage

"An unfair advantage will make the product difficult to be copied or bought" (Maurya, 2010). When identifying the unfair advantage, it is important to be objective and not to list things that are not really advantages. The business model shall be able to work wether this is identified or not, however not identifying or identifying the wrong advantages can be highly risky if overconfidence is built upon it. For the FDD tool some unfair advantage could be, for example, a close relationship with a manager in one large HVAC vendor company, having in the team a highly recognised and knowledgeable people in the industry and/or academy developing solutions for a very new type of revolutionary system, etc. In any case, it is important to note that unfair advantages might not last long and must be exploited mostly during the star up phase when customer relationships are being built.

A.2.6. Cost structure

Cost structure simply corresponds to the expenses needed to develop, maintain and improve the tool. This includes licenses, personnel, consumables, etc. It is important to be objective about costs, don't underestimate them but also don't overestimate them since this directly impacts the revenue streams.

A.2.7. Revenue streams

"The revenue streams represent the cash a company generates from each customer segment (costs must be subtracted from revenues to create earnings)" (Osterwalder et al., 2010). This means that there are potentially at least as many revenue streams as customer segments are identified. They are also linked to the exploitation strategy. Revenue streams will need trial and error and a good customer interaction before they can be refined for the product. In the example of a FDD tool, the following revenue streams can be applied:

- **Usage fees**: the customer pays for using the tool.
- **Subscription fees**: in this case the FDD solution is presented as a service to the customer where a third party is utilising the tool and just providing the customer with results and recommendations coming out of it.

- **Licensing**: here the FDD is given to third parties for inclusion into their business models to complement applications they might already have or to provide consultancy on behalf of the tool developer.
- **Foreground knowledge:** one interesting revenue stream is that of using the developments as foreground knowledge to apply for research and/or commercialisation funding. This path could generate revenue at the same time as allows more research to be done on the tool, as well as it provides a good platform for having other people testing the solution. It also may ease the path for early implementation and identification of early adopters as these will very likely be within the project's consortium.

A.2.8. Customer segments

"The Customer Segments Building Block defines the different groups of people or organizations an enterprise aims to reach and serve" (Osterwalder et al., 2010). For the FDD tool, some customer segments can include building owners, facility managers, HVAC manufacturers, municipalities and governments, policy makers, etc.

A.2.9. Channels

"The Channels Building Block describes how a company communicates with and reaches its Customer Segments to deliver a Value Proposition" (Osterwalder et al., 2010). Channels are the means to achieve the exploitation strategy. With the FDD tool's example, an exploitation strategy might be as follows:

- Web advertising of the tool shall be established with appropriate contacts so customer may reach developers and require services.
- Buildings and alike facilities can be engaged directly by contacting energy or facility managers and interacting with them showing the benefits of the application of the solution and how they can profit when using the FDD tool in their facility (value proposition).
- Indirectly, if the tool is licensed to third party companies they will provide another channel of exploitation.
- The FDD tool could be sold as an integrated part of an ESCO service or energy management consultant. In both cases, the software could be sold under software as a service (SaaS) model with subscriptions paid monthly.

- Municipalities, governments and policy makers can be engaged directly, through support of ONGs and/or industrial/stakeholders associations promoting energy efficiency, local or national politicians involved or campaigning for a greener planet and through awareness in local communities that will become a force pushing for development of legislation and standards promoting reduced energy consumption and GHG emissions. This is an indirect channel as its objective is to raise awareness and to create the need for tools like the one being developed.
- A continuous customer relationship group can be in charge of maintaining established customers and try to promote through them the use of the FDD tool in other places.
- Successful stories shall be exploited in any possible way, from web/TV advertisements to the use of public spaces and workshops to increase awareness of the benefits of the FDD solution. Facilities with high visibility (sport centres, airports, universities, etc.) should be exploited to the maximum and any advertisement made through them or in their spaces is sure to reach a broader range of possible customers and possibly very specialized and highly profitable market targets.

The above represents only a small portion of the opportunities, it is important to be proactive and be continuously promoting and improving the solution and associated services in order to attract more customers.

APPENDIX B

MINIMAL INSTRUMENTATION

Minimal data set for buildings (CASCADE Consortium, 2012c)

B.1. WHOLE BUILDING / ZONES

Table B-1. Minimal data sets for whole building and/or zone.

item	measured value	unit	time resolution	remarks
consumption	Total consumption of electricity	kWh	1-5 min	
	Total consumption of fuels	kWh	1-5 min	e.g. gas, oil, biomass
	Total consumption of district heat	kWh	1-5 min	
	Total consumption of district cold	kWh	1-5 min	
	Total consumption of water	kWh	1-5 min	
Weather	Outdoor air temperature	°C	1-5 min	own weather station or from weather data provider
	Outdoor rel. humidity	% R.H.	1-5 min	
	Global irradiation	W/m^2	1-5 min	
indoor conditions and occupancy	indoor temperature	°C	1-5 min	One or more reference zones
	indoor relative humidity	% R.H.	1-5 min	
	Number of PAX	PAX	h	From Flight Data Base

B.1.1. Energy conversion systems

B.1.1.1. Boilers

Table B-2. Minimal data set for boiler.

item	measured value	unit	time resolution	remarks
consumption	consumption of fuels	kWh	1-5 min	e.g. gas, oil, biomass
generation	Heat generation	kWh	1-5 min	
	Boiler temperature	°C	1-5 min	
	Hot water supply temperature	°C	1-5 min	
	Hot water temperature set point	°C	1-5 min	
	Hot water return temperature	°C	1-5 min	
control signals	Boiler status	-	1-5 min	ON/OFF
	Burner control signal	-	1-5 min	

B.1.1.2. Combined heat and power plant

Table B-3. Minimal data set for combined heat and power plant.

item	measured value	unit	time resolution	remarks
consumption	total consumption of fuels	kWh	1-5 min	e.g. gas, oil, biomass
generation	heat generation	kWh	1-5 min	
	electricity generation	kWh	1-5 min	
	hot water supply temperature	°C	1-5 min	
	hot water temperature set point	°C	1-5 min	
	hot water return temperature	°C	1-5 min	
control signals	CHP status	-	1-5 min	ON/OFF

B.1.1.3. District heating / District cooling

Table B-4. Minimal data set for district heating and district cooling systems.

item	measured value	unit	time resolution	remarks
Primary side	Heat/Cold consumption	kWh	1-5 min	
	Hot/Cold water supply temperature	°C	1-5 min	
	Hot/Cold water return temperature	°C	1-5 min	
	Hot/Cold water supply temperature set point	°C	1-5 min	
	Primary valve control signal	%	1-5 min	
	Pressure	kPa	1-5 min	
Secondary side	Hot/Cold water supply temperature	°C	1-5 min	
	Hot/Cold water return temperature	°C	1-5 min	
	Hot/Cold water supply temperature set point	°C	1-5 min	
	Pressure	kPa	1-5 min	
	Hot/Cold water supply temperature	°C	1-5 min	

B.1.1.4. Compression chiller

Table B-5. Minimal data set for compression chillers.

item	measured value	unit	time resolution	remarks
consumption	Electricity consumption	kWh	1-5 min	
generation	Chilled water supply temperature	°C	1-5 min	
	Chilled water return temperature	°C	1-5 min	
	Chilled water supply temperature set point	°C	1-5 min	
	Pressure	kPa	1-5 min	
	Heat sink temperature	°C	1-5 min	Air, ground water, ground
	Cooling water supply temperature	°C	1-5 min	In case of water cooled chillers
	Cooling water return temperature	°C	1-5 min	

B.1.1.5. Cooling tower

Table B-6. Minimal data set for cooling towers.

Item	measured value	unit	time resolution	remarks
consumption	Fan electricity consumption	kWh	1-5 min	
	Water consumption	m3	1-5 min	
System physical data	Cooling water supply temperature	°C	1-5 min	
	Cooling water return temperature	°C	1-5 min	
	Outside air wet bulb temperature	°C	1-5 min	For wet cooling towers
	Pressure	kPa	1-5 min	

B.1.1.6. Heat pumps

Table B-7. Minimal data set for heat pumps.

item	measured value	unit	time resolution	remarks
consumption	Electricity consumption	kWh	1-5 min	
generation	Chilled water supply temperature	°C	1-5 min	
	chilled water return temperature	°C	1-5 min	
	chilled water supply temperature set point	°C	1-5 min	
	Pressure	kPa	1-5 min	
	Cooling water supply temperature	°C	1-5 min	
	Cooling water return temperature	°C	1-5 min	

B.1.1.7. Solar thermal plants

Table B-8. Minimal data set for solar thermal plants.

item	measured value	unit	time resolution	remarks
consumption	Electricity consumption circulation pump	kWh	1-5 min	
System data	Supply temperature	°C	1-5 min	
	Return temperature	°C	1-5 min	
	Collector temperature	°C	1-5 min	
	Pressure	kPa	1-5 min	optional
Control signals	Pump control signal	-	1-5 min	
	Valve control signal	-	1-5 min	

B.1.2. Energy distribution systems

B.1.2.1. Water loops

Table B-9. Minimal data set for water loops.

item	measured value	unit	time resolution	remarks
Consumption	Electricity consumption circulation pump	kWh	1-5 min	
System data	Supply temperature	°C	1-5 min	
	Return temperature	°C	1-5 min	
	Supply temperature set point	°C	1-5 min	
	Pressure	kPa	1-5 min	optional
Control signals	Pump control signal	-	1-5 min	
	Valve control signal	-	1-5 min	

B.1.3. Energy storage systems

B.1.3.1. Thermal storage

Table B-10. Minimal data set for thermal storage.

item	measured value	unit	time resolution	remarks
System physical data	Primary side supply temperature	°C	1-5 min	
	Primary return temperature	°C	1-5 min	
	Secondary side supply temperature	°C	1-5 min	
	Secondary side return temperature	°C	1-5 min	
	Supply temperature set point	°C	1-5 min	
	Tank temperature at height n	°C	1-5 min	Several sensors might be needed accordingly to tank height
	Pressure	kPa	1-5 min	optional

B.1.4. Energy delivery

B.1.4.1. Air handling units

Table B-11. Minimal data set for air handling units (part 1).

Item	measured value	unit	time resolution*	remarks
Consumption	Electricity consumption supply air fan	kWh	1-5 min	
	Electricity consumption return air fan	kWh	1-5 min	
	Heat consumption preheater	kWh	1-5 min	
	Heat consumption post heater	kWh	1-5 min	
	Cold consumption cooler	kWh	1-5 min	
	Water consumption humidifier	m3	1-5 min	
System physical data	Outdoor air temperature	°C	1-5 min	
	Temperature after heat recovery	°C	1-5 min	
	Mixed air temperature	°C	1-5 min	Measurement after the mix box
	Temperature after preheater	°C	1-5 min	
	Temperature after (post)-heater	°C	1-5 min	
	Temperature after cooler	°C	1-5 min	
	Supply air temperature	°C	1-5 min	2 measurement in cold and hot air ducts for dual duct AHU
	Return air temperature	°C	1-5 min	
	Exhaust air temperature	°C	1-5 min	
	Supply air duct pressure	Pa	1-5 min	2 measurement in cold and hot air ducts for dual duct AHU
	Return air duct pressure	Pa	1-5 min	

Table B-12. Minimal data set for air handling units (part 2).

Item	measured value	unit	time resolution	remarks
System physical data	Outside air humidity	% R.H.	1-5 min	
	Supply air humidity	% R.H.	1-5 min	2 measurement in cold and hot air ducts for dual duct AHU
	Return air humidity	% R.H.	1-5 min	
Control signals	Outside air damper	-	1-5 min	Status
	Mixed air damper	-	1-5 min	Status
	Heat recovery control signal	-	1-5 min	For rotational HRC
	Set point supply air temperature	°C	1-5 min	
	Set point room/zone temperature	°C	1-5 min	
	Frost thermostat status	-	1-5 min	
	Supply air duct pressure set point	-	1-5 min	
	Return air duct pressure set point	-	1-5 min	
	Supply air fan control signal	-	1-5 min	
	Return air fan control signal	-	1-5 min	
	VAV boxes control signal	-	1-5 min	

B.1.4.2. Fan coils

Table B-13. Minimal data set for fan coils units.

item	measured value	unit	time resolution	remarks
System physical data	Supply air temperature	°C	1-5 min	
	Return air temperature	°C	1-5 min	
	Zone temperature	°C	1-5 min	
Control signals	Chilled water valve control signal	-	1-5 min	
	Hot water valve controls signal	-	1-5 min	
	Fan speed	-	1-5 min	
	Fan coil status	-	1-5 min	Enabled/off
	Supply air minimal temperature	°C	1-5 min	
	Zone temperature set point	°C	1-5 min	

APPENDIX C

COMPLEMENTARY DATA FOR CASE STUDY 4.1

Code for the case study in section 4.1 can be found in the CD enclosed in this thesis in the zip file under the name 4.1. For this case study, code was developed in Java using NetBeans 7.1 IDE.

For the grey-box models, the folder 'code' contains all the Java code while the folder 'data' contains all the raw and pre-processed data used to train the neural networks and also the results from the training.

For the black-box models, the folder 'EPM' contains the source code and results from using the PROBEN1 dataset

APPENDIX D

COMPLEMENTARY DATA FOR CASE STUDY 4.2

Models and code for the case study in section 4.2 can be found in the CD enclosed in this thesis in the zip file under the name 4.2.

The folder 'ePlus' contains the model of the Swimming Pool Hall in EnergyPlus.

The folder 'matlab' contains source code to enable communication between Simulink and BCVTB

The folder 'simulink' contains the Simulink AHU model.

Finally, the file system.xml is the BCVTB model of the integrated system.

APPENDIX E

COMPLEMENTARY DATA FOR CASE STUDY 4.3

Models and code for the case study in section 4.3 can be found in the CD enclosed in this thesis in the zip file under the name 4.3.

Models are developed using the Modelica modelling language under the Dymola 2015 environment. Calibrated models utilising developed library (AHU_09Total.mo) and LBNL library (AHU_09_Fluid_Total.mo) are present.