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Author(s)	Corry, Edward
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A Semantic Web Approach to Enable the Holistic Environmental and Energy Management of Buildings

Edward Corry, BE (Civil)

Civil Engineering

National University of Ireland, Galway

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Abstract

Narrowing the performance deficit between design intent and real-time performance is a complex and involved task, impacting on all building stakeholders. Buildings are designed, built and operated with the use of increasingly complex technology and throughout their building life-cycle, produce vast quantities of data. However, many commercial buildings do not perform as originally intended.

The use of data in a cross-domain manner and the concept of enterprise level data are areas in which the building industry lags considerably behind others. Traditional methods of information capture in the architecture, engineering and construction (AEC) domain do not lend themselves to the effective provision of a holistic environmental and energy management solution for building performance assessment, prediction and informed modification.

Existing methods of performance assessment fail to take into account the wealth of information available throughout a building and exclude whole categories of information including social media, occupant communication, mobile communication devices, occupancy patterns, human resource information and financial data. Building codes are prescriptive and do not encourage a continuous performance assessment mindset amongst building owners and users.

The performance gap is dominated by the twin concerns of interoperability and a lack of holistic environmental and energy performance information. This thesis provides a dual strand approach to the problem, describing how heterogeneous building data sources can be transformed into semantically enriched information. These data can serve as a data service for a structured performance analysis approach, at the enterprise level.

In parallel, a semantically enriched performance management framework is introduced, which builds on the homogeneous data described in the first strand. The Performance Framework is an approach to performance management using scenarios to describe performance and methods for capturing this performance in a series of defined performance objectives. These techniques, when applied together, result in a more holistic interpretation of building performance.

A series of demonstrations are provided which illustrate the use of cross-domain data, first in an unstructured manner, and finally, using the scenario modelling approach, where a structured path is described through cross-domain data. Although the use of cross-domain data is beneficial for many building stakeholders, the building management context is considered throughout, in the form of the building manager.

This thesis demonstrates how the semantic web approach can be combined with the environmental and energy management of buildings. The work describes how multi-disciplinary data sets can be described in a homogeneous manner and leveraged to drive a performance assessment approach. The work improves on other performance management techniques as it provides a cross life-cycle, cross-domain approach to the problem, enabling a true holistic assessment of building performance.

I would like to dedicate this thesis to Louise and our children, Seán, Eoghan and Síofra.

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other University. This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration, except where specifically indicated in the text.

Edward Corry, BE (Civil)
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Glossary

AEC Architecture, Engineering and Construction Industry.

AHU Air Handling Unit.

ATC Adaptive Thermal Comfort.

BEPS Building Energy Performance Simulation.

BER Building Energy Rating.

BIM Building Information Models.

BLC Building Information Life-cycle.

BMS Building Management System.

BPM Business Process Management.

BRE U.K. Building Research Establishment.

BREEAM Building Research Establishment Environmental Assessment Method.

CAD Computer Aided Design.

CPU Central Processing Unit.

CSV Comma Separated Value List.

DL Description Logics.

DOE US Department of Environment.

EPBD European Performance in Buildings Directive.

EU European Union.

EUI Energy Use Intensity.

FOAF Friend of a Friend.

GBCA Green Building Council of Australia.

GHG Greenhouse Gases.

GUI Graphical User Interface.

GUID Globally Unique Identifier.

HRM Human Resource Management.

HVAC Heating Ventilation and Air Conditioning.

ICT Information and Communications Technology.

IDM Information Delivery Manual.

IFC Industry Foundation Classes.

IoT Internet of Things.

IPCC Intergovernmental Panel on Climate Change.

LEED Leadership in Energy and Environmental Design.

MVD Model View Definition.

NEAP Non Domestic Energy Assessment Procedure.

NEB New Engineering Building.

NUIG National University of Ireland, Galway.

OWL Web Ontology Language.

PAO Performance Assessment Ontology.

PDF Portable Document Format.

PF Performance Framework.

PFP Performance Framework Platform.

PMV Predicted Mean Vote.

PPD Predicted Percentage Dissatisfied.

PROBE Post-Occupancy Review of Buildings and their Engineering.

RDF Resource Description Framework.

RDFS Resource Description Framework Schema.

RFID Radio Frequency Identification.

RH Relative Humidity.

RIF Rule Interchange Format.

SIOC Semantically-Interlinked Online Communities.

SPARQL Protocol and RDF Query Language.

SSN Semantic Sensor Network XG.

SWE Sensor Web Enabled.

SWRL Semantic Web Rule Language.

URI Uniform Resource Identifier.

URL Uniform Resource Locator.

USGBC U.S. Green Building Council.

W3C World Wide Web Consortium.

XML Extensible Markup Language.

XSD XML Schema Definition.

Chapter 1

Introduction

1.1 Motivation

This work is motivated by the need to improve the management of building performance through the greater use of building related data. The two main drivers of this work relate to energy efficiency and data transformation. Energy is a key issue in a global context, and buildings account for roughly 40% of global energy use (World Business Council for Sustainable Development, 2009). At the same time, for many reasons, buildings do not operate efficiently (Claridge et al., 1996; Liu et al., 2003; Mills, 2009). There are very strong economic (Houser, 2009; McKinsey & Company, 2009), social (Gasper et al., 2011), environmental (Huovila, 2007) and legislative (European Union, 2010a) mandates to improve the environmental and energy performance of the existing building stock and to ensure new construction meets more stringent performance requirements, rather than satisfying prescriptive regulations.

One of the key factors affecting building efficiency relates to information management and use throughout the Building Information Life-cycle (BLC), in particular, the use of cross domain data. A cornerstone of improved building efficiency is improved data interoperability, the ability of data and applications to interact. This research illustrates how a greater use of the available data sources in a building can lead to improved efficiency levels and illustrates how some of the barriers to improved cross domain data use might be overcome.

Hitchcock (1996) characterised the BLC as a long-term decision making process. From the initial planning decision to the final decommissioning stage, choices are made which impact on the building. Twenty five years ago, he described how a decision making process which involves diverse participants, changing objectives and a long time-span, required systematic information management and yet the flow of information was generated and transformed in the context of disconnected islands of information. In the following two decades, huge advances have taken place in the field of building information management and yet, the life-cycle decision making process is still characterised by a series of domain experts collaborating together at various stages and employing proprietary data capture and management techniques. Today, most building design related information is documented and communicated in the traditional paper-based forms (Crosbie et al., 2011; Fallon and Palmer, 2007; Hitchcock, 1996), such as 2-D drawings and product specifications, and design intent is not retained due to poor documentation and inadequate communication between collaborators in the BLC.

The chapter describes how the research is motivated by a concern to improve building performance management through greater use of building related information across the life-cycle. A brief account is provided of the main driver of the work, the buildings and the energy problem and the main enabler of the work, the information revolution currently under way. Buildings are not operating effectively, despite a generation of research into the issue, and buildings are consuming an enormous and ever growing amount of energy. As was the case twenty years ago (Hitchcock, 1996), decisions are still made in the absence of key information, throughout the life-cycle and the full impact of decisions is often unclear (Hitchcock, 2003).

It is a rapidly changing world, where 90% of digital data did not exist two years ago and where key enabling technologies are emerging which move the goalposts in terms of what is can be achieved in the Information and Communications Technology (ICT) industry with regard to data management and transformation. Several early adapters in the ICT and Architecture, Engineering and Construction Industry (AEC) industries are rapidly describing future road-maps for the transformation of building signal data into useful information (Bartlett, 2013; Cylon Active Energy, 2013; GreenBiz.com, 2013).

Significant engineering problems arise from poor information management and utilisation experienced throughout the BLC and these problems contribute significantly to inefficient building operation. Key enabling ICT technologies now allow for the development of novel products and services for the holistic management of buildings throughout their life-cycle.

In recent times, the Building Information Models (BIM) movement has emerged in the AEC industry, providing parametric 3-D models of buildings and associated information. The BuildingSMART Alliance (BuildSMART, 2011) are a champion of data exchange within the industry, driving the Industry Foundation Classes (IFC) data model as a basis for data exchange and improved interoperability. BIM has a central role to play in any holistic, cross-life-cycle performance management solution. In the broader context of the explosion of data experienced in the past decade, BIM must be considered as just one silo of information and not the entire silo.

Building managers, city planners, utility providers, large ICT companies and service providers are all increasingly aware that the full picture is not available when it comes to data in buildings. Emerging technologies allow key stakeholders to consider data in ways not previously possible.

This thesis describes a path to a more holistic and broader building performance management structure, based on key cross life-cycle analysis techniques, driven by a focus on semantic data sharing, encompassing other traditional and non-traditional sources of performance data. Based on this research, cross life-cycle metric analysis is now possible, providing measurable key performance indicators from design to demolition.

1.1.1 Energy Perspective

Climate change is one of, if not the key challenge of our time. The theory behind climate change is well known (APS, 2007; EPA, 2014; IPCC, 2007, 2014; Karl, 2003). In a nutshell, climate change has been linked to the burning of fossil fuels leading to much higher concentrations of Greenhouse Gases (GHG) in the upper atmosphere. These gases, including carbon dioxide (CO_2), methane, nitrous oxide and fluorinated gases, are affecting the delicate heat balance in the atmosphere, trapping heat in the atmosphere, resulting in an increase in the global mean temperature. As the mean temperature increases, all manner of knock-on effects are experienced which significantly affect weather patterns, sea-levels, water provision, crop levels and other areas affecting life on the planet.

Since the invention of the steam engine, by Thomas Newcommen in 1712, the manner in which people use fossil fuels has changed. The level of GHG in the atmosphere first started to increase during the industrial revolution as a result of the massive associated increase in the burning of fossil fuels to power new industries. The second half of the twentieth century has seen a rapid increase in carbon emissions, with levels in 2008 16 times the 1900 level and one and half times the 1990 level (EPA, 2013). Building related GHG emissions have more than doubled since 1970 to 9.18 giga tonnes of CO_2 in 2010 (IPCC, 2014).

In the developed world, buildings generally consume energy in a wasteful manner (IPCC, 2014) with a high reliance on HVAC and lighting systems. Estimates vary, but it is suggested that in some countries, the buildings sector accounts for up to one third of all GHG (Huovila, 2007). Worldwide, the Intergovernmental Panel on Climate Change (IPCC) stated, that in 2010, buildings accounted for 32% of total global final energy use and 19% of energy related

GHG emissions (IPCC, 2014). European buildings account for 40% of total energy use and 36% of total CO_2 emission (European Union, 2010a).

Improved building efficiency is a key response to the global warming challenge (Hartkopf et al., 1997; Huovila, 2007; Pérez-Lombard et al., 2009). It is also widely accepted that buildings do not operate efficiently (de Wilde, 2014; Granderson et al., 2013; Mills et al., 2004; O'Donnell, 2009) and existing building stock is considered to waste considerable amounts of energy each year. Most of the energy use in non-residential buildings occurs during the operational phase of the BLC (Sartori and Hestnes, 2007) and median energy savings from merely operating a building optimally can be as high as 15% (Mills et al., 2004).

When commissioning is combined with retrofitting measures, the energy savings can increase significantly. Taking the United States as an example, about 118 million residential and commercial structures generated 39 percent of the country's primary energy consumption (EIA, 2011). When looked at more closely, these buildings consume 72% of electricity in the country, of which 50% is generated from coal, a fuel high in greenhouse gases, particularly CO_2 (American Physical Society, 2008). As significant losses occur in the generation and transmission of electricity, efficiencies made during the building life-cycle can lead to significant savings in primary energy use.

Worldwide, but particularly in developing economies, there is an enormous demand for buildings and access to electricity. The 7 billionth person was born in 2012, up from a population of about 4 billion people in 1974. Western societies are most profligate when it comes to greenhouse emissions where citizens have a far greater Energy Use Intensity (EUI) than less developed countries, but the enormously populous countries such as China and India are catching up rapidly with hundreds of millions of people moving to a more energy intensive, urbanised way of life (Figure 1.1). The massive growth from these emerging economies is expected to double or even triple GHG emissions by 2050 (IPCC, 2014).

Fig. 1.1 CO_2 growth from emerging economies, in giga tons. (Buildings and Climate Change Status, Challenges and Opportunities, United Nations Environment Programme). The bands indicate two possible outcomes towards 2040. Removed due to copyright restrictions

Considerable savings are possible in the sector, using available technology, 25-30% efficiency gains are possible with marginal investment in efficiency programmes. It has been suggested that potential exists for energy savings between 50-90% on new buildings (Confederation of British Industry, 2007). What is clear is that buildings are the leading cause of GHG emissions and these emissions are growing steadily. One vista, whereby the existing "business as usual" approach is followed, leads to a massively polluting buildings sector by 2050 (Huovila, 2007). Another path exists whereby emissions could be significantly reduced by 2050, by utilising new technologies and approaches to the BLC (Huovila, 2007). Whichever path is chosen, it is clear that the buildings sector is the significant factor in climate change and no significant improvement can take place without changes in the sector.

Although inefficiency is reflected throughout the life-cycle, the most energy intensive period is the operations phase. It is reckoned that savings of 20-25% in energy use exist for the average building just by incorporating an effective operation and measurement strategy (Amundsen, 2000; APPA, 2002; Hirschfeld et al., 1997; Jones, 2006; Knight, 1995; Mills et al., 2004; World Business Council for Sustainable Developement, 2008). Buildings change and evolve over time and frequently, original design intent is not retained throughout the life-cycle. The well known 1:5:200 ratio between capital costs, building-related costs and business operating costs (Evans et al., 1998) has been challenged (Hughes et al., 2004), but the initial premise of the ratio as a means to focus owners on long-term costs of ownership as opposed to initial costs, is no less valid (Eclipse Reserach Consultants, 2005).

Of course, a poorly performing building in energy terms may also be poorly performing across other criteria also. Green design could add value to buildings, as such buildings tend to have high occupancy rates, lower operating expenses, increased rental rates, etc. (Institute for Building Efficiency, 2011) because they are comfortable and satisfying places in which to live and work.

Many strategies and technologies are being employed to tackle performance inefficiencies in the building industry, broadly grouped into improved design, construction and operation. There is a strongly held view that minor physical modifications, including improved insulation, coupled with a relentless drive for operational efficiencies can and does lead to significant energy savings (Neumann and Jacob, 2007; O'Sullivan et al., 2004; Piette et al., 2001). This type of solution requires a holistic interpretation of the building to be taken, with a strong focus on the data-sets available in modern buildings. Data must be considered as an asset in the management of facilities and treated accordingly.

1.1.2 Information Perspective

Over the past four decades, the digital revolution has swept through western societies. A visitor from the 1970s would have great difficulty finding a frame of reference to compare how life operates today with his or her own time. In that period, technology has impacted on almost every facet of life. A quote attributed to Thomas Watson, the president of IBM, famously predicted in 1943 that a market existed for maybe 5 computers in the world. While the quotation may be apocryphal, it serves to illustrate just how limited a role computers played in the world less than a lifetime ago.

It is now reckoned that by 2020, there will be over 200 billion physical assets worldwide (Meunier et al., 2014) with some level of Central Processing Unit (CPU) intelligence and over 50 billion devices (Evans, 2011) capable of connection to the internet. That statistic becomes more understandable when you realise how many CPUs are in the average kitchen or auto-mobile. These devices generate enormous amounts of data. The digital universe is expanding by 40% per annum. In 2013, it was estimated to amount to 4.4 billion zettabytes of data (1 zettabyte is the equivalent of 10^{21} bytes). By 2020, that figure is predicted to reach 44 billion (IDC, 2014). 90% of all digital data has been produced in the past two years and most of it is unstructured (IDC, 2014). Currently, perhaps 20% of digital data is tagged and analysed in some manner. This figure is expected to reach 40% by 2020 (IDC, 2014). Many of the devices which produce these data are found in buildings, or are portable in nature and used by building occupants. In terms of creating, capturing and transforming digital data, the buildings industry is at a tipping point, where it can now transform data in ways that were not even imagined a decade ago.

Traditionally, the relational database was the catch all approach to warehousing and retaining data. New approaches are emerging to deal with new types of information. In the AEC domain currently, data exist in individual silos and remains in them until it is no longer considered useful. Cross-domain analysis of data is beginning to emerge and emerging technologies and ideas such as Big Data, the Internet of Things (IoT), Cloud computing and machine to machine communication have the capability to deal with and transform these and other types of data in a useful manner (Bartlett, 2013).

In the AEC domain (Bartlett, 2013), machine to machine computing moves the AEC maintenance goalposts from preventative to predictive maintenance. The keystone of the internet is the connectivity it allows between nodes. You cannot watch over all data, but when a toaster, or air handling unit, or jet engine is able to communicate status updates, the potential exists for machines to communicate with each other.

The concept behind the internet of things is well known. Increasingly, all manner of devices are connected to the internet and, in a building context, you can command several systems in your house remotely. As the volume of devices connected to the internet increases and the range of functionality increases, the internet can have a transformative effect on how activities are carried out in future. Big data and the techniques associated with it are leading to new ways of handling vast amounts of data and making sense of it. Buildings have thousands of data points and dozens of intelligent systems and components. Accessing, observing and using the data available from these systems in a holistic manner that considers the building in its entirety is a relatively new field, largely driven by the climate problem, but enabled by the technological revolution happening around us.

Three billion extra middle-class consumers are expected to join the global economy by 2030 (Dobbs et al., 2011). In the context of increasing worldwide demand for energy resources, improving building energy efficiency must represent a key part of any strategy for the reduction of demand side energy usage. The McKinsey Group have identified a resource challenge which cannot be met by just supply side improvements alone, and have identified 2.9 trillion dollars of resource productivity potential savings, representing 30% of total energy demand in 2030 (Manyika et al., 2013). The sector identified with the greatest potential for savings is the building efficiency area. There is little doubt that buildings do not operate as designed and that significant savings are achievable in the sector. The McKinsey Group have predicted at least 340 billion dollars in fuel savings by 2020 (Manyika et al., 2013), by embracing open data and improving interoperability. The technology did not exist until recently and the capability is now there to instrument buildings at a much greater level and transform the data from these systems, leading to much greater efficiencies.

Figure 1.2 describes how value can be derived from signals. Initially, signals must be gathered into data-sets, in a format that allows ease of access. These data can then be analysed in a structured fashion, leading to increasing levels of information and knowledge. Ultimately the key value of signal data lies in the ability to extract insight and drive actions based on it. Signals in the AEC context have considerable value when used to drive performance management efforts.

Fig. 1.2 Turning signal into value. The enormous technological jumps made in the recent past, with key enabling technologies such as the Internet of Things and Big Data present an opportunity for the AEC domain to address significant legacy challenges (GreenBiz.com, 2006). Removed due to copyright restrictions

1.1.3 The Computer Integrated Construction Landscape

Boddy et al. (2007), in a comprehensive review of the computer integrated construction research landscape, divided information exchange in the construction industry into four main categories (Figure 1.3). The diagram illustrates how the majority of the research takes place to the left of the vertical dividing line and is mainly concerned with data structures. Of this research it is split between software application inter-working and process integration.

What the diagram illustrates is that the vast majority of the computer integrated construction research is dominated by activities such as schema definition, monolithic applications, and the integration of processes. Boddy et al. (2007) also goes on to suggest that these approaches are a somewhat *spent avenue for further research* when one considers the upfront work needed in terms of standards and schemas required for integration, as well as the modifications to applications.

Fig. 1.3 The computer integrated construction research landscape (Boddy et al., 2007). Removed due to copyright restrictions

This work increases significantly when a large international standards effort is required, with consequent long lead in times for changes. At the other side of the diagram, little research is taking place in the quadrant defined by process integration and semantic description and Boddy et al. (2007) suggests this is the area with most research potential. Boddy et al. (2007) strongly suggests research into more process based integration systems where semantic analysis comes to the fore, would be more fruitful. The findings of Boddy and others suggest that the modelling efforts such as IFC require extensive up front investment and stakeholder commitment in order to ensure successful model definition process when a new data exchange protocol is required. The fact that semantic web enabled data definition can be achieved with less up-front cost is highly appealing in a world where data changes so rapidly.

In the information context, this research focuses on semantic web concepts as key enabling technologies, in order to provide a technological underpinning to the holistic environmental and energy management of buildings. These concepts are explored in greater detail throughout this thesis.

1.2 Problem Statement

The problem this research is concerned with straddles the ICT and building efficiency arenas. Typically, buildings do not operate efficiently and buildings do not operate as they were designed to operate. This issue has many causes, but a primary reason is due to the lack of interoperability and subsequent data transformation in the AEC industry. Significant benefits are associated with improved efficiency levels in buildings and this work approaches the problem from a cross life-cycle information perspective.

The issues surrounding silos of information, identified in Section 1.1.2 have not been solved in the thirty years since they were first recognised. Key enabling technologies have emerged over the past five years which can overcome many of these interoperability issues, including the IoT, Big Data and the Semantic Web. Recent advances in semantic web technologies, in particular, provide a structured way of linking information repositories, enabling the development of innovative, web-based, multi-stakeholder environmental and energy management services.

Two perspectives are critical when dealing with the issues raised in the literature review in Chapter 2. First, the building management perspective is concerned with the entire lifecycle of the building and generating a holistic assessment of building efficiency. Building performance must be considered as a three-legged stool, of design, construction and operation. There is a recognised need for a performance management framework which spans the lifecycle of a building, presenting quantifiable information to key building stakeholders.

The second perspective reflects the ICT concern around data in buildings. Data cannot be restricted to domain and application specific silos, restricting cross-domain and holistic analysis techniques. The thesis approaches the work from a dual ICT and building management perspective and presents a roadmap to a better way of supporting building operation and management.

1.2.1 Information Management

Modern buildings generate enormous amounts of data but much of this data are either used entirely for control purposes or remains in the silo in which it originated. The AEC industry is littered with what might be called domains of information. A domain can be considered as a function or department in an organisation for instance. Large facilities will be populated by firms with several business functions integrating with the building in different ways. The finance department might manage the utility billing aspects. The human resources function might manage space allocation. Technical services might control IT infrastructure and finally the facilities management team manage the physical facility. Each of these functions generates and retains data about the building in an entirely task oriented manner. The data created tends to stay in the domain and is not shared across other domains. Data gathered by systems other than the building management system is generally ignored and little or no cross domain data analysis takes place, mainly due to the lack of data interoperability between diverse data systems in the industry.

All manner of data are present in a building, from BMS and control systems throughout the building (access, security, fire, communications, etc.), facility management systems and of course systems associated with the function of the building itself. Some of these systems are interconnected in a manner that allows data sharing, while all have some level of intelligence and produce data of some sort.

Most often, a BMS system will retain operational data using a flat file structure and this information is rarely used for historical performance evaluation. Other data are retained in a wide variety of electronic and paper based systems, included spreadsheets, relational databases, comma separated value lists, proprietary formats, Portable Document Format (PDF) and so on. Ownership of these resources is often fragmented and data fidelity and quality are questionable. Crucially, these systems often produce different types of data, often about the same building objects, in different contexts. For example, a room may be conditioned by a BMS, have access controlled by a security system, have a communications system, a booking schedule, etc. Data for all these systems usually resides in data silos associated with the specific domain and the data is rarely considered in a cross-domain manner.

When dealing with the static repositories containing design and as built information, the story is no less confusing. Hard copy drawings or PDF scans are the order of the day. Some more recent buildings may offer an as built building information model. A landscape of poor data management and poor interoperability dominates the industry.

Decision making is the key to good building management. A poor information management structure hinders good decision making.

1.2.2 Performance Assessment

There is a clear problem around the efficiency of buildings generally and much of this problem, as identified by Hitchcock and others (Gillespie et al., 2007; Hitchcock, 2003; Turner and Frankel, 2008), can be traced to the transfer of data, such as design intent, throughout the life-cycle and the assessment of performance efficiency against design intent. The assessment and monitoring of performance efficiency, fault detection and performance management is limited by lack of access to pertinent data in a reliable and accessible format. As mentioned, the industry is at a tipping point in the information age, where the technology exists to capture, interpret and use building information in a trans-formative manner.

Coupled with the data problem is issue around what to do with data when you capture it. Some methodologies exist to analyse and transform building data into useful information. The present design-build-operate-process generates disconnected and difficult to access information or volumes of information that are not entirely relevant to performance related activities (Abram et al., 2011). Simon (1971) captured the problem neatly when he said

What information consumes is rather obvious: it consumes the attention of its recipients. Hence a wealth of information creates a poverty of attention and a need to allocate that attention efficiently among the overabundance of information sources that might consume it.

Capturing data is one thing. Transforming and interpreting data accurately and in a timely manner is quite another.

1.3 Point of Departure

Several initiatives are underway to describe building related data in a more usable manner and many of these focus on the interoperability issues between data sources. Similarly, many practitioners have worked on the issue of the performance gap, or indeed the chasm between design intent and actual performance. A detailed literature review is presented in chapter 2, which describes some of these initiatives. Some of the proposed solutions include systems of metrics to evaluate building performance throughout the building life-cycle.

Building on this work, this research illustrates how many untapped silos of information exist in the AEC domain and how these silos might be accessed, interpreted and utilised as part of a broader performance evaluation framework. Building performance in the context of this research is concerned with the environmental and energy management of buildings.

Figure 1.4 is a concept diagram illustrating the three key stages of this research and identifying the contributions to knowledge from the work. The diagram describes the path the research takes from the current situation of inefficient building performance, characterised by a significant performance gap, to a state where a more holistic level of building performance management is possible. The image tells a story of a two pronged approach to the problem, the data interoperability track and the performance management track. Both tracks are inter-twined.

The first section describes the current situation regarding building efficiency in the AEC industry, a sector dominated by proprietary software systems and application dependent data sets, leading to bespoke analysis solutions dealing with elements of performance, at stages of the BLC. Holistic, cross life-cycle analysis rarely takes places in the current environment.

The second section illustrates solutions to the performance gap from a data interoperability perspective first. Interoperability describes the ability of tool-sets and data to integrate with each other. At the data level, buildings retain data in heterogeneous data silos, allowing poor interoperability with other domain data. The conversion of such data to a homogeneous format improves the levels of interoperability between data sets. This conversion process must take place at the data level and be platform and application independent. Unstructured

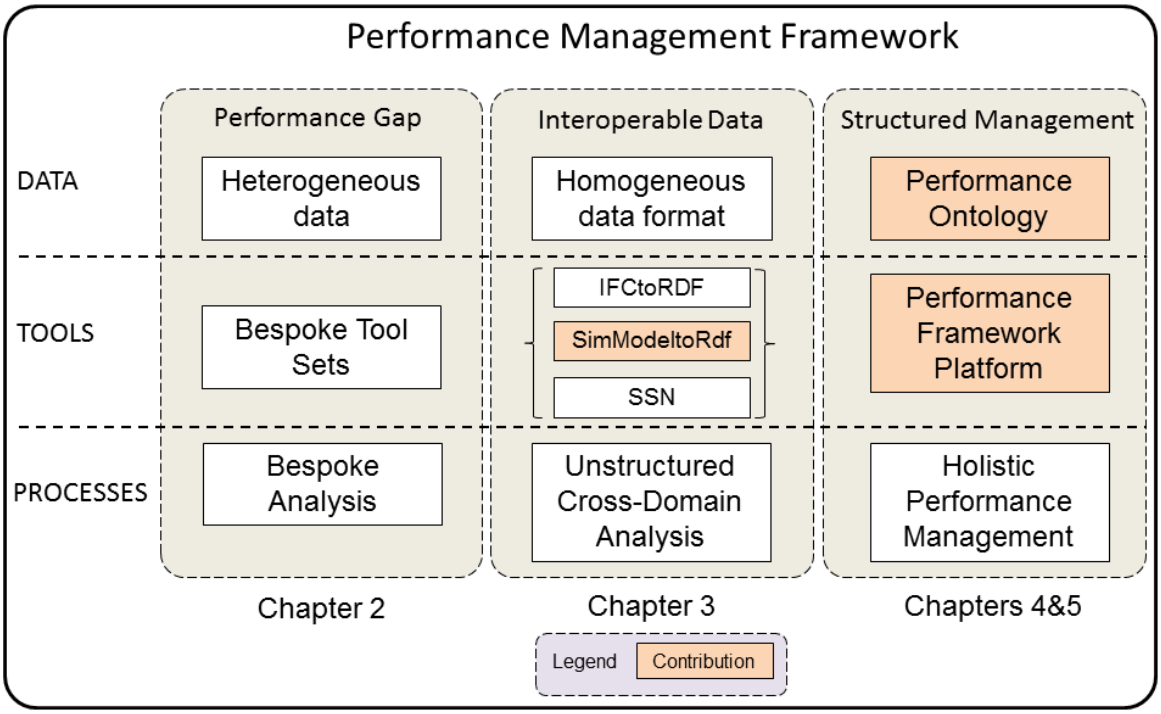


Fig. 1.4 Concept diagram of thesis, broadly illustrating key aspects of the research.

cross-domain analysis of homogeneous data sets is possible, but is of little use in the absence of a structured performance management rule based approach.

Section 3 describes how a structured performance management function can build upon open and available data sets, leading to a place where a holistic interpretation of building performance is possible.

1.4 Significance of Research

There are 200 million buildings in the EU and 80% of these buildings will exist in 2050 (Bribián et al., 2011). Reductions in GHG emissions from the building stock must come from existing buildings. Enabling building owners to accurately correlate design intent with building performance efficiency can significantly impact on the efficiency levels of the building (Raftery et al., 2009).

This work provides a road-map from the current status-quo to an environment where AEC data can be accessed, transformed and interpreted in a holistic fashion. Furthermore, it describes how building owners and managers, armed with accessible data sets, can consider building performance in a cross-domain manner, using a structured performance management approach.

In the longer term, as more data become available, the ability to rapidly integrate such data into existing systems and architectures will confer advantage on those who embrace the data revolution today. The world is moving quickly in this area and it is hoped this research will present a route to a better way of supporting building operation by embracing these technologies.

1.5 Research Questions

This work hypothesises that useful data exist in silos in buildings which is not being used or accessed effectively currently. Furthermore, building data can be semantically enriched into a more homogeneous format and this semantically linked data can be used to drive a performance assessment and management framework. There are two interlinked research questions that this work considers. Semantically mismatched, heterogeneous data can be pushed towards a more homogeneous and accessible format and that a value exists in the exercise. Ultimately this format can form the basis of an enterprise level data integration and analysis approach.

1. Information as a means to an end or a dominant force: Is the use of cross-domain data relevant to optimal building performance?
2. Can the data linking technologies be used to integrate cross-domain data in the context of building performance?

1.6 Thesis Structure

The thesis is laid out as follows:

- Chapter 2 is an extensive literature review on building performance efficiency, the performance gap and the interoperability problem;
- Chapter 3 is focused on research question 1 and introduces the idea of cross domain data and the semantic web, providing an account of a number of experiments in this area;
- Chapter 4 is focused on research question 2, dealing with the concept of an ontology and provides a framework for a semantically driven performance management framework;

- Chapter 5 provides a demonstration of the concepts outlined in Chapter 4;
- Chapter 6 provides a number of conclusions based on the research and describes how these might impact on future research.

1.7 Publications

Various aspects of the research presented in this thesis have been published previously in various publications. The thesis refers to these works throughout and the works expand on many of the topics discussed.

1.7.1 Journal Publications

- Corry, E., O'Donnell, J., Hu, Shushan., Pauwels, P., Keane, M. *A performance assessment ontology for the environmental and energy management of buildings.*, Automation in Construction, *submitted*

- Hu, Shushan., Corry, E., O'Donnell, J. *The implementation of a semantically enriched performance management system*, Automation in Construction, *submitted*

- Corry, E., O'Donnell, J., Curry, E., Coakley, D., Pauwels, P., Keane, M. (2014). *Using semantic web technologies to access soft AEC data.* Advanced Engineering Informatics, DOI: 10.1016/j.aei.2014.05.002

- O'Donnell, J., Corry, E., Hasan, S., Keane, M. M., Curry, E. (2013). *Building performance optimization using cross-domain scenario modeling, linked data, and complex event processing.* Building and Environment, 62(0), 102-111, doi:10.1016/j.buildenv.2013.01.019.

- Curry, E., O'Donnell, J. Corry, E., Hassan, S., Keane, M. (2013). *Linking Building Data in the Cloud: Integrating Cross-Domain Building Data using Linked Data.* Advanced Engineering Informatics, 27(2), 290-302 doi: 10.1016/j.aei.2012.10.003

- Costa, A., Keane, M. M., Torrens, J. I., Corry, E. (2013). *Building operation and energy performance: Monitoring, analysis and optimisation toolkit.* Applied Energy, 101(0), 310-316, doi: 10.1016/j.apenergy.2011.10.037.

- O'Donnell, J., Boyle, N., Hong, L.T., Corry, E., Cao, J., Laefer, Debra. *LiDAR point-cloud mappings for energy simulation of exterior building facades*, Automation in Construction, *submitted*

1.7.2 Conference Proceedings

- Pauwels, P., Corry, E., and O'Donnell, J. (2014) *Representing SimModel in the Web Ontology Language*. Computing in Civil and Building Engineering (2014): pp. 2271-2278. doi: 10.1061/9780784413616.282
- Pauwels, Pieter, Corry, E, O'Donnell, J. (2014). *Making SimModel information available as RDF graphs*. In Bob Martens, A. Mahdavi, R. Scherer (Eds.), 10th European Conference on Product and Process Modelling, Proceedings (pp. 439–445). Presented at the 10th European Conference on Product and Process Modelling, London, UK: Taylor and Francis Group
- Coakley, D., Corry, E., Keane, M. *Validation of Simulated Thermal Comfort using a Calibrated Building Energy Simulation (BES) model in the context of Building Performance Evaluation and Optimisation*, In Proceedings of the 13th annual International Conference for Enhanced Building Operations. Montreal Canada, 2013,
- Corry E, Coakley D, O'Donnell J, Pauwels P, Keane M. *The role of linked data and the semantic web in building operation*. Proceedings of the 13th annual International Conference for Enhanced Building Operations. Montreal, Canada, 2013.
- Corry, Edward, Marcus Keane, James O'Donnell, and Andrea Costa. *Systematic Development of an Operational BIM Utilising Simulation and Performance Data in Building Operation*. In IBPSA Building Simulation 2011. Sydney, Australia, 2011.

1.7.3 Workshops

- Pauwels, Pieter; Van Deursen, Davy; Madrazo, Leandro; Costa, Gonçal; Granholm, Leif; Corry, Edward; Curry, Edward; O'Donnell, James; Törmä, Seppo; Oraskari, Jyrki; *Discussion and Workshop Conclusions: Supporting Decision-Making in the Building Lifecycle using Linked Data*, in LDAC 2012, Ghent, Belgium, LDAC 2012, 2012.

Chapter 2

Issues in information performance management

This chapter will provide a review of building performance, focusing on the following areas:

- The performance gap, Section: 2.1
- Data transfer and the building life-cycle, Section: 2.2
- Using semantic web technologies to support information exchange, Section: 2.3
- Conclusions and proposed approach, Section: 2.4

The topics chosen reflect two of the main challenges identified in the area of building performance currently, interoperability and performance assessment. Figure 2.1 illustrates the section of the thesis concept diagram concerned with chapter two. The diagram describes the path taken in this thesis from the current situation, common in the AEC industry, where building data are retained in application-specific data formats, preventing the development of a more complete interpretation of building environmental and energy performance. The very nature of the way in which data are created and retained in the industry mitigates against cross life-cycle building performance analysis, resulting in myriad bespoke data analysis solutions, each looking at a particular aspect of performance.

Buildings generally do not operate as expected and as the chapter progresses, it becomes apparent why unavailable, inadequate, insufficient and ambiguous information is a key contributor to this problem. The information issue is composed of two parts, the lack of interoperability among AEC applications and domains, and the consequent failure to develop structured performance assessment frameworks throughout the life-cycle. The chapter then

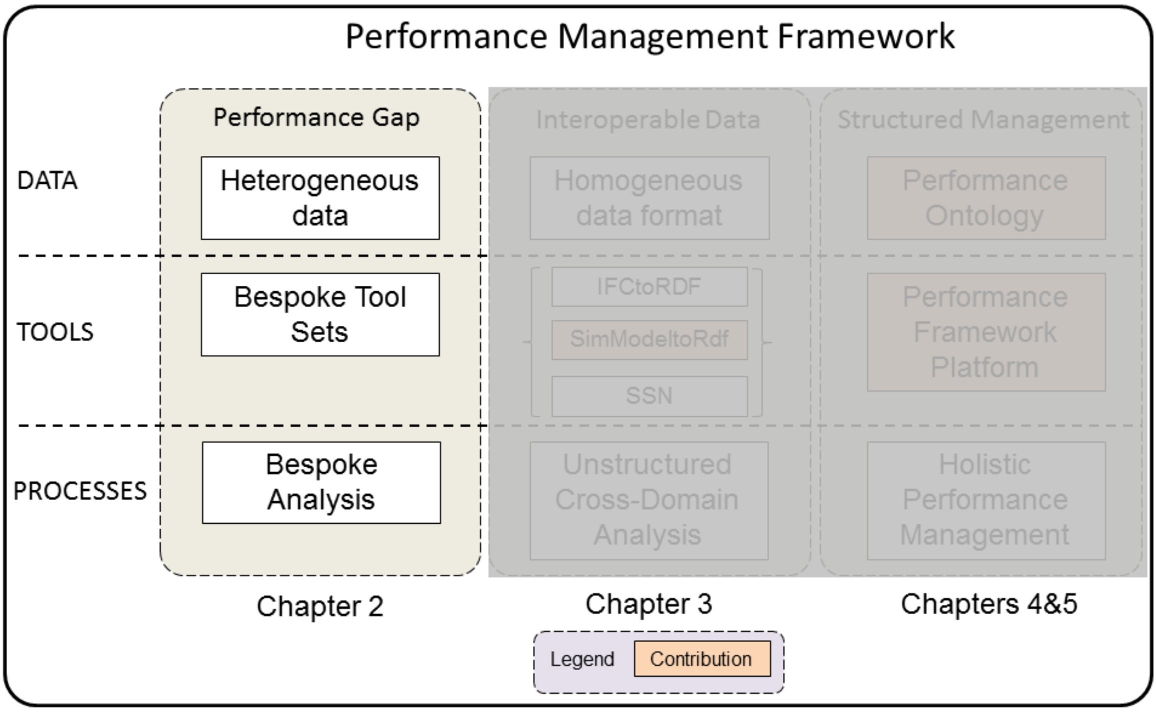
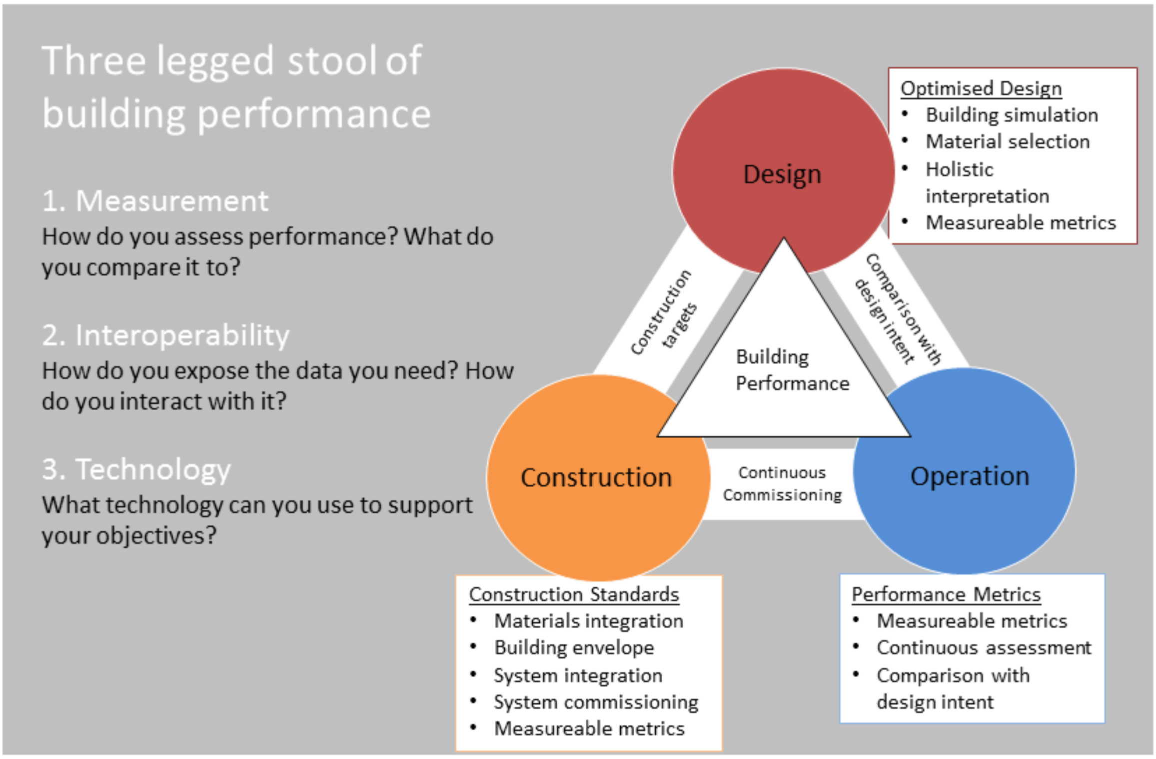


Fig. 2.1 Thesis concept diagram, illustrating the disjointed nature of the current performance management process.

closes with a number of conclusions based on the literature review and proposes an approach for the research. The area of building performance is extremely broad and this review is not intended as an exhaustive search. Instead, it focuses on the information areas associated with the recognised performance gap in the industry and aligns closely with the two research questions identified in the previous chapter.

Is there a value in information being used outside of its initial purpose and could such data integration serve as an enabler in building performance management efforts? How might such data integration take place, and what impact does such sharing have on a specified building performance management approach? These research questions reflect a dual ICT and building management problem, and any solution must address both sides of the issue. A very clear message emerges from this work. Heterogeneous data needs to be transformed into homogeneous data, enabling a move away from bespoke, limited performance analysis, towards a holistic performance management approach, driven by homogeneous data sets. The ability to access cross life-cycle data in such a way allows specialists to then move toward cross-domain analytics.

There is significant domain variance, whereby different elements of the AEC life-cycle perform very different tasks, using different tools and skill-sets and produce incompatible information. Yet the holistic management and maintenance of facilities is a multi-domain problem encompassing financial accounting, building maintenance, facility management, human resources, asset management and code compliance. Scofield (2012) described how building performance was a three legged stool Figure 2.2, encompassing the design, construction and operation of buildings, incapable of standing if one leg is missing.



Three legged stool of building performance

1. Measurement
How do you assess performance? What do you compare it to?

2. Interoperability
How do you expose the data you need? How do you interact with it?

3. Technology
What technology can you use to support your objectives?

Optimised Design
- Building simulation
- Material selection
- Holistic interpretation
- Measureable metrics

Construction Standards
- Materials integration
- Building envelope
- System integration
- System commissioning
- Measureable metrics

Performance Metrics
- Measureable metrics
- Continuous assessment
- Comparison with design intent

Fig. 2.2 The Three Legged Stool of Building Performance. Without any of the three legs, the stool is destined to fall over. Performance cannot be monitored if it is not measured and key performance indicators are imperative throughout each stage of the life-cycle.

Building performance must be considered from all three perspectives. Too often, the industry suffers from a lack of joined up thinking when it comes to optimising building performance with the focus being on specific aspects of the life-cycle and the lack of a holistic interpretation of performance. As a result, there is a significant performance gap between design intent and actual building performance, and this gap increases throughout the operations phase of the life-cycle.

2.1 The Performance Gap

The energy performance of a building is just one of the many performance aspects which may be assessed to determine the overall performance level. Other environmental performance indicators include thermal comfort, air quality, acoustic performance, lighting levels, noise levels, etc. The energy footprint of buildings has received the most attention in recent years. The AEC industry has clearly noted that buildings are not performing as expected and often deviate from design intent by a factor of 2 (Clarke et al., 2002; PROBE, 1995). Buildings can consume up to twice as much energy as originally predicted during the design stage.

This gap between expected performance and actual performance has been identified as the "Performance Gap". Buildings specifically designed to perform optimally regularly fail to meet expectations (Persson and Tanner, 2005; Scofield, 2002; U.S. Green Building Council, 2009) and as Figure 2.3 illustrates, the difference can be substantial. Some of these cases are now discussed further.

Fig. 2.3 The performance gap between the design model and the measured EUI for 16 LEED buildings in Illinois. 12 of the 16 buildings fared worse than the original design model (U.S. Green Building Council, 2009). Removed due to copyright restrictions

There is no single cause or reason for such a large discrepancy between design intent and actual performance and as Figure 2.4 suggests, the many causes appear throughout the life-cycle. Perhaps an analogy from another area of manufacturing engineering might be reasonable. In common with the AEC industry, other energy intensive sectors of the economy are undergoing a similar period of introspection and assessment in a drive to reduce energy costs. The car industry is no different and there has been a marked move away from the large 4x4 type *gas guzzlers* of old, toward smaller engined diesel cars. All cars sold in the European Union (EU) for instance need to display a specific CO_2 emission rating, given in g/km. In many countries, taxation on vehicles is based on this metric and consumers are very aware of it when making a purchase. A closer look at how the emissions figure for auto-mobiles is derived shows how cars are assessed over a number of standard tests and although some evidence suggests these tests do not mimic actual driving activity closely enough, by and large, cars perform as specified.

Fig. 2.4 The Performance Gap Growth from Design to Operation (ARUP, 2013). Removed due to copyright restrictions

When one considers how cars are designed, tested, manufactured and sold, it is clear why there is a good correlation between actual performance and design intent. Cars undergo rigorous and expensive testing procedures prior to production, and automated plants ensure that each car is manufactured to very precise tolerances. One can say that one instance of a car from a model range is the same as the next. The key factor in how the car performs is the owner and generally, cars have a single operator. In contrast, buildings are one-off constructions and have several *operators* with the ability to modify aspects of performance.

The BLC is a much more fragmented process, whereby a number of stakeholders collaborate for a limited period to design, build and operate a one-off facility. Often the relationship between the parties is adversarial in nature (Forbes, 2011). The building is usually constructed almost entirely on-site, without the benefit of factory based construction methods, and is constructed by domain experts who often have little interaction with each other and are focussed only on completing their aspect of the construction process. The design of the building itself may or may not include a performance simulation model (Coakley et al., 2014). The criteria used to produce this model may no longer be relevant due to building modification, or were incorrect initially. Buildings are then operated with varying levels of reference to the original operations manual.

The construction industry is perhaps the only industry that goes to the build stage without adequate virtual testing (Bazjanac, 2004). Of course there are many reasons for this, grouped around the ownership, operation and life-cycle of buildings. For instance, a building is often built speculatively by a developer, or perhaps part of a design and build project for an owner. The key innovations in the building are often focused on the design and construction phases, with the specification of complex Heating Ventilation and Air Conditioning (HVAC) systems and so forth. Often, little focus is placed on the operations phase of the building. Designers and builders have less motivation to ensure the building operates as designed and more to ensure the building is well constructed.

It can be quite difficult to ensure that design intent is retained through out this process so that owners get what they think they asked for (Scofield, 2009). Much work has gone into the specification of a clear handover process following initial commissioning, to overcome some of the many issues associated around this stage (Fallon and Palmer, 2007). Often, once the building has been handed over, the management of the building rests with the building manager. In the absence of formalised performance management systems in place, the building manager retains key design and operation information, often in his or her head. This person may resign or retire at some point and institutional knowledge is lost. Similarly, the building manager often lacks reliable and timely information and associated tools, which can be used to trouble shoot poor performance and optimise efficiency.

There is a considerable lack of information regarding the performance of buildings in general and as a result, we rely on a number of studies which compare actual and predicted building performance. The Post-Occupancy Review of Buildings and their Engineering (PROBE) studies illustrate how predictions can be unrealistically low (Menezes et al., 2012), due to inaccurate design assumptions and modelling tools, while issues surrounding management and controls, occupancy behaviour and build quality can lead to poor actual performance levels.

The Carbon Trust (2012) have also studied this issue in detail and have categorised some of the common faults associated with buildings exhibiting such a performance gap, including inadequate predictions at design time, poor communication of performance intent from the design team, inadequate testing of design, overly complex building systems and controls, poor construction practice, inadequate commissioning, poor measurement approach, and incorrectly operated buildings. These issues span the entire building life-cycle.

The Zero Carbon Hub (2014) research encountered similar issues in the area of new low carbon home construction. It reported that although there was a lack of study in this area, an undeniable issue existed, caused by insufficient technological understanding, industry culture, poor integration of energy and carbon performance in the design phase, and poor feedback mechanisms amongst others. Bordass et al. (2004) points to the gap resulting from slippage occurring throughout the development life-cycle from initial design assumptions, ending in a poorly performing building a distance away from the original assumptions. ARUP (2013) describe the issue similarly, as a gap that increases throughout the life-cycle and suggest solutions must take the form of a feedback loop, feeding back to design and feeding back to operation.

It is clear that the performance gap in the AEC industry is pronounced and its causes are multi-faceted. De Wilde, in the most recent review of this area, identified three broad areas from where the performance gap originates (de Wilde, 2014), including issues pertaining to the design stage, issues rooted in the construction stage (including handover) and issues that relate to the operational stage.

These three areas are now used as a basis to introduce some of the roots of performance gap issues in buildings. There is no silver bullet or single solution which can be applied to the performance gap problem, but several initiatives are underway to address many of the issues now described. The response from the design community is two-fold. First to ensure that design methodologies are based on accurate assumptions and secondly, there is much greater awareness among the design community of the importance of first designing a robust (de Wilde, 2014) building and then communicating this design in a clear and unambiguous fashion.

2.1.1 Design

The design stage may broadly be thought of as spanning the period from initial building conception to the exchange of contractual documents with a construction company. When considering the performance gap, it is important to consider the route taken to arrive at the design performance value and then the route taken to measure actual building performance.

All manner of discrepancy, assumption and error can exist in both sides of the equation, including incorrect assumptions concerning occupancy, weather, usage, electricity load and so on. Measurement of actual performance can also be notoriously problematic. de Wilde (2014) mentions communications issues between client and designer or indeed members of the design team, leading to poorer outcomes (Carbon Trust, 2012; Newsham et al., 2009). Many buildings evolve over time in terms of use and occupancy. As these factors change, the energy footprint of the facility also changes.

Several publications point to the impact occupants have on building performance and as such, it is difficult to hold designers to account for unpredictable or unplanned occupancy behaviours and patterns (Fabi et al., 2012; Haldi and Robinson, 2011; Yu et al., 2011). Technology is evolving at a furious pace and many high performance buildings might be seen as test beds for new technology. Integrating several such systems may be a further step into the unknown. Considering the performance gap, how can we know if the discrepancies are due to the initial prediction or the actual performance? Were assumptions made at design time valid? In some cases, the design predictions for regulatory compliance do not account for all energy uses in buildings, particularly around the area of unregulated electricity use, such as plug-loads (Carbon Trust, 2012; Menezes et al., 2012).

As the design proceeds, sometimes, a whole building energy simulation model is constructed, populated with existing design parameters. Various commercial and freely available tools exist for energy simulation, including DOE-2, EnergyPlus, TRNSYS, IDA ICE and IES. Coakley et al. (2014) provides a comprehensive review of the methods of matching building energy simulation models to measured data. Coakley et al. (2014) describes how energy simulation can be categorised into three distinct approaches:

1. Black-box approach;
2. Grey-box/parameterestimation;
3. Detailed model calibration;

Coakley et al. (2014) describes how various issues associated with the Building Energy Performance Simulation (BEPS) discipline, broadly broken into modelling and calibration issues, all of which can lead to inaccuracies between BEPS results and actual performance and describes the problem as one of over-specification and under-estimation. Models of large scale systems, such as a building are very difficult to validate. There is an inherent uncertainty in the building simulation discipline where there are so many inputs and few outputs, leading to difficulties pinpointing which parameters are affecting which outputs.

Similarly, designers choose parameters which may or may not reflect actual building conditions. Poor BEPS results can emerge from incorrect methodology, poor tool selection and inexperienced modellers. Similarly, the phrase "garbage in garbage out" suggests that even with the best software, model and modeller, incorrect assumptions regarding the building will lead to unreliable outcomes from the model (Coakley et al., 2014; de Wilde, 2014).

The design stage of the BLC can introduce a variety of errors and incorrect assumptions, which left unchecked, will result in a gap in performance during the operation phase. Many efforts have been made to improve the design process and these are now discussed.

2.1.2 Improved Design

The Building Energy Performance Simulation (BEPS) discipline is striving to improve the accuracy of building models and many authors point to the benefits of a well calibrated building model (Maile et al., 2012; Raftery et al., 2010). Manufacturers play a role in the development of systems which are easy to build and overcome many of the thermal issues associated with building envelopes.

Improved design can be considered in two parts. First, the specification of high-performance materials and secondly the consideration given to design factors impacting on overall performance. The choice of site, building orientation, awareness of climate conditions, awareness of occupant patterns and behaviour are all key requirements at the design stage of the process. Improvements in the BEPS discipline are driven by feedback taken from buildings and the calibration of building models with actual performance is an area that is bearing fruit (Maile et al., 2012).

2.1.3 Building Certification

Broadly speaking, there are a number of responses legislators can take to encourage more efficient energy use in the AEC domain. Ratings or certification systems, successfully applied to appliances in the 1980s, have been introduced to describe the performance of building stock. These certification schemes fall into two main categories, (1) a prescriptive approach, specifying elements required in a project, and (2) a predicted performance approach. Software exists which allows for a prediction of future performance in comparison with a reference building (CEC, 2005; SEAI, 2012). Regions and countries routinely offer financial inducements to modify existing building stock in favour of upgraded envelope components and HVAC equipment. Further measures available to legislators lie at the supply side of the equation, including the imposition of higher taxes on GHG emitting fuels.

Perhaps the key legislative approach to the reduction of greenhouse emissions has been the introduction of minimum standards, which have been introduced and amended frequently since the 1970s. Since then, regulations governing the design and construction of buildings have increased incrementally, particularly those focusing on the conservation of fuel and energy. Building designers are restricted to the clear regulations which exist defining the requirements of the building, in terms of energy efficiency, including the European Performance in Buildings Directive (EPBD) (European Union, 2010b), Title 24 (CEC, 2005) and ASHRAE Standard 90.1 (ASHRAE, 2004a). Traditionally, these standards and directives were prescriptive in nature, requiring a checklist approach to ensure the building complied.

In the case of the EPBD for instance, which is implemented in various national policies throughout the 27 member states of the EU (Andaloro et al., 2010), buildings also need to show that the calculated primary energy consumption associated with the operation of the building and the related CO_2 emissions do not exceed a specified target value (Department of the Environment, 2008). In the case of Irish legislation, the Non Domestic Energy Assessment Procedure (NEAP) provides a framework for the calculation of primary energy consumption. This type of software is available to building designers as a means to ensure that the predicted energy performance is within the norms of the official standard. These types of tools are not to be confused with design tools.

Ultimately, the goal of the energy certification approach is to mandate the building industry to provide high performance buildings as a matter of routine. At this point, throughout the EU and much of the United States and other countries, onerous requirements exist in terms of the provision of performance certification for existing buildings and highly performance focused design requirements for new buildings. Buildings cannot be traded or let without this rating in place. Such measures lie firmly on the design side of the building life-cycle and although most certification schemes require a prediction of future performance, actual performance does not figure.

At national level, new buildings must now meet stringent targets and in Ireland, new buildings, or existing buildings for sale or let, must have a Building Energy Rating (BER).

Furthermore, a Display Energy Certificate is (DEC) is required to be displayed on all public buildings with a floor area greater than 1000 m^2. What these and other similar measures describe is a rating system enshrined in legislation and implemented with mixed results at the national level by the 27 member states (Andaloro et al., 2010). The latest version of the Part L (Department of the Environment, 2008) mandates designers to achieve a certain emissions standard on any new build. This approach is somewhat similar to that in California (CEC, 2005) and other areas.

2.1.4 Voluntary Building Assessment Schemes

In tandem with increased legislation, a range of voluntary building environment assessment schemes have emerged for the commercial building sector, each providing specific ratings for buildings and encouraging the design of buildings to a particular environmental standard.

The Leadership in Energy and Environmental Design (LEED), developed by the U.S. Green Building Council (USGBC) (USGBC, 2002), Building Research Establishment Environmental Assessment Method (BREEAM), developed by U.K. Building Research Establishment (BRE) (BREEAM, 2005), and Green Star (GBCA, 2013), developed by the Green Building Council of Australia (GBCA), are three of the most common voluntary schemes. All three methodologies are accepted as guides to the sound environmental design of buildings.

Each methodology describes the environmental commitment of a building by considering the various environmental areas affected, including waste disposal, water, energy consumption, materials, comfort levels and so on. The building is then rated or compared against an established baseline for similar buildings. The schemes differ in their approach to the rating process and the scoring weight which is attributed to the various environmental criteria, and the energy rating achieved can vary significantly between methods (Roderick et al., 2009). Questions exist over energy savings claims experienced in buildings designed to a particular energy assessment scheme and normal building stock.

Famously, the New Buildings Institute commissioned a report on LEED certified buildings, concluding that such buildings used 25-30% less energy than conventional buildings (Turner and Frankel, 2008). Newsham et al. (2009) also suggested that some LEED buildings have been shown to consume 18-39% less energy than their conventional counterparts, but other LEED buildings have been shown to consume 28-35% more energy and the energy performance of such buildings has little correlation with the the certification level of the building. However, Scofield (2009) points out that there has been little energy-consumption data to support the assertion that LEED buildings are more energy efficient and challenged the findings of the New Buildings Institute report. On closer examination of building energy consumption data, Scofield (2009) showed that both the site energy and source energy of LEED and non-LEED buildings are statistically equivalent. Gifford (2008) also questioned the legitimacy of claims that the LEED approach actually saved any energy.

Whilst the legislative and building rating approaches have a significant role to play in the creation of high performance buildings, studies illustrate why such rating systems do not provide the whole picture when it comes to building performance. Relying on the design aspect alone to ensure an energy efficient building is naive, especially when you consider that the majority of a building's energy use takes place in the operational phase of the BLC (Cole and Kernan, 1996; Sartori and Hestnes, 2007).

2.1.5 Construction, Commissioning & Handover

The next stage of the BLC is the construction stage and while it consists of a number of sub-phases, it encompasses the period from contract signing to building handover. Modern building constructions are a complex process involving several groups of specialists, coming together often in-hospitable conditions to construct a high performance facility. Ensuring that a building is constructed to the required standard and is faithful to the design is a central plank of high-performing buildings.

In the case of two key environmental performance strategies, air-tightness and insulation levels, the devil is really in the detail. Air-tightness describes the process whereby uncontrolled air changes in the building are reduced to as close to a minimum as possible. Blower tests can be performed and results measured in air-changes per hour. Achieving high levels of air tightness is an extremely involved task and one which can be severely affected by the work of others not in tune with the requirements. If a building designer assumes a certain level of air-tightness and this is not achieved during construction, then this will introduce a performance gap. Similarly, insulation levels are crucially important, with the thermal conductivity of the building envelope forming a key parameter of any performance calculation exercise.

Envelope insulation must be consistent throughout the building envelope and cold-bridging needs to be identified and removed. In conjunction with legislative instruments mentioned previously (Department of the Environment, 2008), building designers are mandated to specify minimum building component standards. In the case of u-values ($W/m^2/°K$) for walls for instance, these values are calculated using a composite calculation. The result on the ground is entirely dependent on how the wall is constructed.

In the absence of very detailed and accurate design drawings illustrating clearly the interfaces between insulation and the building envelope or the installation of the air tight membrane, performance assumptions made during the design phase become less reliable. Similarly, the installation and commissioning of the HVAC and building control systems is a complex task with the potential for many performance related issues.

In terms of performance, much work has gone into the area of commissioning (Liu et al., 2003; Mills, 2009), post-occupancy evaluation (Lee et al., 2013) and information management (CIBSE, 2006; Fallon and Palmer, 2007). Traditionally, following initial commissioning of the HVAC system and the completion of the building process, the building was handed over to the client. This handover process usually included a range of drawings, specifications and product manuals, generally paper based, in a collection of ring binder folders. Sometimes, the information is available in PDF, a format which cannot be interpreted by a computer. This collection of documents was usually placed in the building manager's office and consulted from time to time as faults emerged. Recent efforts have attempted to put a clear structure around this handover process, providing a documentation road-map to ensure that design intent and as-built construction information is retained into the operations phase (CIBSE, 2006; Fallon and Palmer, 2007). This information transfer is discussed in more detail in the information transfer section of the work.

2.1.6 Operation

The operations phase of the building life-cycle accounts for a large proportion of the performance gap. The issues which cause this gap can be loosely categorized under the following headings:

- Occupant behaviour
- Building Use
- Operation practices

When predicting the future performance of a building at design stage, the designer needs to make a range of assumptions. Perhaps the most difficult assumptions concern occupancy patterns and behaviour. For instance, plug load forms a significant amount of the total unregulated energy use in a facility and is something that can vary widely (ARUP, 2013). The patterns of occupancy can also play a pronounced role in performance. Many large buildings are operated at night time by a skeleton staff, whilst consuming conditioning energy for a much larger population. Over time, the nature of the use of a building is modified and this also impacts performance.

As the client manages the building following handover, tweaks and adjustments are made to the building management system. Over time, the actual performance deviates considerably from design intent, or at least the assumptions that governed the design in the first place. Often, design intent is not communicated properly and is therefore not understood by the building management. In the traditional approach, as the performance gap increases, costs rise and eventually an expert is hired to “reset” the building and process repeats itself again, with peaks and troughs in performance levels. Usually, the building manager is swamped with data and alarms, and operates in a fire-fighting mode. Building management systems tend to operate in real time, with little attention given to historical patterns. There is a lack of precise and timely information, presented in an accessible manner for the building manager.

Unpredictable occupant behaviour (Lee et al., 2013), changes in building usage, and sub optimal system settings will lead to significant performance slippage, and this is reflected through the non-residential building stock in the world.

2.1.7 Performance Assessment

Performance tends to deviate from the ideal over time as slippage enters the system in the form of tweaks to the BMS, insufficient maintenance and changed occupancy patterns. One key solution to the performance gap problem lies in the area of measurement. Based on the timeless concept, you cannot manage what you do not measure (Chartered Institution of Building Services Engineers, 2012), performance measurement and assessment is is of vital importance. One approach which has proved very successful is the Continuous Commissioning (Batista et al., 2014; Liu et al., 2002) approach. It seeks to extend the commissioning phase to the full operational life-cycle of the building, using commissioning techniques to continually optimise and tweak building performance.

A lack of clarity as to what constitutes ideal performance, allied to poor data capture, storage and analysis techniques lead to inadequate levels of performance measurement. Several efforts have been made to address these issues. The performance metrics (Fowler et al., 2005; Gillespie et al., 2007; Hitchcock, 2003; O’Sullivan et al., 2004) approach breaks down performance to its constituent parts and creates quantifiable metrics around these elements, which can be assessed throughout the operational phase of the BLC. The performance framework approach (O’Donnell, 2009) extends the metrics concept to include a wider performance framework applicable throughout the entire life-cycle of the building and describes scenarios of performance. Issues concerning the capture and visualisation of data are addressed by Neuman (Neumann and Jacob, 2008) in the BuildingEQ project. What these approaches have in common is an attempt to define performance in terms of constituent parts and then assess this performance over time.

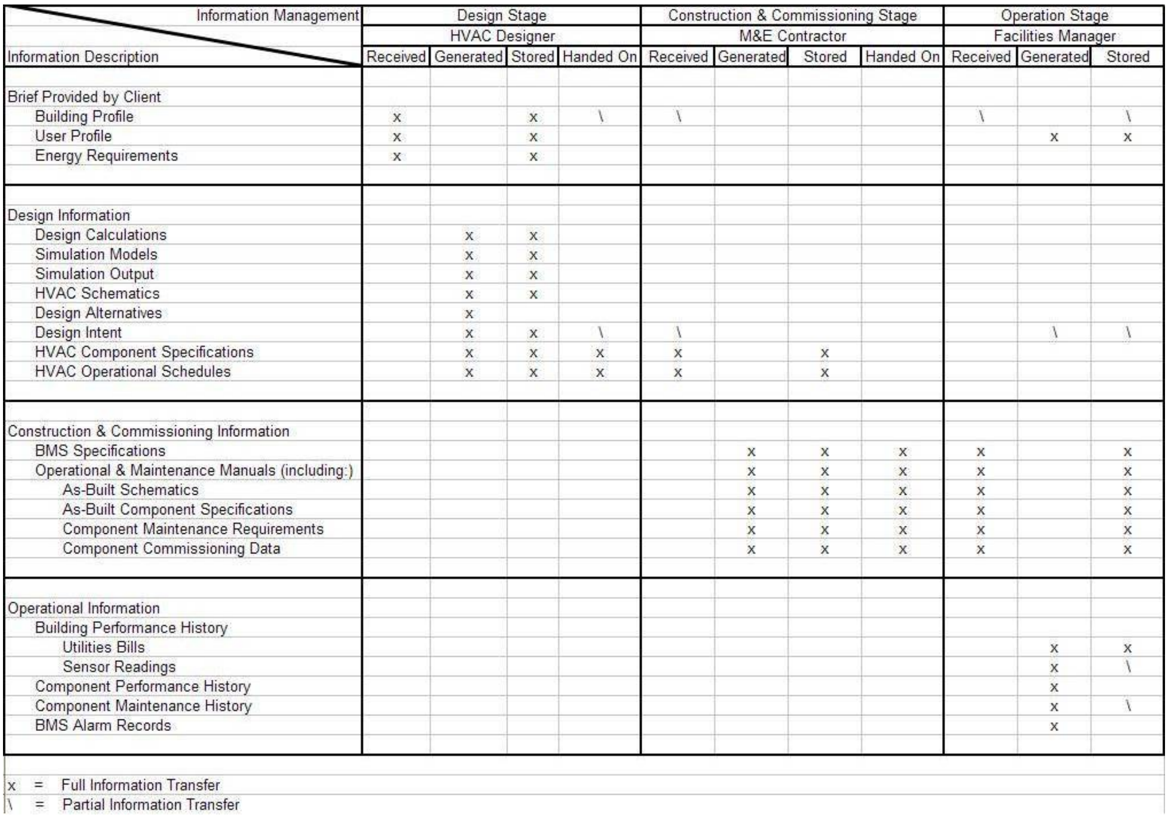
As occupants play such a major role in the performance of buildings, post-occupancy evaluations are critically important in ascertaining how occupants feel about the building and if the environmental performance is as expected over time. It is imperative that this is not seen as a box ticking exercise, but rather a vital part of the commissioning process.

2.2 Data Transfer and the BLC

Throughout the BLC, information is gathered about a facility. This information serves different purposes, primarily driven by the stage of the BLC. This information is generally fragmented and paper or spread-sheet based. A building file is typically handed over on completion of the building and this file is usually paper-based or PDF soft-copy. Routinely it is incomplete and often key areas like operations and maintenance consist of manufacturer's product brochures. The current AEC process tends to gather data for specific purposes and then discard it once the purpose is complete.

Eastman (2008) has outlined the fragmented nature of the building process and Teicholz (2004) explained how over 60% of firms involved in the construction industry have less than 5 employees. The transfer of information across the building life-cycle must be seen against this backdrop. Although some efforts are being made to structure the handover of building information (Fallon and Palmer, 2007), it remains a disjointed affair. This reality is reflected in many of the buildings encountered as part of this research, where key operational requirements such as environmental operation procedures were often absent or poorly documented.

An analysis of the definition, capture and loss of AEC data is illustrated in Figure 2.5. It shows how in the current AEC approach, streams of information related to a particular phase of the BLC often die once that stream is complete. If the information generated at design time, from simulation models and design calculations, could be captured accurately, it could form the basis of an operational phase performance assessment programme, providing a benchmark for building performance over time. One of the key limiting issue, preventing the transfer of such information through the life-cycle relates to interoperability between the various domains involved in the life-cycle and this point is expanded on in section 2.1.



Information Management	Design Stage				Construction & Commissioning Stage				Operation Stage		
	HVAC Designer				M&E Contractor				Facilities Manager		
Information Description	Received	Generated	Stored	Handed On	Received	Generated	Stored	Handed On	Received	Generated	Stored
Brief Provided by Client											
Building Profile	x		x	\	\				\		\
User Profile	x		x							x	x
Energy Requirements	x		x								
Design Information											
Design Calculations		x	x								
Simulation Models		x	x								
Simulation Output		x	x								
HVAC Schematics		x	x								
Design Alternatives		x									
Design Intent		x	x	\	\					\	\
HVAC Component Specifications		x	x	x	x		x				
HVAC Operational Schedules		x	x	x	x		x				
Construction & Commissioning Information											
BMS Specifications						x	x	x	x		x
Operational & Maintenance Manuals (including:)						x	x	x	x		x
As-Built Schematics						x	x	x	x		x
As-Built Component Specifications						x	x	x	x		x
Component Maintenance Requirements						x	x	x	x		x
Component Commissioning Data						x	x	x	x		x
Operational Information											
Building Performance History											
Utilities Bills										x	x
Sensor Readings										x	\
Component Performance History										x	
Component Maintenance History										x	\
BMS Alarm Records										x	

x = Full Information Transfer
\ = Partial Information Transfer

Fig. 2.5 Information Flow across BLC (O'Donnell, 2009). Information usually remains in the stage it orginated in and is not used across the life-cycle.

2.2.1 Computerised Building Information

In common with many other manufacturing industries, the AEC industry has embraced computer aided design and life-cycle management tools, with varying degrees of success. Pauwels (2012) categorised these as modeling applications, archive applications, calculation applications and visualization applications. These systems define, capture, transform and retain all manner of building related information encountered throughout the BLC.

2.2.2 Modelling Applications

Modelling applications are one of the most common AEC type systems and describe a set of tools which capture a description of a building or element of the building digitally.

The process of conveying building information has remained largely static for centuries, with drafting skills used by Christopher Wren when designing London's St. Paul's Cathedral still being used in architectural offices up until recently. The core principle of this this type of drafting was the transmission of information in 2-D, through a series of elevations, plan views and sections. The original premise of a Computer Aided Design (CAD) system was to automate the task of drafting. As such, the original focus of CAD applications was to represent 2-D geometry via graphical elements, such as lines, arcs and symbols.

In this context, walls, for example, are merely represented as parallel lines (Howell and Batcheler, 2005). These drawings require interpretation by the reader to extract information from them and an acute visual awareness to be able to visualise the building in 3-D. A modern building requires thousands of separate drawings to convey the design intent of the various domains to the actors in the construction phase of the BLC. Following commissioning of the building, these drawings are consigned to a building file and stored in a repository. The once-off nature of building construction means that the interpretations taken from these plans will disperse quickly upon facility completion.

Object-based parametric modelling was originally developed in the 1980s. It represents objects by parameters and rules that determine the geometry, as well as some non-geometric properties and features. The parameters and rules allow the objects to automatically update according to user control or changing contexts (Eastman, 2008). In this way, parametric based BIM are a world away from CAD and paper-based 2-D drawings, which are merely a collection of lines on a page, without any inter-relation between each other. A building information modelling application allows the designer to define a wall object, with associated properties such as materials, u-value, strength, etc. and then to define a relationship between the wall and window and door objects, etc (Figure 2.6).

Fig. 2.6 3-Dimensional parametric model (The BIM Hub, 2014) Removed due to copyright restrictions

As the BIM represents the entirety of the building geometry, views and sections can be extracted from the model to provide architectural drafts of the building, but also, the model can be interrogated by down-stream applications to provide quantities, scheduling information, simulation information, etc. 2-D paper based and CAD drafting techniques provide a snapshot of a building, from a particular perspective. Originally, the BIM was a 3-D model, containing geometric data about a building. Now, the information contained in these models is being exploited by a variety of domains across the BLC, such as design, construction, scheduling, cost, fabrication and operations (See, 2007; Thomas, 2010; Watson, 2011).

2.2.3 Archive Applications

Pauwels (2012) discussed these types of applications from design perspective, but they also apply to other areas of the building life-cycle. The two key archive types concerned with building performance are the operations and maintenance manuals, generally received on building handover, and the building management system BMS archive.

As previously described in Section 2.2, the operations and maintenance archive typically consists of PDF documents, product specification brochures, schematics, etc. The BMS archive is generally retained in a series of Comma Separated Value List (CSV) files or as part of a relational database, and stored for a defined period of time. These files contain set point data from each of the set-points on the BMS and are time stamped. In some installations, these data are retained in a relational database. These data could be considered as key historical performance data, retained at a specific time resolution, perhaps 15 minutes. Usually, it will include data for CO_2 levels and temperatures in building zones and HVAC equipment. It may also include some performance data from HVAC equipment, but more likely, these types of data will be held separately. Utility data will be held in a separate archive and the resolution of these data will depend on the complexity of the metering system installed. Utility usage information will take the form of billing information from the supplier.

2.2.4 Calculation Applications

All manner of calculation environments exist in the AEC environment, including BEPS software, structural design analysis software, etc. (Pauwels, 2012). These applications interpret data in various ways, using a coding structure based on the relevant standards of the discipline. The BEPS tools interpret a wide range of parameters and provide an outcome based on these. Often, these calculation tools serve a unique purpose and their output forms the basis of further calculations, or reports. A BEPS developed for a large building will form the basis of a HVAC sizing exercise. A structural analysis calculation will be used as a basis for element sizing and placing.

Usually the output from these calculation tools is lost at this point and the model and underlying assumptions is discarded. Some calculation tools, quantity surveying and scheduling tools mainly, allow for a direct data transfer between a building model and the tool itself, but more often, the basic model underlying the calculation needs to be assembled from the beginning.

2.2.5 Visualization Applications

Visualisation applications render a view of the building or a particular aspect of the building, in 2-D or 3-D format. Originally, these tools were closely based on the model applications, allowing visualisations of the underlying geometric model. Building data, other than the basic geometric data are also available and visualisation of building performance is also possible.

Underlying the four different modes of data application in the AEC industry is an issue relating to data transfer and interoperability. These tools rarely communicate or transfer data with each other and the information retained in each system tends to remain in that system.

2.2.6 Interoperability

Interoperability is defined as the ability to manage and communicate electronic product and project data between collaborating firms' and within individual companies' design, construction, maintenance, and business process systems. Studies have identified that the construction industry lags behind other capital intensive industries like the automotive and aircraft sectors in the design, construction and operation processes (Flager and Haymaker, 2009). Clashes and errors frequently do not become apparent until construction has begun and significant amounts of workforce downtime are inevitable in a situation where poorly specified components need to be modified on site. Tolerances in the industry are often notoriously generous, with much work carried out on site, subject to the vagaries of traffic, weather and location and away from the closely monitored factory floor.

Fig. 2.7 Labour productivity index for US construction industry and all non-farm industries from 1964 through 2003 (Teicholz, 2004). Removed due to copyright restrictions

Figure 2.7 indicates the growing disparity between productivity increases in the construction industry as against all other non-farm industries. (Non-farm employment describes employment in goods, construction and manufacturing companies in the United States and does not include farm workers, private household employees, or non-profit organization employees (United States Federal Reserve Board, 2014)).

One of the chief reasons (Teicholz, 2004) identified is the fragmented nature of the construction industry and varied level of ICT adoption and collaboration amongst the various members of a project team. These problems are further compounded by the large number of small companies that have not adopted advanced information technologies (Gallaher et al., 2004). Under each of the four categories of AEC computer application described (modelling, archive, calculation and visualisation) lies a vast array of applications and tools designed to perform very specific tasks during the life-cycle. The flow of information between these tools and domains is usually inadequate or lacking completely. The interface points between these systems, where two or more interpretations come together (Pauwels, 2012), can result in poor information transfer.

2.2.7 Interoperability and the AEC Industry

If you consider just the design phase of the the BLC, a tremendous amount of effort is expended designing and specifying the various elements of the building. Several disciplines are involved and each discipline tends to use its own tools to drive this design. As the work is so diverse, the data models used to capture the design intent of each domain tends to vary from the others. There is little interoperability between these systems and when a data transfer is required, it is often a torturous one-one interface process that is followed. Pauwels (2012) talks of the idea of sharing of information in the wild, between applications, where data fidelity is compromised as repeated conversions take place. With each conversion, the fidelity of the original data is further eroded.

In the design world, ideally, there should be a seamless transfer of information between systems. As each design tool is used to model a specific part of the building and has been designed with that focus only, the underlying data model is adapted to serve purely that purpose. As the design progresses, the data model is saved in the proprietary format of the application. Any conversion of this format to another data format used by a separate application leads to losses.

A number of challenges need to be addressed when integrating data from different sources (Shen et al., 2010) and these are loosely classified as Data mismatch, Object Identity, Abstraction Levels and Data Quality. These issues need to be considered whenever data transfer is specified between diverse model based applications. The AEC industry employs all manner of computer applications to perform tasks as diverse as structural analysis and room booking. Each system tends to serve a very specific purpose and data transfer between these tools is usually limited. Mostly, these tools and systems act independently, with little or limited interaction with other life-cycle systems and tools. Interoperability might be described as the ability of separate software systems to exchange data with each other. There is little interoperability between these often closely related AEC systems, leading to cost over-runs, incorrect specification and sub-optimal performance of the building life-cycle in general. One well known report costed this inadequate interoperability at 15.8 billion dollars per year (Gallaher et al., 2004), with most of this cost arising to owners during the operational phase of the life-cycle.

2.2.8 Information Exchange

Computerised information exchange takes place in a number of different ways in the AEC industry. There are two broad options in this regard. One is the proprietary model whereby a product vendor incorporates a proprietary building model in their suite of products. Proprietary platforms tend to use internal data models to capture and store data. This data model is used throughout the software suite and the user is restricted to using the particular tools provided by the vendor. When the user tries to use another software application, a conversion of some sort needs to be made between the proprietary data model and the new model found in the second application. This type of transfer is fraught with difficulty as there are so many interface points involved, where potential for information loss and degradation exists (Figure 2.8).

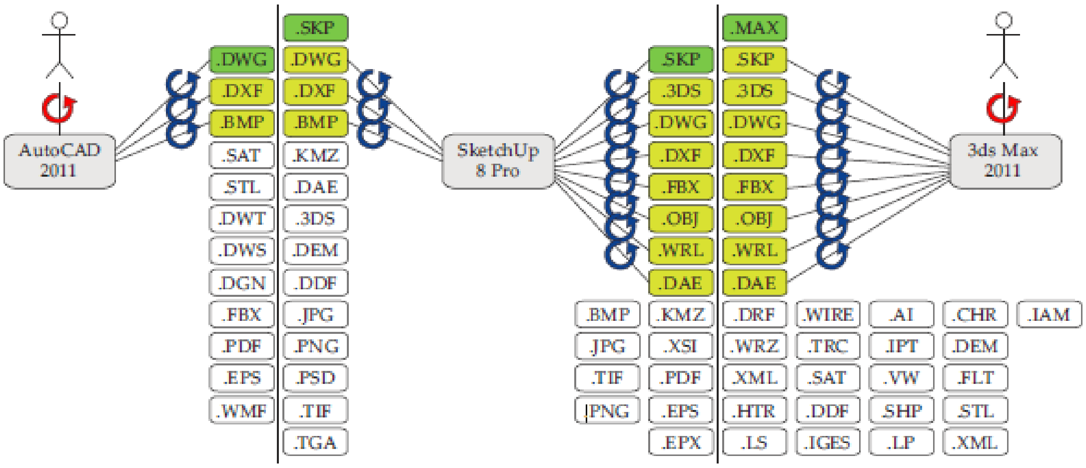


Fig. 2.8 The possible information flows between Autodesk AutoCAD 2011, Google SketchUp 8 Pro and Autodesk 3ds Max 2011, with native file formats in green, possible exchange formats in yellow. (Pauwels, 2012)

A second solution is to utilise a non-proprietary, open data model to allow unrestricted data exchange between applications. Some efforts have been made to standardise the transfer of data between systems and a central part of the development of BIM is the capture of data centrally and the transfer of data between various domains. This approach specifies an underlying data model which is used to retain all the relevant building related information.

2.2.9 IFC

A data schema is a data structure which describes concepts in a particular domain. BuildingSMART have developed a common data schema that makes it possible to hold and exchange data between different proprietary software applications (International Organization for Standardization, 2013). The data schema comprises information covering the many disciplines that contribute to a building throughout its life-cycle: from conception, through design, construction and operation to refurbishment or demolition.

IFC can be used to exchange and share BIM data between applications developed by different software vendors without the software having to support numerous native formats. As an open format, IFC does not belong to a single software vendor; it is neutral and independent of a particular vendor's plans for software development (BuildingSMART, 2011). Designers and other software users can ensure that software in use is compliant with the open IFC standard and truly interoperable by certifying the software with BuildSMART to check that it meets the IFC standard and clarifies the scope of their interoperability (BuildingSMART, 2011). The literature from the BuildingSMART alliance suggests a centralised data structure, or a series of models, containing all relevant information, queried and updated by the various applications throughout the life-cycle. The central model is then modified over time. This approach is perhaps best described as a hub and spokes type arrangement, with the hub the central repository and the spokes leading to the various applications using data from the repository.

Although efforts to describe the exchange of data for a range of sub domains in the AEC industry are ongoing (NIBS, 2007; See, 2010; Venugopal et al., 2012), the seamless exchange of information with various applications is as of yet not a reality (Jeong et al., 2009; Pauwels, 2012; Sacks et al., 2010). Data is still lost at each of these interface points and model fidelity is compromised. As illustrated in Figure 2.8, there are still significant interface points between the numerous proprietary data models and the IFC environment. The Model View Definition (MVD) process is being used to extend the transfer of information in a number of domains and some of this work is spearheaded by the IFC Solutions Factory for instance (See, 2010). This group is concerned with the development of standardized information exchange for the building industry, using the IFC information Model. The BuildingSMART alliance control the evolution of the IFC data format.

The MVD approach utilises Information Delivery Manual (IDM) techniques (See, 2010) to graphically represent the data relationships required, extending the IFC model to achieve this. Currently the IFC Solutions Factory website lists over 27 MVDs that have been generated for various areas throughout the BLC in order to allow data exchange between

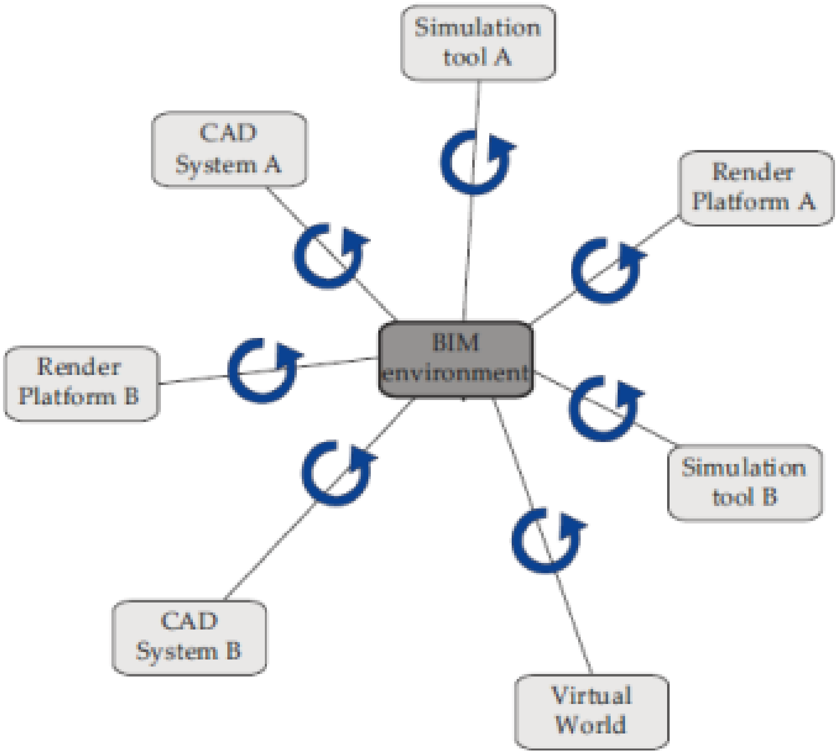


Fig. 2.9 The centralised information flow follows a hub and spokes type pattern. (Pauwels, 2012)

systems using IFC. However, IFC by itself is not sufficient to enable interoperability with systems outside of the AEC domain and conversion step between the original data model and the final data model leads to information loss and inefficiency due to re-modelling efforts (Gallaher et al., 2004). Ultimately, the centralised data structure is incapable of providing a framework for the capture of all building data and this becomes particularly evident as you move further away from building geometry exchange. Both the centralised data format and the proprietary software suite approaches are quite restrictive in the manner in which they allow information transfer and information exchange takes place at the application level.

2.3 Using semantic data to support information exchange

The bottlenecks associated with information exchange in the AEC industry centre around the interface points (Pauwels, 2012) between data structures. These interface points occur at the application level, where transfers between incompatible data formats result in data loss. Another method of information exchange is to base the transfer at the data level, rather than the application level (Bizer et al., 2009). The semantic web approach, discussed in greater detail in Section 3.1.3, essentially links individual pieces of information using a directed, labelled graph.

Using this approach, each individual element in a domain can firstly be uniquely referenced and then its relationship with other objects described. A "triple" describes the subject-object-predicate approach, one object can be clearly related to another. These triples can then be combined to provide a web of linked data. This web of data allows connections to be made between objects at the data level. Pauwels (2012) describes how this information exchange approach differs from the centralised information structure and the proprietary suite approach in two respects. First semantic web technologies rely on a common language for describing information, namely the Resource Description Framework (RDF) (Manola and Miller, 2004), and secondly that semantic web technologies appear to be deployed on a global scale (Bizer et al., 2009, 2011).

2.4 Conclusion

The BLC today, as it was in the 1980s and 1990s, when Hitchcock (1996) described it as such, is a series of decisions. The difference between now and then is that the range and volume of data available on which to base these decisions is enormous. Unfortunately, this data is often lacking, inaccessible or just ignored when decisions are made about building operation.

There is a pronounced performance gap between predicted building performance and actual performance. Some buildings are designed as exemplar green buildings and yet they barely perform to the baseline described by their own code. Difficulties surround the capture, management and exchange of AEC data. These difficulties inhibit the management of building performance, primarily because it is extremely difficult to derive a holistic, enterprise-wide assessment of a building's performance. In a similar vein, it is also quite difficult to break down the performance of a building into its constituent parts, or to ascertain if a building is performing to standard or not.

Many of these problems originate in a world where decisions are made without due regard to the necessary data. Approaches to solve the performance gap do not address this problem at all in some cases, or fully in others. Approaches to improve the data exchange capability of AEC software applications have their place, but are stymied by an excessively restrictive evolutionary process. The semantic web approach to data management is a promising solution to some of the impasses found in the AEC industry currently, and it forms the basis of this research thesis. Is information in the AEC industry just a means to an end or can it act as a dominant force in the management of building performance.

The AEC industry is riven by small factions interacting with sometimes limited success, using incompatible software. The linked data approach could be used to overcome some of these information exchange issues. The next section explores the concept of cross-domain data, and queries whether there is a value to the use of softer data sources in the decision making process of building owners and operators. Chapter 4 focuses on how the myriad data sources might be exposed, managed and interpreted in a repeatable and coherent fashion.

Chapter 3

Integrating cross-domain data at a semantic level

Energy informatics is the process of analysing, designing, and implementing systems to increase the efficiency of energy demand and supply systems (Watson et al., 2010). This work involves the collection and analysis of energy data sets to support optimization of energy distribution and consumption networks (Watson et al., 2010). The new energy informatics discipline has, at its core, the use of energy data and information technology in a complementary manner, to reduce energy use. In the context of the environmental and energy performance of buildings, energy informatics describes a process of integrating AEC data with ICT to drive performance improvement efforts.

The first research question asked if information was just a means to an end in terms of its original purpose, or has it greater role to play, when considered with other data. Is the use of cross-domain data relevant to optimal building performance? Is information just useful in its own specific domain silo, or is there merit to interpreting it in conjunction with other domain data, in a cross-domain manner, in support of effective environmental and energy management.

The concept of cross domain data is now introduced, along with issues concerning the use of cross domain data in the AEC industry specifically. Figure 3.1 illustrates part two of the thesis concept diagram, describing the transformation of data into a homogeneous data format using a number of converter tools. Creating links between data sources in a semantic manner has been determined, during the course of this thesis, as a suitable approach to the capture and interpretation of AEC data.

A crucial outcome from this process is the identification of homogeneous data sets, capable of being linked semantically, providing meaningful information, at the data level.

These data adapters are described in detail. A demonstration of semantic web techniques, used to overcome cross-domain data sharing restrictions, is introduced in the chapter.

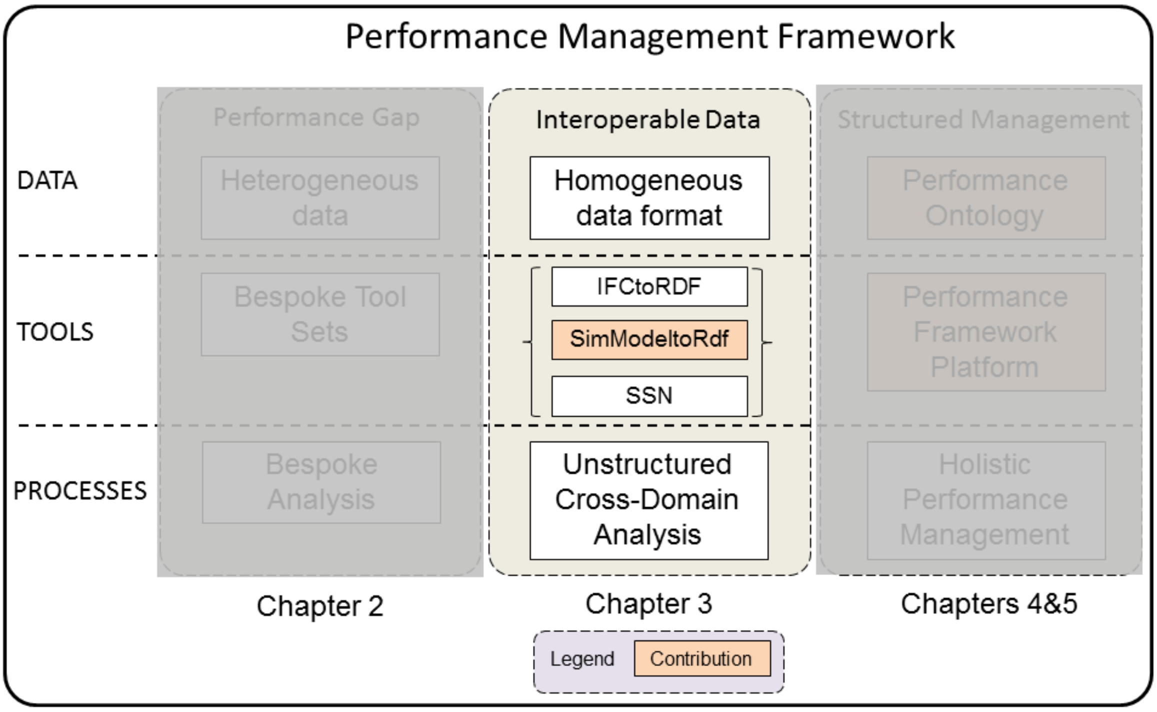


Fig. 3.1 Concept diagram illustrating key concerns in Chapter 3 of this work, the creation of homogeneous data and an illustration of unstructured cross-domain data analysis on this data.

Figure 3.2 emerges from the concept diagram of the thesis (Figure 3.1) and describes the process, in a data context, how heterogeneous data sources are first transformed into a homogeneous data format and then used to drive data analysis at the enterprise level. As the thesis progresses, a description is provided as to how a structured performance assessment approach can be integrated with such data to drive performance management in buildings. Once data are available in a semantic manner, several different uses can be made of it. The key point is to consider the data as a service to drive cross-domain activities. The circular graphic at the bottom right of the graphic indicates that the data transformation process is a cross-lifecycle one. Each of these data silos may be investigated throughout the BLC.

Figure 3.3 illustrates how many heterogeneous data sources form the entry point to the hypothesis proposed in this thesis. Once these data sources can be accessed, attempts can be made to combine them in a homogeneous manner, to form useful information that supports effective environmental and energy management. This chapter is concerned with exposing some of this information in a homogeneous format and considering if some of the previously unused softer data sources available have a relevance in a building management context.

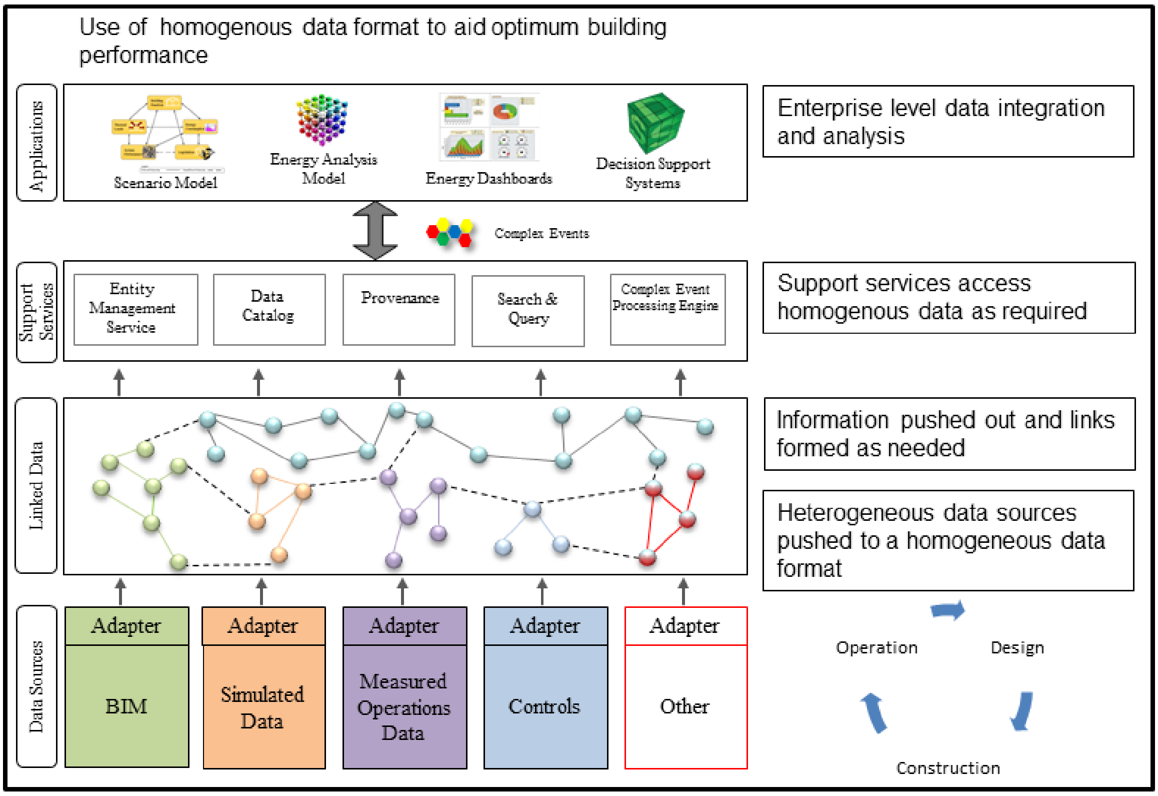


Fig. 3.2 Heterogeneous data sources in the AEC industry leading to a homogeneous data format. This data is used as a service to drive various performance management efforts in a cross-domain manner.

Having illustrated how AEC data can be described semantically, the chapter goes on to illustrate how use can now be made of this semantically enriched and accessible data in the context of building environmental and energy management.

This chapter is structured as follows:

- Cross-Domain Data, Section: 3.1
- Soft Data Examples in Use, Section: 3.2
- Integrating scheduling data with building operating strategy, Section: 3.3
- Determining Occupant Comfort Levels, Section: 3.4
- Conclusion, Section: 3.5

3.1 Cross-Domain Data

Figure 3.3 illustrates how heterogeneous data sources exist in the buildings domain and difficulties surround the transformation and integration of these sources. Chapter 2 explained how many initiatives are underway to allow the integration of such heterogeneous data in a more homogeneous format. These methods generally consider a data structuring approach and the difficulties with such approaches have been illustrated clearly (Boddy et al., 2007) and described in Section 2.3.

The integration of data at a semantic level is a more promising approach for the integration of non-homogeneous AEC data sources, allowing greater information knowledge to be defined around building objects and rapid links to be made between disparate data sources. This research is concerned with the support of holistic environmental and energy management of buildings. Accessing data in a cross-domain manner is a critical response to this issue.

With the rapid increase in the types of data source available in buildings, using highly structured, standards-based definitions to define data exchange between these domains is impractical. Instead, a much more dynamic response is called for, where data can be *pushed* forward in a homogeneous fashion, as needed, and rapid linking and interpretation of this information can take place in an relatively unstructured fashion. The semantic web approach allows this type of inter-connection between data.

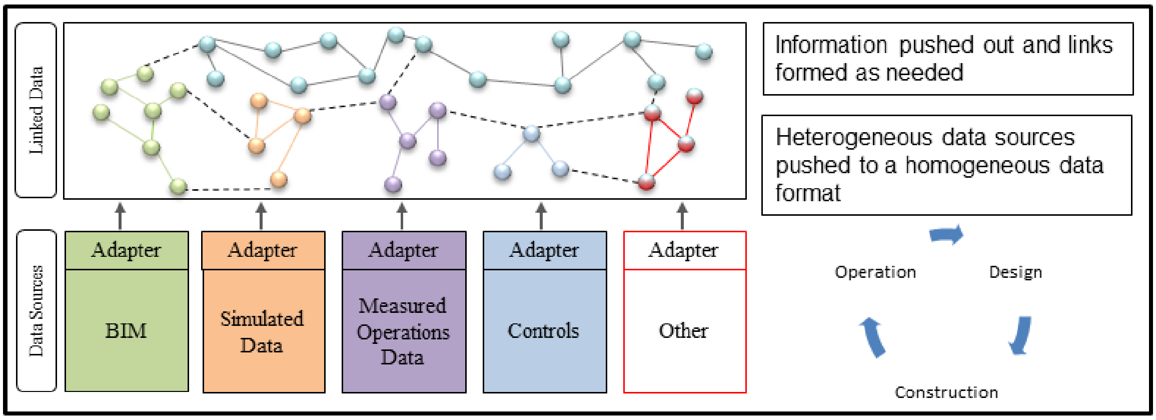


Fig. 3.3 The initial stage of the process involves the identification and conversion of heterogeneous data into a homogeneous format.

In order to design, construct and more importantly, operate buildings to the satisfaction of owners, occupants and legislators, a deep understanding of holistic environmental and energy management is required. Decision makers need access to the information and tools required to cost-effectively assure the desired performance of buildings (Hitchcock et al., 1998). Traditionally, buildings have been managed using a small subset of the data available in a building, namely the data that is made available via BMS. Considering buildings as a whole, there are several streams of data that currently exist to serve particular domains and remain untapped in the building performance sphere. Although buildings are generating increasing volumes of data during their operational phase, these data sources are not being exploited to provide an enterprise type view of building performance. With the explosion in intelligent devices over the past two decades, these data sources are now all around us in buildings.

The holistic management and maintenance of facilities is a multi-domain problem with many stakeholders, often with contrasting objectives. The holistic management of building performance must be seen in this multi-stakeholder context. Rather than capturing and retaining building data in individual silos, there is a clear need to define a cross-domain operational strategy in a comprehensive and structured manner. Cross-domain data integration allows for the enterprise level assessment and management of building performance. The creation of consistent, continuous and unambiguous building performance information is seen as a key enabler for building optimization.

The lack of interoperability manifested in poor electronic data exchange, management and access has a significant cost to the decision making process in general (Gallaher et al., 2004). In order to ensure optimal performance, several studies have shown that one must continually measure and monitor performance (Liu et al., 2003; Neumann and Jacob, 2008; Piette et al., 2001). Modelling, measuring and benchmarking of building performance is set to become the industry norm (Green Buildings Discussion Group, 2012), as more types of data become more available.

The following section considers what some of these new data sources might be and describes how they might be integrated using semantic web technologies.

3.1.1 Hard and Soft Building Data

For the purposes of this research, building data sources are considered on a continuum from hard to soft. *Hard* data sources are understood as sources which are readily accessible to the existing BMS and consist of quantifiable data that is relatively straight-forward to aggregate and infer information from, as the data are usually numerical in nature and stored digitally. On the other hand, *soft* data sources are sources that are not generally accessible to the building management infrastructure and are often qualitative rather than quantitative in nature, making it difficult to draw particular inferences from.

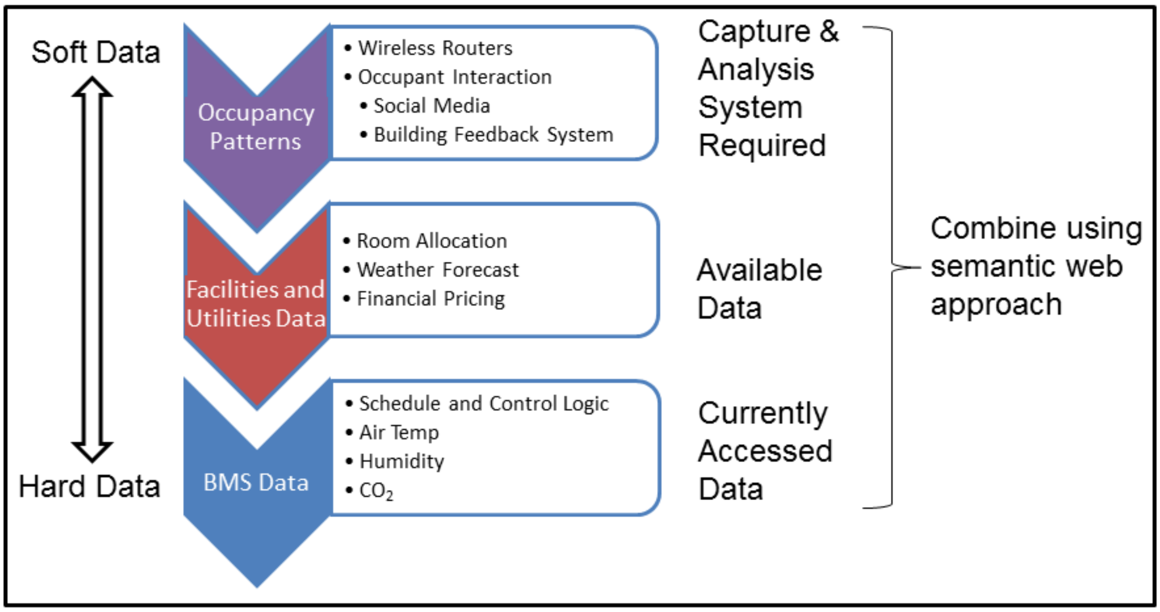
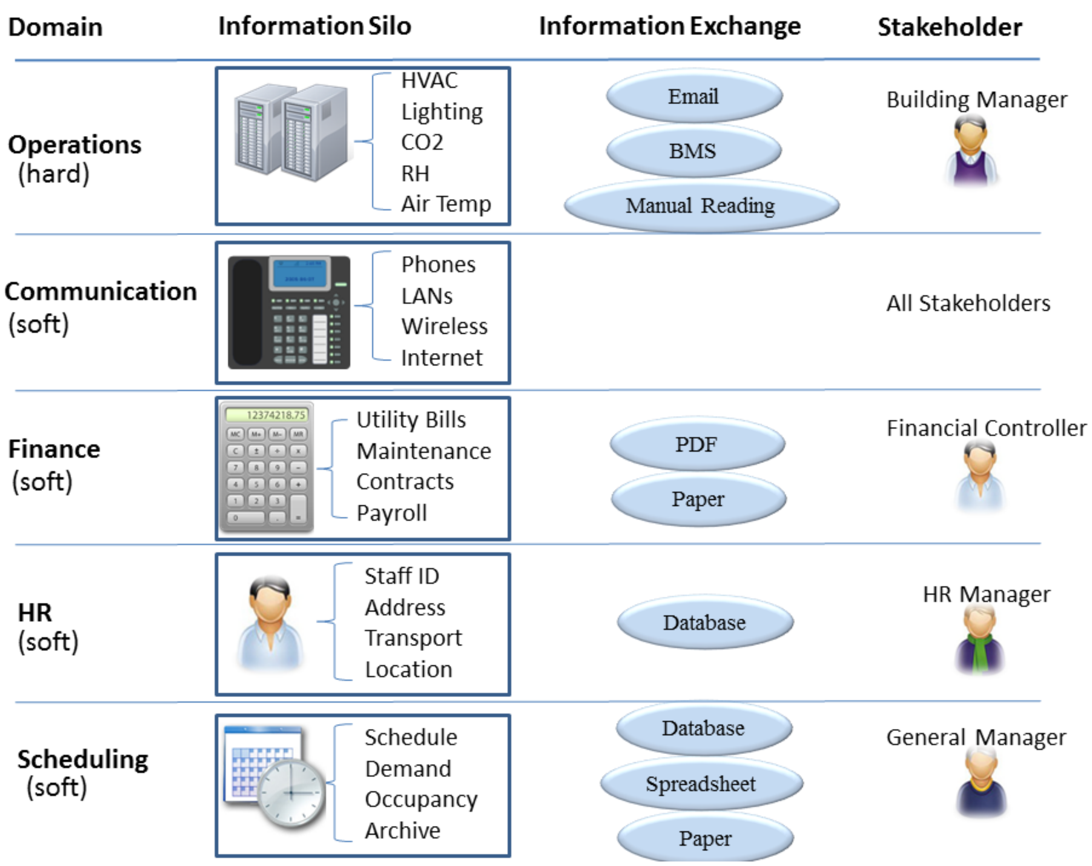


Fig. 3.4 Continuum of hard and soft data sources relating to occupancy and scheduling currently not integrated in any meaningful way during building operation.

Figure 3.4 illustrates a continuum of data sources related to building occupancy and scheduling. These sources can be considered in terms of hard and soft data. Currently most of these sources are not used to inform the building management process. Some sample hard data sources currently used in the building performance management space are illustrated in Figure 3.5, together with some of the possible softer data sources. There is a wide spectrum of data sources available throughout a building, even when just considering the narrow area of scheduling and occupancy patterns. Some of these sources are readily accessible and exist in a format that require analysis, whilst others require a greater degree of assessment and interpretation.

The list of building-related data in Figure 3.5 is far from exhaustive and the diagram illustrates how the various domains independently retain an array of building-related data that is most often not integrated with the building management structure or made available, on a cross-domain basis, to the building stakeholders. Typically, this type of information is captured by sensor objects (Watson et al., 2010) and is retained in some electronic format and used for some specific domain purpose. There is little or no interoperability between these domains. The silos of information described in Figure 3.5 are can be considered as examples of the heterogeneous data sources described in Figure 3.3. We now focus on considering how some of these data sources can be provided in a homogeneous format.

There is scope to use soft data sources in a qualitative manner, to inform building users



Domain	Information Silo	Information Exchange	Stakeholder
Operations (hard)	HVAC Lighting CO2 RH Air Temp	Email BMS Manual Reading	Building Manager
Communication (soft)	Phones LANs Wireless Internet		All Stakeholders
Finance (soft)	Utility Bills Maintenance Contracts Payroll	PDF Paper	Financial Controller
HR (soft)	Staff ID Address Transport Location	Database	HR Manager
Scheduling (soft)	Schedule Demand Occupancy Archive	Database Spreadsheet Paper	General Manager

Fig. 3.5 Some of the disconnected data silos across AEC domains resulting in incomplete representations of building performance.

as to the impact of their preferences on building performance and to modify behaviour accordingly. In 1957, Simon et al. (2004) described how humans intertwine rational and social factors when making decisions (Watson et al., 2010). By illustrating how decisions impact on building performance, users may modify behaviour. Ultimately, the purpose of most buildings is to provide a comfortable and safe environment for occupants to live and work. By enabling building occupants to engage with the building and understand the impacts of their actions on building performance, it is possible to engender a sense of involvement with the building community.

3.1.2 Interoperability Challenges

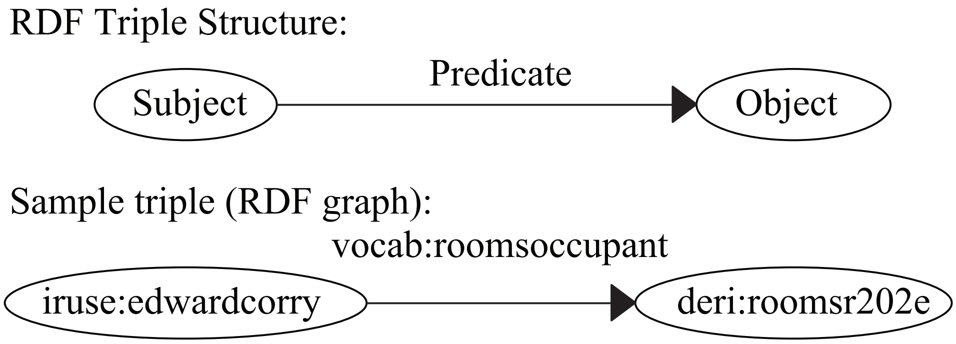
There are few methodologies available that are aimed at providing an analysis of building operation to all interested stakeholders. Data stored in one domain area are often relevant to other domains. Due to the critical lack of information interoperability, it is quite difficult to get a complete cross-domain view of a building in terms of interaction of data streams in a clear and structured manner. The IFC standard promotes interoperability within the building and construction domain, and for IFC in particular (BuildingSMART, 2011). However, IFC by itself is not sufficient to enable interoperability with systems outside of the AEC domain (Jeong et al., 2009; Pauwels, 2012). Although efforts to describe the exchange of data for a range of sub domains in the IFC industry are ongoing (Shen et al., 2010), not all building related information is currently described in the BIM process. As described in Chapter 2, the software suite approach suffers from similar restrictions once you try to converse with non-compliant software applications.

Structured data in the AEC industry are available in multiple formats such as CSV, Extensible Markup Language (XML) and the record sets returned from various relational databases. To integrate structured data it is necessary to first map those data to a common format. Having equivalent formats however does not guarantee consistency as the originating sources may state what is essentially the same fact differently. These differences exist at both the data description (schema) and actual data (individual object) levels. Consolidating information from different sources therefore requires methods for identifying and reconciling different representations at both the schema and object levels (Yap, 2011).

3.1.3 Semantic Web Technologies

The semantic web was conceived by (Berners-Lee et al., 2001) as a network of interlinked, uniquely referencible entities that describe the meaning of concepts through a directed, labelled graph. Each node in this graph represents a particular concept or object in the world and each arc in this graph represents the logical relation between two of these concepts or objects. When viewed together, the graph represents a set of logic-based declarative sentences. In this manner, two objects or concepts can be linked together in a subject object predicate format, forming a triple. Further relationships can then be constructed from these triples. In this way, a meaning of sorts can be created about a domain, or area of knowledge, which can be processed by a computer. The link between these nodes represents the relationship between these objects.

As triples are added together, a web of information is created. The semantic web uses RDF language (Prud'Hommeaux and Seaborne, 2008) to represent these data structures and connect them to other, similar structures. An RDF graph is constructed by applying a logical AND operator to a range of logical statements containing concepts or objects in the world and their relations. These statements are often referred to as 'RDF triples', consisting of



Sample triple (RDF/XML syntax):

```
<?xml version="1.0"?>
<rdf:RDF xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
      xmlns:vocab="http://www.vocab.deri.ie/">
<rdf:Description rdf:about="http://www.iruse.ie/staff/name/edwardcorry">
  <vocab:roomsoccupant>
   <rdf:Description
      rdf:about="http://www.lab.linkeddata.deri.ie/2010/deri#roomsr202e">
   </rdf:Description>
  </vocab:roomsoccupant>
</rdf:Description>
</rdf:RDF>
```

Sample triple (N3 syntax):

```
@prefix iruse: <http://www.iruse.ie/staff/name/> .
@prefix vocab: <http://www.vocab.deri.ie/> .
@prefix deri: <http://www.lab.linkeddata.deri.ie/2010/deri#> .

iruse:edwardcorry    vocab:roomsoccupant    deri:roomsr202e
```

Fig. 3.6 A triple consists of a subject, predicate and object. Each of these has a unique URI. A sample RDF graph is given in three forms: graph syntax, RDF/XML syntax and N3 syntax.

a subject, a predicate and an object, implying directionality in the RDF graph (figure 3.6). Directionality implies the direction of the predicate between subject and object is important. In this case, the subject is *edwardcorry* and the object is *room202e*. The predicate describes the direction. In the example in Figure 3.6, *edwardcorry* is an occupant of *room202e*. Every piece of the RDF graph, whether object, subject or predicate, is uniquely defined through a Uniform Resource Identifier (URI).

Several triples can be joined together and, in this manner, a collection of information can be exposed. For instance, other information can be published relating to the room, or the other occupants. The technique allows the user to uniquely reference the subject, predicate and object using a URI, allowing data sharing to take place at the data level, rather than the application level. RDF is especially powerfully when attempting to integrate cross-domain data as a series of triples can be quickly accumulated concerning the same object. Explicit relationships can be established between cross-domain data sets.

The resulting RDF graph can be converted into a textual representation that follows a specific syntax (Pauwels et al., 2011), including Protocol and RDF Query Language (SPARQL), N3, XML and Turtle. These syntaxes are ways of describing RDF in a machine readable format.

Several triples can be joined together and, in this manner, a collection of information can be exposed. For instance, other information can be published relating to the room, or the other occupants. The technique allows the user to uniquely reference the subject, predicate and object using a URI, allowing data sharing to take place at the data level, rather than the application level. This is a key distinction between the BIM approach and the semantic web approach.

RDF is especially powerfully when attempting to integrate cross-domain data as a series of triples can be quickly accumulated concerning the same object. Explicit relationships can be established between cross-domain data sets.

Several vocabularies or ontologies have emerged to describe specific domains of data including Friend of a Friend (FOAF), Dublin Core and Semantically-Interlinked Online Communities (SIOC). These vocabularies provide further meaning to domain objects and relationships. An object may be referenced in a number of domains, using different ontologies. This research applies semantic web techniques in the AEC sector to enable greater cross-domain data sharing.

3.1.4 Ontologies and Domain Description

Ontologies are described in more detail in Chapter 4 and are briefly introduced here. Ontologies are explicit, formal conceptualizations used to describe an area or domain of knowledge in a machine accessible manner and are based on a well-defined syntax, efficient reasoning support, formal semantics, sufficient expressive power, and convenience of expression (Antoniou, 2004). Broad discussion of the ontology concept is variously provided by (Da Silva et al., 2006; Hitzler et al., 2012; Jurisica et al., 2004; Panetto et al., 2012). Various descriptions are used to describe an ontology, but some terms are critical. An ontology provides an explicit description of a domain, including the concepts, the properties and attributes of these concepts, associated restrictions, using a common vocabulary. The purpose of an ontology is to enable the reuse of domain knowledge, providing a means of exchanging this information with interested actors.

The basic RDF graph uses the subject-object-predicate triple structure to define meaning between objects, with the predicate indicating the nature of the relationship. This structure is limited in terms of categorising and providing a broader context for objects. The Resource Description Framework Schema (RDFS) extends the RDF data model to include support for classes, subclasses, types and other concepts. These predefined RDFS constructs are defined using RDF statements. A similar approach is used to define ontologies using Web Ontology Language (OWL), where further predefined constructs are available, including properties of objects and rules governing relationships between objects. Although RDFS and OWL offer more predefined constructs than RDF, they are implemented using RDF constructs from the underlying RDF data model. Various syntaxes exist to describe RDFS and OWL including XML, N3, Turtle and SPARQL.

3.1.5 Using linked Data to Overcome the Interoperability Limitations

Linked Data is a best-practice approach used to expose, share, and connect data on the Web based upon W3C standards. In contrast to documents, Linked Data is not aimed at human consumption, it is processed and queried by computers, similar to relational data stored in conventional databases. Linked data technology uses web standards (Lassila and Swick, 1999) in conjunction with the four following basic principles for exposing, sharing, and connecting data:

- Use a standardized way to identify objects: The use of URI (Berners-Lee et al., 1998) (similar to a Uniform Resource Locator (URL) to identify things such as a person, a place, a product, an organization, or an event—or even concepts such as risk exposure or net profit—simplifies data reuse and integration.

- Use a standardized way to get data about objects: URI are used to retrieve data about objects using standard web protocols. For a person, this could be his or her organization and job classification; for an event, this may be its location, time, and attendance; for a product, this may be its specification, availability, price, or some other feature.

- Use a standardized way to represent data: When someone looks up a URI to retrieve data, provide the data using standardized formats, ideally in following semantic web standard approaches, such as RDF and SPARQL (Prud'Hommeaux and Seaborne, 2008).

- Use a standardized way to interlink information: Retrieved data may link to other data sources, thus creating a data network (e.g., data about a product may link to all components it is made of, which may link to all suppliers).

Linked data technology can be accommodated with minimal disruption to existing information infrastructure, as a complementary technology for data sharing, and should not be seen as a replacement for current ICT infrastructure (e.g., relational databases, data warehouses). The objective is to expose the data within existing systems, but only link the data when its needs to be shared (Mentes, 2012). The approach is not to replace or substitute existing systems in the AEC industry, but rather describes an application which would sit atop the various existing architecture, accessing relevant data streams and utilising these to drive information flow to the relevant parties in building operation.

3.2 Soft Data Examples in Use

These demonstrations are focused on specific heterogeneous AEC data sources and transforming them into data. The purpose behind these demonstrations is to illustrate how such data can be used in a cross-domain manner, to provide greater meaning in the context of environmental and energy management. Figure 3.7 illustrates the place of these demonstrations in the overall context of the data transformation taking place in this thesis.

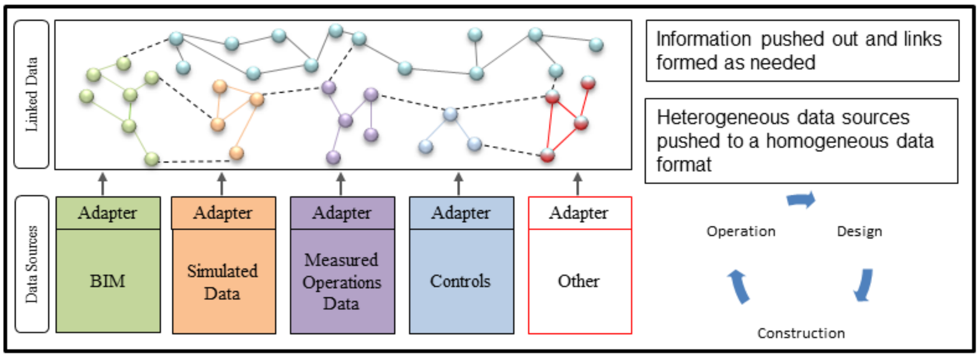


Fig. 3.7 These demonstrations are focused on this stage of the data transformation diagram, specifically the conversion of heterogeneous data sources into homogeneous data and the querying of this data in a non structured manner.

Two demonstrators are documented to show how cross-domain data could be integrated with existing data sources using semantic web technologies. The demonstrators are not intended to serve as an exhaustive exploration of the viability of these data sources as indicators of building performance, but as an illustration of how diverse data sources can be accessed and transformed using semantic web technologies. The demonstrators illustrate how data from random sources can be easily transformed into RDF and integrated with other data.

The first demonstrator explores how scheduling data might be integrated with building operation data to illustrate how such data can be used in a cross-domain manner to support specific stakeholder processes. This experiment is not intended to predict actual savings from the integration of cross-domain occupancy data, but is designed to show how data from the unconnected domains of facilities management and scheduling, can be integrated to allow a greater degree of understanding of building environmental and energy requirements.

In a typical university or other large scale campus, the scheduling software built into the individual building's BMS is manually populated. In many cases, the system is configured to operate during office hours, when the facility is occupied, taking account of holidays, etc. During the design phase of the project life-cycle, expected occupancy patterns are taken into account when deciding on the optimum schedule. Often, little attention is actually paid to occupancy patterns during the operational phase of a facility, leading to uncomfortable and over-conditioned situations in the building. Controlling HVAC systems using occupancy data is a recognised means of managing building performance (Erickson et al., 2009). Room occupancy numbers are often scheduled by the scheduling function in the university, the admissions office. The schedule and occupancy pattern changes from year to year, but this is not reflected in the BMS settings. Essentially, the activities of one domain can have knock on effects on other domains in the building.

The building used to carry out the demonstrations is the 14,000 m^2 New Engineering Building (NEB) on the National University of Ireland, Galway campus (Figure. 3.8). This is an ideal demonstrator as it is a heavily instrumented building and utilises a complex mixed-mode heating and cooling system together with an innovative climate facade used to provide extensive natural ventilation. The building has a complex energy management centre, controlling a complex range of technologies, including:

- 500kW thermal, 350 kW electrical natural gas-fired Combined Heat and Power Unit
- 950 kW pellet biomass boiler
- Computer controlled night purging
- Three highly efficient natural gas condensing boilers

- District heating system feeding the nearby Sports Centre and swimming pool
- Climate wall with top-vented stack control and solar control via blinds
- Ground source heat pump
- Natural stack ventilation

The NEB is particularly interesting given that 90 percent of the building's occupants are students who attend lectures and engage in practical coursework in the building. They generally do not see themselves as stakeholders in the building and are often not aware of the controls available to them in the building or how their behaviour impacts on the environmental and energy management of the building. The building is managed remotely, by an energy consultancy firm, based entirely on hard data emanating from the BMS. The on-site building manager on the other hand deals almost entirely with soft data feedback in the form of queries from the building occupants.

Fig. 3.8 New Engineering Building (NEB), NUI Galway, Ireland.

3.3 Integrating scheduling data with operating strategy

3.3.1 Available data

The university admissions office uses timetabling software to administer the use of university lecturing facilities. This centralised room booking/scheduling service operates separately from the BMS. The room booking schedule changes from year to year and as a result, spaces are conditioned when no occupants are present, whilst others are not conditioned, despite students being present. This type of scheduling mismatch is replicated in many buildings.

Some studies show that occupancy can be used as an indicator to schedule demand-led air conditioning systems, together with the traditional air temperature, external air temperature and relative humidity readings (Kwak et al., 2012, 2014), whilst others suggest methods of interpreting occupant satisfaction with indoor ambient temperatures (Jazizadeh et al., 2011). Buildings are generally conditioned to satisfy maximum occupancy, but the maximum level often does not describe occupancy patterns, particularly in a lecture setting.

Existing systems used in other domains that provide numerical data can provide a basis for performance analysis (ITOBO, 2008) and, when considered with other hard data sources, can provide further qualifying data about performance. Sources of this sort of data include facility scheduling software, infrared sensors, swipe card systems, wireless routers and personal Radio Frequency Identification (RFID) trackers. Other studies have investigated methods of measuring real time occupancy using a variety of technologies, including infrared detectors and door and window opening sensors (Díaz et al., 2011), RFID sensors (Li et al., 2012) and Wi-Fi connection hotspots (Wong et al., 2008).

Many of these technologies are highly complex and rely on complex algorithms to determine the occupancy level of a space. Furthermore, these methods do not overcome the interoperability issues associated with cross-domain data analysis. Semantic web technologies can be used to expose occupancy scheduling data from a completely separate, autonomous building domain and deliver it to other interested parties in the facility. Although questions exist over the usefulness of static occupancy schedules to drive HVAC scheduling, this type of softer data can serve as an indicator of building use and, when viewed in conjunction with other traditional hard data sources, can serve an important function.

G018 is a large lecture theatre with banks of seating facing down into a lecture podium. Table 3.1 shows the BMS schedule for the lecture theatre G018, indicating the hours when the space is being conditioned. This pattern reflects an effort on behalf of the university to maintain a conditioned space, whilst keeping costs low. This is the type of information currently available to the building manager about this space, as returned by the BMS.

Table 3.1 BMS schedule of operation for lecture theatre G018. Cells coloured grey represent times when the space is conditioned.

Time	Mon	Tue	Wed	Thu	Fri
08:00-09:00	Off	Off	Off	Off	Off
09:00-10:00	On	On	On	On	On
10:00-11:00	On	On	On	On	On
11:00-12:00	Off	Off	Off	Off	Off
12:00-13:00	Off	Off	Off	Off	Off
13:00-14:00	Off	Off	Off	Off	Off
14:00-15:00	Off	Off	Off	Off	Off
15:00-16:00	On	On	On	On	On
16:00-17:00	On	On	On	On	On
17:00-18:00	Off	Off	Off	Off	Off

Table 3.2 BMS schedule overlaid with occupancy pattern. The blue background indicated when the room is conditioned and the numbers relate to the amount of students scheduled to be in the room at that time.

Time	Mon	Tue	Wed	Thu	Fri
08:00-09:00					
09:00-10:00	237		237	200	237
10:00-11:00		237	237	237	200
11:00-12:00	237	180	180	145	237
12:00-13:00	237	200	237	200	149
13:00-14:00			145		
14:00-15:00	221	237	145		140
15:00-16:00	221		120	160	140
16:00-17:00	149		250	160	
17:00-18:00	200			160	

By comparing this schedule to the room booking schedule (Table 3.2), those times in the week can be found when a fully occupied room is conditioned and when an empty room is not conditioned.

The next section describes how these data sets might be described semantically and integrated.

3.3.2 Combining the data sets

Using semantic web technologies, it is possible to explicitly link semantic representations of building objects, such as rooms, while they are retained in various different data silos. In

Figure 3.9, the room concept is used by four different data models, each model representing a different context. First, the *BMS* uses the concept of the room to represent the location of sensors and HVAC services. *Human Resource Management (HRM) software* uses the room concept to define where a staff member is based. The *BIM modeling environment* uses the room concept to define a geometric space with respect to the remainder of the building, while the *campus scheduling software* uses the room concept to define where an event, in this case a lecture, takes place with a given number of participants.

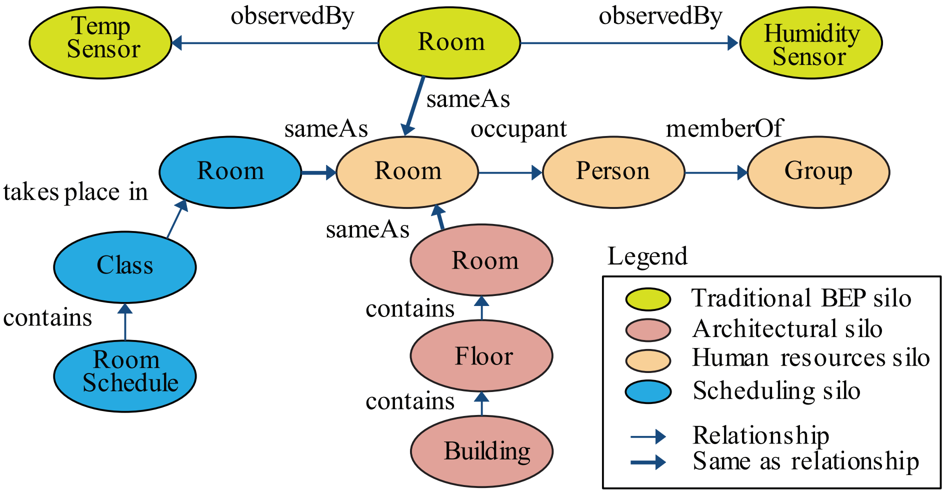


Fig. 3.9 Diagram illustrating the relationship between the BMS, the room booking system (MS Excel), BIM and human resource management (HRM) systems, linked using the Room entity.

By exposing these four diverse data streams in RDF and linking them together as in Figure 3.9, ways of analysing these data with a view to greater operational efficiency in the space, based on optimising the BMS schedule can be explored. Taking the BMS scheduling data, a rudimentary calendar using Google calendar and exported to the iCal file format (Listing B.1). The iCal file format was used as a means to capture calendar data as it is a schema which can be easily transformed to RDF, using an existing conversion service. One of the key pillars of the semantic web initiative is the reuse of existing ontologies to describe data. Throughout this work, we exploit existing adapters and conversion tools to convert heterogeneous data to semantically enriched information. Tools such as these are developed organically and typically supply an ontology describing the domain and a means of converting exiting data to RDF. As buildings impact many stakeholders, across domains, this approach allows data to be easily accessed. The information tends to be *pushed* out semantically from the domain and then used as required by cross-domain services.

The web-based iCaltoRDF converter (TheWebKanzaki, 2004) is used to convert this output to RDF, using the RDF calendar ontology (Connolly and Miller, 2005) (Listing B.2). This system uses the RDF Calendar (Connolly and Miller, 2005) to integrate calendar data with other semantic web data.

A similar process is used to convert the room occupancy schedule to RDF. The key idea here is that further information is gathered about the component relating to each time slot. In this case, the time slot relating to Mondays, from 7 to 8 AM, can include a summary reference of ``off``, but also a summary reference of ``237``, indicating the number of students time-tabled for the space. In this manner, two separate schedules can be integrated. The resulting data set can be used by semantic web technologies to illustrate the occasions when the space is being conditioned, although no occupants are present. Armed with this information, the manager can review the BMS schedule and perhaps decide to modify it. Using a metric (Gillespie et al., 2007) to describe this objective, the building manager can be provided with quantifiable data on the efficiency of the BMS schedule.

Expanding the range of data sources available gives key stakeholders greater awareness of what is happening throughout the building. In this case, the lecture theatre is conditioned for 20 hours a week. By incorporating occupancy schedules into this analysis, it can be seen that the room is being conditioned for 5 hours when no lectures are scheduled. Furthermore, the room is not conditioned at all when the bulk of the students are present, during the middle of the day.

Of course this is a simplified example and these correlations should not be looked at in isolation, but rather should be used as part of the entire solution, incorporating environmental and energy simulation outcomes, temperature and CO_2 profiles and soft data, including emails, twitter feedback, etc., to optimise performance on a continuous, dynamic basis.

Table 3.3 A modified BMS schedule, still operating for 20 hours. Cells coloured grey represent times when the space is conditioned.

Time	Mon	Tue	Wed	Thu	Fri
08:00-09:00					
09:00-10:00	237		237	200	237
10:00-11:00		237	237	237	200
11:00-12:00	237	180	180	145	237
12:00-13:00	237	200	237	200	149
13:00-14:00			145		
14:00-15:00	221	237	145		140
15:00-16:00	221		120	160	140
16:00-17:00	149		250	160	
17:00-18:00	200			160	

Table 3.3 shows an example of a modified schedule that may be implemented, based on a variety of other factors.

3.3.3 Discussion of Results

Using the suggested approach, the BMS schedule can be considered in conjunction with other relevant data sources. A similar type of analysis can be performed using other data sources, including financial pricing for utilities and the comparison of operating conditions with weather data. When such data are available and incorporated with existing BMS data, various possibilities for the optimisation of building performance emerge. These possibilities fall into a number of categories:

1. Management of building performance
    (a) Minimal use of energy whilst meeting stakeholder requirements
    (b) Meeting stakeholder requirements at reduced cost
2. Understanding stakeholder requirements
    (a) Base decisions on actual operation rather than design stage requirements
    (b) Use stakeholder information to optimise stakeholder satisfaction

3.3.4 Further Work in this Area

Capturing occupancy patterns in buildings is quite a difficult undertaking. In the case of a university building, some indication of occupancy might be gathered from the room booking service. Another data source that might additionally be used, is provided by the wireless network. Students can remotely access course information through this network using a wireless enabled device. An analysis of wireless router patterns throughout the week would also be informative when trying to gauge the true occupancy of the space.

Neither approach provides a complete solution to the issue. The room booking service does not take into account absenteeism amongst students or cancelled lectures, whilst the mobile phone analysis requires each student to have a wireless enabled phone in class.

Using semantic web technologies, it is possible to gather this type of information for the rooms in the building. Sensor information, for instance, can be described using the Semantic Sensor Network XG (SSN) ontology. As you delve more into the realm of soft data, it becomes more difficult to infer useful information from the data. For instance, in this case, students are not required to log into the wireless network and it is feasible that a room could be full, without anybody accessing the wireless network. Looking at a chart illustrating usage patterns of the wireless network will not be particularly useful for the building manager in terms of an occupancy analysis, but it may serve as a pointer when used in conjunction with other data sources, such as the room booking and BMS schedules.

3.4 Determining Occupant Comfort Levels

The second demonstrator focuses on soft data related to building use which is difficult to quantify and integrate with existing operational structures. The idea behind this demonstrator is to generate a sense of ownership and ambient awareness amongst a group of building occupants and to encourage them to post tweets describing some of their interactions with the building. Twitter, the micro social media web application allows users to communicate with others in a public fashion, using 140 characters or less. Conversations can be organised and directed in a particular way using tags. It is felt that this type of feedback would provide building managers with instant feedback on building issues as they arise and could also serve as a type of barometer for occupant satisfaction. Again, this is not a typical source of data for building managers. This demonstration illustrates how this type of data can be captured and transformed using semantic web technologies.

The outcome from both demonstrators is a set of building-related data exposed in RDF graphs, which can then be easily accessed and queried using semantic web technologies. The concluding section describes how semantic web technologies form the basis of an energy centric performance management tool used to integrate these data sets in a cross-domain manner.

The second demonstrator identifies a range of data sources which may be generated around the area of occupant comfort. These data sources tend to be more qualitative in nature and in some cases may be difficult to derive meaning from. The purpose of this demonstrator is to outline how these sources might be captured and interpreted using semantic web tools. The study was based on the area of occupant comfort, particularly thermal comfort. This work consisted of a Twitter survey, a measurement-based Predicted Mean Vote (PMV) (Fanger, 1970) study, a survey-based PMV study, and a simulation-based PMV study.

With the advent of social media, a new range of data sources have now emerged, providing softer, but no less useful information in the form of chatter and instant feedback. These information sources represent an opportunity to engender a sense of behaviour and connectivity amongst all stakeholders in a building community. It is now possible to open dialogue with building stakeholders and these dialogues can be focused to encourage feedback, on a range of topics, not least being building operation.

Furthermore, dialogue can be instigated outside the traditional formal channels of information transfer of building operation where information is restricted to a hierarchical gatekeeper approach, where all information is diverted to a centrally placed manager who interprets or filters this information. The paper proposes a range of scenarios which outline the relevance of social media to stakeholder dialogue and demonstrate how these scenarios might be realised by linking the social media information silo with existing building information silos.

In this demonstration, the occupant is considered as a sensor. An investigation is made of instantaneous, qualitative occupant feedback to elicit responses to certain conditions in the space. The Twitter social media site is used as a medium to communicate with the occupants, in a effort to engender improved human-building interaction and behaviour. A broader discussion of the data-sets is provided in the following section.

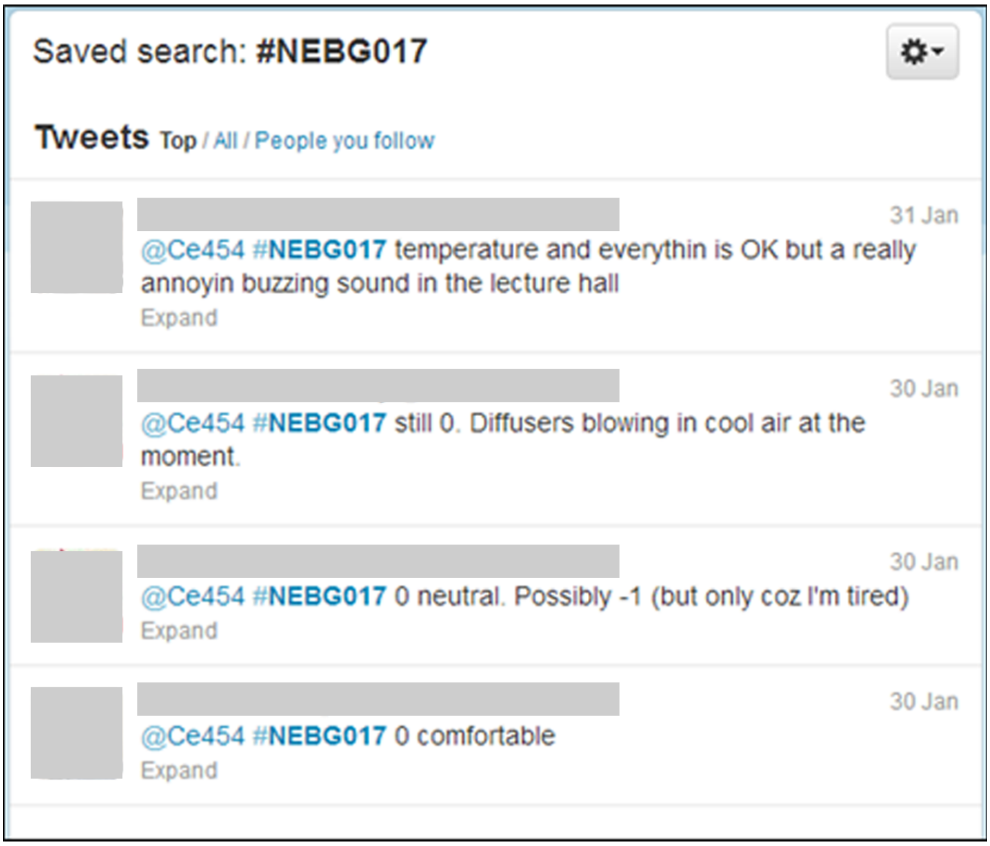
3.4.1 Available Data

An aspect of building performance that is studied in the second demonstrator is that of stakeholder satisfaction (Pati et al., 2006, 2009). More precisely, an experiment was carried out using the Twitter micro-blogging site. Using the NEB as a test bed (Figure 3.8), a group of 65 final year engineering undergraduates were encouraged to follow a particular Twitter account (`CE454`) and to post commentary on building performance as they encountered it, throughout the day. This work differs from other studies (Lehrer and Vasudev, 2011; Mankoff et al., 2007) in this area by the manner in which the data are extracted from the social media domain and exposed in RDF. The key point of this work is to make information more accessible using semantic web technologies.

Table 3.4 PMV thermal comfort scale.

PMV value	Thermal Comfort
+3	Too Hot
+2	Warm
+1	Slightly Warm
0	Neutral
-1	Slightly Cool
-2	Cool
-3	Cold

Based on an initial survey of the group, 35 percent declared that they used social media more than 8 hours per week, with Facebook (89 percent), YouTube (78 percent) and Twitter (78 percent) being the dominant sites accessed. Although almost half the respondents to the survey declared that they never or rarely accessed social media sites during class time. The remainder of respondents accessed such sites throughout the college day. It is important to note here that the group of students surveyed take an Energy Systems (CE454) course and should thus not only be more keen to use information technology, including social media, but they should also be more aware of the energy systems surrounding them in a building.


Saved search: #NEBG017

Tweets Top / All / People you follow

31 Jan
@Ce454 #NEBG017 temperature and everythin is OK but a really annoyin buzzing sound in the lecture hall
Expand

30 Jan
@Ce454 #NEBG017 still 0. Diffusers blowing in cool air at the moment.
Expand

30 Jan
@Ce454 #NEBG017 0 neutral. Possibly -1 (but only coz I'm tired)
Expand

30 Jan
@Ce454 #NEBG017 0 comfortable
Expand

Fig. 3.10 Twitter response relating to the main lecture theatre.

The students were asked to comment specifically on a number of zones within the building and these were each given a specified # name. The zones included a large lecture hall (`#NEBG017`), two computer suites (`#NEBCompG` and `#NEBComp1`) and the restaurant area (`#NEBCanteen`). The students were asked to reply using the following format: `@CE454 #Location, PMV, comment`. In this way, related tweets could be identified easily on Twitter. The students tended to spend a lot of time in these spaces and they were encouraged to comment on the thermal comfort conditions in the spaces, based on the PMV thermal comfort scale (Fanger, 1970), ranging from +3 to -3 as shown in table 3.4. This response is very much a qualitative response to reflect the students reaction to the thermal conditions in the space. It is important to add here that the computer suites (`#NEBCompG` and `#NEBComp1`) tend to be considerably warmer than the other rooms.

By encouraging building occupants to tweet about the comfort levels in the building and comment on general building issues, a Twitter feed can be created for the building (example in Figure 3.10). These tweets can also be structured in a particular format which lends itself to analysis.

Students were also asked to comment generally on the building and in this case, the `#NEBGen` tag was used. It was unclear what type of feedback would emerge from this channel and whether it could be a useful flow of information about unknown issues encountered by building occupants.

3.4.2 Findings of Social Media Experiment

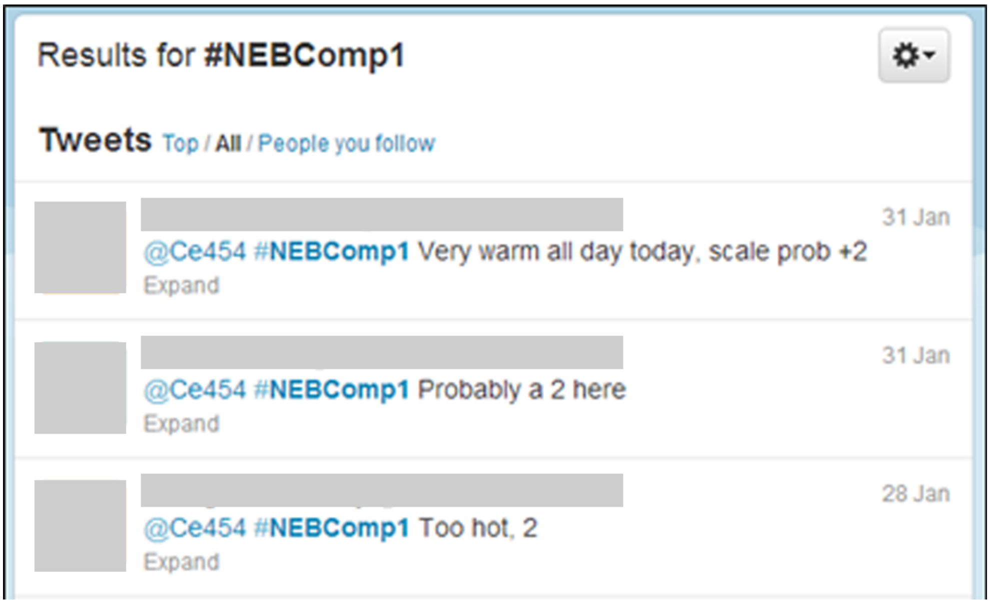
Although most students in the group signed up to Twitter and followed the research account, there was little activity on the account regarding spaces where the thermal conditions were neutral, or classed as 0 on the PMV scale. The twitter handle `CE454` was used to post 26 tweets in total. The twitter response to the main lecture theatre, `#NEBG017`, was quite limited, with perhaps 3 tweets in total, and consistently placed the occupant satisfaction level at 0. This corresponded strongly with actual thermal comfort measurements in the space, suggesting a PMV reading between -0.8 and 0, throughout the day.

In contrast to this, the computer suite 1, `#NEBComp1`, generated much more comment on Twitter, around 10 tweets (Figure. 3.10). Many of the respondents felt the temperature in the space was too hot. This correlated strongly with the thermal comfort analysis of the space, which tended toward a PMV of +3 (too hot).

When students were asked specifically about the thermal conditions in the computer room, some evidence of ambient awareness was evident, where a user could see a relevant response and respond to that also (Figure 3.12).

52 responses were received in total, over a period of three weeks. Users seemed to respond only when something was making them uncomfortable. For example, 'loud mechanical' and excessive 'wind' noises were reported, together with high temperatures in the computer suites. People were less motivated to respond when conditions were satisfactory.

Some of the responses were quite interesting from a building management perspective. For instance, the building has a main fresh water supply that is used to service a number



[redacted] 31 Jan
@Ce454 #NEBComp1 Very warm all day today, scale prob +2
Expand

[redacted] 31 Jan
@Ce454 #NEBComp1 Probably a 2 here
Expand

[redacted] 28 Jan
@Ce454 #NEBComp1 Too hot, 2
Expand

Fig. 3.11 Twitter results for `#NEBComp1`, indicating an issue with the thermal comfort levels in the space.

of water dispensers located throughout the building. This system was inoperative recently and this featured in a couple of tweets. Similarly, unusual noises were reported in a tweet, including excessive wind noise and loud mechanical sounds. When these issues were discussed with the building manager, he described an on-going issue with the fountain system in the building and an AHU problem with the computer suite.


[redacted] 29 Jan
@Ce454 #NEBCompG Room is full #NEBComp1 Temp = +2
Expand

[redacted] 29 Jan
[redacted] #NEBCompG #NEBComp1 @Ce454 thanks Mark. Consensus seems like #NEBComp1 is not very comfortable
Expand

[redacted] 30 Jan
@Ce454 it never is.. ever! only when its practically empty and even then its debatable! #DefinatelySomethingWrongThereTed

Fig. 3.12 Twitter feedback on uncomfortable computer room.

The experiment illustrated a lack of connection between building occupants and a key building stakeholder, the building manager. Based on the findings from the experiment, it was established that the ground floor computer suite was particularly uncomfortable from time to time, with excessive noise being present. The Building Manager, unaware of these concerns prior to the experiment, carried out an investigation in the computer suite and instigated some remedial action. This type of outcome illustrates the benefit inherent in the use of cross-domain data, even data which is not quantifiable in nature.

3.4.3 Combining the Data Sets

Having identified the Twitter data source, this information could be exposed semantically. The Online Presence Ontology (Stankovic et al., 2008) can be used to describe a Twitter message as an RDF statement in Listing B.3. This statement can then be interpreted using semantic webs tools. The aim of the Modelling Online Presence is to enable the integration and exchange of online presence related data and utilises a Semantic Web ontology (OPO) to represent data about Online Presence in RDF. This ontology describes data generated using various online messaging and blogging services and how it might be published in RDF. Again, the goal of the semantic web initiative is to utilise existing ontologies to expose data using RDF.

3.4.4 Discussion of Results

The NEB has a number of areas which are considered slightly uncomfortable. This demonstration provides significant pointers to known and unknown problems in the building, for a key stakeholder, the Building Manager. These pointers provide greater context for the manager when viewed in conjunction with other, more standard environmental and energy measures in the building, for example BMS data.

There are a number of findings from this experiment. First of all, it is not clear that Twitter or micro-blogging in general can be used to accurately survey the population of a large building. Taking the engineering building as an example, it is inhabited by a large group of technically capable people, with access to a free building-wide wireless network. The group of students surveyed are positively disposed to the question of building operation as they take an Energy Systems course. Despite this, the participation levels of the group were low. Perhaps the main observation was that people were more motivated to respond when affected negatively by a specific issue. It is difficult to know what value to place on such communication, and it is important to devise strategies to over come the Twitter background noise, which can dominate such interactions. Social media interaction should be seen as a complementary source of information, and it should not in any way replace the traditional data sources used to operate buildings.

The Twitter feed returned some unexpected responses, including feedback on noise levels throughout the building and the quality of the fresh water. As an information source, however, the Twitter feed can only be analysed to a limited level. In common with other micro-blogging sites though, Twitter is beginning to combine geo-location tags allowing conversations to take place in geographical context (Kaplan and Haenlein, 2011). In the wider world, this type of functionality has an impact in terms of informing attendees at events occurring at a given location for example .

A third conclusion that can be made, is that micro-blogging occupants could easily become a type of autonomous mobile sensor, identifying issues with building performance and posting those issues in a visible way to the wider building community, focusing the attention of the building manager on the issue. This type of communication can drive the holistic environmental and energy management of a building. The author feels that this is the area in which Twitter might be most useful, the identification and publication of issues as they arise.

Lastly, it can be concluded that semantic web ontologies exist which allow the interpretation of micro-blog posts semantically. These semantically enriched data-sets can then be used by the appropriate semantic web technologies to form an improved and integrated perspective on available building data.

3.5 Conclusion

In conclusion, identifying and accessing other data sources is a very relevant step in trying to create a more holistic environmental and energy management framework. It has been illustrated, using just two examples of building-related data, how cross-domain scheduling data can be captured and used and also, how micro-blogging sites such as Twitter could be used to identify occupant issues with building performance.

When integrated into a wider building management framework, using semantically enriched data-sets, these extra data sources are particularly useful. Developing this level of integration has proved to be a significant challenge, particularly when integrating cross-domain data. The demonstrations illustrated the benefits of using semantic web technologies to resolve some of these interoperability issues.

Ultimately, not all building-related data sources will be of equal value and developing interoperability between some of the more qualitative sources is of limited value. It must be stressed that significant benefits exist in terms of holistic environmental and energy management through the capture of differing perspectives of other key building stakeholders. Buildings are operated by more than one stakeholder and any context where greater communication is generated between these stakeholders will lead to improved performance management efforts.

By the same token, data sources which can give a clear indication of real-time building occupancy patterns are very worthwhile and there are a host of such sources throughout modern buildings. Quantitative data that exists in separate AEC domains lends itself more easily to analysis and there are clear benefits to exposing these data sources to the building management framework. There are over 200 million buildings in the EU and as enabling technology develops, it is clear that vast quantities and types of softer data will emerge from modern buildings, in the areas of communication systems, automated control systems, financial, human resources, etc.

Exposing data sources on their own and presenting heterogeneous data in a homogeneous fashion has limited relevance in the absence of a structured assessment framework which can make sense of these data. Such a framework requires a structured ontology to accurately describe the data interactions required in cross-domain data analysis and is discussed in the following chapter.

Chapter 4

A semantic web driven holistic building performance management system

4.1 Introduction

This thesis has identified the performance gap (Section 2.1), between design intent and actual performance, as a major problem in the AEC industry today. An absence of a life-cycle performance management approach and a profound lack of data interoperability are key causes of this performance gap.

Figure 4.2, the concept diagram around which this thesis is structured, illustrates how diverse data streams can be accessed to enable cross-domain data sharing and ultimately holistic building performance management. It broadly charts the course of this work, from the performance gap and the issues surrounding it in Chapter 2, through unstructured cross-domain data interpretation in Chapter 3, to a performance management approach, underpinned by a homogeneous data format. The final stage of this figure is now described in this chapter, the creation of structured performance management framework based on the availability of homogeneous data.

As mentioned in Section 1.1.2, data are being produced at an extraordinary rate, and in the case of modern, highly instrumented buildings, more data are produced than any facility manager can be reasonably expected to interpret. Chapter 3 concluded that AEC data could be accessed in a cross-domain manner, although just pooling AEC data semantically is not sufficient to drive performance management measures.

A building manager and other key building stakeholders must be able to navigate easily through the masses of data available without floundering. What follows is the description of a structured performance management approach, clearly linked semantically with other AEC

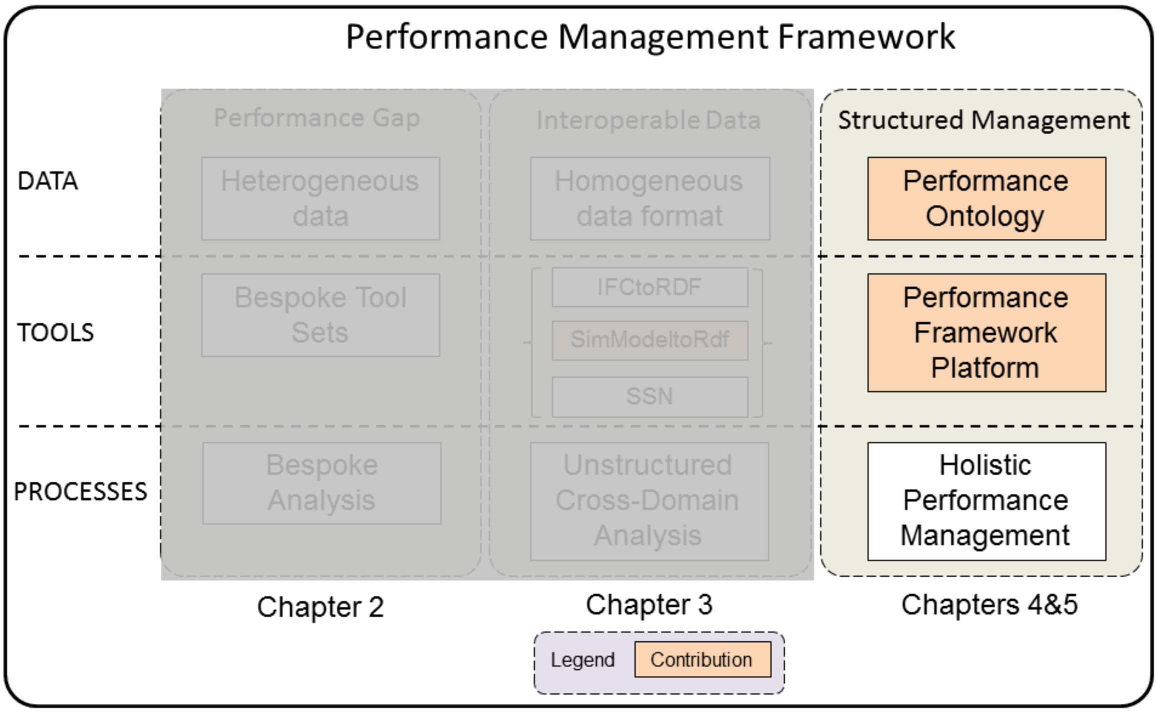


Fig. 4.1 Concept diagram illustrating the key concerns of Chapter 4, the use of a performance framework structure to drive cross-domain data analysis efforts.

data. The method uses a metric driven approach to enable interested parties to interpret building data in a coherent and relevant manner. A holistic performance management approach, based on semantically enriched AEC information, is now presented and Chapter 5 presents a software implementation of the concept. The remainder of this chapter is constructed as follows:

- The performance assessment approach is described briefly in Section 4.2;
- An automated approach to performance assessment is presented in Section 4.3, describing how semantic web technologies can be used to define performance assessment concepts;
- A number of RDF adapters are introduced in Section A. These adapters are used to convert non homogeneous data sources into RDF. These tools and techniques play a central role in the process, as described in Figure 4.2.

4.2 Performance Assessment

4.2.1 Adding structure to homogeneous data

The second research question posed by this thesis pondered whether data linking technologies could be used to integrate cross-domain data in the context of building performance.

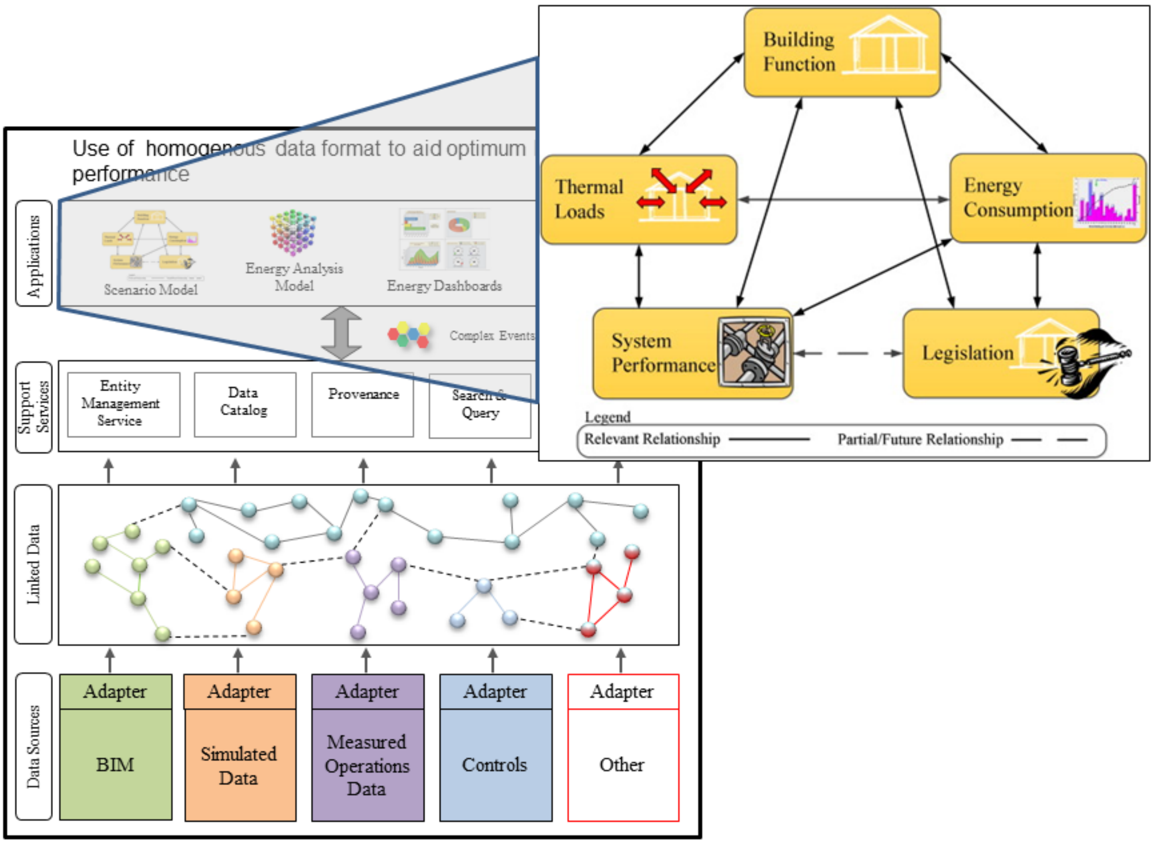


Fig. 4.2 Using homogeneous data sets to drive scenario modelling efforts

Versions of Figure 4.2 have been used throughout this thesis to convey the challenges faced in the research and to describe in a data context, the broader concepts illustrated in Figure 4.1. Chapter 3 described how a series of adapters could be employed to convert heterogeneous data into a format where links could be made easily between diverse data sources. This approach described how the RDF triple could be used to describe semantically, the relationship between building objects, such as physical spaces, buildings, rooms, and HVAC equipment, typically found in the AEC domain.

A closer look at Figure 4.2 shows how the various adapters can be used to describe the native data formats using the RDF data model. Ultimately, what remains is a series of homogeneously described, disjoint data sources, indicated by the dashed lines in the diagram. Links need to be created between these domains, in a manner that aids the key stakeholders in the management of building performance. This chapter illustrates how a structured performance management approach can be applied across various homogeneous data, using semantic web principles.

In particular, the scenario modelling technique, exploded in Figure 4.2, is described. This technique builds on the concepts described by Hitchcock Hitchcock (2003) and expanded on by O'Donnell (2009), by allowing these metric based techniques to be interpreted semantically.

Up to now, the thesis has described how the performance gap problem can be addressed from a data perspective, namely the publication of AEC data in a homogeneous context. Now, the focus moves to the second factor causing the performance gap, the lack of a cross life-cycle performance management framework. This chapter now describes a holistic environmental and energy approach to building management.

4.2.2 Performance Assessment

The issue of substandard performance has been discussed in detail in Section 2.1. Briefly, Figure 4.3 describes a variety of data silos within a typical building. Without a means to access this heterogeneous data and an adequate structure to interpret the information, the benefits of cross-domain access are limited. The lines between the domains indicate the sort of manual interventions and communications that might take place between actors in these domains, causing a type of cross-domain data exchange.

They key observation is that the interaction is completely ad-hoc, manually driven and unstructured. This type of interaction leads to confusion, extra work and poor information. The process is usually not repeatable and is expensive in terms of manual input.

AEC data needs to be communicated effectively and transformed into intelligent information. Modern buildings are highly instrumented and much of the information gathered is not usually communicated beyond the primary system it was gathered for.

A performance management framework to improve and model a more structured domain interaction is now presented. The presentation includes a description as to how the framework might by used to aid the communication of sensed data and how this data might be transformed into usable information, in a structured manner, using semantic web technologies.

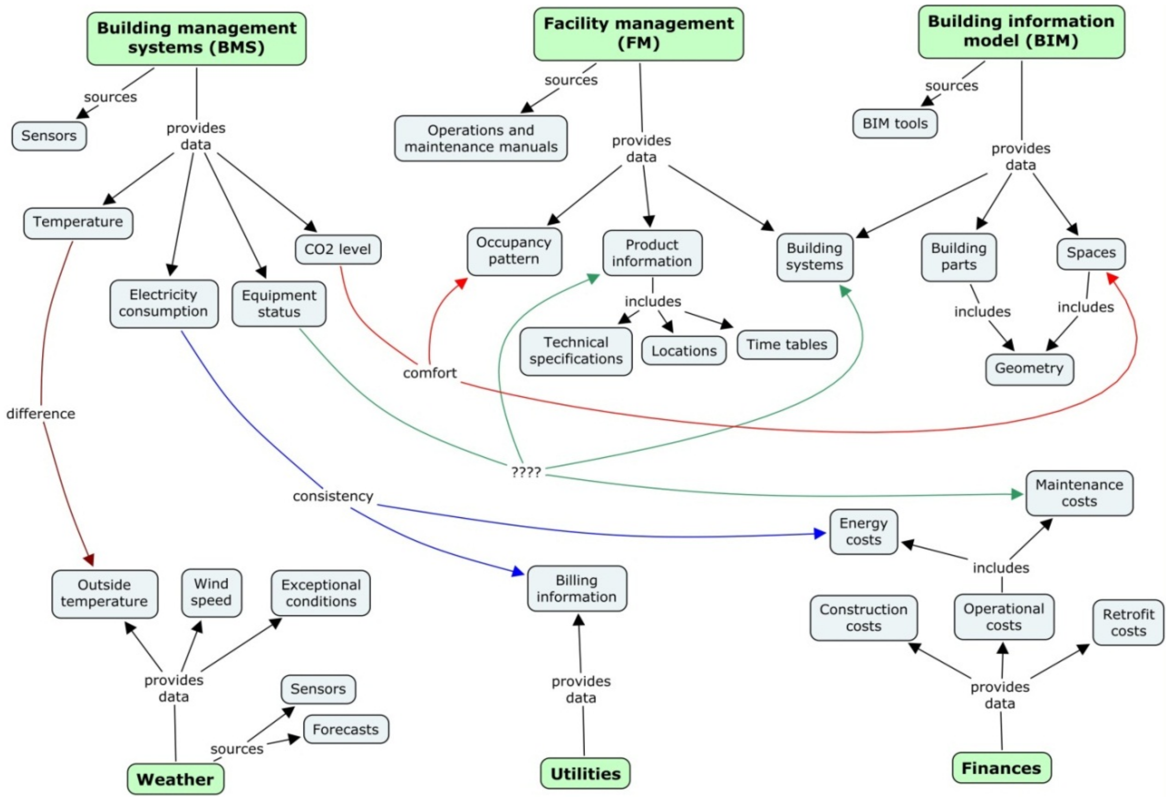


Fig. 4.3 Building data retained in data silos, lacking any functionality to enable cross-domain data sharing and access. In practice, connections are made manual, on a one-to-one, unstructured basis.

4.2.3 The Performance Framework

In any domain, performance assessment must be based on a measurement process of some kind, the evaluation of metrics with data. Legislative pressure, increased concern for the environment and higher energy prices have driven building owners to concentrate on the performance of buildings. Breaking performance down into a series of measurable components and employing a comprehensive continuous commissioning strategy has been shown to improve building performance dramatically (Costa et al., 2009; Liu et al., 2003; Neumann and Jacob, 2007).

The performance framework is one such approach, which describes a clear relationship between a specific building objective, an associated metric and data stream. A quantifiable metric can be described to evaluate a particular aspect of performance and that metric can be explicitly linked to a relevant data stream. In this way, overall building performance can be broken down into constituent parts and measured. The scenario modelling technique is built on the concept of performance being broken down into quantifiable metrics, which can be evaluated across the life-cycle. The concept is illustrated in Figure 4.4.

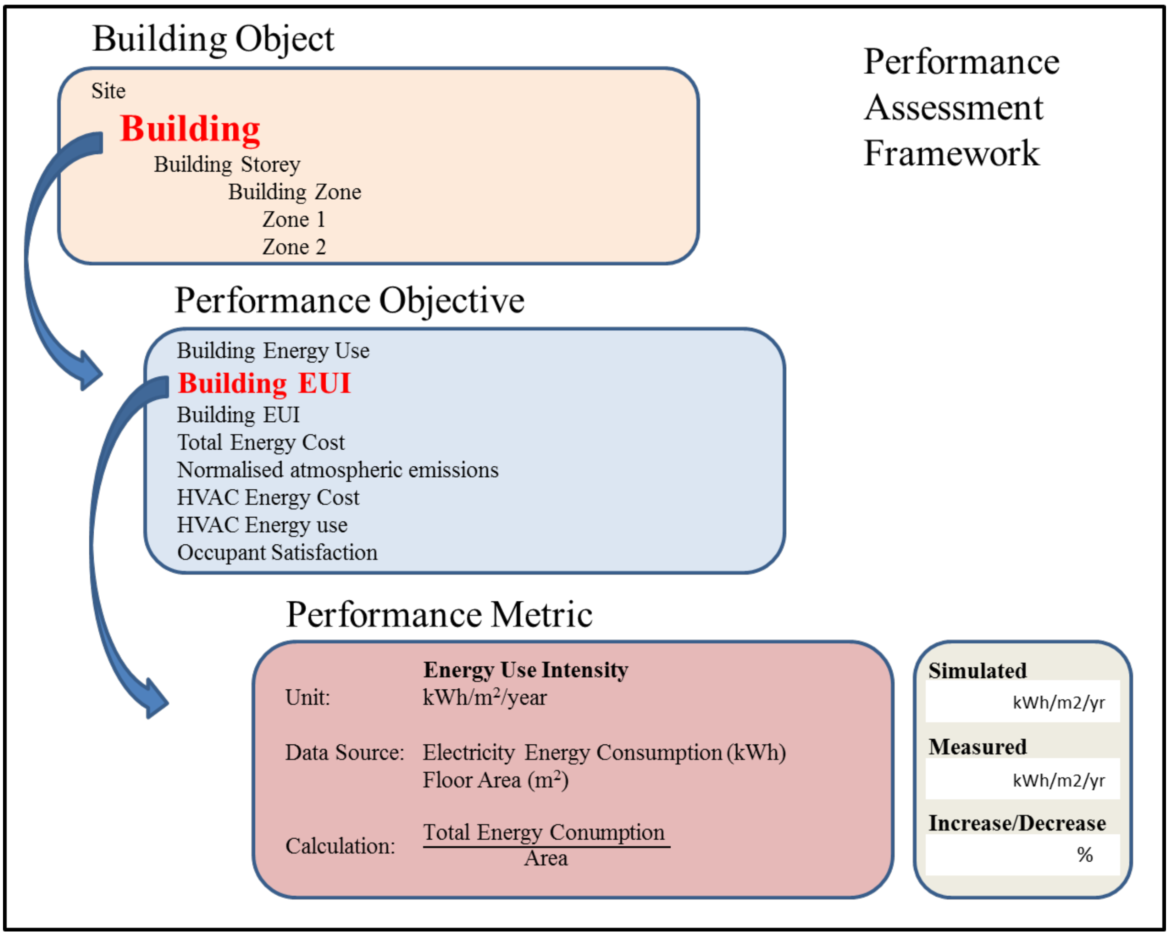


Fig. 4.4 Performance objective linking specific building object to a measurable objective and associated data streams. The performance assessment application combines several of these objectives into a scenario model in order to holistically interpret performance

The key elements of the performance framework include:

- Performance aspects are used to categorise elements of the scenario and include Building Function, Thermal Loads, Energy Consumption, System Performance and Legislation
- Performance objects are building objects against which specific objectives can be created and include Site, Building, Building Storey, Zone and various HVAC systems.
- Objectives are assessments of some aspect of the environmental and energy performance of a building. Objectives are categorised by performance object.
- Performance metrics are quantifiable methods of assessing performance objectives. Each objective has a particular metric associated with it, which includes relevant

algorithms. A pointer to specific data streams is also included.

The performance framework should be seen as a whole BLC activity, concerning the environmental and energy performance of the building. The first part of the process involves the selection of appropriate scenarios during the design and commissioning phase of the life-cycle, a process intended to be carried out by an energy analyst. This structure can easily be implemented using standard spread-sheet software, but such a solution requires a considerable skill level on behalf of the operator and also fails to take into account the issue of data capture and visualisation. A stand-alone system with a dedicated data capture and transformation structure allows for a robust solution to be put in place, which can be used by operators of various skill levels and backgrounds. Several examples of the performance framework in use are available in (O'Donnell, 2009) and a general description of performance metrics is provided by (Hitchcock, 2002, 2003; O'Sullivan et al., 2004).

Various groups have identified the minimal data set or ideal data set to underpin building performance analysis. The minimal data set is defined as the minimum or ideal amount of data required to accurately assess the performance of a building and its system (Neumann and Jacob, 2008). The framework is intended to build on an identified minimal data set within a building and transform these data into useful building management information. Greater access to data sources will allow for more granularity in the analysis and ultimately more useful information on the building performance.

Adopting a methodology such as the performance framework also allows for design intent to become a core part of the building operation strategy, serving as a benchmark for operational performance. This is largely a design and documentation process, recording key design data in a format that can be analysed against performance data. The work can then be expanded upon by formally transforming these raw data and making it available in a context specific manner to relevant stakeholders, such as energy managers, engineers and building owners. The Performance Framework (PF) allows the performance metrics to be monitored against design intent using data produced by the measurement framework (e.g. sensors and meters).

4.3 Automating the Performance Assessment Process

It is quite possible to define and quantify performance metrics using paper based methods, individually accessing each data silo separately. This process is not practical in a large facility and it requires significant knowledge on behalf of the Building Manager to accomplish. Furthermore, the greater the volume of data, the more overwhelming it becomes. The interoperability problem described in Chapter 2 makes automated transfers of information between data silos in the AEC domain difficult and Chapter 3 describes, in a general manner, how some of these interoperability concerns may be overcome by the use of semantic web technologies.

Providing key building stakeholders with contextualised information relating to the environmental and energy performance of buildings is a key goal of this research. An approach to this issue is now presented, which builds on the concepts introduced in Chapter 3. A performance ontology is presented which describes how homogeneous performance data can be accessed in an application independent manner. This work expands on that described in Chapter 3 by providing a structured, robust framework, rather than merely using homogeneous data in an unstructured, ad-hoc manner. At this point, a brief description of ontologies is required.

4.3.1 Ontologies and Domain Description

Ontologies were first introduced in Chapter 3 as a part of a wider discussion on semantic web techniques. The thesis up to now described how AEC data could be published semantically in an unstructured fashion. Accessing the information in a more structured manner allows a more meaningful interpretation of the data to take place. A performance ontology is a way of describing a domain in a structured manner, providing context between objects in the domain. What follows is a description of what an ontology is in semantic terms and how a performance ontology is central to the work of this thesis.

There are many definitions for the word *ontology*, but reference is made here to the definition often used in computer science, "*An ontology should effectively communicate the intended meaning of defined terms and relationships within a domain*" (Gruber, 1993).

Ontologies are explicit, formal conceptualizations used to describe an area or domain of knowledge in a machine accessible-manner and are based on a well-defined syntax, efficient reasoning support, formal semantics, sufficient expressive power and convenience of expression (Antoniou, 2004). Broad discussion of the ontology concept is variously provided by (Da Silva et al., 2006; Hitzler et al., 2012; Jurisica et al., 2004; Panetto et al., 2012). Various descriptions are used to describe an ontology, but some terms are critical. An ontology provides an explicit description of a domain, including the concepts, the properties and attributes of these concepts, associated restrictions, using a common vocabulary. The purpose of an ontology is to enable the reuse of domain knowledge, providing a means of exchanging this information with interested actors.

The basic RDF graph uses the subject-object-predicate triple structure to define meaning between objects, with the predicate indicating the nature of the relationship. This structure is limited in terms of categorising and providing a broader context for objects. The RDFS extends the RDF data model to include support for classes, subclasses, types and other concepts. These predefined RDFS constructs are defined using RDF statements. A similar approach is used to define ontologies using OWL, where further predefined constructs are available, including properties of objects and rules governing relationships between objects. Although RDFS and OWL offer more predefined constructs than RDF, they are implemented using RDF constructs from the underlying RDF data model. Various syntaxes exist to describe RDFS and OWL, including XML, N3, Turtle and SPARQL.

A key benefit of this relationship structure is the ability to relate objects to each other in a meaningful way. By describing the nature of the relationship between, say, a movie comedy subclass and the movie super-class, we can infer that all comedies are movies and inherit the same properties from the super-class. Similarly, if we have a motor-vehicle super-class, requiring information on the number of seats, we can restrict to a passenger car subclass, those vehicles having at least two seats. In the AEC domain, a building may be considered residential provided it has a kitchen and bedroom. Dedicated rule languages, including the Semantic Web Rule Language Semantic Web Rule Language (SWRL), the Rule Interchange Format (RIF) and N3Logic can build on these relationships between resources to allow a rule based-reasoning process (Pauwels, 2012).

4.3.2 A performance management framework

Currently, a range of AEC data is published in RDF format. Much of these data are originally described in native data formats and can be converted to RDF using a range of data converters. For the purposes of this research, we focused on three key adapters and ontologies, and each of these is described in detail later in the chapter:

- IFCtoRDF data service (Section A.0.1)
- SIMModelToRDF conversion service (Section A.0.3)

- Semantic Sensor Network ontology (Section A.0.4)

Each of these approaches defines how certain AEC data should be defined semantically. One of the two key issues identified earlier in this thesis, Section 2.2, described the huge problem associated with data integration and interoperability in the industry. These adapters provide a bridge across this divide and illustrate how AEC data can be described homogeneously, at the data level, separate from applications and tool-sets.

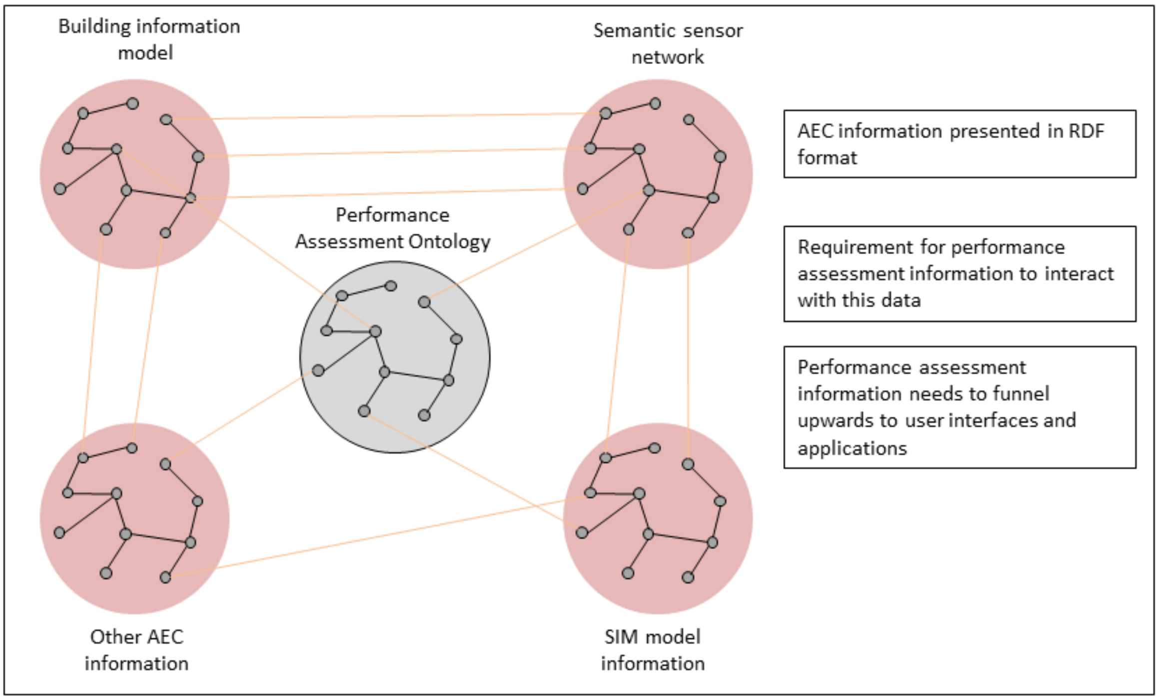


Fig. 4.5 Linking separate homogeneous data sources using a performance framework ontology

Figure 4.5 illustrates how these separate domains or data sources, presented in RDF format, using a domain ontology can be accessed using a performance framework ontology. In the performance management area, we are interested in accessing information about the building geometry, the building HVAC systems, scheduling information, sensor information, etc.

At a broader level, we would like access to occupancy patterns, financial data, weather data, etc. Many of these data sources are described by an existing ontology , while others are yet to be defined. The circles in Figure 4.5 represent separate AEC data sources, previously described natively, in application dependent, heterogeneous data formats, now represented homogeneously.

It was described in Section 1.2.2 how performance assessment and management could be driven by key life-cycle performance assessment metrics, but that this approach was restricted due to the nature of often inaccessible, heterogeneous data sources. Figure 4.5 describes how such a performance management structure can now be implemented more effectively, using homogeneous data sources.

4.3.3 The Performance Assessment Ontology and the Semantic Web

In order to interpret the now homogeneously represented data in a manner which aids key building stakeholders, the data needs to be considered in terms of a measurement framework. The performance framework (Section 4.2.3) is a published performance management approach and serves as a suitable basis for the definition of performance management using the semantic web.

The scenario modelling process can be considered an enterprise level data integration and analysis function, building on homogeneous data sets. One solution to aid this integration process is to avail of an ontology to define the performance assessment domain and subsequent relationships with other ontologies, as described in Section 4.3.1. The performance assessment ontology is intended to describe the assessment domain, detailing how metrics can be defined and related to specific objects of interest. In this work, we are interested in linking various subsets of AEC data together using the performance framework technique.

The sections illustrate how performance might be evaluated semantically and how the ontology could be integrated with other ontologies prevalent in the AEC domain. While an ontology such as this is unusual in the AEC domain, the world of business and Business Process Management (BPM), in particular, makes use of similar ontologies to drive business performance assessment efforts. This work builds on some of these ideas (Pedrinaci and Domingue, 2009; Pedrinaci et al., 2008).

4.3.4 The Performance Framework Ontology

The performance framework relates static building objects to dynamic data sets through the concept of a performance objective. These objectives need to be evaluated over time, using performance metrics. Metrics can be considered the most elementary aspect of the performance framework and the idea of quantifying something in an ontology has been encountered previously. Pedrinaci et al. (2008) described how a metric might be implemented in an ontology, albeit in a BPM context. Defining the metric is the key element of the Performance Assessment Ontology (PAO), from which the remaining elements of the performance framework evolve.

Hitchcock (2002) describes how performance metrics are intended to explicitly represent each performance objective using quantitative criteria in a format that provides value across the life cycle of a building project. Such metrics must be capable of being either predicted or measured at various stages of the project so that the achievement of each performance objective can be evaluated and a detailed description of how such metrics are defined is provided in (Hitchcock, 2002).

In the performance framework ontology, we use Pedrinaci's description of a metric as the basic building block of the ontology (Pedrinaci and Domingue, 2009). The basic ontological representation of metrics (Figure 4.6) can be categorised into two groups (Pedrinaci et al., 2008), functional metrics and aggregation metrics. Functional metrics are metrics which can be evaluated over a fixed number of inputs or parameters. Aggregation metrics are intended to take an arbitrary number of individual inputs, of the same kind (Pedrinaci et al., 2008), for instance, an average, maximum or minimum, of a set of sensor readings.

Fig. 4.6 BPMN Metrics ontology (Pedrinaci and Domingue, 2009) forms the basis of the performance framework ontology. The approach illustrates the reusable nature of the semantic web, allowing a process used to describe one domain adapted to use in a completely different area. Removed due to copyright restrictions

Aggregation metrics are computed over a population in order to obtain an overall perception of some aspect of interest such as the maximum temperature reading, achieved using a population filter (Figure 4.6). The aggregation of data semantically is an extremely difficult proposition and perhaps futile, in that considerable resources are available which can achieve this already. By retaining the aggregation construct, or functional construct associated with a metric in RDF, software algorithms can be used to perform the associated calculation outside of RDF.

The aggregation constructs are unary functions which take a list of readings as input and return a computed quantity and Pedrinaci et al. (2008) achieved this functionality, using the COBRA interface. Pedrinaci et al. (2008) also allowed aggregation metrics to have a nested definition where a given function metric could be evaluated over each instance of the population prior to the computation of the aggregation function. This structure allows metrics such as the maximum of the average temperature readings in a facility. An example of a functional metric being used to populate an aggregation metric would be the average daily thermal comfort level in a space. The functional metric is used to compute the thermal comfort level at a given moment in time, while an aggregation metric is used to derive an average of the comfort levels throughout the day.

Pedrinaci's metric definition includes the following aggregation functions: Count, Maximum, Minimum, Average, Standard Deviation, Variance, Sum, and Prod. This metric (Figure 4.6) definition is used as the initial element of the performance framework ontology. Performance metrics are used to evaluate performance objectives and these objectives then form the scenario. This information is also captured in the ontology (Figure 4.7).

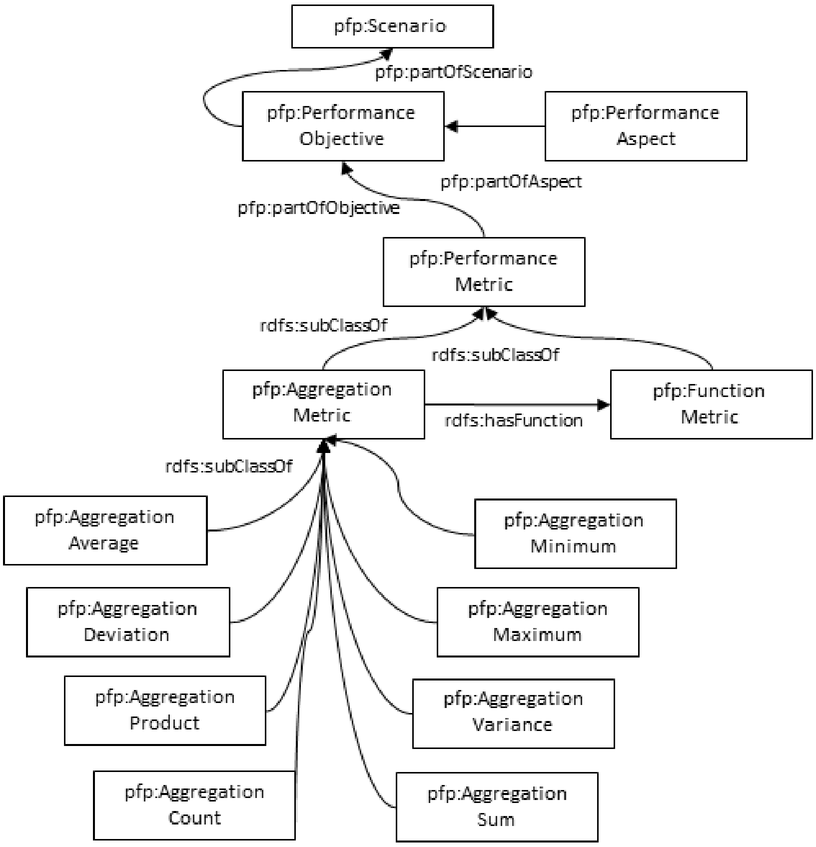


Fig. 4.7 Ontology representation of the performance framework platform.

4.3.5 Using the Ontology in a Building Context

Quantifiable elements of performance are a necessary component of performance management. Specifically, we are interested in performing calculations on performance data in a repeatable manner, requiring an explicit link to specific data sources. In order to evaluate each metric, a metric assessment relationship needs to be defined, illustrating the links between the metric and associated data. Figure 4.8 represents the initial placement of the PAO with respect to sources of data in the wider AEC domain and these relationships are now explored further.

The performance framework based metrics allow building managers to specify assessment

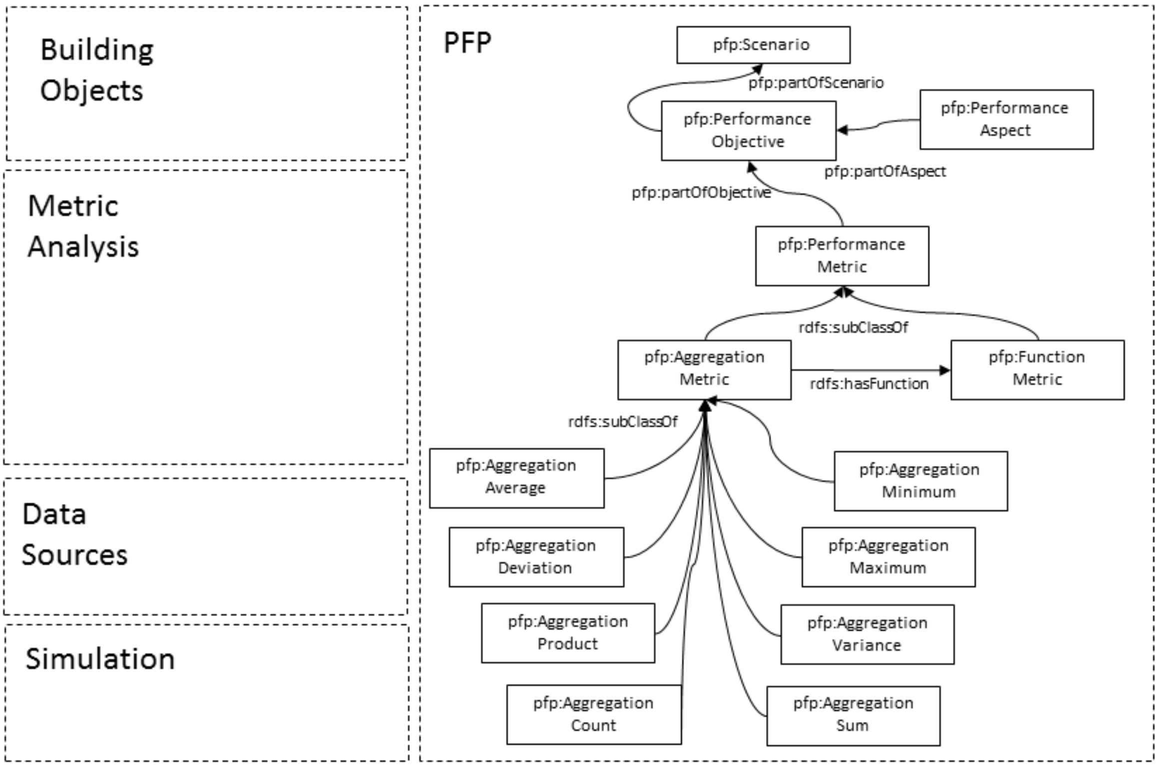


Fig. 4.8 Performance framework ontology and the wider AEC domain

metrics in a domain independent way. There are two types of metric, a functional metric which evaluates a particular function, based on input parameters, and an aggregation metric, which is used to perform standard aggregation actions on a list of data. A functional metric can be interpreted as a metric which implements a particular function. A simple functional metric in the context of building data would relate to a single instance value of outdoor dry bulb temperature (List 4.1).

Using the various data adapters mentioned previously, is it quite easy to say link a zone described in a geometric model with a sensor described by the SSN ontology. It is quite difficult to link these objects to specific data outcomes, and in the case of aggregation functions, it is not possible to describe lists of data in RDF. RDF is used to retain the metric and the relationships between building objects, but an external algorithm is provided to compute the metric.

Listing 4.1 Metric associated with Outdoor Dry Bulb Temp. This metric should require a single instance as an input and a single output

```
Outdoor Dry Bulb Temp
Input: temp \celsius
```

```
Output: temp \celsius
```

Performance metrics are described in terms of their inputs and the nature of the evaluation required on these inputs. In the case of a functional metric, the associated function is described as a property of the metric, while for an aggregation metric, the type of aggregation is recorded. These metrics are then interpreted and evaluated using the Performance Framework Platform, as described in Chapter 5. List 4.1 describes on a pseudo-code level, the algorithm used by the Performance Framework Platform (PFP) to compute the metric. In this case, no calculation is required.

A more advanced functional metric might call for some element of calculation to be carried out, based on input parameters, leading to a single value output. An example might be the calculation of an EUI figure for a building. This calculation requires energy consumption levels and building area as inputs (List 4.2). In this case, the calculation is retained as a property of the metric and evaluated using the Java-based PFP. Several performance metrics are defined as part of this work and are referred to in the following sections. Each of these metrics describe a calculation common in the domain, such as the calculation of thermal comfort, EUI, etc.

Listing 4.2 Metric associated with energy usage intensity. This metric requires multiple inputs and provides a single output

```
Building Energy Usage Intensity
Input: Total Energy Consumption
Input: Floor Area
Calculation: Total Energy Consumption/Floor Area
Output: Energy Usage Intensity
```

The second type of metric is an aggregation metric, which can be specified to describe a particular aggregation function to be performed on a set of data. In this case, we are typically dealing with sensor output data. The key consideration here is that the data are all of the same type, in the form of a list. A data filter is defined, which describes the parameters by which a data stream might be broken into a list, based perhaps on date or time parameters. This filtered stream is linked with the metric instance and associated with the performance metric (List 4.3). Figure 4.9 illustrates the relationship between the aggregation metrics and the data filter. The evaluation of the metric takes place outside the RDF structure, in the performance framework software.

Listing 4.3 Aggregation metric associated with total energy use. This metric is required to perform an aggregation function on a list of data, returning a single output.

```
Total Energy Use
Input: List of energy use by source
Aggregation: Sum
Output: Total Energy Use
```

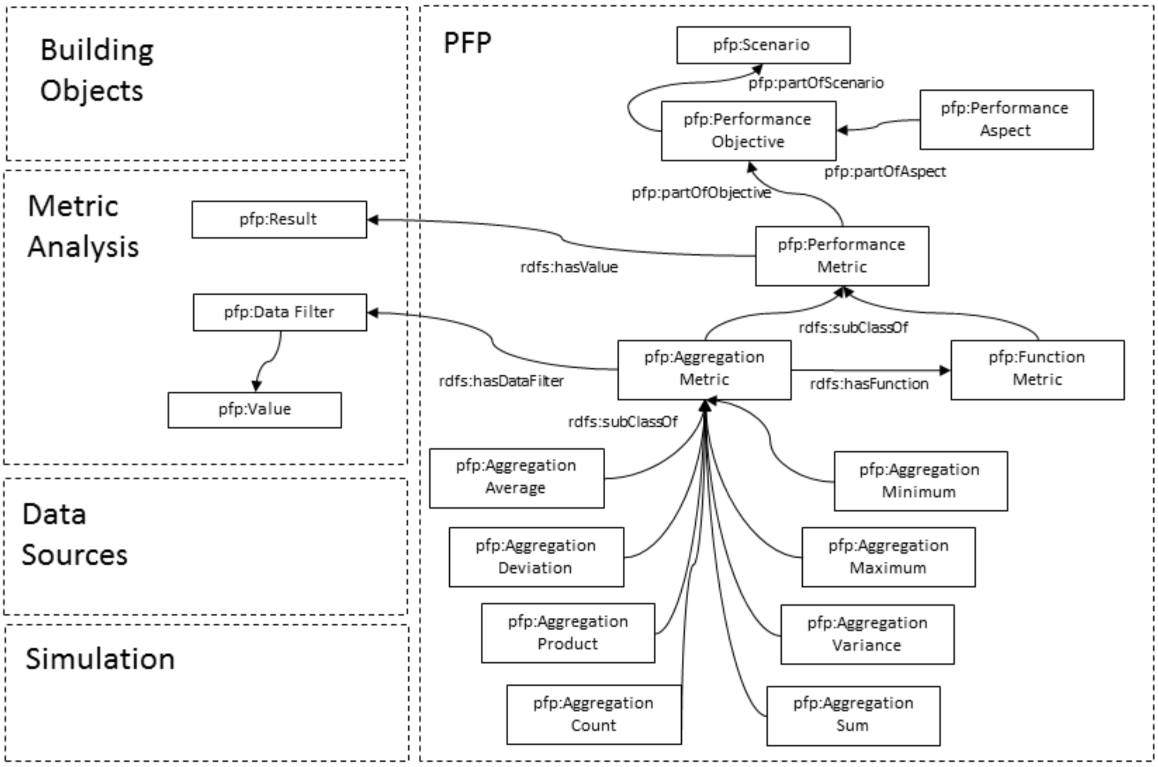


Fig. 4.9 Performance framework ontology linking with metric assessment

The metric structure, integrated with the performance framework platform, allows for the interpretation of specific sets of numerical data in a structured manner. Various unit ontologies also exist, which may be used to define numerical values returned (Haas et al., 2014).

Interpreting a list semantically is extremely difficult. We can achieve the desired outcome by retaining key information about the data we wish to analyse in the performance metric instance and then evaluating this using the PFP tool.

If we consider a collection of data points gathered in a typical building, say daily dry bulb temperature and we wish to find the average of these data points, we might structure the metric similarly to list 4.4. In this case, the metric retains a link to the data source in question and a time period. The PFP software interprets these inputs and returning a list.

Listing 4.4 Aggregation metric associated with average dry bulb temperature. This metric determines an average from a list of data, returning a single output.

```
Average Daily Dry Bulb Temperature
Query Input: Data source
Query Input: Time period
Query Output: List
Data Filter: List
Aggregation Metric Input: List
Aggregation Metric Output: Value
```

Pointing metrics at the data sources involves linking to other areas in the semantic web. The next section describes how metrics, defined using the performance ontology can be linked using the SSN.

4.3.6 Performance Ontology and the SSN ontology

Although metrics can be evaluated against many types of data, from sources spread throughout the building, sensor output forms a significant block of available data in any modern building. Accessing these data is a critical aspect of any performance management approach. As described in Section A.0.4, the SSN can be used to describe sensor data and publish it semantically.

Figure 4.10 is a subsection of this ontology and illustrates how a *SensorOutput* is retained as an *ObservationValue*, an outcome from the act of sensing which has taken place. This observation value serves as an basis for the evaluation of performance metrics intended to measure sensor data in some fashion. This SSN ontology is used to describe the sensors in the domain and provide a raw value to which the PAO can relate. This observation value forms the basis of the metric assessment.

Fig. 4.10 SSN Ontology, illustrating sensor output (Barnaghi et al., 2011). Removed due to copyright restrictions

Linking to sensor data modelled using the SSN ontology allows us to access all manner of defined properties relating to sensors. The observation value is linked to the performance metric as illustrated (Figure 4.11). The nature of this link is relevant. A simple functional metric, with a single input and single output, can be easily modelled, with the metric linking directly to the observation value. A more complex metric, involving a list of data requires the use of a filter, to group population values into a list. This list can then be linked to the relevant aggregation metric. At this stage, there is a clear link between the performance metric, clarity on the nature of the metric, and an explicit link to data sources. The scenario modelling endeavour requires further links to be made to other domains of data, and these are now explored further.

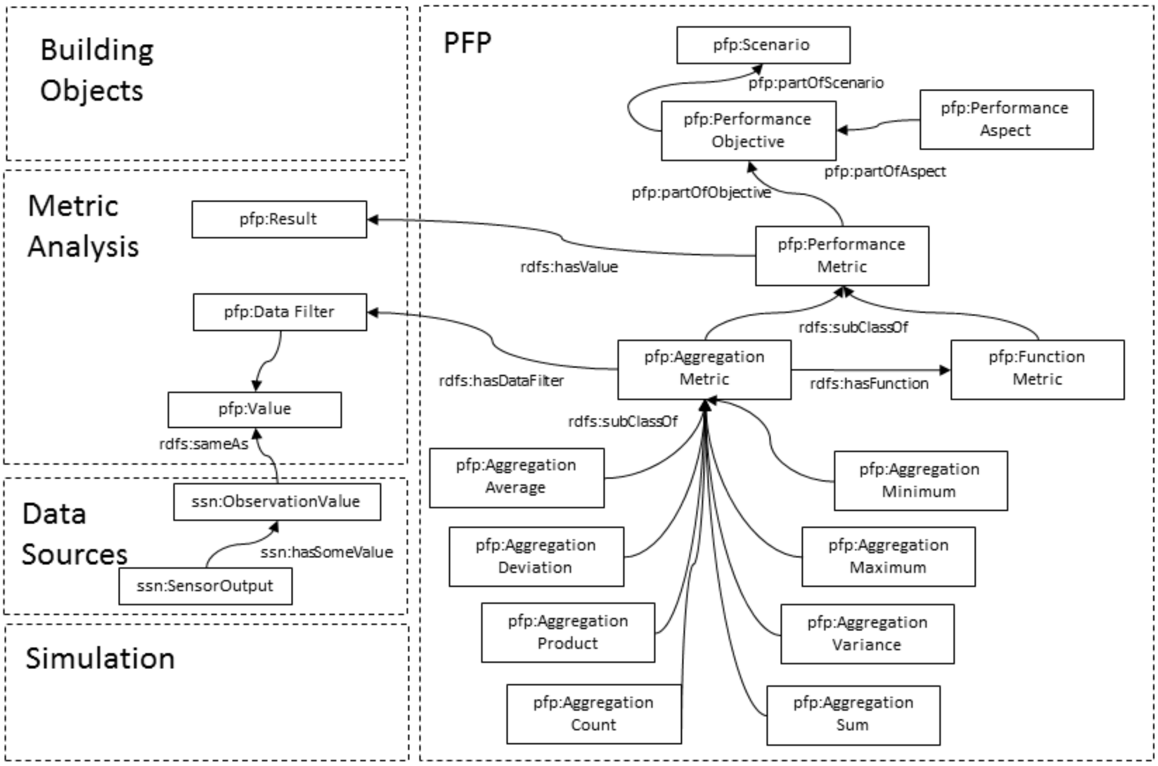


Fig. 4.11 Performance framework interaction with the semantic sensor network.

4.3.7 Linking the Performance Ontology to a Location

The IFCtoRDF ontology was described previously in Section A.0.1. This ontology can be used to convert building geometry stored in IFC format to RDF. The PF is concerned with relating performance objectives to specific building objects. Table 4.1 describes a sample of the possible metrics associated with some building objects. A more exhaustive list is available as part of Chapter 5. It is important that objectives can be associated with a particular building object and that data sources are also associated with particular objects or spaces. For instance, for a given zone, we would like to explicitly link to available sensors in that zone.

This type of interaction allows for the interpretation of building performance at a much more granular level. A key requirement of the PF is that explicit links can be created that illustrate the location of specific devices in the building. For example, if you wish to

Table 4.1 Sample performance objectives and associated building objects

Performance Objectives	
Building Object	Performance Objective
Site	Outdoor Dry Bulb Temp
	Outdoor Dry Bulb Temp
	Outdoor Humidity
	Average Daily Outdoor Temperature
	Wind Speed
	Wind Direction
	Available Natural Light
Building	Total Energy Use
	Outdoor Dry Bulb Temp
	Total Energy Cost
	Total HVAC EUI
	Number of Complaints
Zone	Zone Temperature
	Zone Humidity
	Zone Air Velocity
	Predicted Mean Vote (PMV) or Percentage of People Dissatisfied (PPD)
	Zone Occupancy Level
	Zone Lux Level

understand the thermal conditions in a space, you would be interested in the sensor data for the space, the scheduling data for the space and the physical expression of the space.

Figure 4.13 is a representation of how the IFCtoRDF data service describes a zone and related building objects. It is possible to relate the building location, the sensor location and the performance objective semantically. Similarly, objects defined using the SIMmodeltoRDf ontology can be quickly linked to objects defined with the IFCtoRDF ontology. Figure 4.12 illustrates how a building zone might be related to a performance objective, defined using the performance ontology. In a similar fashion, the physical sensor device might be related to the zone.

The purpose of the PF approach is to break down building performance into defined, measurable components or objectives. When creating an objective, generally, the user is interested in relating the objective to a specific building object or location. Looking at the various data domains defined in Figure 4.12, locations are defined several times and in different ways. Sensors have a defined location. Building objects have a defined location.

We would like to relate specific performance objectives to a relevant building object. The IFCtoRDF ontology exists to enable the description of building information modelling

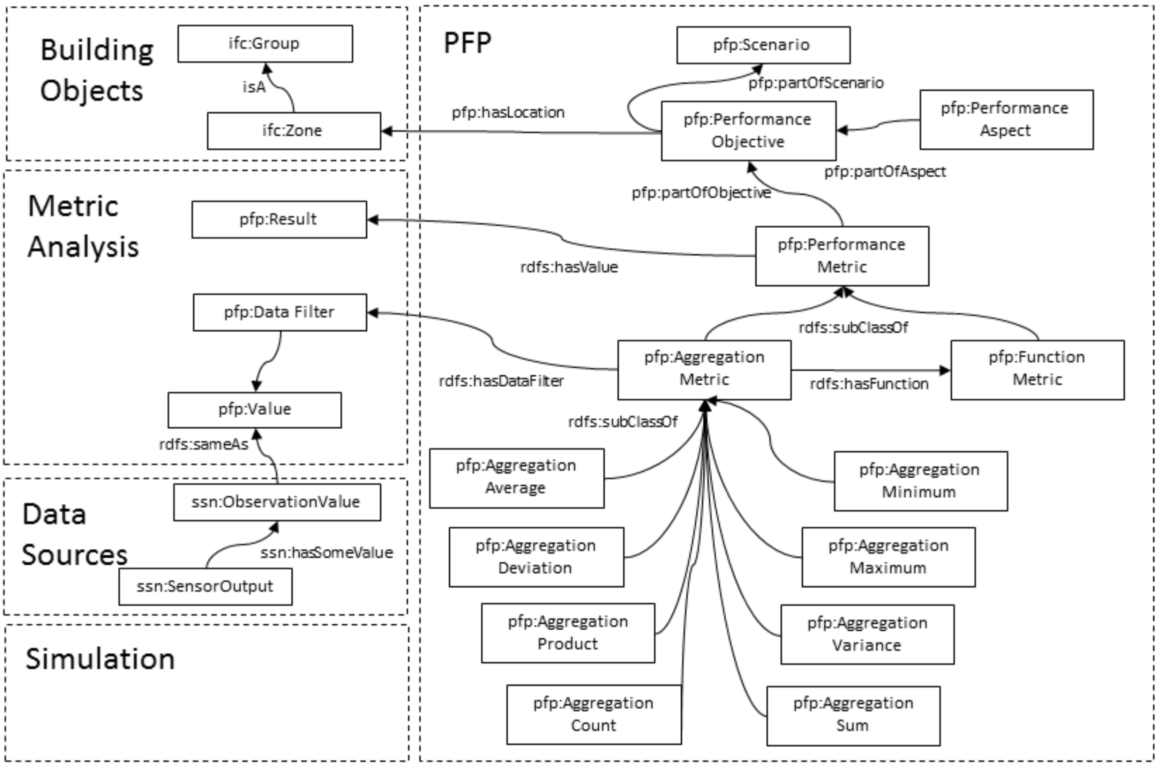


Fig. 4.12 Building objects related to the PFP ontology

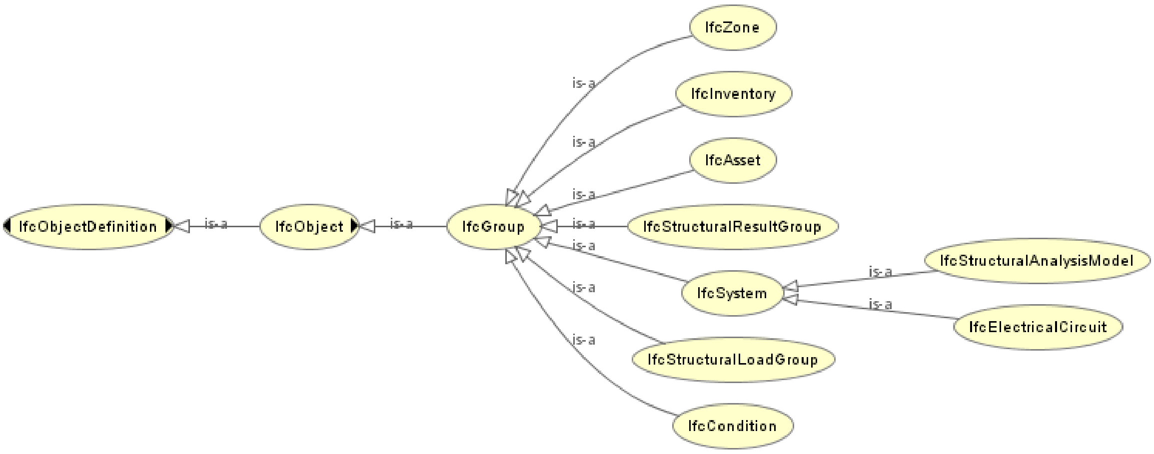


Fig. 4.13 Zonal representation in IFCtoRDF ontology

data semantically. For instance, a building zone is particularly relevant in the performance management context. The IFCtoRDF ontology illustrates how each IFC building component can be described semantically (Figure 4.13). Figure 4.12 illustrates how a location might be linked to the ontology.

An implementation of this ontological approach is provided in Chapter 5, using a Java based application to create and interpret scenario models defined using this ontology. A number of "adapters" mentioned in this section are described in Appendix A. These adapters have a crucial role to play in the performance management process as they provide the bridge to the enable the conversion of application specific, restricted data into a more homogeneous data format.

4.4 Conclusion

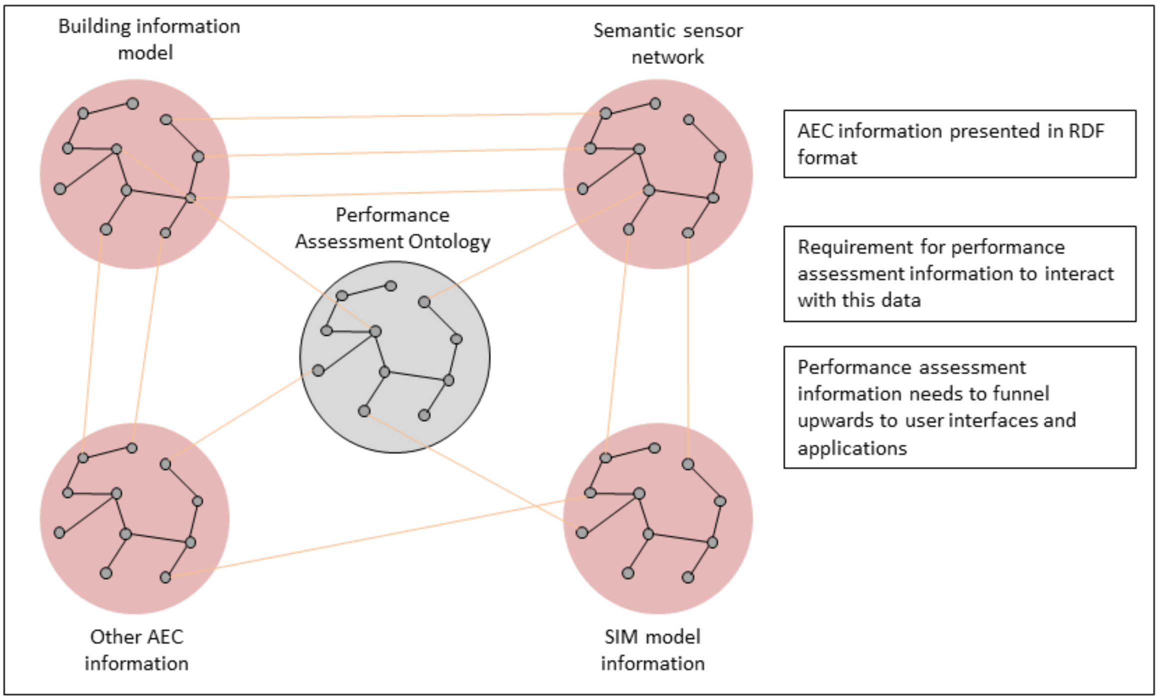


Fig. 4.14 Linking separate homogeneous data sources using a performance framework ontology

This chapter introduced a structured method of holistically managing building information, using semantic web technologies. The performance ontology is intended as a structure to model a performance measurement system, enabling access to homogeneous data in a structured way. The second research question in this thesis asked if data linking technologies could be used to integrate cross-domain data in the context of building performance. This ontological approach illustrates that a performance management platform can be described, which uses building data in a cross-domain manner.

Furthermore, the work clearly describes an approach to data management in the AEC domain, which can challenge the two key factors of the performance gap, namely performance assessment and interoperability. In order to test the ontological approach described in this chapter, the Performance Framework Platform (PFP), based on the Performance Framework Ontology is introduced in Chapter 5 and a sample implementation is presented.

As illustrated by Figure 4.14, first referenced in Section 4.3.2, we are now in a position to test structured interaction between a range of AEC data sources, using a powerful, metrics based ontology. This approach describes a clear path through the masses of data facing the typical building manager described earlier.

Chapter 5

Performance Framework Test Environment

5.1 Introduction

This chapter is concerned with providing a tangible demonstration of the key advances described throughout the thesis. The thesis opened with the observation that buildings tended to use more energy than initially predicted. A thorough literature review of the area identified interoperability and a lack of available performance management structures as key contributing factors to the performance gap problem.

Figure 5.1, the key concept diagram used throughout this thesis, describes the path to holistic performance management processes, from the current bespoke type analysis prevalent in the industry. Chapter 3 described how a series of adapters can be used to convert heterogeneous building data to a homogeneous data format. Presenting building data homogeneously merely addresses the interoperability issue described throughout this work. It is also necessary to navigate through the homogeneous data in a structured manner. The third column of the figure describes how a performance framework platform could be constructed, based on a performance assessment ontology integrating with homogeneous AEC data. Chapter 4 described the semantic relationships governing such an assessment platform in detail.

This chapter presents a physical implementation of each stage in the transformation described in Figure 5.1, from heterogeneous, restricted data silos, to a homogenous, RDF data format, and onto a structured performance management implementation. This implementation considers some of the AEC data around the area of thermal comfort and illustrates how this information might be used to provide a greater level of interpretation for the Building

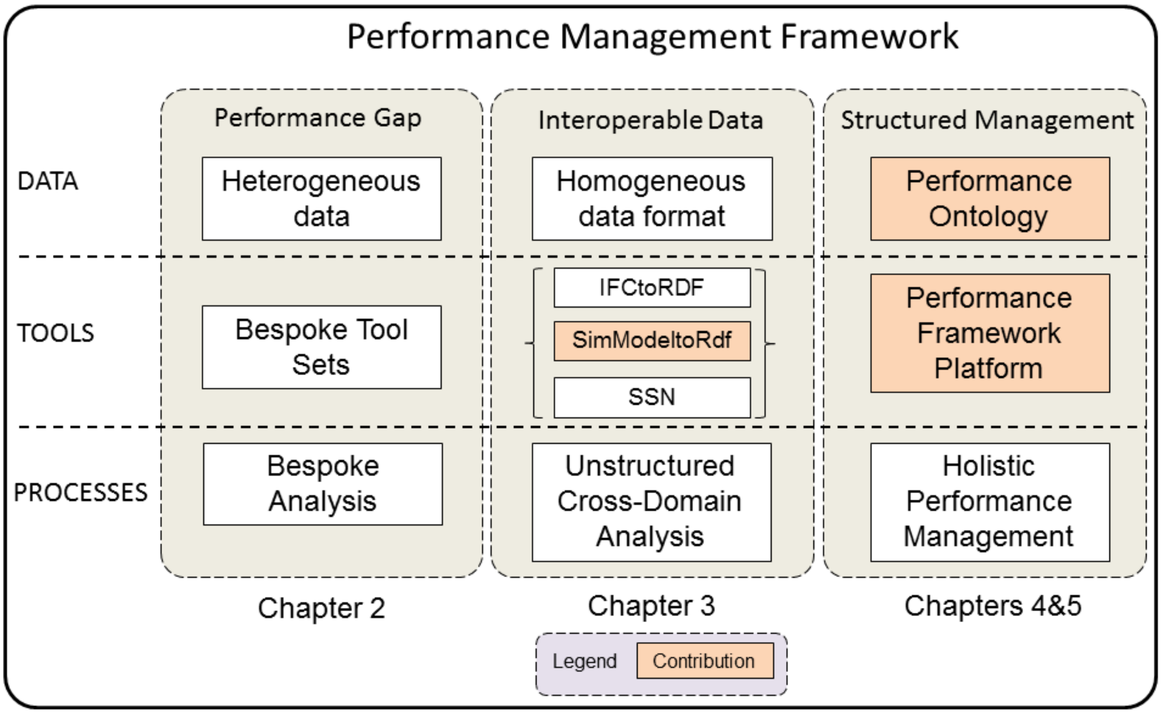


Fig. 5.1 Concept diagram illustrating the key concerns of Chapter 4, the use of a performance framework structure to drive cross-domain data analysis efforts.

Manager, in a performance management context. The approach outlined in this example provides a more holistic level of performance awareness for the Building Manager, but the broader cross-domain approach allows for homogeneous data to be used as a service for many different types of cross-domain data analysis. Key information also can be provided to other stakeholders at the enterprise level also.

In order to prove the concepts outlined in this thesis, a Java based application has been developed which interprets building information data semantically. The application can be used to describe a performance assessment structure, providing links between various building data sources in a homogeneous manner.

The experiment charts a clear path from the raw heterogeneous data formats, through conversion adapters and the homogeneous data format, to a structured performance management interpretation of this data. This experiment uses thermal comfort, a key measure of occupant comfort as the key focus of the work. The ground floor computer suite in the NEB was considered slightly warm by many occupants. A comprehensive thermal comfort analysis of the space was conducted, as part of wider study of building performance carried out in the college. This demonstration uses some of the raw data sources captured in this study as a basis for cross-domain analysis. These sources were supplemented by other hard and soft data sources available in the space.

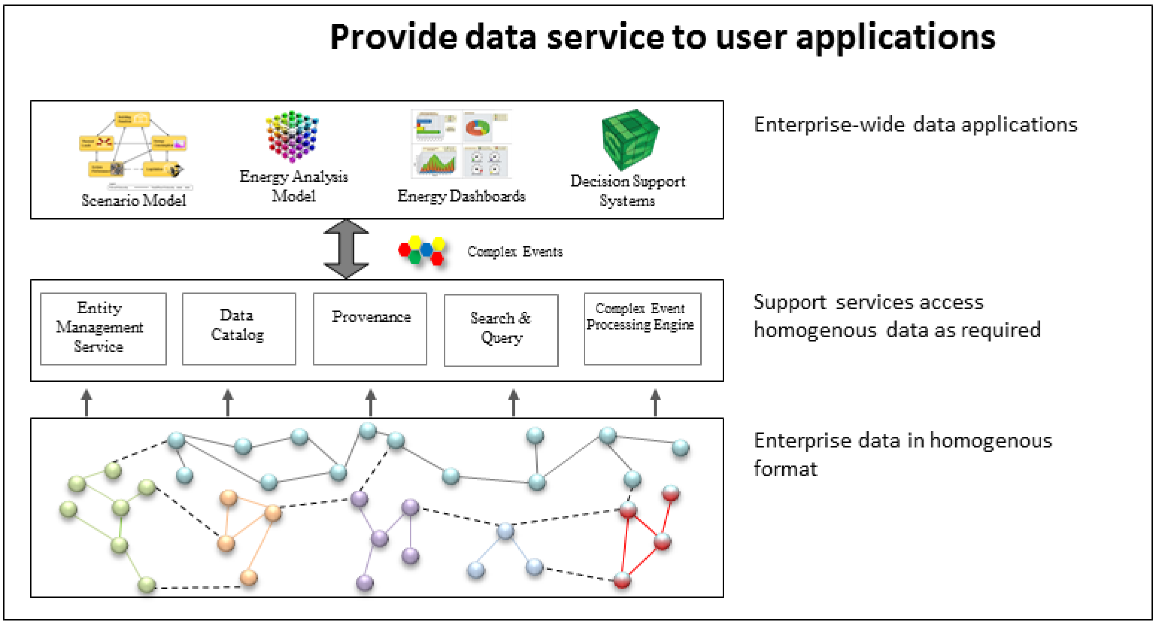


Fig. 5.2 Data transformation structure, indicating the conversion of heterogeneous data sources to homogenous data sources and the interpretation of these data sources using structured tool-sets.

The chapter is divided into a number of sections:

- A description of the materials and methods used in the implementation, including the data sets and technology used, is described in Section 5.2
- An examination of the results of the implementation is provided in Section 5.3.
- The conclusions which can be drawn from this implementation are described in Section 5.4

5.2 Materials and Methods

This implementation is concerned with the thermal conditions in a space, and describes how these conditions can be considered semantically with the aid of the performance framework tool. There are four main elements to this experiment and these are described below:

- A series of heterogeneous building data sets, relevant to the thermal comfort study, are identified.
- These data sets are semantically enabled, where possible, using a range of data adapters.

- The performance framework tool is used to create a scenario model, assessing the ground floor computer lab, from a number of perspectives.

- The scenario model is evaluated against available data sets and used to provide a more holistic interpretation of building performance.

The implementation considers thermal comfort in detail, and a brief account of the concept is now provided. The PMV and Predicted Percentage Dissatisfied (PPD) thermal comfort indices form the basis of the ISO 7730 thermal comfort standard, and are used to predict the mean response of a large group of people to thermal conditions. There are a number of components that contribute to thermal comfort including metabolic rate, humidity, air velocity, clothing, air temperature and radiant temperature. PPD and PMV readings provide a useful indicator of stakeholder satisfaction with thermal conditions in a space. The PMV is an index that predicts the mean value of a large group of people on the 7-point thermal sensation scale.

The thermal comfort of a building is considered a key stakeholder requirement in most organisations. Although thermal comfort is very much a personal response to conditions, depending on a wide variety of factors, studies have shown that thermal comfort conditions tend to correlate, across geographical areas, cultures and climate zones (ASHRAE, 2004b). There appears to be uniformity in occupant complaints due to thermal conditions once these conditions fall outside a narrow benchmark (Federspiel, 1998). We are interested in using the scenario modelling technique to create performance objectives around the comfort levels of the space and use the data linking techniques mentioned to access relevant data to evaluate these objectives. The implementation draws on a range of soft and hard data sources available in the room and utilises these data to provide a more holistic interpretation of building performance.

Figure 5.3 describes the initial part of the implementation, where the key data adapters described in Section A are used to transform raw data into a homogeneous data format.

Each conversion process is described in detail, beginning with the conversion of the BIM data associated with the space into RDF. The purpose of this stage of the experiment is to illustrate how building data can be converted to RDF, using a series of data adapters, providing a homogeneous collection of data sets. It is important to note that the linking between these data sets will have taken place at the next stage of the implementation. The dashed lines between the data sets in Figure 5.3 reflect the possible connections available between the sets, and will be implemented when a scenario model is created to navigate through the data.

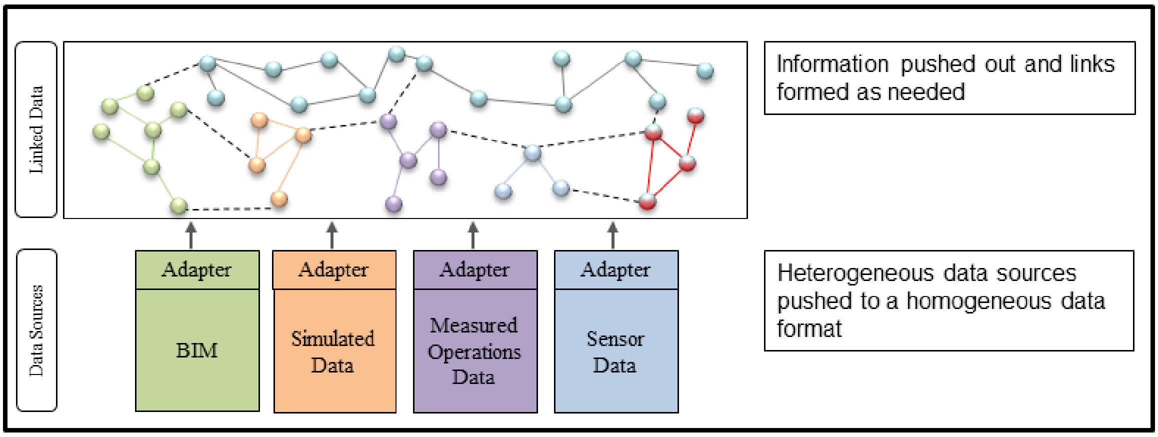


Fig. 5.3 The data transformation process for this implementation takes BIM, simulated, sensor and measured data and transforms elements of it into RDF.

5.2.1 IFCtoRDF conversion

A sample building information model was constructed of the room to illustrate the geometric properties of the space. The model contained one zone and was created using the ArchiCAD tool. An IFC data model is written using an EXPRESS schema, in this case (IFC2x3). The IFCtoRDF conversion uses an OWL ontology which maps each IFC entity to an element in the OWL ontology.

The model was converted to RDF using the IFCtoRDF converter (Section A.0.1). List B.4 illustrates the sample BIM model, retained in IFC, prior to conversion. List B.5 is an RDF representation of the BIM following conversion. The outputted graph can then be uploaded to a triple-store type application such as the Virtuoso server (Openlink Software, 2014), and SPARQL queries can be run against the data-set.

5.2.2 Semantic description of sensor devices in RDF

The SSN, described in Section A.0.4, is used to describe sensors semantically. In this experiment, the room has a number of sensors, including two temperature sensors and a humidity sensor, which provide the BMS with data. The experiment also included a number of other sensors to measure air velocity, surface temperature and radiant temperature. The data output from each of these sensors was captured in various mediums, including spreadsheets and flat-files. The semantic web is an excellent resource when dealing with objects and relationships between objects. It is less useful when dealing with data sets and existing technology is perfectly adequate to accommodate such data. What is necessary is to illustrate how the sensor data can interact with sensor definitions.

Month	Outside Dry-Bulb Temperature	Air Temperature	Mean Radiant Temperature	Operative Temperature	Relative Humidity	Predicted Mean Vote
	°C	°C	°C	°C	%	
January	7.84	22.884	24.357	23.620	37.845	0.965
February	7.98	22.927	24.432	23.680	38.760	0.979
March	9.53	23.502	25.842	24.672	36.779	1.109
April	7.86	23.409	26.015	24.712	32.447	0.925
May	11.42	23.875	26.547	25.211	38.961	1.036
June	12.40	23.993	26.780	25.386	41.074	1.076
July	14.52	24.130	26.766	25.448	46.165	1.115
August	14.08	24.052	26.691	25.372	44.782	1.094
September	13.91	23.953	26.384	25.168	47.393	1.075
October	12.06	23.588	25.447	24.518	45.958	1.136
November	10.63	23.470	25.398	24.434	42.051	1.104

Table 5.1 Simulated thermal comfort data for G146.

For the purposes of this experiment, sensors were defined using the SSN approach and in the case of a temperature sensor, this is described (in part) by list B.6.

This RDF description provides information concerning the static information about the sensor, including location, what the sensor measures, unit of measurement and so on. It is important to differentiate between this type of static sensor information and the actual sensor output. We wish to perform various types of mathematical operations of such data and while a range of tools are available to covert, say, CSV data to RDF, the performance platform described in the next section is designed to integrate semantic data with various data-streams. Essentially, the tool enables the user to select sensors based on the building object in question. For example, if a zone is selected as a building object, then a list of available sensors in that space should be returned also, together with a breakdown of the static sensor information. A link can then be made to the specific output stream of the relevant sensor.

5.2.3 Simulation Data

A simulated PMV result was also generated for the space, based on previous work by Coakley et al. (2012). For the purposes of this exercise, we are interested in the PMV outcome from the simulation exercise and the results are provided in the Table 5.1. Based on various input parameters to the model, a PMV for the space was determined at around 1, indicating a slightly warm space.

Typically, building energy simulations are not carried out on many buildings for a many reasons, particularly cost. Section A.0.3 describes the SimModeltoRDF conversion service and details some of the challenges restricting the broader acceptance of simulation modelling in the AEC industry. Unfortunately, even when a simulation exercise is carried out on a building, the data are often removed from the operative decision making process as time goes on. Simulation output is critically important to the effective management of a building and providing a Building Manager with predicted and actual performance data will lead to better outcomes.

5.2.4 Measured Data

This implementation is concerned with some of the data gathered as part of a broader experiment into thermal comfort. The measurement data for the study came from a combination of thermal comfort metering equipment, hand-held temperature/relative humidity meters and BMS data. In order to account for room temperature gradient and air temperature, t_a readings were taken locally at each work station, using a hand-held thermometer. Radiant temperature, t_r was recorded at a single location, using a QuestTemp 36 Thermal Comfort Meter. As per the CIBSE guide (Race et al., 2006), an operative temperature was calculated by:

$$t_o = \frac{t_a + t_r}{2} \tag{5.1}$$

An operative temperature of around 24 °C was derived for the space, a relatively high figure compared to other rooms in the building, reflecting the preponderance of electrical equipment in the space. Relative Humidity (RH) was recorded using the QuestTemp 36 Thermal Comfort Meter, with an average value of 31.78%, indicating a slightly dry, uncomfortable space, relative to recommended figures of 40 and 70% for occupied spaces (Race et al., 2006).

Air velocity V_a readings were taken at a central point, using the thermal comfort meter with a value of 0.229 m/s ± 0.096%, indicating air velocity would have a negligible impact on thermal comfort in the space. Clothing and is an important parameter in the calculation of the PMV and is measured in units of clo (1 clo = 0.155 m^2 °C/W). Values for typical clothing arrangements are provided by ASHRAE (2004b). Participants in the study calculated the required *clo* values to reflect the clothes they were wearing and submitted the result online.

An average clothing insulation of 0.86 ± 0.26, with a negligible difference between male and female. The clothing surface temperature for each participant was also calculated, using an FLIR thermal imaging camera, with a relatively high correlation between measured and

Fig. 5.4 Thermal image of participating student, taken with an FLIR thermal imaging camera.

Var	Air Temp t_{air}	Mean Rad Temp t_{rad}	Op Temp t_{op}	Rel Hum RH	Air Vel v_a	Act Level	Clo Value	Clo Temp t_{clo}	TCL	Comf Vote CV	PMV	PPD
°C	°C	°C	%	m/s	met	clo	°C	°C				%
Mean	24.18	24.14	24.16	31.76	0.23	1.10	0.86	29.06	28.20	0.8	-0.2	14
Min	18.00	22.40	21.00	21.90	0.00	0.80	0.31	23.40	24.73	-2.0	-2.8	5
Med	24.00	23.70	23.80	32.00	0.20	1.00	0.82	29.00	28.14	1.0	-0.2	9
Max	30.00	33.30	28.65	55.00	0.60	2.40	2.00	37.00	31.05	3.0	1.6	98
Std. Dev.	1.36	1.50	1.10	5.04	0.1	0.16	0.26	2.00	0.99	0.9	0.6	15

Table 5.2 Summary of measured and surveyed values for New Engineering Building Computer lab.

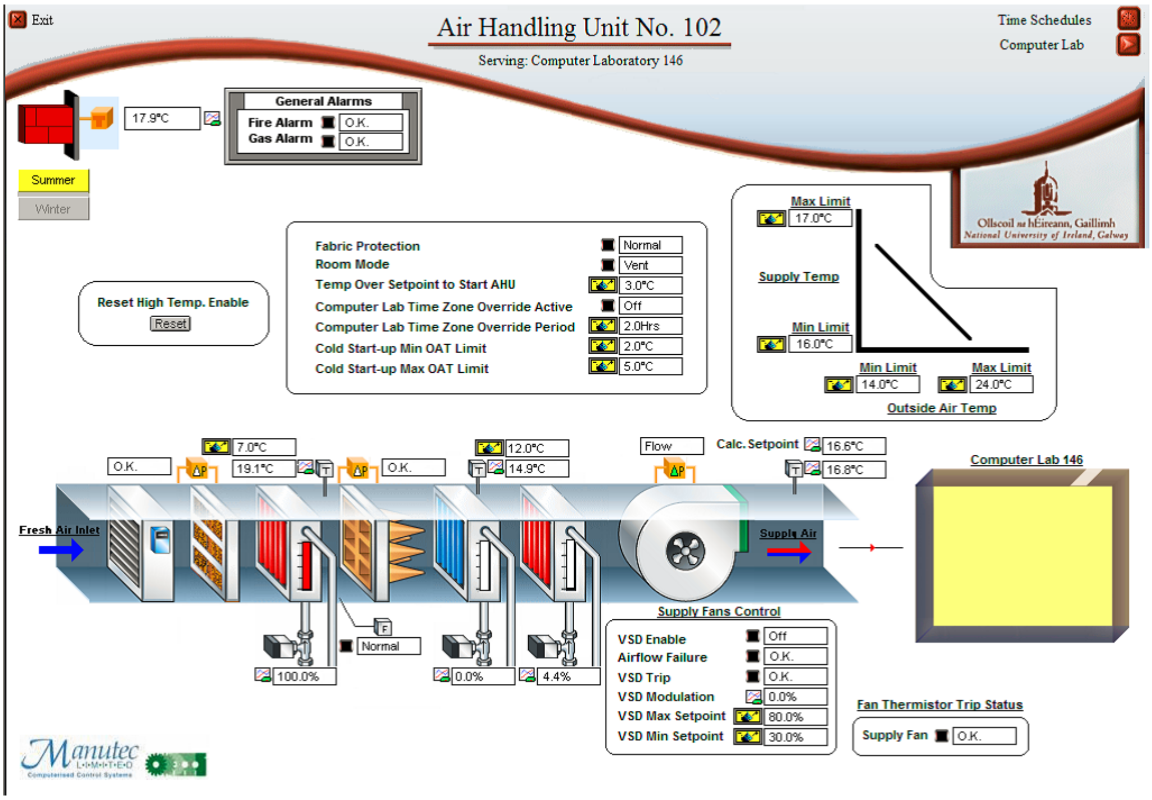
calculated clo values (Figure 5.4). Participants used standardised tables provided to assess their metabolic rate (ASHRAE, 2004b), with an average recorded metabolic rate of 1.1, which tallied with a sedentary, seated office activity. In the context of students who move between lecture halls throughout the day, this assumption may be invalid.

Table 5.2 provides a tabular description of the measured data gathered during the experiment. We use this raw data, in conjunction with the other raw data sources described in this section, in a cross-domain manner to drive a performance management tool-set.

5.2.5 System Data

The computer suite is served by an AHU, described by Figure 5.5. The software depicted in the image provides the main feedback on space performance to the building manager.

Usually, a Building Manager relies on this type of information, the front-end application



Air Handling Unit No. 102

Serving: Computer Laboratory 146

General Alarms

Fire Alarm	O.K.
Gas Alarm	O.K.

Fabric Protection	Normal
Room Mode	Vent
Temp Over Setpoint to Start AHU	3.0°C
Computer Lab Time Zone Override Active	Off
Computer Lab Time Zone Override Period	2.0Hrs
Cold Start-up Min OAT Limit	2.0°C
Cold Start-up Max OAT Limit	5.0°C

Supply Fans Control

VSD Enable	Off
Airflow Failure	O.K.
VSD Trip	O.K.
VSD Modulation	0.0%
VSD Max Setpoint	80.0%
VSD Min Setpoint	30.0%

Fan Thermistor Trip Status

Supply Fan	O.K.

Fig. 5.5 BMS representation of AHU servicing the G146 computer suite.

of the BMS. The system is operated on a control logic based on a series of set-points. The type of data available for the AHU, is described in Table 5.3.

For example, the amount of heat added to the incoming air depends on the outside air temperature, as evidenced by the temperature compensator graph on the top right hand side of the image. Other set-points are in use also. If the room temperature the AHU services is three degrees above the set-point, the AHU is brought into use to provide cool air. The system is reactive in that it reacts to a certain control being triggered and supplies cold and warm air depending on the control. In the case of the computer suite, the BMS is operating effectively and as designed.

For the day in question, there was a rise in the temperature of the incoming air as it passed through the AHU. The supply air, on the date of the experiment, was around 11-12 °C. As it passed through the frost coil, it was heated by about four degrees. The AHU is operating as designed, although the room was considered warm.

It was not apparent to the Building Manager, based on this screen, that the computer suite was being slightly over-heated, with a consequent loss in thermal comfort and energy. When viewed in conjunction with other data though, it became clear that the room was receiving

Table 5.3 Some of the data points associated with the Air Handling Unit serving the computer suite

Data point
Calculated Supply Set-point
Main Chilled Water Valve Position
Supply Fan Airflow
Main Hot Water Valve Position
Temperature following Frost Coil
Supply Duct Temperature
Computer Laboratory Temperature
Frost Coil Heating Valve Position
Computer Laboratory CO_2

too much heat, with a consequent energy and comfort loss. This is illustrated more clearly when a scenario is created for thermal comfort in the space.

5.2.6 Using homogeneous data sets as a service

This stage of the implementation builds on the cross-domain performance data specified in the previous sections, using a structured performance management toolkit. Figure 5.6 is a sub-section of the key data transformation image used throughout this thesis and illustrates the place of this section in that context.

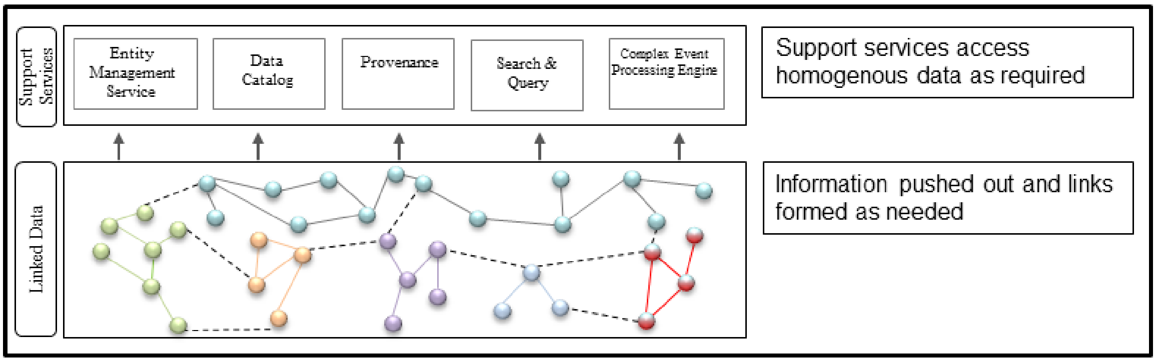


Fig. 5.6 Data as a service. Semantically described data can now be used to drive higher level services and links can be made as needed between the various data sources provided in the previous section.

A key point to note here is that these data sets are not linked when initially converted and links are only created as needed, depending on the requests from the application software at the higher level. The type of activity which might be carried out on the data include entity management, data cataloguing, provenance checking, search and query of the mixed data sets and complex event processing, involving the use of reasoners. These support services provide data on demand to the top level applications.

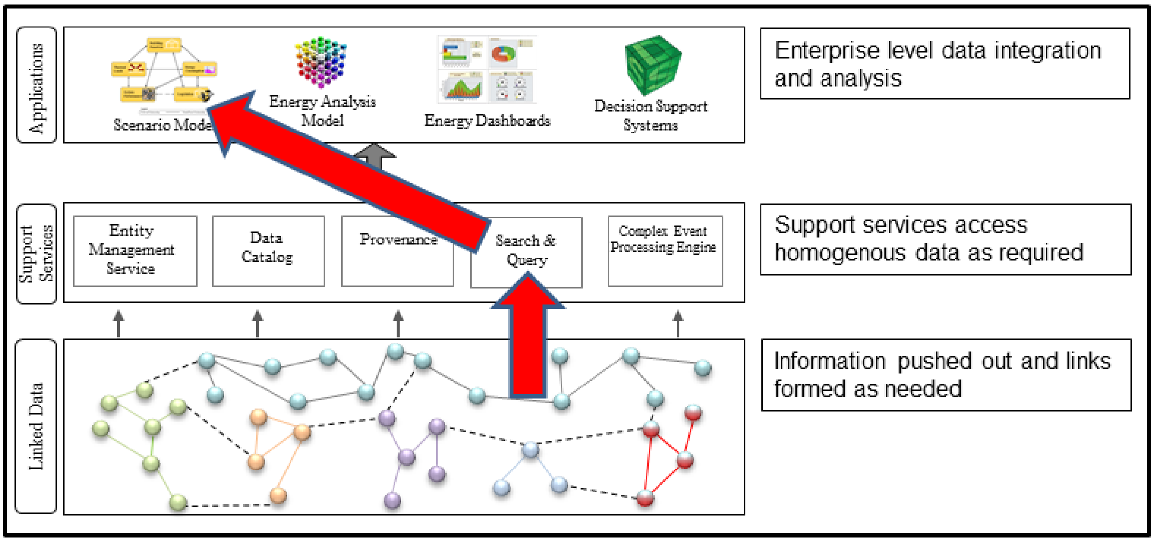


Fig. 5.7 Data as a service. Semantically described data can now be used to drive higher level services and links can be made as needed between the various data sources provided in the previous section.

Figure 5.7 illustrates the path now taken in this experiment from the homogenous, disjoint data sources, through to the scenario modelling application, using a search and query approach to transform the underlying data.

5.2.7 Performance Framework Platform

The PFP is intended to provide a basis for the development and assessment of building performance throughout the BLC. Using this approach, key building stakeholders can determine how a building is performing in real time and how the performance compares with design intent. By creating an ontology that represents this performance framework in RDF, it is feasible to create and publish scenario models representing specific building performance objectives in RDF. These scenarios can then be related to other published data in RDF. An application has been implemented which accesses AEC building information in RDF format and creates a performance framework linked to this information.

The PFP tool uses the RDF based building model described in Section 5.2.1 as a basis for a performance assessment exercise. The tool navigates through the data, extracting key building objects and creates a hierarchy, allowing the user to visually navigate through the key building elements. This is the first stage of the scenario modelling process, whereby the user is able to access specific building objects and link them directly to specific objectives. The building used for this demonstration was a three storey building, representing a bank, with a banking hall and associated offices, maintenance and public space. The type of building objects available in the tool currently include:

- Building Level
- Building Storey Level
- Room Level
- Zone Level
- System Level

Each object on this list has a series of objectives to which the object may be linked.

The PF tool extracts information relating to each of these and displays it for the user to select. Once a model of the building is available in the program, the user is then free to create a performance measurement framework composed of specific objectives for key building objects. A list of possible objectives has been created and is uploaded to the program. This list can be amended as more objectives are required. The list also contains specific metrics associated with each objective and an algorithm describing how the metric is to be evaluated, measurement units, etc. Finally, the list details the specific type of data source required to carry out the evaluation.

Once the RDF building model has been imported to the application, the user has the option to create a scenario model, in line with the scenario modelling concept described in Section 4.2.3. Upon naming the scenario, the user is presented with a screen which lists the available performance aspects, described in Section 4.2.3. At this point, the user can select a specific building object and an aspect to relate. The user is then presented with a list of objectives depending on the chosen object type. The user is able to choose from a specific list of objectives which are pre-defined (Figure 5.8).

Having selected the appropriate objective, the user is then presented with the metric associated with the predefined object previously chosen. This metric retains an algorithm or aggregation function, based on the nature of the metric and the user can assign parameters for these functions. Possible data sets, based on those appropriate to the object chosen are presented at this stage also. The scenario can then be saved in RDF format and evaluated or modified throughout the life-cycle of the building (List B.7). The scenario represents a measurable and repeatable assessment of building performance and is stored in a format which will allow greater integration with other data domains.

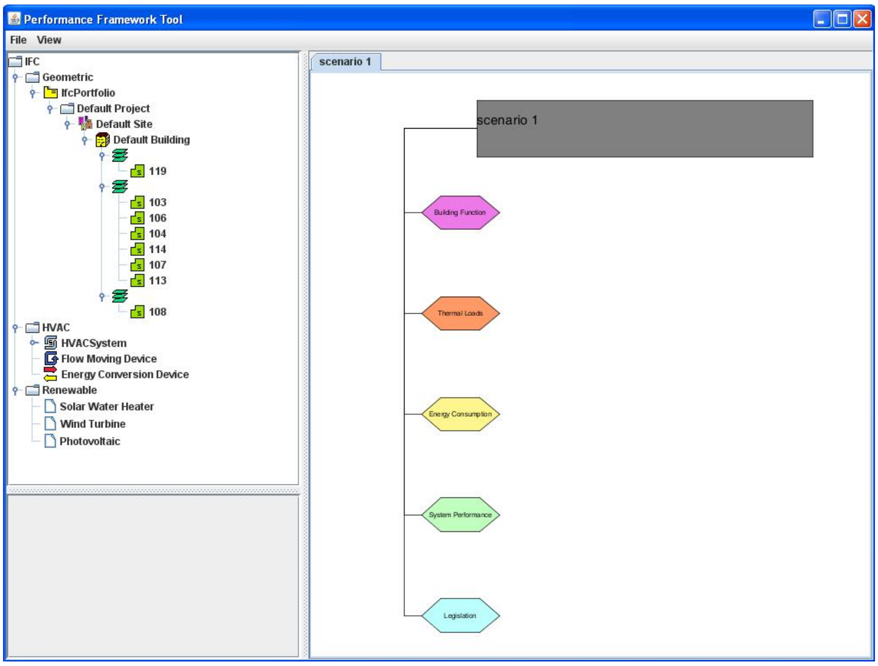


Fig. 5.8 Main screen of the performance framework platform. The building objects are displayed in the top left hand frame, while a scenario is presented in the frame on the right. This frame includes performance aspects but no objectives have been created yet.

In this example (List B.7) we see that the Performance Objective *ZoneTemp* is explicitly linked to the building object with the specific Globally Unique Identifier (GUID). Similarly, the Objective has an associated organisation, creating actor and creation time and is related to the Performance Metric Zone Temperature. We can extend the relationship to link the assessment framework to other data sources. So, theoretically, the building object manufacturer might publish data about a specific object. Using the semantic web approach, we can access this data and link it easily to other non AEC data.

5.3 Results

For this experiment, a scenario model has been created to reflect some key concerns in the area of thermal comfort in a space. The scenario model contains a number of objectives which are crucial to understanding the status of the space currently and historically. The scenario model, described in Figure 5.9, refers to two separate performance aspects, *Building Function* and *System Performance*. All objectives are associated with G146 zone, which encompasses the entire computer suite. Three objectives are used to describe three specific aspects of performance in the space.

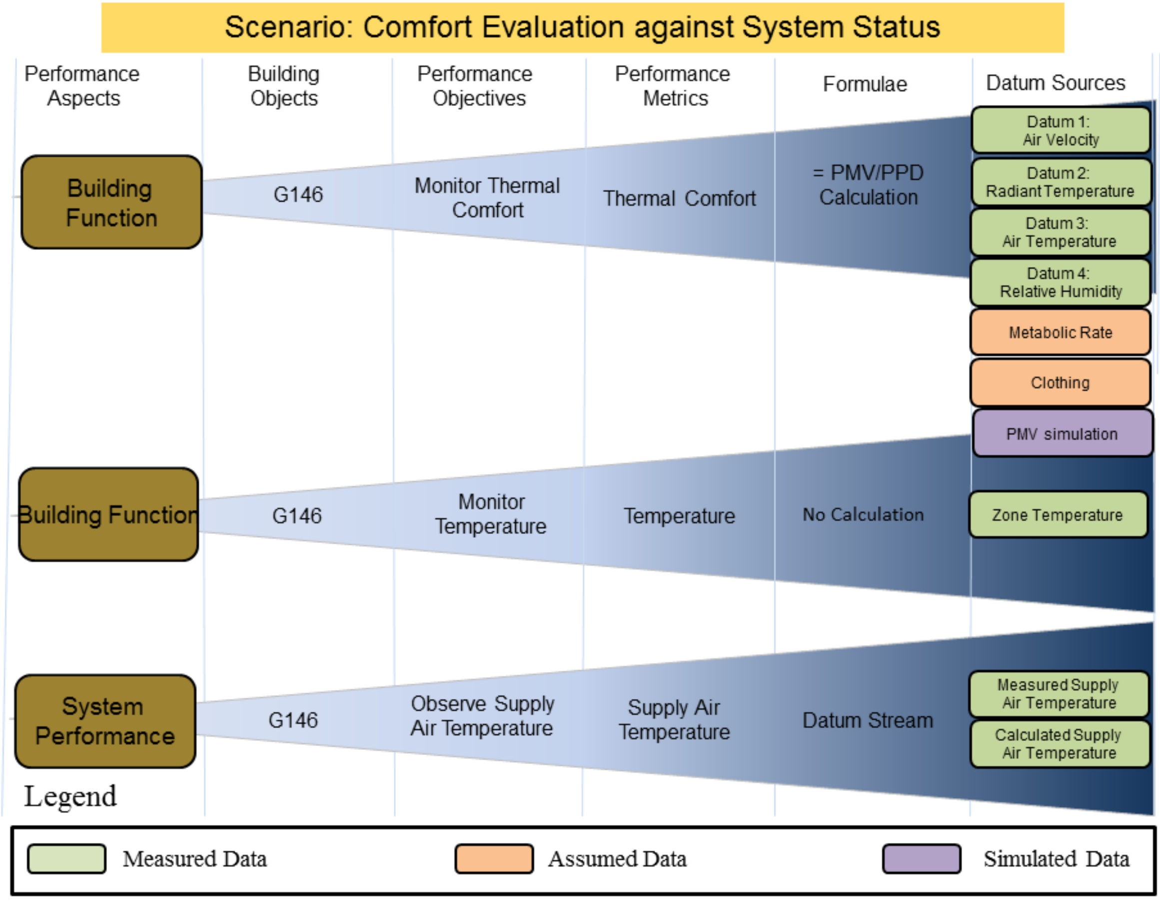


Fig. 5.9 Scenario model, created from combination of two performance objectives. The scenario can be used to compare the thermal comfort levels in the space against the system status in the zone.

First, the thermal comfort objective is used to describe thermal comfort in the space and is quantified using the associated thermal comfort metric, which returns a PMV value. The metric applies the stored calculation formula to return this value. The metric also must be associated with the relevant data sets and in this case, these are provided from the measured data identified in Section 5.2.4. This object is associated with the *Building Function* performance aspect as thermal comfort is considered a key building function. This objective links to two separate types of data, measured and manually assessed or that entered by users.

The thermal comfort objective is also measured against simulated thermal comfort data. The data are taken from a simulated data source and this approach clearly allows the integration of design and performance outcomes in a single performance management system.

A similar process is followed for the second objective, detailing temperature conditions within the space. The objective is measured by a functional metric which simply returns the temperature value for the space current at that time. The objective is associated with the *Building Function* performance aspect as temperature is a reflection of the function of a building. The data used to populate this metric are measured data from the BMS.

The third object relates to system performance and reflects the performance of the air handling system supplying the zone. The three objectives, taken together, constitute a scenario model for the zone. When the model is evaluated, a clear picture emerges of the thermal conditions in the space and how they relate to design intent. Figure 5.10 illustrates how the thermal comfort objective is described using the software.

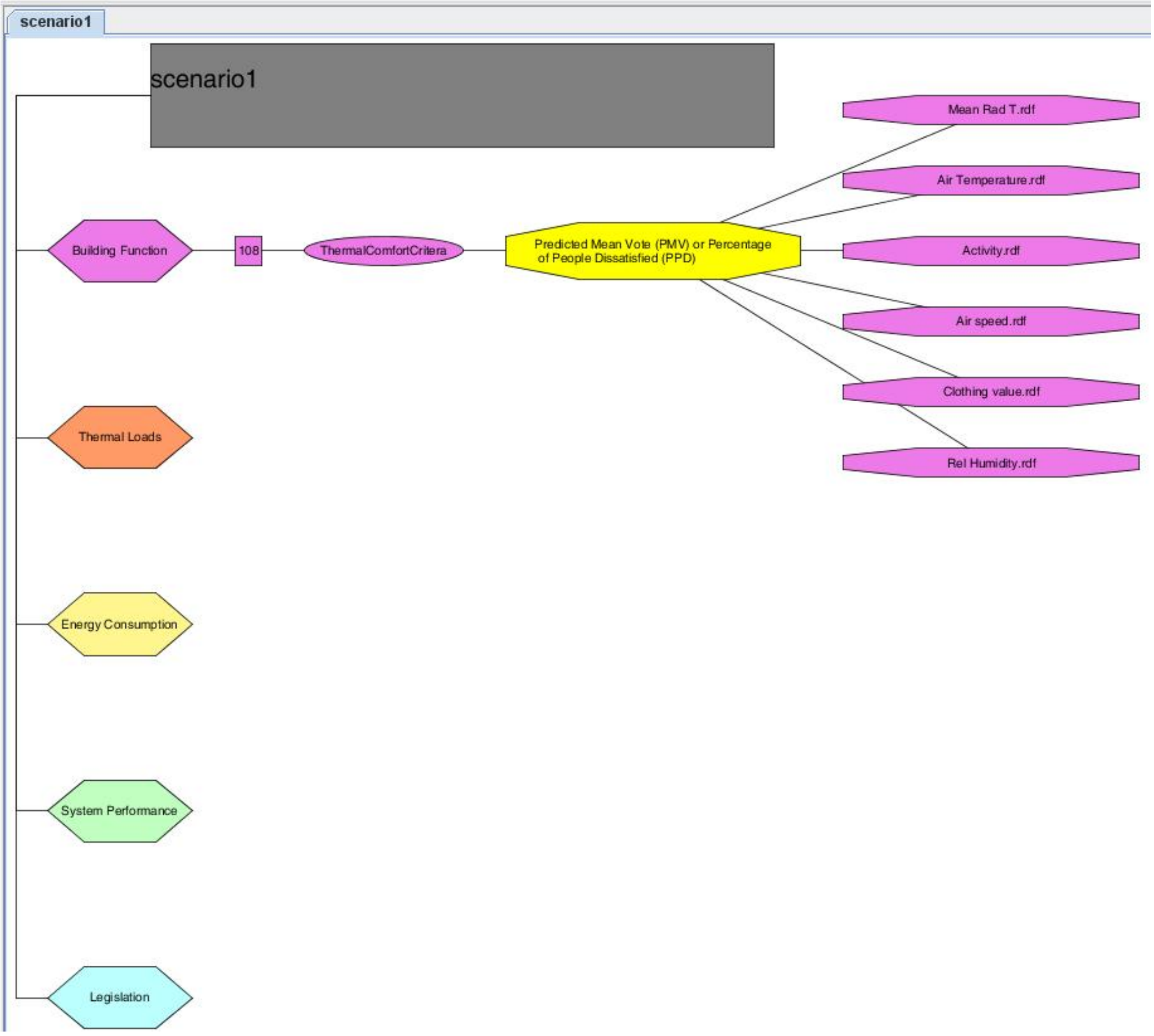


Fig. 5.10 Thermal comfort scenario model as described using the performance framework platform.

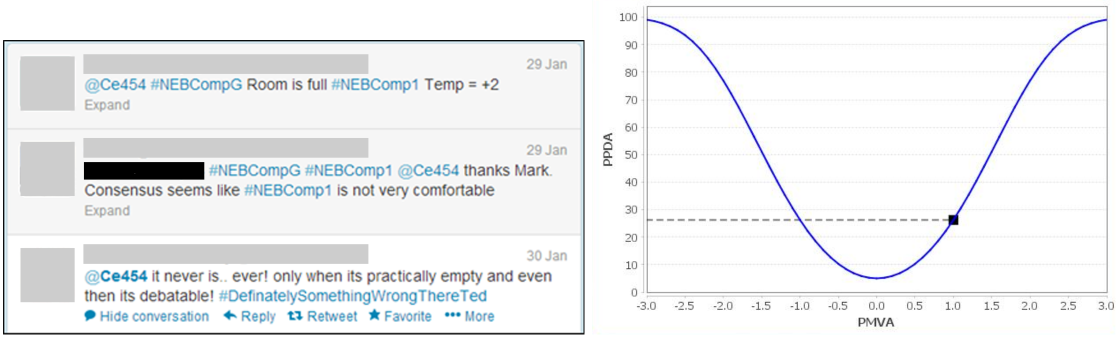
The thesis research questions mentioned the use of data linking technologies to describe performance management. The scenario model described can also be saved in RDF, based on the performance framework ontology described in ChapterSemantic Web Technologies and a structured performance system (List B.8). Being able to retain this type of information in RDF allows the user to return to the scenario over time and evaluate it against particular data sets of interest. In this way, the scenario can be considered as a type of stored procedure, which can be evaluated repeatedly over time.

The approach described creates a far more powerful communication to the Building Manager, allowing him to visualise a number of different aspects of performance, measured by different systems, at the same time.

At this point, we have three distinct sources of data that we would like to consider in some way to better inform us about performance in the space. A building manager might be interested in assessing the thermal performance of the space, following occupant complaints. His first port of call will generally be to the BMS to determine if anything is out of range in the space. A brief look at our initial performance objectives suggest the temperature, CO_2 and relative humidity readings for the space are within range.

The PMV readings for the space would inform the manager that the space is somewhat uncomfortable. The measured and simulated PMV values compare favourably, indicating that the thermal comfort levels, while warm, are within design parameters. Capturing these measurements in an overall scenario is the essence of scenario modelling.

Figure 5.11 represents soft data about the room. The PMV calculation describes the thermal comfort level as described by the occupants, and suggests that the thermal conditions in the room are warm. Tweets suggest that the room conditions and conditions throughout the building are warm also. This type of soft information can be used to complement the harder data typically available to the Building Manager.



[redacted] 29 Jan
@Ce454 #NEBCompG Room is full #NEBComp1 Temp = +2
Expand

[redacted] 29 Jan
[redacted] #NEBCompG #NEBComp1 @Ce454 thanks Mark. Consensus seems like #NEBComp1 is not very comfortable
Expand

[redacted] 30 Jan
@Ce454 it never is.. ever! only when its practically empty and even then its debatable! #DefinatelySomethingWrongThereTed

Fig. 5.11 (a) Twitter feedback (b) Measured PMV

The Building Manager typically relies on the BMS to ascertain the performance levels of a building, and would base his or her opinion on images such as those in Figure 5.12. These images suggest that the room is operating as intended and they do not indicate a problem in the space. It is only when these traditional images, derived hard data sources, are supplemented by information derived from soft data sources, that a holistic interpretation of performance is possible.

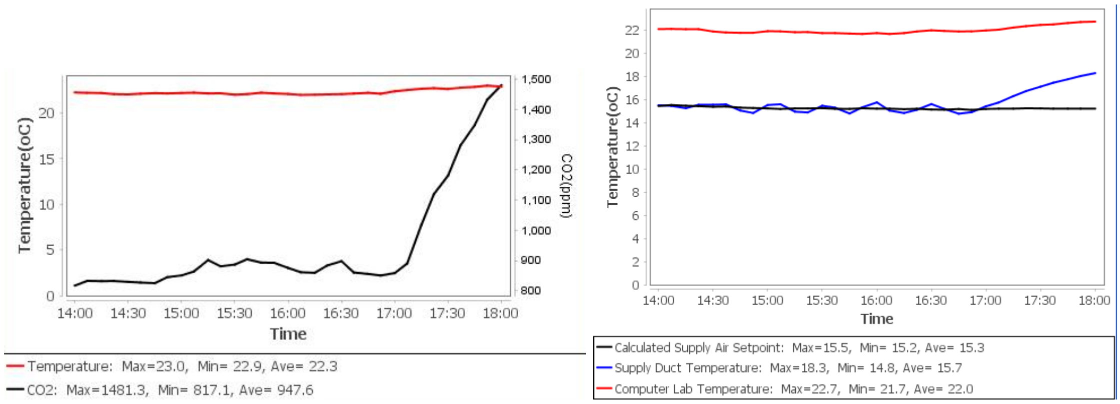


Fig. 5.12 (a) Measured Room Temperature (b) AHU system performance including room temperature, calculated and supply duct temperatures

When viewed in conjunction with each other, Figure 5.11 and Figure 5.12 suggest that the room is too warm, and that the supply air temperature (Figure 5.12) is too high. A closer look at the temperature objective and the AHU objective are the first suggest that perhaps the space is not conditioned correctly. The temperature of the space hovers around 22-23 °C, while the supplied air is around 16 °C. We can see from the thermal comfort reading that the space is somewhat warm. It would suggest that the AHU control needs to be modified somewhat to reduce the temperature of supplied air to the space. A further point to note is the spike in the supply duct temperature at 5 pm as the AHU is turned off. A spike is also seen on the measured CO_2 level for the space. This type of scenario analysis is at the core of the performance framework approach and provides the building manager with contextualised information, based on several data sources.

The key point illustrated here is not the condition or otherwise of the space, but that a performance analysis has been conducted on the room, utilising data from a number of sources, in a structured and repeatable manner. As described in Chapter 1 of this thesis, simulation outcomes are generally not retained in a usable, electronic format and over time, as performance deviates from design intent, there is often no easily accessible record to identify ideal performance from. By the same token, without a clear frame of reference in terms of an objective for a space, a building manager is reliant on experience and institutional knowledge to identify and resolve issues.

5.4 Conclusion

This research suggests that there is significant value to the complimentary use of soft information sources together with the more traditional hard data sources. Furthermore, due to the increasingly large volumes of data available in modern buildings, a structured performance assessment approach must be provided to navigate through this data.

This demonstration illustrates how building performance data can be exposed in a homogeneous manner, allowing a greater element of cross-domain data sharing and interpretation. The experiment uses various thermal comfort data as a basis for a scenario modelling exercise. Using the performance framework platform, a scenario model was created and published in RDF. Explicit links were made to appropriate data sources, allowing the interpretation of various performance objectives.

The key illustration of the effectiveness of the technique was provided when a series of objectives describing various aspects of performance in the space were combined into a scenario model, allowing the user to interpret several sources of data in a structured and measured fashion. The chapter opened with the hypothesis that linked data sources could be used to drive cross-domain data efforts. It is clear that such efforts are indeed possible in this area. These observations are now expanded on in the conclusion to this work in the following and final chapter.

A key finding from this research is the role soft data sources can play in *complementing* the more traditional data sources available to the building manager. When used in conjunction with a structured performance assessment framework, a more holistic interpretation of building performance is possible. It is important to consider the value to place on feedback derived from softer data sources. In most cases, it is suggested that such data can serve as a pointer to deeper, underlying issues and may prompt the building manager to look at BMS type more closely. What is clear is that providing building information in a homogeneous data format opens up significant possibilities in terms of building performance.

Chapter 6

Conclusion

The key observation at the beginning of this work is of an industry producing buildings which rarely live up to their design billing in terms of performance. The initial premise of this thesis was that buildings do not operate as intended, with a significant performance gap between predicted and actual performance levels experienced.

In Chapter 2, the performance gap was explored during a thorough literature review and two key causes were identified; the lack of data and application interoperability in the industry and a lack of cross life-cycle, holistic performance assessment. It was illustrated how the performance gap problem is most pronounced during the operation phase of the life-cycle. An exploration was made of the interoperability challenge faced in the AEC industry and an account of the efforts made to combat this challenge was included. A second, complementary focus of the literature review concerned performance management in buildings. Perhaps the key observation from this stage of the work is that buildings are a considerable distance behind other complex manufactured products in terms of performance management.

Based on the literature review conclusions, it became obvious that a dual approach to the performance gap problem was required. First, the issue had to be considered from a data perspective, with a focus on the provision of usable AEC data in an accessible manner. Building data tends to be retained in silos associated with the particular domain in which it was created. The data are often in a data format which is application-specific and inaccessible. It is difficult to manage performance in the absence of data. The second approach concerned the issue of performance management itself. There is a pressing need for a cross life-cycle performance assessment and management approach, which can provide a holistic interpretation of the environmental and energy status of a building.

Figure 6.1 emerged as the key concept diagram of the thesis and describes the three key stages of the work. The first stage describes the situation in the industry currently, where

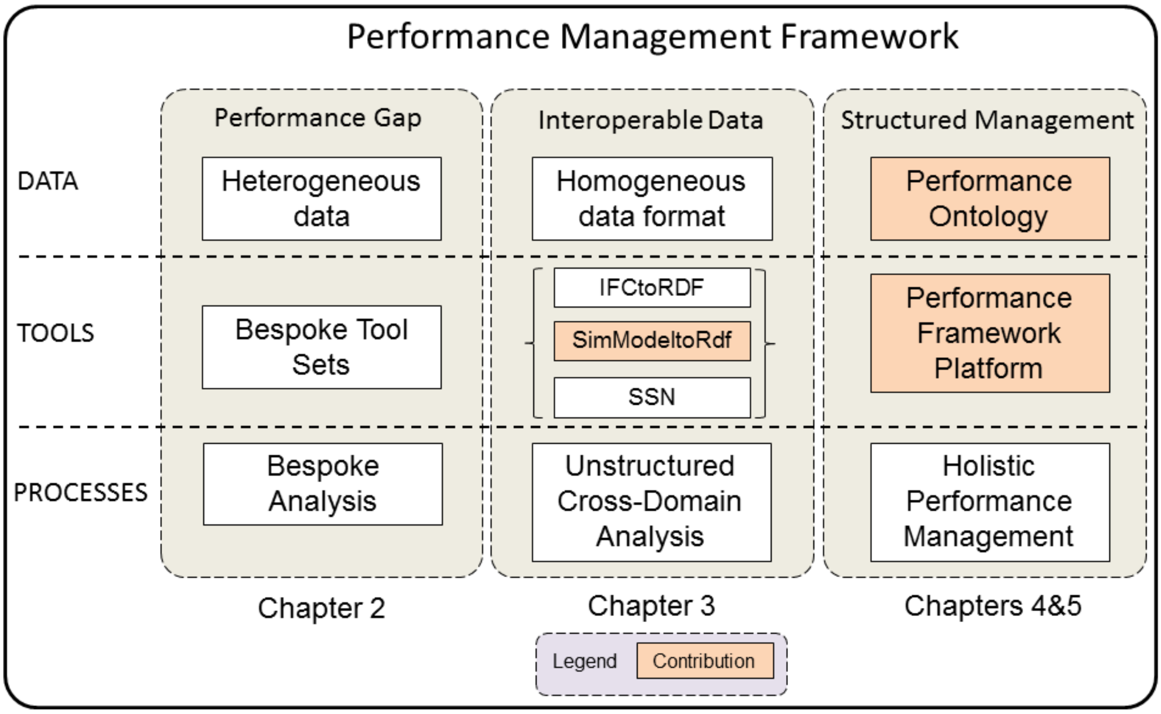


Fig. 6.1 Thesis concept diagram, illustrating the disjointed nature of the current performance management process.

a performance gap is prevalent and there is a distinct lack of a comprehensive building performance assessment and management framework. The literature review identified the heterogeneity of the data as a barrier to integration. It also suggested that the structured, data-model dependent building information modelling approach was somewhat unwieldy when dealing with new data domains outside its core competencies.

The second stage of the work involved the transformation of building data into a more homogeneous data format. The data format chosen was RDF, a semantic data model, where meaning in data is conveyed as part of the data structure, the RDF triple. This work involved the used of a series of adapters, one of which was developed as part of this research, to convert AEC data from native formats to RDF. When different data sources are available in a homogeneous data format, cross-domain analysis becomes possible.

The first research question asked whether there was a value to the extraction of data from its original silo and and interpreting it in a broader context, together with other diverse data sources in the building. This cross-domain analysis of data suggests that data from an entirely different area to building control for instance, might be interpreted alongside control data, providing hitherto unavailable information. This approach was expanded upon in Chapter 3. A detailed implementation of the concept was provided and it was illustrated how traditional building information sources could be supplemented by newer sources of information from other domains. Chapter 3 concluded that there was value in the use of cross-domain data in a performance management context, but in the absence of a structured analysis methodology, the data was difficult to navigate.

The second research question asked whether linking data technologies could be used to integrate cross-domain data in the context of building performance. Could a structured performance assessment approach be used to improve performance management in buildings, using data linking technologies to overcome interoperability issues? Chapter 4 presents an approach to performance management which builds on semantic web data and which provides a means to manage performance across the life-cycle. The approach built on the scenario modelling concept, of a series of performance objectives being used to quantitatively assess building performance in a granular manner. A performance ontology was introduced, which described a performance management framework, interlinked with other AEC data domains. This approach provided a clear means to navigate through homogeneous data sets in a structured manner.

Chapter 5 provides an in-depth implementation of this performance management approach. The implementation involved the presentation of cross domain data in a structured manner to a key building stakeholder, the building manager, in a way that enhanced his understanding of the building. A space that was considered too warm by occupants was examined from a number of different perspectives and the data used to drive a number of performance objectives, combined into a scenario model, based on the performance ontology. The outcome was a series of quantifiable metrics evaluated against measured and simulated data, providing the manager with a more holistic assessment of performance in the space.

These contributions address the two inter-linked concerns evident in the building community at present, around the areas of interoperability and performance assessment. This work clearly illustrates how a holistic, cross life-cycle performance management framework can be described and driven by the use of semantic web technologies. The relevance of the interoperability challenge to improved performance is difficult to over-state and this approach overcomes some of the key restrictions encountered by other solutions proposed in this area.

Publishing data semantically in the cloud exposes the information at a data level, rather than encapsulating it in a more rigid, formal schema and allows the data to be interacted with, in a more dynamic fashion. Furthermore, retaining the information using a cloud based approach overcomes many of the access limitations found currently in the industry. BIM is an enormously important approach in the AEC domain and clear, verifiable productivity gains are apparent on projects which utilise BIM effectively. BIM has a large role to play retaining static building information, geometry, material properties and so forth. As the range of data available in the industry broadens, and the need to interact with non-AEC domain data grows, it is becoming clearer that a BIM needs to be thought of as another silo of data in a world where the range of data silos is broadening all the time. Greater benefit can then be made from this BIM when it is combined with other data sources in a cross-domain manner.

The semantic web approach to data interoperability is certainly a very relevant solution, particularly when dealing with AEC data not encompassed by the BIM movement. The concept of sharing data at the object level, divorced from applications, allowing the use of data as a service, is compelling. The conversion process required to convert from heterogeneous data formats to a homogeneous data format still requires considerable effort and while the possibilities available to tool designers with homogeneous data sets are considerable, it is difficult to see the AEC industry widely adopting such an approach without a more straightforward conversion process. In a world where data are expanding at a truly exponential rate and the level of inter-connection between digital devices is all encompassing, the question must be asked, can the AEC industry ignore the advances made in other industries? Perhaps the key advantage semantic web technologies hold over BIM based solutions is in the use of reasoners. Reasoners can be used to navigate through RDF graphs based on specified rule sets. As more AEC data becomes available, the opportunity to use reasoning engines grows also.

Big Data, the Internet of Things and Machine to Machine communication were briefly discussed at the start of this thesis. These ideas are set to dominate into the future as more and more devices have internet capabilities and the volume of digital data increases exponentially. New approaches to data management and use are necessary as the volume of data available threatens to swamp existing systems and methodologies. The AEC industry is in an excellent position to benefit from these new approaches and technologies. Net zero carbon buildings are already a reality, with a key limiter to their greater availability being the interoperability problem. The key ideas proposed in this thesis of homogenous, available data and a structured building performance management approach dovetail neatly with the ideas behind Big Data, IoT and machine to machine communication. These new technologies offer a significant opportunity to drive the environmental and energy management of buildings forward and represent an excellent opportunity for future work.

6.1 Future Work

This research points the way to a cross life-cycle building management solution driven from a semantically enriched open data structure. This approach to building management and data aggregation allows data to be considered in ways not previously possible. This thesis considered the use of cross-domain data from the building manager perspective. Contextualised, cross-domain data was delivered in an accessible and usable format.

In future, the needs of other key stakeholders must be considered. Effective buildings are buildings where occupants are content. A facility to bring the occupant further into the management of building performance needs to be considered. Similarly, the future will see more machine to machine communication, where machines communicate status updates to each other. Wireless sensors, integrated with smart metering technology can allow predictive maintenance rather than preventative maintenance. Sensors embedded in utility grids can point to leaks and outages when coupled with intelligent rule systems. Further work in this area would involve a type of predictive maintenance approach toward facility management.

As data becomes more freely available and sensor networks expand, the performance management approach can be scaled up to include clusters of buildings. A strong case can be made for a web of buildings, where building performance could be managed at a campus level more effectively. This thesis uses terms such as management to describe the activities possible from semantic data sets. In future, with the use of reasoning engines and rule based parameters, a form of performance optimisation could take place.

Presenting information in an open, non-application dependent format, which can be linked easily at the data level presents the AEC industry with many opportunities to overcome age old difficulties. Merging this type of information with a performance management approach presents owners and building managers with the tool-sets necessary to overcome the significant performance gap in the domain.

This research has identified significant benefits to the assessment of cross-domain building performance data in a structured way. A clear path has been described where the dual issues of interoperability and performance assessment can be addressed using semantic web technologies and it is hoped that these two inter-twined solutions can be implemented in a commercial manner.

Appendix A

AEC data semantic conversion services

The following sections describe, in detail, the conversion services used in Section 4.3.2. Each of these approaches provides the means to convert existing heterogeneous AEC data into homogeneous, semantically described data.

A.0.1 IFCToRDF data service

BIM, as discussed in Section 2.2.9, describe the capture of building information in a computerised data model, usually a parametric 3-D model. IFC forms the open data exchange format supported by the (BuildingSMART, 2011). Support exists from tool vendors for this open data standard and most offer an export function to the allow the presentation of BIM in IFC format.

IFC can also be converted to RDF as has been demonstrated by Pauwels et al. (2012). Using this approach, IFC files can be made available as RDF graphs in the semantic web and then linked with other RDF data. The IFC-to-RDF conversion service is based on an OWL ontology describing the IFC (BuildingSMART, 2011). This ontology serves as an alternative representation of the EXPRESS schema of IFC. The creators of the IFC ontology built on a previous approach for use with EXPRESS schemas (Beetz et al., 2009).

This complex approach maps each element in the EXPRESS file onto its nearest equivalent in OWL, producing a reasonably sound ontology. The method follows three distinct steps (Pauwels et al., 2012).

1. For the generation of classes and properties for each ENTITY definition in the EXPRESS schema, a corresponding owl:Class is generated with the appropriate properties. EXPRESS attributes are converted into the corresponding OWL properties (owl:DatatypeProperties and owl:ObjectProperties).

2. Appropriate basic restrictions are generated and added to the ontology. Using the rdfs:subClassOf construct, a hierarchical ontology structure is created for super-type and subtype relations in EXPRESS. Currently, ABSTRACT SUPERTYPE constructs in EXPRESS are represented by the appropriate combination of rdfs:subClassOf and owl:disjoint constructs in OWL. Also, the rdfs:range and rdfs:domain constructs are completed for the generated properties. Simple owl:DatatypeProperties are completed with the corresponding XML schema data type in their ranges. Properties that represent SELECT types in the EXPRESS schema are completed with an owl:unionOf construct in their range.

3. The generation of advanced restrictions for classes and properties is the last step in the conversion process and is yet to be implemented in the conversion service. This step represents the more advanced features of the EXPRESS schema including cardinality restrictions and value restrictions for properties. Also the OPTIONAL, UNIQUE and DERIVE keywords are currently not included in the OWL ontology and could be considered as advanced restrictions for classes and properties.

Although the ontology is not fully complete, it can be used to generate RDF instances, allowing a file-based conversion service to use exported IFC files and convert them to RDF graphs. The generated RDF class instances are named using the applicable EXPRESS ENTITY name and the line number in the IFC file. For instance, the line in IFC (Pauwels et al., 2012) that is shown in listing A.1 is converted into the RDF concept, shown in listing A.2.

Listing A.1 Schematic outline for the SimFlowMover class

```
#4796 = IFCAXIS2PLACEMENT3D(#3,$,$);
```

Listing A.2 Schematic outline for the SimFlowMover class

```
ifcAxis2Placement3D 4796
```

The conversion process allows the user to upload an IFC file (UGent Multimedialab, 2009) and the resulting RDF triples are made available in file format or can be browsed in an online SPARQL endpoint (UGent Multimedialab., 2009). This ontology and associated tool-set allows the rapid conversion of BIM based models to RDF, providing a basis for further integration with other RDF compliant data sources.

A.0.2 SimModeltoRDF data service

Some buildings undergo a building energy performance simulation at design time and it has been recognised that simulation tools have a significant role to play in the management of building performance during the operation phase of the life-cycle and not just at design time. One of the limitations associated with the BEPS process is the difficulty in interfacing simulation tools with other design tools, resulting in significant rework being required. Simulation tools, such as EnergyPlus and DOE-2, use internal custom schema definitions (IDD and BDL, respectively) as opposed to standardised schema definitions (defined in XSD, EXPRESS, and so forth).

In (Bazjanac et al., 2011), a SimModel was proposed, bringing such models (IFC, gbXML, EnergyPlus, DOE-2) together into one centralised schema. This approach was intended to move towards an industry-validated terminology aligned with the IFC and away from tool-specific, non-standard data models. It remains to be seen whether or not the SimModel ontology will eventually indeed be used in a centralised manner or not. If it is not, it still makes sense to combine SimModel information with other building models available in the AEC project and with data outside the AEC project (e.g. more static references, such as material information and geographic information).

SimModel is primarily used as an internal data model by the Simergy software developed at LBNL (LBNL, 2014; See et al., 2011). The tool was conceived as a platform that facilitates data flow to and from BEPS tools to and from potentially any building modelling tool (Bazjanac et al., 2011). Data flow is possible to and from BIM models in IFC, DOE-2 software or tools that use the DOE-2 engine, EnergyPlus, and tools with gbXML export. These tools are typically used for BEPS. Data from any of these environments can be mapped to and from the SimModel data model using the Simergy software (LBNL, 2014), (Figure A.1)

“Simergy” is a comprehensive Graphical User Interface (GUI) for the US Department of Environment (DOE) building energy simulation program EnergyPlus (LBNL, 2014; O’Donnell et al., 2013; See et al., 2011), providing an intuitive schematic editor for HVAC systems. The tool uses a space-based building model, which can be populated from the sources shown in Figure A.1 (O’Donnell et al., 2013).

The underlying SimModel is an object-oriented data model which defines all object / attribute / relationship sets used for BEPS, and is represented using the XML markup language (O’Donnell et al., 2011). This representation is closely aligned to the IFC data model.

In order to present SimModel information in an accessible format, a conversion ser-

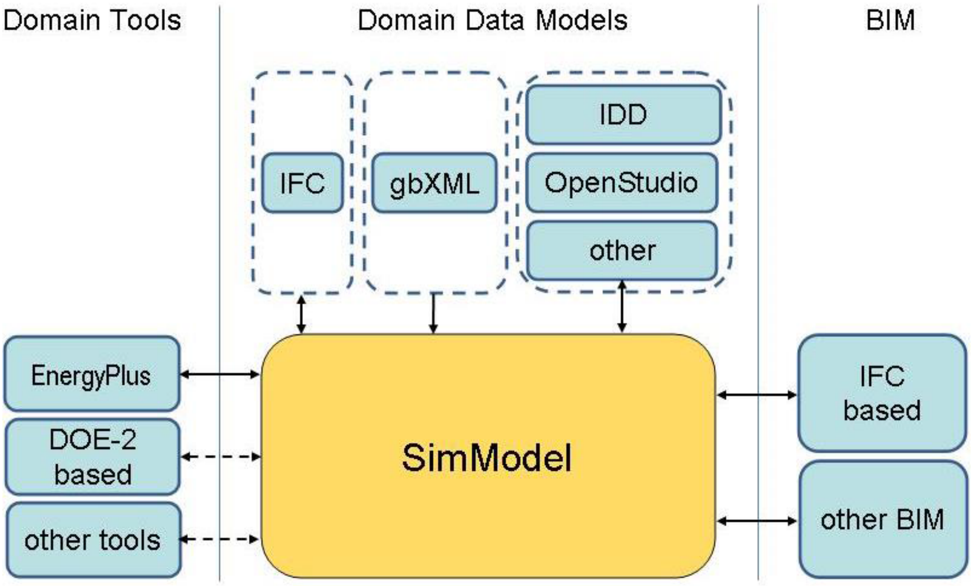


Fig. A.1 The SimModel related to existing building energy performance software and models (Bazjanac et al., 2011).

vice (Pauwels et al., 2014) has been built to parse the SimModel to an OWL based SimModel ontology.

An indication of the SimModel hierarchy and structure was documented before (Bazjanac et al., 2011; O'Donnell et al., 2011). The model has a 'project' node at the top of its hierarchy, which is decomposed by various design alternatives. Each design alternative is then eventually decomposed by a 'building' node, which includes 'building elements', 'zones', 'HVAC systems' and 'other systems'. The nodes 'building elements', 'zones', and 'HVAC systems' hereby map directly to the diverse domain models displayed in figure A.1. The node 'other systems' is included to enable future extensions of the SimModel (e.g. addition of electrical systems).

A.0.3 SimModel To RDF conversion

The conversion process from SimModel into an OWL ontology began with the XML Schema Definition (XSD) files representing the SimModel. The six following XSD files are available, each representing a part of the SimModel data model.

1. SIM core http://www.lbl.gov/namespaces/Sim/SimModelCore simcore.xsd
2. SIM building model http://www.lbl.gov/namespaces/Sim/BuildingModel simbldg.xsd

3. SIM resources general http://www.lbl.gov/namespaces/Sim/ResourcesGeneral simres.xsd
4. SIM resources geometry http://www.lbl.gov/namespaces/Sim/ResourcesGeometry simgeom.xsd
5. SIM MEP model http://www.lbl.gov/namespaces/Sim/MepModel simmep.xsd
6. SIM Model

All six XSD files are tightly linked together with cross-references to each other's classes. SimModel contains a few hundred classes and it is hierarchically structured using classes, types and subtypes (O'Donnell et al., 2011). In the XSD files, this results in a hierarchy of *xs:complexType* elements.

A schematic outline is given below for the *SimFlowMover* class and three of its six subtypes (Default, Fan, Pump, PumpSet, ReturnFan, SupplyFan) in the SIM MEP model of the SimModel.

Listing A.3 Schematic outline for the SimFlowMover class

```
complexType SimFlowMover
  abstract complexType SimFlowMover_Default
complexType SimFlowMover_Default_Default
  abstract complexType SimFlowMover_Fan
complexType SimFlowMover_Fan_NightVentilation
complexType SimFlowMover_Fan_ZoneExhaust
  abstract complexType SimFlowMover_Pump
complexType SimFlowMover_Pump_ConstantSpeedReturn
complexType SimFlowMover_Pump_ConstantSpeedSupply
complexType SimFlowMover_Pump_UserDefined
complexType SimFlowMover_Pump_VariableSpeedReturn
complexType SimFlowMover_Pump_VariableSpeedSupply
complexType SimFlowMover_Pump_VarSpeedCondensateReturn
complexType SimFlowMover_Pump_VarSpeedCondensateSupply
```

In the converter application, each of the five XSD files is parsed and converted into a corresponding OWL ontology file, while keeping track of the cross references. Each class or subtype is converted into an OWL class (owl:Class), referring to an upper class when required, as shown below.

Listing A.4 OWL class representing the SimFlowMover

```
simmep:SimFlowMover_Fan
rdfs:subClassOf simmep:SimFlowMover ;
rdf:type owl:Class .
```

For each class, the required properties are generated as *owl:DatatypeProperty* or *owl:ObjectProperty* declarations (List A.5) resulting in a complete representation of the SimModel in five ontology files.

Listing A.5 OWL class property declarations

```
simmep:simFlowMover_SimFlowMover_Name
rdf:type owl:DatatypeProperty;
rdf:type owl:FunctionalProperty;
rdfs:domain simmep:SimFlowMover;
rdfs:range xsd:string .
```

This conversion service allows the conversion of SimModel data, containing schema definitions in BEPS tools, such as EnergyPlus, IFC geometry, Open Studio, gbXML, etc, to RDF graphs. These graphs can be used by more advanced semantic web technologies, such as reasoning engines with a basis in Description Logics (DL) or SPARQL query interfaces, or as part of a wider BLC management solution. This ontology allows for the rapid extraction of key systems information, particularly relating to the design of a building and exposing it in BLC format and is the only data model which currently contains simulation preferences in RDF.

A.0.4 The Semantic Sensor Network

As sensors of various descriptions as so common in buildings, it is important to be able to define sensors and how they relate to their environment adequately. Sensors are devices which sense and measure physical properties, such as motion, temperature, sound, humidity, etc., and return these pieces of data in the form of a stream to a processing or storage device of some kind. Sensors form the *eyes and ears* of any performance management system, providing the raw data on which the decision making process is based.

Fig. A.2 SSN Ontology stimulus (Anantharam et al., 2013). Removed due to copyright restrictions

In previous times, a building might have had a limited number of sensing devices available, but as described in Section 1.1.2, there has been an explosion in the number and range of intelligent devices. The volume of data produced by these devices is enormous and accessing it in a coherent manner is a complex undertaking. One solution is to describe sensors and the process of sensing semantically, using an ontology, defining the relationships between sensors and their environment. Several ontologies have been developed to describe sensors, categorised in Barnaghi et al. (2011). Perhaps the most noteworthy ontology used to describe this area is the SSN (Compton et al., 2012). This sensor ontology was produced by the World Wide Web Consortium (W3C) SSN Incubator Group (Compton et al., 2012) and had two main objectives:

1. The development of an ontology for describing sensing resources and data;
2. The extension of the Sensor Web Enabled (SWE) languages to support semantic annotations.

The ontology is based on the concept of a stimulus prompting an observation (Figure A.2), defining the stimulus as a link to its environment (Figure A.3).

Fig. A.3 SSO Ontology Design Pattern (Barnaghi et al., 2011). Removed due to copyright restrictions

The ontology describes sensors as elements of a system, deployed on a particular platform, with specific measuring capability. This modular approach allows the sensors and the domain of sensors to be broken down into easily digestible information with clear links to other ontologies available (Figure A.4).

A sensor is considered an object which can observe a feature of interest. Information concerning the accuracy, lifespan, range, precision, etc. about the sensor is also retained. An observation is a particular instance of the use of the sensor, when it has been used to capture information about a feature of interest and these data, together with associated meta data is also retained. The ontology can be linked with others to allow for network definition, measurement, etc. Using this approach, we can easily define a sensor in RDF and allow this information to be easily linked to other semantic information (List A.6).

Fig. A.4 SSN Ontology Modules (Barnaghi et al., 2011). Removed due to copyright restrictions

Listing A.6 RDF sensor description, generated using the web based application (Digital Enterprise Research Institute (DERI), 2011) specified in (Leggieri et al., 2011)

```
<?xml version="1.0" encoding="UTF-8"?>
```

```
<rdf:RDF xmlns:rdf="http://www.w3.org/1999/02/22-rdf-
   syntax-ns#"
  xmlns:ns0="http://www.w3.org/2000/01/rdf-schema#"
  xmlns:ns1="http://purl.oclc.org/NET/ssnx/ssn#"
  xmlns:ns2="http://spitfire-project.eu/cc/spitfireCC_n3.
     owl#"
  xmlns:ns3="http://www.loa-cnr.it/ontologies/DUL.owl#"
  xmlns:ns4="http://purl.org/dc/terms/">

  <rdf:Description rdf:about="http://spitfire-project.eu/
     sensor/SmBank-12">
    <ns0:type rdf:resource="http://purl.oclc.org/NET/ssnx/
       ssn#Sensor"/>
    <ns1:observedProperty rdf:resource="http://spitfire-
       project.eu/property/Temperature"/>
    <ns2:uomInUse rdf:resource="http://spitfire-project.eu
       /uom/Centigrade"/>
    <ns3:hasValue>10.2</ns3:hasValue>
    <ns4:date>14-09-16T10:14Z</ns4:date>
  </rdf:Description>
</rdf:RDF>
```

Section 4.3.1 describes how AEC data can be illustrated using semantic web technologies and gives a brief glimpse into the vast collection of semantically enabled tools and technologies available to achieve this. Merely exposing semantic data will not serve any purpose on its own. Anantharam et al. (2013) described some of the challenges which must be overcome when dealing with sensor data, and also other semantic information. These challenges include:

- Discovery;
- Access;
- Search;
- Integration;
- Interpretation;
- Scalability.

None of these challenges are trivial. Up to now, it has been described how data can be discovered, accessed, searched and integrated using semantic technologies. The next chapter details how this information might be interpreted, using a structured approach such as the performance framework described in chapter 5 and as illustrated in Figure 4.5.

Appendix B

Sample code structures

A considerable amount of code has been created as part of this research process and some of this is referred to at various stages throughout the thesis. These code snippets are not included for completeness.

B.1 Code blocks relating to Chapter 3

Listing B.1 BMS Schedule in iCal format.

```
UID:qhfaru4esobl8ts8mm7qi0jgl8@google.com
CREATED:20130531T221206Z
DESCRIPTION:
LAST-MODIFIED:20130718T131250Z
LOCATION:G017
SEQUENCE:0
STATUS:CONFIRMED
SUMMARY:OFF
TRANSP:OPAQUE
END:VEVENT
BEGIN:VEVENT
DTSTART:20130606T070000Z
DTEND:20130606T080000Z
DTSTAMP:20130718T132918Z
```

Listing B.2 BMS schedule in iCal format converted to RDF data.

```
<component>
```

```
    <Vevent>
        <dtstart rdf:parseType=’Resource’>
            <dateTime>2013-06-07T07:00:00Z</dateTime>
        </dtstart>
        <dtend rdf:parseType=’Resource’>
            <dateTime>2013-06-07T08:00:00Z</dateTime>
        </dtend>
        <dtstamp rdf:parseType=’Resource’>
            <dateTime>2013-07-18T13:29:18Z</dateTime>
        </dtstamp>
        <uid>qhfaru4esobl8ts8mm7qi0jgl8@google.com</uid>
        <created>2013-05-31T22:12:06Z</created>
        <description></description>
        <lastModified rdf:parseType=’Resource’>
        <dateTime>2013-07-18T13:12:50Z</dateTime>
        </lastModified>
        <location>G018</location>
        <sequence>0</sequence>
        <status>CONFIRMED</status>
        <summary>OFF</summary>
        <transp>OPAQUE</transp>
    </Vevent>
</component>
```

Listing B.3 RDF representation of a Twitter message sent by the `CE454` account, based on examples created by the Online Presence Ontology working group.

```
<?xml version="1.0"?>
<rdf:RDF xmlns:opo="http://online-presence.net/opo/ns#"
  xmlns:foaf="http://xmlns.com/foaf/0.1/" xmlns:rdf="http
  ://www.w3.org/1999/02/22-rdf-syntax-ns#" xmlns:sioc="
  http://rdfs.org/sioc/ns#">
 <sioc:UserAccount rdf:about="http://online-presence.net/
   opo/examples#CE454">
  <foaf:accountServiceHomepage rdf:resource="http://www.
    twitter.com/" />
  <foaf:accountName>CE454</foaf:accountName>
 </sioc:UserAccount>
```

```
  <opo:OnlinePresence rdf:about="http://online-presence.
     net/opo/examples#CE454Presence">
    <opo:customMessage>
      <sioc:Post rdf:about="http://online-presence.net/opo
         /examples#CE454Status">
        <sioc:content>@Ce454 #NEBGen What are conditions
           like in the NEB today? Computer rooms seem to
           be an issue? Do people miss the water fountains
           ?</sioc:content>
      </sioc:Post>
    </opo:customMessage>
    <opo:startTime>2013-01-25T09:50:11</opo:startTime>
    <opo:declaredOn rdf:resource="http://online-presence.
       net/opo/examples#CE454TwitterAccount" />
  </opo:OnlinePresence>
</rdf:RDF>
```

B.2 Code blocks relating to Chapter 5

Listing B.4 A sample element of the IFC representation of the experimental space

```
#124= IFCBUILDING(’15GqFEMjLDFgXv3ASgSXgN’,#13,’AWS-3’,$,$
   ,#121,$,$,
.ELEMENT.,$,$,#102);
#134= IFCRELAGGREGATES(’001mfTdIn1aB4mC3g3gUyv’,#13,$,$
   ,#88,(#124));
#136= IFCDIRECTION((1.,0.,0.));
#140= IFCDIRECTION((0.,0.,1.));
#144= IFCCARTESIANPOINT((0.,0.,0.));
#148= IFCAXIS2PLACEMENT3D(#144,#140,#136);
#151= IFCLOCALPLACEMENT(#121,#148);
#154= IFCBUILDINGSTOREY(’1UxgNwGU11xhkuP45fAEoG’,#13,’
   Ground Floor’,$,$,
```

Listing B.5 An RDF representation of a BIM model following conversion by the IFCtoRDF converter service

```
<component>
    <Vevent>
        <IfcBuildingStorey rdf:about="http://ninsuna.elis.
           ugent.be/IFC-repo/Room/AWS-3_Ar15#
           GUID037fa3d473bae4cf3aab377a65e793">
        <compositionType rdf:datatype="http://www.w3.org
           /2001/XMLSchema#string">_ELEMENT_</
           compositionType>
        <containsElements rdf:parseType="Resource">
            <rdf:first rdf:resource="http://ninsuna.elis.
               ugent.be/IFC-repo/Room/AWS-3_Ar15#
               GUID0fb9b3c97d02f4eddae71cd551e94b"/>
            <rdf:rest rdf:resource="http://www.w3.org
               /1999/02/22-rdf-syntax-ns#nil"/>
        </containsElements>
        <decomposes rdf:parseType="Resource">
            <rdf:first rdf:resource="http://ninsuna.elis.
               ugent.be/IFC-repo/Room/AWS-3_Ar15#
               GUID0f70c47d08b8d4a4799d510da22c20"/>
            <rdf:rest rdf:resource="http://www.w3.org
               /1999/02/22-rdf-syntax-ns#nil"/>
        </decomposes>
        <elevation rdf:datatype="http://www.w3.org/2001/
           XMLSchema#decimal">157.48031</elevation>
        <globalId rdf:datatype="http://www.w3.org/2001/
           XMLSchema#string">0t_Zr7EwvCywgpTwPUUJLF</
           globalId>
        <isDecomposedBy rdf:parseType="Resource">
            <rdf:first rdf:resource="http://ninsuna.elis.
               ugent.be/IFC-repo/Room/AWS-3_Ar15#
               GUID0dcab9d173d2f43e49539a5a2622a8"/>
            <rdf:rest rdf:resource="http://www.w3.org
               /1999/02/22-rdf-syntax-ns#nil"/>
        </isDecomposedBy>
    </Vevent>
</component>
```

Listing B.6 An RDF representation of a temperature sensor, as provided by the web based application (Digital Enterprise Research Institute (DERI), 2011) described in (Leggieri et al., 2011)

```
<rdf:Description rdf:about="http://spitfire-project.eu/
  property/Temperature">
  <ns0:type rdf:resource="http://purl.oclc.org/NET/ssnx/
    ssn#Property"/>
  <ns1:measuredIn rdf:resource="http://spitfire-project.
    eu/uom/Centigrade"/>
 </rdf:Description>

 <rdf:Description rdf:about="http://spitfire-project.eu/
   uom/Centigrade">
  <ns0:type rdf:resource="http://purl.oclc.org/NET/muo/
    muo#UnitOfMeasurement"/>
  <ns1:prefSymbol>C</ns1:prefSymbol>
 </rdf:Description>

 <rdf:Description rdf:about="http://spitfire-project.eu/
   sensor_stimulus/silver_expansion">
  <ns1:type rdf:resource="http://purl.oclc.org/NET/ssnx/
    ssn#Stimulus"/>
  <ns0:isProxyFor rdf:resource="http://spitfire-project.
    eu/property/Temperature"/>
 </rdf:Description>

 <rdf:Description rdf:about="http://spitfire-project.eu/
   sensor/SmBank-1/capabilities_Comp_Suite-1">
  <ns1:type rdf:resource="http://spitfire-project.eu/
    sensor/Comp_Suite-1/capabilities"/>
 </rdf:Description>

 <rdf:Description rdf:about="http://spitfire-project.eu/
   property/Battery_Life_Time">
  <ns2:measuredIn rdf:resource="http://spitfire-project.
    eu/uom/month"/>
 </rdf:Description>
```

```
  <rdf:Description rdf:about="http://spitfire-project.eu/
     foi/http://spitfire-project.eu/foi/http://spitfire-
     project.eu/foi/108">
    <rdf:type rdf:resource="http://spitfire-project.eu/foi
       /Room"/>
  </rdf:Description>

</rdf:RDF>
```

Listing B.7 RDF representation of scenario model with explicit links to specific building objects

```
<component>
    <Vevent>
<http://performanceframework/instances#ZoneTemp>
      a       <http://performanceframework/ontology#
         PerformanceObjective>;
      <http://performanceframework/ontology#
         forBuildingObject>
              "http://ifc.mmlab.be/IFC-repo/Bank.ifc#
                 GUID0ed1c5aea265842e28d2bc38a665a0" ;
      <http://performanceframework/ontology#
         hasCreatingActor>
              <http://performanceframework/instances#
                 organisation12345D>;
      <http://performanceframework/ontology#
         hasCreationTime>
              "2013-11-08T22:38:36.781Z"^^<http://www.w3.
                 org/2001/XMLSchema#dateTime>;
      <http://performanceframework/ontology#
         hasPerformanceAspect>
              "http://performanceframework/ontology#
                 BUILDINGFUNCTION";
      <http://performanceframework/ontology#
         hasPerformanceMetric>
              <http://performanceframework/instances#
                 zoneTemperature>
    </Vevent>
```

```
</component>
```

Listing B.8 RDF representation of temperature performance objective

```
<component>
    <Vevent>
<http://performanceframework/instances#ZoneTemp>
        a       <http://performanceframework/ontology#
           PerformanceObjective> ;
        <http://performanceframework/ontology#
           forBuildingObject>
                "http://ninsuna.elis.ugent.be/IFC-repo/
                   Small%20Bank/
                   small_bank_demo_bldg_AC13_Mac_WithSB_ForRDF
                   #GUID05ac2b7fcdb2644619dfd9e532ca33" ;
        <http://performanceframework/ontology#
           hasCreatingActor>
                  "Ed Corry";
        <http://performanceframework/ontology#
           hasCreationTime>
                "1970-02-01T16:35:01.937Z"^^<http://www.w3
                   .org/2001/XMLSchema#dateTime> ;
        <http://performanceframework/ontology#
           hasPerformanceAspect>
                "http://performanceframework/ontology#
                   BUILDINGFUNCTION" ;
        <http://performanceframework/ontology#
           hasPerformanceMetric>
                <http://performanceframework/instances#
                   Zone Temperature >
    </Vevent>
</component>
```

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