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Improved HVAC commissioning using wireless sensor networks

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Abstract

Commercial buildings present a significant potential for energy saving, in particular through the operation of their air-conditioning systems. Regulations and policies are driving towards better energy efficiency, but are mainly focused on the design stages. In practice, there is a performance gap between design and operation of new buildings. One of the causes of this gap is the failure to commission buildings for energy efficiency and comfort.

Historically commissioning is limited to design compliance and security checks and would need to scale up to account for the necessity of reducing new buildings' energy footprint. However, due to inevitable delays in the construction process, commissioning tends to stop when the building reaches 'practical completion'. It is thus difficult to increase the commissioning scope pre-handover. Additionally, currently available measurements are not suitable to go through the remaining 'snag' list or understand comfort and energy issues.

This thesis examines the potential and practicality of using wireless sensor networks (WSN) to perform a post occupancy commissioning (PO-Cx) process for energy and occupants' comfort performance. Requirements for such a WSN are determined from analysing building commissioning practices and the faults they fail to identify. An ad hoc WSN prototype is developed and verified. A proof of concept is established through a six-month deployment on a newly refurbished university building.

It is concluded that WSN is a key tool to integrate energy performance and comfort to the commissioning of new buildings. The possibility to install them with minimum disruption of an occupied building and to analysis the data remotely means that it is easy to perform additional commissioning tasks post-handover. Recommendations to develop a commercial WSN for PO-Cx application are given and general strategies for PO-Cx are discussed based on the experience acquired.

Declaration

I hereby declare that the work presented in this thesis is my own and has not been submitted previously for examination elsewhere. All external sources of information used to produce this thesis have been acknowledged.

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Chapter 1

Introduction

1.1 Motivation of the research

In developed countries, building consumption represents about a third of the total primary energy consumption (Pérez-Lombard et al., 2008). With growing concerns regarding climate change and fossil resource availability, buildings need to become more energy efficient. In the past decade, governments have been incentivising clients and contractors to deliver more efficient buildings through policies and regulations. The European Union's Energy Performance of Buildings Directive (EPBD) requires every member state to include energy requirements in their building regulations (EU, 2003). In the meantime, voluntary certification schemes, like LEED[1] (US) or BREEAM[2] (UK), have emerged, rewarding clients calling for high environmental requirements. However, those measures have mainly impacted the design stage and the performance of in-use buildings can be disappointing (Bordass, Cohen, Standeven and Leaman, 2001a) even for buildings with strict environmental requirements. Design software error margin, equipment over-sizing, equipment selection (revising performance downwards to achieve cost reduction), faulty installation or settings, and weak control strategy or energy management add up to create a gap between as-designed and as-operated energy consumption.

With the tendency to air condition new non-domestic buildings, heating ventilation and air-conditioning (HVAC) systems represent an increasing part of new building energy consumption (Pérez-Lombard et al., 2008) and improving their efficiency is a growing

[1] Leadership in Energy and Environmental Design
[2] Building Research Establishment Environmental Assessment Methodology

concern. Additionally, design for low energy buildings is leading to increasingly complex HVAC systems. This builds up the chances of inefficient operation, due notably to stakeholders misunderstanding how the system should work. Throughout the building's life cycle, different strategies are under investigation to improve their operation and to reduce the gap between as-designed and as-operated energy efficiency. Among those strategies commissioning is noteworthy, as it is the link between performance requirements and operations.

Commissioning can be defined as a "quality-oriented process for achieving, verifying and documenting whether the performance of a building's systems and assemblies meet defined objectives and criteria" (Visier, 2004). There are several types of commissioning processes depending on the objectives set and the life cycle stage of the building under consideration. Within those strategies, the initial commissioning (I-Cx) process, aimed at new buildings or major refurbishments, is of particular interest as it has the potential to ensure the good realisation of initial performance before considering other in-use measures, which tend to be based on performance degradation. In the UK, the initial commissioning scope includes setting building systems to work and demonstrating their compliance with design and is generally performed under the responsibility of the main contractor.

In the meantime, the development of Wireless Sensor Network (WSN) technology in the past decades has enabled the access to additional, continuously and simultaneously monitored data points for extended periods without incurring a high permanent cost. Many scientific fields are taking advantages of this new capability. For example, WSN enable environmental monitoring in places where human presence would disturb the observable phenomenon and no power source is available (Mainwaring et al., 2002). WSN can provide rapid installation, limited disruption of building activity (Healy, 2005, Jeong et al., 2008) and lower costs compared to wired systems (Kintner-Meyer, 2005). In the context of building systems, WSN are mostly used to complement existing sensing capabilities, notably after retrofits, but the great flexibility of such systems have the potential to offer a vast range of possibilities that is likely to grow in the coming years.

1.2 Problem statement

Historically, the purpose of commissioning has been to ensure health and safety, and design compliance. As a result, buildings are often delivered when they are considered to reach 'practical completion' meaning that the building is in an acceptable state to be occupied even if minor problems might remain. At this stage commissioning would have been limited to ensuring that the building systems can deliver the design flow rates and temperature, giving no guaranty regarding the level of comfort provided or the incurred energy costs. Additionally, there would rarely be the opportunity to adjust for real occupancy patterns, behaviour and yearly weather variations. Seasonal commissioning (SCx) would normally be included in the commissioning scope, but would be limited to test the systems at their maximum cooling and heating loads. This does not give any indication on how the systems operate in intermediate loads, which represent the majority of their yearly operating time.

Additionally, what has been left aside during the construction process is unlikely to be compensated for after the building is handed over to facilities management (FM). FM's main objective would be to limit occupant complaints, making energy performance secondary. Thus, if automated system settings are not fully working or do not account for occupants comfort over the full range of weather conditions, FM might be tempted to operate systems manually, which is likely to result in the systems being 'on' all the time unnecessarily. Moreover, some types of FM contracts are based on performance improvement, meaning that in those cases it is more interesting for FM contractors to inherit a building with poor energy performance when they take control of it to facilitate improvement later on.

Energy consumption becoming an increasingly worrying matter calls for extension of the scope of commissioning to energy efficiency. In practice, inevitable delays in the construction process and the aspiration to occupy the building as soon as possible result in a progressive reduction of the commissioning programme. This limits the possibilities to increase the commissioning scope before handover. To overcome these barriers the initial construction process can extend beyond handover into the early occupation of the building. This would go along with the 'Use & Aftercare' stage introduced in the latest revision of RIBA's Plan of work (RIBA, 2013).

The idea to evaluate building operating performance after the building gets occupied has

been growing in the past decade. For example, initiatives like Probe (Cohen et al., 2001) or Soft landing (Way and Bordass, 2007) introduced the concept of post occupancy evaluation (POE), which consist in assessing occupant satisfaction and overall energy performance of a new building to give feedback on its design and highlight operational problems. Looking in more detail into the system operation, Isakson et al. (2004) proposed a method to systematically report the available building management system (BMS) data to perform seasonal commissioning and Painter et al. (2012) used a temporary overlay of sensors to commission a naturally ventilated building in use. All these methods can contribute to understanding new buildings' operation better, but none of them propose a comprehensive strategy for in-use building commissioning.

Building on top of the post-occupancy evaluations mentioned above, this thesis proposes to investigate a post-occupancy process to overcome the lack of possibilities to integrate energy and comfort in the traditional I-Cx process. In typical construction contracts, contractors would normally have a 6 months to one-year liability period during which they are bound to fix reported problems. In the perspective of shifting the building services industry from a product-oriented industry to a service-oriented industry, this liability period could be turned into energy and comfort performance commissioning. This would lead to ensure compliance with the client brief instead of the design.

Implementation of such a post occupancy commissioning (PO-Cx) process requires the availability of a low-cost set of appropriate data. Using traditional Cx instrumentation, this can be compromised by substantial spatial separation between data points and high labour costs. Examples in the research literature solve the data collection problem by using BMS data, which is readily available in most commercial buildings. This poses several problems in the perspective of a PO-Cx process. First, the BMS system is the last one to be commissioned and handed over and it is not uncommon for the BMS system not to be fully operational several months after the rest of the systems have been handed over. Second, part of the operational problems potentially comes from the BMS (e.g. sensor calibration issues, sensors located in a non-representative location, noise in the signal...). Third, the data requirements to complete commissioning are much higher than the 'exception based' BMS that will have been installed for in-use building monitoring purposes. Indeed, most BMS would have only one temperature sensor per thermal zone, which is not sufficient to fully assess occupant comfort. A complementary source of data is thus needed.

The rapid evolution of WSN technology is recognised to provide an opportunity for the building industry, in particular for energy consumption reduction and system operations (Heller and Orthmann, 2014). Its low installation cost compared to wired controls makes it a suitable option to add control points to the BMS for improved control strategy or after minor retrofit. The lack of wiring also gives greater flexibility on sensor locations, which broadens the possibilities to access data. Indeed, many comfort issues arise from temperature sensors being badly located. On permanent installations, these advantages can be counterbalanced by the need for regular human access to replace batteries. However, for temporary monitoring the battery life can be specified to match the deployment period. A WSN enables temporary access to additional data points with high flexibility and it could support the understanding and fine-tuning of systems' operation in a PO-Cx process.

1.3 Aims and scope

Based on the problems identified in the previous section, the aim of this thesis is to investigate the potential of WSN technologies to extend the scope of commissioning to energy and comfort efficiency. The key objectives to fulfil that aim are detailed below.

The first objective is to critically review the state of practice of building commissioning, recognising the new imperative for high levels of climate control and low-energy performance. The backbone of this research is to understand current commissioning practices and the challenges that prevent commissioning from addressing building energy performance. This is tackled through an extensive literature review (research and professional) and shadowing and interviews of commissioning professionals.

It is unlikely time could be set aside for energy efficiency checks during the I-Cx phase, but this task could be undertaken post-handover as a PO-Cx process. The implementation of such a process requires understanding the type of problems found in new buildings. The second objective is to identify a series of faults that are commonly present in new buildings and affect their energy and comfort performance. It is done by a series of interviews and questionnaires addressed to experienced professionals.

Troubleshooting those faults induces new needs in terms of data collection. The third

objective of this thesis is to identify measurements and data acquisition requirements for a pop-up monitoring™ system to perform PO-Cx. These requirements are established based on a list of measurement use cases to address the typical fault list from the second objective. WSN have been identified as suitable to obtain the additional, continuously and simultaneously monitored data points required.

The fourth objective is to develop and verify the monitoring kit based on the requirements established previously. To prove the validity of the set requirements, a portable WSN (PWSN) prototype is developed and tested in controlled environments. The tests include WSN verification, sensors characterisation, and proxy validation when the physical quantity recorded by the sensor is used to understand another physical phenomenon (e.g. occupancy).

The fifth objective is to evaluate the developed tools on a real building case. To assess the practicality of using WSN for PO-Cx, the developed prototype is installed in a newly refurbished university teaching room and six months of data are collected and analysed. The ability of the PWSN to address the PO-Cx use cases from the fourth objective is demonstrated together with applications of pop-up monitoring™ for fault identification.

Based on those objectives, the remainder of this section aims at delimiting the scope of this study. The end goal of this research is to contribute to reducing energy consumption and improve thermal comfort. Better thermal comfort will improve health and productivity of the occupants, thus improving the quality of the building. Regarding energy, the aim is to reduce delivered energy and energy bills for the building owner, with the bigger perspective of reducing building primary energy consumption and CO_2 emissions to slow down climate change.

This research is mainly based on the UK construction sector and if the technical principles can be easily extended to other countries, their specific construction workflow might need to be taken into account to adapt the specifics and incentives to use WSN for PO-Cx. The choice has been made to address new buildings and major retrofits. As Bordass, Cohen, Standeven and Leaman (2001b) argue, even though new buildings represent only 1% of the building stock, they should not add to the problem. More over once demonstrate on new buildings a lot of energy-saving measures can be adapted to retrofit.

In this thesis, commissioning is looked at in the context of large projects or projects with complex systems. Those are the projects where commissioning is more likely to encounter problems and thus the ones that will benefit the most of improved commissioning. In this context, the main focus will be non-domestic buildings, but, as new dwellings get built with increasing airtightness, they require more complex systems to provide energy efficient ventilation and can thus also benefit from PO-Cx. For the purpose of proof of concept, data have been collected solely on a university building. Universities are an interesting building type to investigate as they occupy a mix of spaces (classrooms, offices, laboratories...), which means they are relatively complex to manage. At the same time, universities tend to have large estates, which means energy savings can have a considerable impact on their running costs.

Regarding the monitoring use cases, only the ones that can be influenced directly by the building operators are considered. Occupants' behaviour and their use of electrical appliances (IT, kettle, etc.) are acknowledged to have a significant influence on building final energy consumption and to contribute to the performance gap, but behaviour is a complex topic that has not been researched much in non-domestic buildings yet (Lopes et al., 2012). Even though it is worth further investigation, as it is more difficult for contractors and FM to shift occupants' behaviour than to improve systems settings, it is left out of scope. According to Pérez-Lombard et al. (2008), HVAC represent 55% of office buildings energy consumption in the UK, followed by lighting with 17%. HVAC systems are thus chosen to be the primary focus of the thesis. The work presented here should ultimately expand to other aspects of the building, such as lighting or airtightness, to tend towards a whole building approach. Those aspects are discussed when it is relevant, although they are left out of the measurements scope.

The data analysis of this thesis is done as post-processing. Since most of the data analysis for PO-Cx would be done off-site, this is not a significant limitation. Real-time data would only be needed if the engineer is on-site regarding a particular matter at which stage the data analysis needed would be relatively simple (e.g. latest time series).

1.4 Key contributions

This section summarises the contributions of this thesis and explains their significance to the research field of building operations. The first outcome of the research is a better understanding of the current commissioning practices and their shortcomings. In addition to reviewing the commissioning process, common operating faults that could be addressed by commissioning are identified. This leads to the recognition of the imperative to commission buildings for energy and comfort in order to be able to close the performance gap.

The second outcome is the introduction of a PO-Cx process to fine tune building systems in use, leading to new strategies to close the gap between designed and operating building energy consumption. A proof of concept is realised through the implementation of PO-Cx on a case study. It is also used to develop troubleshooting strategies to assist with the PO-Cx process.

The third outcome is a set of requirements and recommendations towards a commercial WSN able to assist with building troubleshooting for energy and comfort performance. Through the development, testing and deployment of a PWSN prototype, this study shows the potential of wireless technologies to improve energy efficiency of buildings. It also sheds light on current technological limitations and highlights recommendations for future development.

In general, the findings of this research contribute to improving energy and comfort in operation of new buildings. An emerging way to improve building energy efficiency is to consider building services as a service (e.g. providing heat or ventilation) rather than a product (e.g. installing a boiler or an air-handling unit (AHU)). Some contracts provide long-term binding energy targets to make sure the contractor gets it right. In the same spirit, soft landing advocates a longer involvement to give operational feedback and help understand how the building works. PO-Cx with WSN can be a useful tool to help with all those processes and by demonstrating to the client his building is compliant with the brief instead of the with the design calculation, it improves the delivery process and gives a better reputation to the contractor.

1.5 Thesis overview

Chapter 2 is a literature review on the improvement of building energy efficiency in-use. It starts by looking into the current incentives to reduce building energy consumption and how they have a limited effect on 'in-use' building energy consumption (Section 2.1). Then some background on HVAC systems and their energy consumption is presented (Section 2.2), before giving an overview of the different processes aiming at improving buildings' operating energy efficiency (Section 2.3). This is followed by a detailed look into commissioning and its current limitations (Section 2.4). Once the necessity to extend the commissioning scope has been demonstrated, state-of-the-art data acquisition methods in buildings are reviewed (Section 2.5). This leads to the identification of a list of gaps to orient the research in the rest of the thesis (Section 2.6).

The literature review concludes on opportunities towards building commissioning to improve building energy efficiency. Chapter 3 sets the requirements for such an improved process. Section 3.1 describes the methodology used in the chapter. The chapter continues with the review of state of the art commissioning practices in the UK and other countries (Section 3.2). The limitations of current commissioning practices are identified and lead to the introduction of the concept of PO-Cx (Section 3.3). Then Section 3.4 identifies the typical faults remaining after handover. Those faults and the PO-Cx tasks are used to build a set of requirements for a monitoring system for building troubleshooting, first from a data point of view by drawing up a list of use cases (Section 3.5), then from a system point of view (Section 3.6).

After setting the monitoring kit requirements, Chapter 4 describes the development of a system meeting those requirements and the verification tests of that system. Section 4.1 outlines the chapter's methodology. Then Section 4.2 describes the monitoring system implemented from the requirements of the previous chapter. Section 4.3 reports the experimental verification of the WSN aspects of the system, the result of the characterisation tests of the sensors, and the validation of proxy measurements. Section 4.4 draws the lessons learned from the development and testing of the prototype PWSN.

Chapter 5 presents the deployment of the prototype PWSN on a university case study. Section 5.1 presents the methodology of the chapter. Section 5.2 describes the case study used to deploy the monitoring system and inventories the additional data available. Then

Section 5.3 demonstrates the implementation of the use cases identified in Chapter 3. Section 5.4 demonstrates a practical implementation of the PO-Cx tasks and shows how the PWSN data can diagnose the faults identified in Chapter 3. Finally, Section 5.5 discusses the results from the deployment and the data analysis.

Chapter 6 is a discussion on practical applications of pop-up monitoring™ based on the experimental results presented before. First the benefits of PO-Cx are discussed (Section 6.1). Then Section 6.2 considers the interest of the PWSN for PO-Cx. Section 6.3 examines the other potential applications that could be envisaged using PWSN. Finally, Section 6.4 explores potential leads for further research.

Finally, Chapter 7 presents the conclusions of the thesis (Section 7.1), and summarises the contributions from the thesis (Section 7.2).

Chapter 2

Literature review on opportunities to improve building energy efficiency in use

The energy efficiency of buildings in-use relies on the interaction between a range of fields. The first half of this chapter reviews a broad range of literature on building energy and in particular commissioning as context for the later review of wireless and monitoring technologies. It aims at answering the following questions:

- What are the current drivers for building energy efficiency and how do they perform?
- What is the state of the art of research on improving operational performance of buildings?
- How do new sensor technologies integrate with building management?

Based on this literature review, the research gaps that drive the research are identified.

First the state of the art of energy policy and other incentives to improve new building energy efficiency, in particular in the UK, is drawn up. It shows their limitations and how they lead to an energy performance gap. Background on HVAC is then presented, including how HVAC impacts energy performance thus justifying the necessity of better operated systems. A review of the research towards better 'in-use' building operations is then presented showing the importance of the commissioning process and the limited interest in newly handed over buildings. Taking a closer look at commissioning, the different tools to assist the process found in the literature are reviewed. A review of the different monitoring

techniques and strategies for building systems is then carried out with a special emphasis on WSN.

2.1 Incentives to reduce building energy consumption

2.1.1 Building energy consumption

Over the past decades the growing awareness of climate change and resource scarcity has been revolutionising the basic requirements of the building industry. Not only do buildings need to be functional, they need to be so at a low primary energy and CO_2 emission cost. It is generally reported that about 40% of developed countries' primary energy eventually services buildings of some kind (Pérez-Lombard et al., 2008). Pérez-Lombard et al. (2008) also report that the total energy consumption is likely to rise as the global population keeps growing and emerging economies tend to catch up developed countries' lifestyle. In the meantime, the demand for close indoor climate control has been rising worldwide leading more new non-residential buildings to be air-conditioned (i.e. using mechanical ventilation for cooling and/or heating) (Pérez-Lombard et al., 2008). As a result HVAC systems represent around half of the total building energy consumption and between 10 and 20 % of developed countries total energy consumption (Pérez-Lombard et al., 2008).

2.1.2 Regulation, energy policies and certification programmes

In this context, the improvement of building efficiency is a key concern to slow down the greenhouse gas emissions and governments have been encouraging clients to build more energy efficient buildings through certification programmes and regulations. Many countries have seen the introduction of design certification programmes, like BREEAM in the UK (BREEAM, 2014) or LEED in the US (U.S. Green Building Council, 2009), to encourage clients to undertake ambitious green projects. The European Union has introduced the European Performance of Building Directive (EPBD) requiring that member states write down minimum performance requirements for new buildings in their building regulations (EU, 2003).

EU regulations

The EPBD requires the implementation of a methodology to assess the energy performance of buildings (EU, 2003). In the UK, Energy Performance Certificates (EPC) and Display Energy Certificates (DEC) have been introduced. They are both rating tools that compare building yearly CO_2 emissions to emissions standardised for the building type. EPC and DEC have the same visual layout but represent different things, which can be misleading. Moreover, there is a lack of coherence between EPC and DEC of the same building as outlined by Healy (2013) on a study of 99 buildings. A coherent relation between both tools would be needed to get better comparison between design and operation of buildings. The 2010 update of the EPBD also requires all new buildings to be nearly zero-energy building (NZEB) by the end of 2020 (EU, 2010). Zero Carbon Hub and NHBC Foundation (2011) summarised the full content of the EPBD.

UK regulation and policies

In the UK, the Building Act 1984 is the statue setting the Building Regulations for England and Wales structure (United Kingdom, 1984). It instates the responsibility of the secretary of state to make the details of the Building Regulations. The Building Regulations are meant to ensure the government policies are realised and are separated in 15 sections, 'Part A' to 'Part Q'. The specification for each part is found in 'Approved documents'. 'Approved documents' are not legally binding. They expose the standard to achieve for compliance and propose standard methods to do so. Compliance can, however, be achieved using other methods. The latest version of the Building Regulations is from 2010, but there have been amendments since. Of particular interest is Part L, which covers power conservation (HMG, 2013). It is separated in four parts to address new and existing, as well as dwellings and non-domestic buildings.

Regarding relevant policy for energy conservation, the Climate Change Act passed in 2008 sets a carbon emission reduction target of at least 80% compared to 1990 levels by 2050 (United Kingdom, 2008). The UK government intends to require building information models (BIM) (see Section 2.3.1) with 3D models on all public projects by 2016. This fits in the government scheme to be a more exigent client to improve the public building stock that represents 40 % of the construction GDP of the country (HMG, 2011).

Voluntary certification programmes

In addition to complying with the regulations, building owner can aim at obtaining additional level certification of their buildings. These environmental building assessment schemes encourage owners to set their own target in exchange for improved reputation, aiming at raising public awareness, and prompting the achievement of better performance than the minimum requirements (Lee, 2013). To gain certification, a building is assessed against a list of criteria that determines which level of certification it reaches.

Among those, BREEAM and LEED are the predominant ones, but there is also CASBEE in Japan, BEAM plus in Hong Kong or ESGB in China and many more that account for local contexts. BREEAM was the first of these schemas and was introduced in 1990 by the Building Research Establishment (BRE) (BREEAM, 2014). The latest version spread the credits between management, health and well-being, energy, transport, water, materials, waste, land use and ecology, pollution, and innovation. Since BREEAM 2008, there is a mandatory post-construction review to get the final certificate.

LEED by the US Green Building Council follows a similar format with credit categories organised as sustainable site, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, innovation in design, and regional priority. The later version, LEED v4, has revised several categories to lead to better performance (U.S. Green Building Council, 2014) and is separated between building design and construction, interiors design and construction, building operations and maintenance, neighbourhood development and building design and construction: homes and mid-rise. For each category, a subset of versions exists to adapt for different types of buildings.

2.1.3 Performance gap

Despite the efforts made to reduce the environmental impact of buildings, many studies demonstrate that the operation of buildings tends to be disappointing compared to predicted performance. For example, in a study of 16 'innovative buildings', Bordass, Cohen, Standeven and Leaman (2001b) found a factor 6 difference between predicted and actual carbon emissions. The Carbon Trust evaluates the gap between as-designed and as-operating building performance to be around 16 % on 28 building case studies (Carbon Trust, 2011).

There are also doubts that certified buildings perform better than average buildings. A study on 100 LEED New Construction Buildings found out that more than 25% of the buildings operate 25% worse than their design intent to (Turner and Frankel, 2008) and that the actual level of performance of the buildings did not reflect the level of certification they obtained (Newsham et al., 2009). Moreover, Scofield (2009) opposes Newsham et al. (2009) by arguing LEED buildings do not present significant energy savings when compared to benchmark levels. This might be because the certification is done mainly considering design, neglecting the operational aspect. Even if BREEAM has instated post-construction review and gives credits for post-occupation evaluation (see Section 2.3.3) since 2008, it is not clear how much actual data are collected regarding the building operation before giving the certification.

Countries enforcing ambitious energy performance in their regulations do not seem to obtain as good results as expected either. An investigation of 404 UK recent dwellings, Pan and Garmston (2012) found a third of them do not comply with the Building Regulations in force at the time of design. Pan and Garmston (2012) explain this by the lack of knowledge of the energetic aspects of the Building Regulations from the building industry and the bodies in charge of enforcing it.

From initial design to building operations, various discrepancies can contribute to the realised energy consumption to be disappointing. Based on the study mentioned above, Carbon Trust (2011) identifies the following as causes of discrepancies:

- differences between the design and what is built
- omission of energy consumption sources in the design such as ICT, external lights, or appliance electrical consumption
- special functions of some parts of buildings
- extended operating hours
- variation in occupation density
- building management

The energy consumption that results from the elements listed above come in addition to the loads that are calculated under Part L of the Building Regulations. They are

named 'unregulated loads'. Difference between as-designed and as-built can come from discrepancies between models used for energy calculations and reality as well. The origin of this can be (Summerfield et al., 2011):

- inaccurate input of data (e.g. operator mistake, bad empirical data for material or specifications)
- limitations of the calculation model (e.g. ignored thermal bridge, incorrect use of physical models)
- inaccurate survey or monitoring data

Delivering comfort also seems to be an issue. In a study on 215 buildings in three countries, Huizenga et al. (2006) found acceptable air quality and thermal comfort satisfaction in only 11% of buildings.

If a lot of research is undertaken to design greener buildings, significant reduction of the building stock energy consumption will not happen until more emphasis is put on building operations. This suggests that more research about building energy needs to focus on improving performance in use.

2.2 Background on HVAC systems

HVAC is a major source of energy consumption (Pérez-Lombard et al., 2008). After construction, optimising HVAC energy consumption is also one of the most straight forward way to minimise energy use. Indeed, at that stage there is little that can be done for the building envelope (glazing, insulation, etc.). Influencing the occupants' behaviour is another option, but it is a complex issue (Brown and Cole, 2009) that is left out of the scope of this thesis. This thesis thus chooses to address the reduction of energy consumption from the angle of building services' energy efficiency, and in particular HVAC.

This section aims at putting HVAC in the general context of buildings. It first gives a brief definition of building services, from which HVAC is a subcategory. The relation between HVAC and comfort is then looked at, before giving an overview of HVAC systems.

2.2.1 Building services

HVAC systems are a type of building services. Building services are the systems installed in buildings to make them safe, comfortable and efficient. The Charted Institute for Building Services Engineers (CIBSE) give the following list of building services[1]:

- energy supply (gas, electricity and renewable sources)
- heating and ventilation
- air-conditioning and refrigeration
- water, drainage and plumbing (including hot water)
- day lighting and artificial lighting
- escalators and lifts
- harnessing solar, wind and biomass energy
- communications, telephones and IT networks
- security and alarm systems
- fire detection and protection
- facade engineering

Building services is thus a very multidisciplinary field. Building services are meant to keep people comfortable and safe indoors, and in the new paradigm should do so using minimum energy. Safety-oriented services would normally be commissioned well, as they could otherwise have serious impacts on occupants' security. For energy efficiency purposes, it is more important to look at comfort-oriented services, as providing occupants' comfort and minimising energy consumption are often opposite goals that need to be mitigated.

2.2.2 Comfort

Modern lifestyle leads people to spend most of their time indoors. It is demonstrated that indoor comfort has a significant influence on productivity (e.g. Haynes (2008)) and is thus receiving a lot of attention, especially in commercial buildings. In recent literature, Dounis and Caraiscos (2009) identify visual comfort, thermal comfort and indoor air quality (IAQ) as basic indicators of occupants' comfort. Oral et al. (2004) also consider acoustic comfort.

[1]What is building services: http://www.cibse.org/building-services/what-is-building-services

IAQ and thermal comfort will be looked at more in detail as they are related to HVAC. Discomfort due to bad air quality can come from two aspects: 1) the presence of odours, 2) the presence of pollutants that can lead to irritation or long-term health issues (pollen, radon, tobacco and other chemicals) (Race, 2006, Braham et al., 2010). To prevent discomfort due to bad IAQ, standards provide minimum ventilation rates to ensure the sensation of fresh air, but there is no standardised way to measure IAQ. However, CIBSE guide A provides a guide to convert air changes requirements to CO_2 levels (Braham et al., 2010). For example, 8 L/s per person of fresh air corresponds to an elevation to 600 ppm of CO_2 concentration.

Regarding thermal comfort, the predictive mean vote (PMV) approach developed by Fanger (1970) has been widely used in building standards. It is based on an intensive set of controlled laboratory steady state experiments. The parameters influencing human thermal comfort have been found to be (Fanger, 1973):

- air temperature
- mean radiant temperature
- relative air velocity
- vapour pressure of ambient air
- activity level
- thermal resistance of clothing

The PMV model is based on heat balance and predict the thermal comfort votes of a large group of people on a standard scale going from very cold (-3) to very hot (+3). Standard ISO EN 7730 Brussels (2005) (PH/9, 2005) provides calculation methodologies for the PMV model.

However, the PMV model has been subject to criticism (Yao et al., 2009). It is argued that the PMV considers the body as a passive recipient and thus does not account for the possibility for people to adapt. As a consequence, ISO 7730 tends to exaggerate PMV at extreme temperatures. The PMV model is also not able to account for the empirically observed difference between naturally ventilated and mechanically ventilated buildings (Brager and de Dear, 1998). Lastly, PMV is difficult to measure. Tse and Chan (2008) propose a distributed sensor network to measure PMV and use it for air conditioning control, but a set of several sensors needs to be placed around each person in the

space as airflow and radiant temperature are localised measurements and the method uses textbook assumptions for metabolic rate and clothing insulation.

An alternative approach, called the adaptive approach, has been proposed based on field study results (Nicol and Humphreys, 2002). It is base on the observation that when facing thermal discomfort people act in ways that tend to restore their comfort and that thermal comfort perception is based on one's thermal expectation and varies with the outdoor temperature. Corrective actions can include opening or closing of doors/windows, changing amount of clothes, changing activity level, intake of a cold or hot drink (Yao et al., 2009). There are also differences due to climate, social economy, expectation, psychological, and behavioural adaptive abilities (Yao et al., 2009). They are all parameters that influence thermal comfort perception and are not taken into accounts in the PMV method. Humphreys (1978) demonstrated that the neutral 'comfortable' temperature could be determined based on the outdoor temperature of the preceding days and many other studies have been determining similar relation based on divers assumptions (Ferrari and Zanotto, 2012). Adaptive theories have now been integrated in standards for naturally and mechanically ventilated office buildings (de Dear and Brager, 2002, Braham et al., 2010).

More practical recommendations regarding comfort are also given in standards and guidelines (Braham et al., 2010, Race et al., 2007):

- Humidity has little effect on thermal comfort at standard temperatures in the UK as long as the relative humidity values are not too extreme (Race, 2006). Braham et al. (2010) recommends staying within 40-70%RH.
- Radiant temperature should be close to air temperature, preferably slightly above (Race, 2006).
- Air change is recommended being 10 l/s/person to guaranty the feeling of freshness. The other objectives of fresh air, which are diluting contaminants, carbon dioxide and providing oxygen all have lower requirements and are thus fulfilled as well by an air change of 10 l/s/person (Race, 2006).
- Depending on the ambient temperature and the direction of air movement, air velocity between 0.1 and 0.3 m/s would generally provide acceptable comfort for occupants (Race, 2006).

These recommendations are achieved by careful design and operation of HVAC systems.

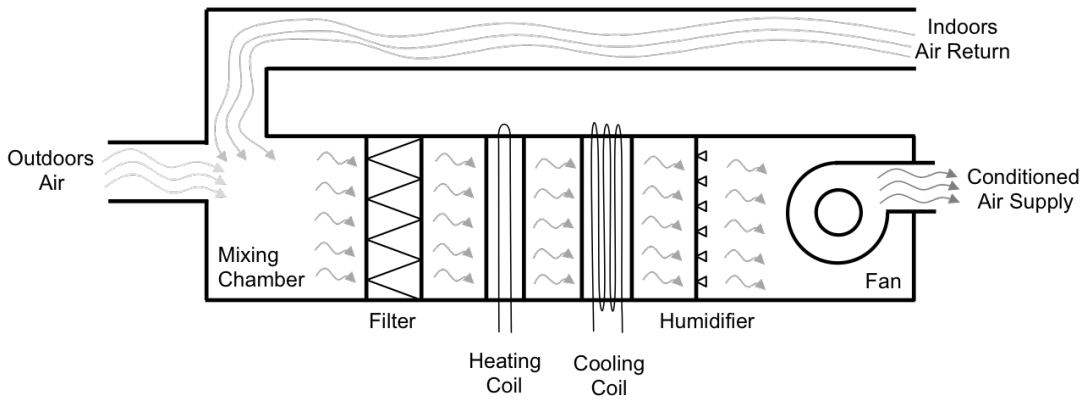


Figure 2.1: Basic air-conditioning system, after (McDowall, 2006)

2.2.3 HVAC systems overview

This section aims at giving a brief background regarding HVAC systems. HVAC systems aim to condition indoor air to provide thermal comfort. McDowall (2006) lists 7 air-conditioning processes:

- heating
- cooling
- humidifying
- dehumidifying
- cleaning
- ventilating
- air movement

Pita (2002) proposes the following classification of air-conditioning systems:

1. *Type of fluid carrying heat/cold*

   - **All-air systems** The ventilation is provided through a central system and local units are providing heating/cooling through hot/chilled water.
   - **All-water systems (or hydronic systems)** Air is conditioned by maintaining constant flow (reheat constant volume systems) or constant temperature (Variable air volume (VAV) systems).

- **Air-water systems** When ventilation is provided through natural ventilation, air-conditioning can be done through local units using chilled or hot water.
- **Steam systems** (CIBSE, 2005)
- **Unitary refrigeration based system** (McDowall, 2006)

2. *Unitary or central systems* In central system heating can be provided by boilers, solar panels, community heating, combined heat and power (CHP); cooling by different types of chillers or district cooling; or both cooling and heating by a heat pumps (CIBSE, 2005).

3. *Single zone or multi-zone*

Figure 2.1 shows the basic air-conditioning paradigm used in this thesis. It is composed of an outside air damper to close the fresh air intake when the system is off, a mixing chamber to mix fresh and return air, a filter to remove dust and other contaminants from the air, a heating and a cooling coil to change the temperature of the air, a humidifier, and a fan to move the air. This would be a standalone system that supplies a single zone. Most air-conditioning systems are variations of this. In addition, every air-conditioning system has transport components, such as pumps and pipes for water systems, and fans and ducts for air systems.

HVAC systems are the biggest source of building energy consumption once a building is in operation. Bad operation of HVAC systems also impacts occupants' comfort and IAQ. HVAC efficient operation should thus be a research priority.

2.3 Methods for improving in-use building performance

Innovations relative to the design phase have been an important area of research in the past 20 years, but they are not enough by themselves to deliver new energy efficient buildings. For green building design to deliver, it is also important to have tools to evaluate and correct in-use performances. The following section gives an overview of the different research areas dealing with improving building operations.

2.3.1 Building Information Model

During building conception a lot of requirements, drawings and other information are issued and exchanged between the different stakeholders. In a context where buildings are getting more and more complex, the multitude of information and the multiplicity of design versions induce mistakes and loss of time and money. To overcome those difficulties the building industry is going towards a general use of building information model (BIM) software to manage information. BIM can enable the creation of a full and intelligent model that organises and centralises information about the project. Currently, BIM is used as a file exchange system for traditional 2D drawings, but has the potential to represents structured data that creates 3D models, or even 4D (costs) or 5D (time) (Cerovsek, 2011). At the moment, efficiency of BIM suffers from interoperability between the different formats used in the different design software and from integration problems, but research is being carried out to overcome these limitations (Cerovsek, 2011).

The current use of BIM in the industry is limited to the design phase, but research is carried out to extend its use in the building life cycle (Volk et al., 2014). This could in turn help to limit the data loss between the different phases of the building life cycle. Davies and Harty (2013) describe the innovation process around the implementation of tablet computers to access BIM models from the construction site on a hospital project. 'Site-BIM' enables contractors to access the latest drawings and to save time by suppressing trips back to the office. It also enables live management of the construction programme as it progresses. Research also proposes to use BIM to manage operation data (Costa et al., 2013, Vähä et al., 2013, Woo and Gleason, 2014).

BIM has the potential to improve building operations by providing an integrated data management tool and thus to improve management on the whole building life cycle.

2.3.2 Commissioning

One of the important processes to ensure good building operations is commissioning (Cx). It is a quality process to ensure that the constructed building complies with the intended design. Cx has proved to be an efficient measure, both cost and energy wise (Kjellman et al., 1996, Mills, 2009). In practice, commissioning is done in a relatively short period towards the end of construction and ends with handover, but there is a push in technical

and research literature to expand the process (Hawkins, 2010, Djuric and Novakovic, 2009, Xiao and Wang, 2009). The working group from the International Energy Agency's (IEA) Energy Conservation in Buildings and Community Systems (ECBCS) Annex 40 identifies four types of commissioning (Visier, 2004):

- **Initial-commissioning (I-Cx)** I-Cx concerns new projects and consists in making sure that the building is compliant with the owner's requirements, building regulations and safety regulations and that it conforms to its design intent.
- **Retro-commissioning (Retro-Cx)** Retro-Cx is done on buildings that did not get commissioned originally. New requirements are agreed with the clients.
- **Re-commissioning (Re-Cx)** Re-Cx should be implemented every 2-5 years after I-Cx or Retro-Cx to prevent a drop in efficiency over time. It is relatively similar to Retro-Cx as it is usually not possible to re-commission the building against designed performance because parts of the design data might be lost. Even in the case where those data would still be available new operational requirements should be set for the process as some functions of the building might have changed. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) integrate both processes under 'Commissioning Process for Existing Building system and assemblies' (Wilkinson, 2012) in a new guideline released in 2015. The combination of both is also found as existing building commissioning.
- **On-going-commissioning (O-Cx)** also referred to as lifetime, life cycle or continuous commissioning® in the literature. O-Cx consists of monitoring the building performance during its occupation with the intention of detecting faults as or before they occur thus improving systems maintenance and performance. See Section 2.3.4 for more detail.

2.3.3 Post-occupancy evaluation

Due to the high number of stakeholders through the different phases of the project, a lot of data are lost at the interface between the different working teams and few lessons are taken from previous failures. The compartmentalisation between stakeholders' responsibilities and a lack of feedback to designer and construction teams also slows down the progress in the building industry compared to other industries (Koskela and Vrijhoef, 2001). To overcome these barriers, and also to make sure buildings in use perform efficiently energy and comfort wise, the initial construction process needs to extend beyond handover. An

increasingly recognised way to do so is post occupancy evaluation (POE). Zimring and Reizenstein (1980) define POE as the 'examinations of the effectiveness for human users of occupied design environments'.

In 1999, the PROBE (post-occupancy review of buildings and their engineering) project looked at 16 state of the art newly built non-domestic buildings to identify ingredients for success and common operating issues to provide practical feedback for the building services industry (Cohen et al., 2001). The process consists of two site visits made by experienced surveyors and collection of energy and occupant satisfaction data via existing industry tools: Energy Assessment and Reporting Method (Field, 2006) and building use studies (BUS) (Arup, 2016). The results of the PROBE surveys have been published in a series of publications called 'Assessing building performance in use' decomposed as follows:

- description of the PROBE methodology (Cohen et al., 2001)
- technical performance synthesis (Bordass, Cohen, Standeven and Leaman, 2001a)
- energy performance synthesis (Bordass, Cohen, Standeven and Leaman, 2001b)
- occupant satisfaction surveys synthesis (Leaman and Bordass, 2001)
- general conclusion and recommendations from PROBE (Bordass, Leaman and Ruyssevelt, 2001)

The study highlighted the need for every building to have a trial period after initial occupancy to evaluate performance, remove small problems that can have a big impact on energy and comfort, and collect information to benefit the industry (Bordass, Leaman and Ruyssevelt, 2001). On the technical level the main issues were poor airtightness, control problems, and systems defaulting 'on' as well as overcomplicated systems (Bordass, Cohen, Standeven and Leaman, 2001a,b, Leaman and Bordass, 2001).

The observations from the PROBE studies have led to the introduction of Soft Landing by BSRIA in 2009 (Way et al., 2009). The objective of Soft Landing is to 1) improve the building services industry by providing feedback to the design team, 2) ameliorate building delivery by looking at buildings' performance in use, and 3) improve building operations by providing a smooth transition between construction and management teams (Way and Bordass, 2007). The process is based on PROBE methodology and involves keeping design and construction stakeholders engaged in the project for its first three years of operation. PROBE and soft landing post-occupancy evaluations mainly use information

from knowledgable surveying, questionnaires to occupants, and ready available data such as utility bills. Even though the idea is growingly accepted, its implementation is far from widespread. This could change from 2016, when all centrally funded government projects will have to undergo a government soft landing process (Bateson, 2015). Government soft landing is a version of soft landing adapted for publicly funded project.

POE is also a growing concept in North America, but lacks systematic implementation as well (Zimmerman and Martin, 2001). Andreu and Oreszczyn (2004) argue that the feedback loop also need to include the architects as they make decisions that have direct impact on the energy and environmental performance of the final building.

POE presents many potential benefits:

- continuous improvement of the industry (Zimmerman and Martin, 2001)
- improved occupants' satisfaction and productivity (Zimmerman and Martin, 2001, Göçer et al., 2015)
- improved agreement between brief, design and occupants' use (Zimmerman and Martin, 2001)
- improvement of professional reputation (Bordass, Leaman and Ruyssevelt, 2001)
- use as benchmarking to improve future projects (Göçer et al., 2015)
- reduces operational costs (Zimmerman and Martin, 2001)

Despite the long-term benefit of POE, its acceptance as a standard procedure is hampered by the following factors:

- need for experienced assessors to perform it (Bordass, Leaman and Ruyssevelt, 2001)
- the split incentive between who pays and who gets the benefits (Zimmerman and Martin, 2001)
- project budgets no longer available for time allocation (Andreu and Oreszczyn, 2004)
- owners' fear to lose revenue if POE results are bad (Zimmerman and Martin, 2001)
- lack of effective data and knowledge management (Bordass and Leaman, 2005)

Olivia and Christopher (2015) classify POE in three categories depending on the main objective of the survey: 1) give feedback to designers, 2) improve building performance,

and 3) confront performance with general knowledge. PROBE fits in category (1) and soft landing sits across (1) and (2), while Menezes et al. (2012), who propose to use POE data to improve the accuracy of energy performance models, stand in (3). Their aim is to use POE monitoring data to replace design assumption by real values to get a more accurate prediction of energy use.

2.3.4 Operation and maintenance

In process industries, operation would be relatively constant once the process is started, but building operation needs to be constantly adjusted to overcome climate and activity influence, and to keep the building within occupants' comfort zone. This means that good in use performance requires good management and maintenance of building systems otherwise the performance will drop overtime. The operation and maintenance phase (O&M) can also be the occasion to implement continuous improvement.

Facilities management

The facilities managers (FM) are in charge of the operation and maintenance of the building once it has been handed over. The work of FM is divided in two types of tasks: 1) Daily operation and 2) Preventive maintenance (Lee and Akin, 2009). Lee and Akin (2009) found that 12% of the time spent by FM goes towards information retrieval. Therefore, efficient information systems are needed. However, at the moment, because of a lack of training and inadequacy of the available tools, tradespeople tend to rely more on memory and data are lost because log books are not updated, passwords are lost, or staff changes (Lee and Akin, 2009). Research to use IT to improve facilities management is carried out (Shen et al., 2010). BIM is an important part of this, but efforts need to be made to ensure BIM models incorporate functions needed for FM (Becerik-Gerber et al., 2012). IT solutions will need to be coupled with better training of FM personal to make sure the systems are used at their full potential and not left in a corner.

Controls

After handover, control systems like BMS (also called BEMS for building energy management system depending on the country) will take care of building operations. The objectives of control systems are to deliver comfort and reduce energy consumption. At the most basic level, control strategies are based on set points, dead bands to avoid systems

switching modes all the time, and schedules. With the increasing complexity of systems and the requirement of closer comfort control, innovative solutions are needed. Based on the developments of computational intelligence a lot of research is carried out in the field of advanced control systems (Dounis and Caraiscos, 2009). Fuzzy logic, neural networks or genetic algorithms, as well as agent based intelligent systems can be used to provide a better interaction between controls and humans (Dounis and Caraiscos, 2009).

This can result in an over-complexity of control strategies. Brager et al. (2015) argues that the constraint on close comfort tend to be too tight and do not necessarily result in the expected level of comfort. Bordass and Leaman (1997) point out that the users are more satisfied if they are in control and that control strategies should allow occupants to override them. To help with decisions regarding new control strategies, Mathews et al. (2000) propose a tool to assess cost and energy efficiency of a control strategy. In a case study example, they predicted 34% energy savings. In any case, the real performance of a control strategy can only be assessed once the building is occupied and room for adaptation need to be left.

Energy management

The Building Regulations require energy metering to take place to enable at least 90 % of the energy to be traceable to its end use and to specifically meter production of renewable systems. In addition, buildings whose useful floor area is greater than 1000 m^2 require automatic meter reading and data collection facilities (HMG, 2013). Jones (2012) argues that there are many problems with how sub-metering is done in the UK and that it requires better training, guidance and regulation to be beneficial on all buildings.

In any case, the generalisation of sub-metering means that a lot of energy data are now available in new buildings where the Building Regulations have been implemented. Chou and Telaga (2014) propose an algorithm based on neural networks to detect abnormal energy consumption in real-time. Energy management require a benchmark to compare normal operations against. This might be done with historical data and machine learning, or using building simulations (de Wilde et al., 2013). Costa et al. (2013) propose to remove the need for experts' experience to do advanced energy management by integrating in a single tool-kit BIM as data management system, fault detection and diagnosis tools and energy models.

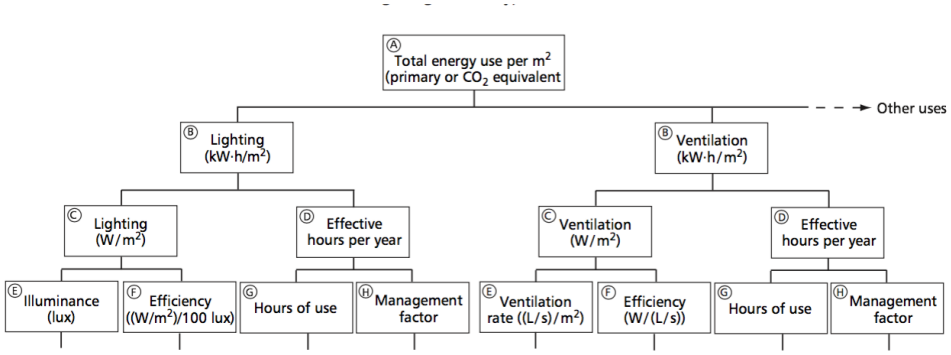


Figure 2.2: TM22 energy benchmark methodology (Field, 2006)

Benchmarking

Benchmarks are a useful tool to put building performance in context compared to other buildings of the same type. This is the logic behind DEC for example. CIBSE Guide F regroups all the benchmarks available in the UK and their limitations for different types of buildings (Cheshire, 2012). Based on those data, 'TM46 - Energy benchmark' (Field, 2008) proposes a technical guide on how to use the benchmarks, including explanation of separable energy use and correction for weather and occupancy. 'TM22 - Energy assessment and reporting technology' (Field, 2006) proposes a component benchmark to use for energy audits or on bad performing buildings (Figure 2.2). The iSERVcmb project has worked on a methodology to provide a more precise component energy benchmark that depends on the type of system and the load required by the space (Knight, 2014).

FDD

Fault detection and diagnosis (FDD) consists in combining real data and models to detect problems in the system and identify where they come from. Intensive research is carried out in this field to help with remedying common HVAC's faults. IEA Annex 25 and 34 completed extensive work on FDD for HVAC (Hyvärinen and Kärki, 1996, Jagpal, 2006). Katipamula and Barambley (2005a,b) review FDD for HVAC systems and propose a classification for the different FDD methods (Figure 2.3).

Quantitative model-based methods are the most accurate as they are based on detailed first principle models but they are usually too time and thus cost consuming for applications in the building industry at present. Qualitative model-based methods use causal

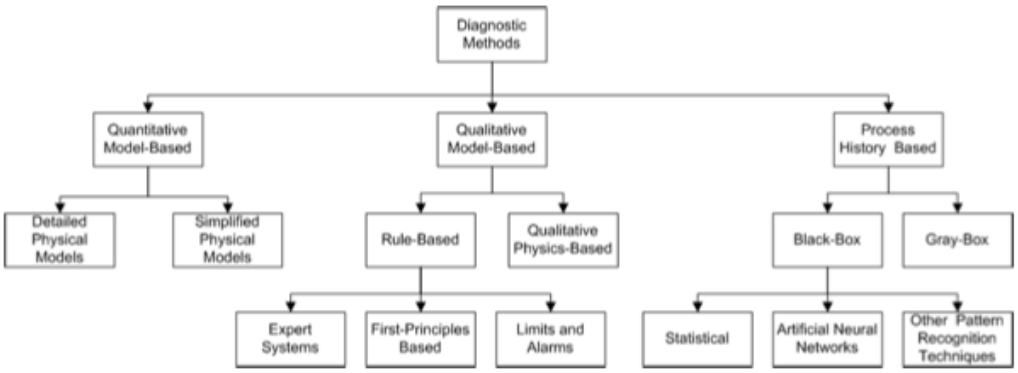


Figure 2.3: Classification scheme for FDD methods (Katipamula and Barambley, 2005a)

relations to interpret qualitative data. The causal relations can come from a set of rules or be derived from physical relationships. Because parts of the measured data are likely to be quantitative data, they need to be converted using fuzzy logic. Those methods can be relatively easy to implement but depend on the competence of the developer, as they are specific to each system. Finally, process history data-based methods use history data to train a model with little or no connection with physics to diagnose faults. It depends on the availability of extensive data for different failure modes.

FDD methods are a useful tool to improve HVAC operations if the necessary monitoring is in place. The challenges FDD is facing are that 1) most methods are system-specific, 2) fault detection is limited to the ones the system is trained for, and 3) they usually assume faultless systems to train the model and detect deviations. Research is required to find simple and transferable methods to evaluate HVAC performance.

Ongoing commissioning (O-Cx)

Ongoing commissioning aims to regularly or continuously reviews the building and its systems' performance to prevent them from drifting or to improve them. A variety of methods have been researched to achieve this. For example, Bruton et al. (2013) suggest establishing O-Cx with FDD methods. Wang et al. (2004) developed a model to measure when filters need to be changed. Most O-Cx methods naturally use BMS data and propose methodologies to make a better use of those data (Feng et al., 2012, Zmeureanu and

Vandenbroucke, 2015). Zibin et al. (2016) propose to use BMS data to automatically calibrate energy models that then can serve as a base for continuous monitoring. Keuhn and Mardikar (2013) note that degradation of the BMS system is often responsible for energy performance degradation and recommend a system-wide programme to periodically review BMS systems.

A comprehensive on-going commissioning method, called Continuous Commissioning® (CC®), has been developed by the Energy Systems Laboratory at Texas A&M Engineering Experiment Station. The process is defined as follows:

> "Continuous Commissioning® is an ongoing process to resolve operating problems, improve comfort, optimise energy use and identify retrofits for existing commercial and institutional buildings and central plant facilities." Liu et al. (2002)

CC® consist in six steps (Claridge et al., 2004): 1) an initial survey to determine the potential benefit of CC® on the building, 2) the installation of initial monitoring to calculate an energy baseline, 3) a survey of the facilities to solve problems and understand energy use, 4) commissioning major equipment to building needs, 5) commissioning entire building to building needs, 6) on-going monitoring. Steps 3 to 6 are then repeated as required. Different tools have been developed to support the process. Detailed methodology can be found in (Liu et al., 2002). Claridge et al. (2004) report that on 150 buildings undergoing CC® the process has resulted in average to 20% energy savings for a pay back time of 2-3 years.

With a similar methodology, monitoring based commissioning (MBCx) combine periodic Re-Cx with continuous monitoring to ensure persistence of energy-saving measures. Minnesota Center for Energy and Environment implemented MBCx on 227 buildings to move away from an audit like Retro-Cx process where the assessor would not spend more than 20 hours on-site and thus have a limited view to the building operation (Plum et al., 2013) and achieved an average of 7.2% savings.

2.3.5 Gaps in research for improved building operation

Once the building is in use the controls play a major role in the energy efficiency of the building. Bad sensor calibration or location, or inappropriate control sequence setting can

have a big impact on energy consumption and comfort. Therefore, it is important for the controls to be properly commissioned. This includes testing the control strategies in the building in use.

Also, most of the maintenance and other operating strategies are based on detecting degradation of performance, thus assuming that building operation was optimised at the beginning. This is one of the reasons why initial commissioning for energy efficiency is critical for total building energy consumption reduction, but it has attracted relatively little attention in the literature. A literature review on commissioning can be found in the following section.

2.4 Review of commissioning tools in the literature

Borrowed from process engineering, commissioning historically was about starting up the building systems. With the increasing complexity of building systems as well as indoor air quality problems (Sterling and Collett, 1994), commissioning has turned into a quality assurance process meant to demonstrate to clients and regulators that the building has met an acceptable standard. With the current push towards energy efficiency it is also becoming a key process for the building life cycle energy consumption.

2.4.1 Overview on the different types of commissioning

An important part of the literature about commissioning focuses on O-Cx, which can be assimilated to advanced monitoring for maintenance and energy management. Part of the tools developed for Retro-Cx and Re-Cx can be adapted to I-Cx, but most of them involve evaluation of retrofit measures or historical data. In Annex 47, out of 18 developed tools only 5 are applicable to I-Cx (Neumann et al., 2010).

To improve the energy efficiency of retail buildings, Loh et al. (2015) recommend including Re-Cx as part of the normal maintenance process. By applying Retro-Cx to a LEED gold building , Schmits et al. (2015) demonstrated an 11.4 % energy saving. Mills and Mathew (2014) reported a median 11% energy saving and 2.5 years pay back on a 24 buildings portfolio study after MBCx.

O-Cx, Retro-Cx and Re-Cx are all useful processes to improve building operations. However, for buildings to be fully efficient, it is important to ensure good realisation of their design and to optimise them at the beginning of their life cycle and after every major refurbishment. However, due to the desire to occupy buildings as soon as possible, the I-Cx programme almost always gets compressed (York, 1998) and Cx is often limited to 'practical completion', allowing non-critical faults to remain. However, those faults might have significant consequences on energy and comfort efficiency. In addition, a testing sequence that takes place over a couple of weeks in an empty building cannot account for climate and occupants influence on the systems' operation. However, limited attention has been paid in the literature to the initial commissioning process especially considering tools to improve the process.

2.4.2 Commissioning tools

To enable the good realisation of commissioning, construction professionals need dedicated tools. Guidelines and checklists developed by professional organisations or local authorities are commonly available to professional. For example, Ginestet et al. (2013) cite PECI[2] as providing a good method to detect a certain number of faults such as air leakage, sensors inversion, etc., even though other issues such as control and programming faults, or bad balancing are not taken into account.

Complementary tools to facilitate commissioning are being researched. IEA's ECBCS programme has dedicated two annexes to commissioning. The IEA annex 40 team has worked on manual functional testing procedures, BMS assisted tools and applications of models for Cx (Visier, 2004). In annex 47, the focus is on automated functional testing and FDD, data visualisation tools, and cost-benefit analysis tool for Cx existing buildings (Neumann et al., 2010). As mentioned before most of the tools developed are for existing buildings.

Tools for initial commissioning found in the literature can be classified under the following categories: procedures, information management, automation of commissioning procedures, modelling for commissioning, and data collection and visualisation.

[2]http://www.peci.org

Procedure

Menassa et al. (2013) propose a procedure for the commissioning of natural ventilation strategies in a mixed ventilation building without the need for complex airflow model. The method can be applied while the building is occupied and is thus suitable for I-Cx and existing building commissioning. Gillis and Cudney (2015) propose to use a four phases quality function deployment, a quality insurance process used in product development and manufacturing, to provide standard criteria to verify the owner's project requirements (American equivalent of the client's brief) is met.

Information management

Nakahara et al. (2004) propose to use a Model Quality Control matrix designed under MS-Excel to manage Cx information. The multilayered spreadsheet links to document and contact to make information easy to access and also provide an inventory of the activities and information necessary to complete commissioning. In a similar way, Hoel et al. (2004) present a framework for a database to facilitate access to information and preparation of documentation. The second option might be more efficient, but with the current trend in the industry the first one would have more chance to be accepted, as stakeholders are more familiar with Excel. In the future, information management for commissioning is likely to be embedded in BIM on larger projects (Wu and Issa, 2012).

Automation

Tools are being developed to automate commissioning procedures such as functional testing. Wang and Wang (2002) propose an FDD method using heat and mass balance residual to identify BMS sensors' bias of a refrigeration system. It can be used for I-Cx and existing building commissioning. CITE-AHU enables automatic testing and analyse of AHU using BEMS (Castro and Vaezi-Nejad, 2005). It is aimed at being used out of the box and at reducing the level of skills required for retro commissioning. It is able to detect and diagnose many AHU common faults, such as sensor temperature fault, wrong valve position, etc. (Ginestet et al., 2013). Since it does not use long record of historical data, it should be usable for initial commissioning if the appropriate sensors have been installed.

Modelling

A lot of modelling used on operating building is based on historical data being available. This is not an option for initial commissioning. Kelso and Wright (2005a,b) suggests using model-based FDD models based on first principle or empirical relationships using design intent values as expected output to overcome this. They implemented such a model for AHU automated functional testing. It was able to detect real and simulated faults. Djuric et al. (2007) propose to use modelling tools and first principal relations for Retro-Cx of bad performing energy saving systems. In a demonstration on a ventilation system with heat recovery wheel, the model was able to find better energy management control and predicted saving between 15 and 30 % if implemented. The method could be used to verify system performance in a new building.

It is important to know the competence level required to use each tool. For example, according to Ginestet et al. (2013) PECI guides require a low level of expertise, when tools like AHU-Cite require an advanced level of expertise. This conditions which stakeholders will take responsibility for the commissioning task. Automation and modelling tools reviewed here present the disadvantage that they need to be customised for each type of system, which makes their implementation costly due to the diversity of building systems available.

2.4.3 Data collection and visualisation during initial operation

The idea that commissioning need to extend into early operations of the building is not new (Sterling and Collett, 1994), but seems to be limited to when major problems remain at handover. A few attempts have been made to overcome this.

Isakson et al. (2004) used the available BMS data of two buildings in Sweden to provide seasonal commissioning during initial occupancy. They worked on automating the realisation of trend-data diagrams from the BMS data. The analysis process of these data was visual and was only done every six months. It means faults could go undetected for a while. This visualisation tool enabled the researchers to identity a significant number of problems, for example outdoor temperature sensors malfunction, or ventilation systems operating longer than expected at night. Unfortunately due to change of ownership, those problems were never solved.

Painter et al. (2012) worked on an overlay of sensors to understand the behaviour of a naturally ventilated building and perform Seasonal Commissioning (S-Cx) of its BMS system. They used standalone data loggers to monitor temperatures and CO_2 concentrations. The study demonstrates that CO_2 sensors are preferable to volatile organic compound (VOC) air quality sensors for air quality monitoring. Looking at the commissioning process on the same building, Short et al. (2009) observe that complex naturally ventilated building need an intensive commissioning phase extending after handover to make sure they operate defect free. They point out that for this type of building it is especially important to test control strategies in real weather conditions, making a short commissioning period inadequate.

Those are good examples of how sensor data can be used at the building early life cycle stage to improve its operation. The methods are easy to adapt to fully equipped buildings with different types of systems. Isakson et al.'s method relies on the BMS system to be fully functional. However, during initial commissioning, the BMS can only be properly commissioned once all the systems have passed electrical and mechanical tests. BMS is thus the last system to be commissioned and its commissioning tend to still be on-going after handover. It is thus difficult to rely on the BMS to perform in-use fine-tuning right after occupancy. The designers are likely to have disengaged from the project by the time the BMS is ready for this kinds of process. In the case of Painter et al. (2012), the availability of these additional data provided insight on the building operation, but the use of standalone data loggers turned out to be time consuming and the use of WSN is recommended by the authors. It can therefore be concluded that more research is needed to elaborate a more comprehensive commissioning tool-kit and strategy for commissioning new and retrofitted buildings in use.

2.5 Review of building systems monitoring and data acquisition methods

With the fast development of new technologies, the possibilities to improve building energy efficiency have increased. This section starts by reviewing the main sources of these inefficiencies before looking at the different applications of building monitoring. Data ac-

quisition techniques and in particular WSN are then reviewed.

2.5.1 Typical faults and sources of inefficiency

To know how to implement any monitoring strategy it is important to have an idea of the kind of problems that will need to be addressed. A number of research projects have sought to identify what the common faults within buildings were. During its international investigation about commissioning, the team for IEA annex 47 observed that the systems where most faults were identified during commissioning are air-handling systems, heating water plants, and chilled water plants (Ferretti and Choinière, 2010). The faults can come from design, construction, commissioning or operation (Ferretti and Choinière, 2010).

The work of IEA Annex 25 (Hyvärinen and Kärki, 1996) aimed at identifying and ranking the possible operating failures of HVAC systems for FDD. The faults are drawn from typical problems encountered by O&M. Table 2.1 lists the ones that were given the greatest importance for heating systems, chillers and heat pumps, and AHU. The importance of the faults have been determined through interviews of professionals and was weighted against their impact on the occupant's comfort, their impact on energy consumption, the frequency of the fault, the severity of the impact on the system, and ease to fix the fault. Some of those faults are difficult to fix once the building is operating. For example, wrong sizing requires major retrofit, which is unlikely to be done for cost reasons. Problems linked to human behaviour are also difficult to act upon. Parts of those faults are linked to building performance degradation and would not be present in a new building and are thus not relevant for initial commissioning. It is interesting to notice that in the fault relevant to commissioning, a lot are related to sensor problems (sensor failure, wrong location, wrong wiring...).

One of the results of the PROBE surveys described in Section 2.3.3 was to identify the common problems found in new buildings. Table 2.2 summaries those common sources of inefficiency for the whole building (Bordass, Cohen, Standeven and Leaman, 2001a, Leaman and Bordass, 2001). Most of these issues need to be acted upon at the design stage, which is coherent with PROBE's objective of giving feedback to designers.

The faults found in the literature tend to be either oriented for design, or maintenance and operations. More research is needed to better understand the faults that should be

Table 2.1: Typical faults of HVAC systems encountered by O&M (Hyvärinen and Kärki, 1996)

System		Failure
Heating system		Bad boiler efficiency
		Defect of sensors (water flow, gas flow)
		Defect of manometers (boiler, gas expansion system)
		Leak of the gas tank
		Boiler, radiator or pump size wrong
		Blockage of boiler pipe and heat exchanger
		Zone temperature too low
		Thermostatic valve defect
		Leaks in pipes
		Defect in valves (three-way valve, non-return valve)
		Heating imbalance between different parts of the building
		Poor hydraulic balance between circuits
		Indoor temperature measurement sensors placed in a non-representative room
		Heating curve badly tuned
		Incorrect calculation of the optimum start or stop by the operational mode controller
		Poor combustion
		Scaling and dirt accumulation in the boiler's heat exchanger
		Leakage of the three-way/two-way valve of the control of secondary circuits
		Deposit of scale on the exchanger of domestic hot water
Chillers and heat pumps	Compression	Lack of refrigerant
		Presence of air in the refrigerant circuit
		Presence of refrigerant in the lubricating oil
	Absorption	Loss of vacuum
		Clogging of condenser tubes
		Clogging of evaporator tube
AHU		Poor air quality due to occupant smoking
		Water leakage from piping due to improper thermal insulation
		Room air temperature deviation due to excessive heat generation
		Room air temperature deviation due to inadequate airflow rate through air diffuser
		Too little or too much air volume in the VAV due to failure of the dumper to adjust
		Clogged air filter
		Abnormal noise or vibration in the ducts
		Room air-temperature deviation due to inadequate position of the diffuser
		False opening signal of the VAV unit due to improper location of the room air thermostat
		Room air temperature deviation due to insufficient flow rate due to contaminated air in pipes

Table 2.2: Summary of inefficiency sources highlighted in the PROBE project

General
Routine operation assumed in brief and design do not match reality
Not enough FM resources compared to the complexity of the systems
Lack of control for the occupants
Access difficulties, meaning building manager will not easily make changes
Poor airtightness
Not enough thoughts regarding potential problems connected to innovation
Rushed handover
Noisy environment (slamming doors,. . .)
Passive measures
Building envelope
- Gap in the fabric (due to increased use of prefabrication)
- Motorised window not airtight when shut
Window and blind design
- Daylight not used because of glare and reduced computer screen visibility
- Poor usability (windows not accessible, windows do not stay open)
- Inappropriate automatic controls (no manual override,. . .)
Advance natural ventilation
- Issue of responsibility for installation and commissioning
- Difficulty to get the controls to work
- Poor reliability of novel components
- Insufficient understanding of occupants' perception and lack of manual override
Mechanical services
Air-conditioning
- Chilled beams and displacement ventilation saving cancelled out by
+ high preheating and humidification loads,
+ extended running hours to compensate infiltration through the fabric,
+ lack of on-site engineer to fine-tune the system.
- Humidification system running regardless of whether it is needed
- Mixed mode system working as fully air-conditioned
(natural ventilation measures not understood by occupants)
Electrical services
Artificial lighting and its control
- Lighting provided when there is good daylight
- Bad integration with local controls
- Not taking account of the cleaners' needs
- Safety requirements lead to unnecessary loads
Controls
- Poor sequencing of boilers
- No sequencing of chillers
- Pump running extended hours
- Heating and humidification continuing operation in warm weather
- Poor user interface of the BMS
- Small 24 hours loads lead the rest of the system
ICT
- ICT equipment left on constantly

fixed by I-Cx at the beginning of new buildings' occupancy.

2.5.2 Building monitoring techniques and application

The requirement to commission a building beyond handover calls for adapted monitoring techniques. In the past decade reduction of sensors' cost, the development of new computational possibilities, and emergence of concepts such as the Internet of Things have opened the door to new possibilities regarding building monitoring. This lead to the generalisation of the installation of extensive BMS in new commercial buildings and researchers have been looking into how to make the best use of this new capability. This section gives an overview of the latest research developments using building monitoring to improve building energy issues.

Monitoring overview

Talking about POE, Preiser (2001) distinguishes three levels of enquiries. This classification is also relevant for monitoring. Reflecting the order of increasing costs, the three levels are: *indicative* that consist in verifying performance, *investigative* if the objective is to gather information for future designs, and *diagnostic* for processes that aim at finding ways to improve performance. Similar levels of depth of performance evaluation can be found in (ASHRAE, 2012) as basic evaluation, advanced analysis, and diagnostic measurements. Olivia and Christopher (2015) underline the key steps to set up a successful monitoring strategy as being: knowing 1) the objectives of the evaluation, 2) its subject, 3) the type of feedback wanted, 4) which stakeholders are interested in them, and identifying 5) the types of indicator and 6) the resources available to conduct the evaluation.

Monitoring applications

Building monitoring can have a wide range of applications, the first of them begin to improve smart controls (Chu et al., 2005, Paulson et al., 2013). Piette et al. (2001) propose an information monitoring and diagnostic system, based on high-quality sensors, communication hardware and software and a web-based interface for data visualisation, to improve BMS operations. The tool is found to free time from FM for other tasks and to save energy leading to a 5 years pay back. Vakiloraya et al. (2013) use measurements to determine the optimum temperature set point of a central cooling plant. Sensor data can also be integrated with occupants' feedback on their comfort using social media to improve com-

fort control (Yun and Won, 2012). Extra sensory data can also facilitate the integration of FDD to BMS (Costa et al., 2013).

Similarly, there is a wide range of projects using sets of sensors for energy monitoring. Brown et al. (2010) monitored gas, electricity and water on 300 buildings to investigate how to use sub-hourly energy data. They argue that energy data are still used as daily or weekly readings even though there is much more information available. Lin and Hong (2013) used the energy simulation tool EnergyPlus to compare space heating demand calculation using the standardised US weather to 30 years of actual weather data in two different climates on two different office building types. The energy consumption prediction could vary from 25% in excess to 34% of underestimation. Thus, the necessity to monitor weather to understand building energy consumption.

MBCx (Mills and Mathew, 2014, Harmer and Henze, 2015) and CC® (Claridge et al., 2004) also make use of monitoring tools to lead to building improvident. Göçer et al. (2015) propose to use BIM and geographical information systems (GIS) to visualise and analyse POE data.

Building data can also be compared to model-based energy benchmarks to detect abnormal building operations (de Wilde et al., 2013, Lin and Hong, 2013, Teyssedou et al., 2013). Morrissey et al. (2004) propose to integrate BMS measured data in BIM together with benchmark metrics (building codes, and manufacturer's specifications) and simulated data to track building performance during its whole life cycle. Finally, access to real data enables to fine tune design and energy models to have better comparison points with building operations. Woo and Gleason (2014) integrate WSN data to BIM to build benchmark models for energy management. Raftery et al. (2011) demonstrate how to calibrate building energy models using half-hourly energy measurements. Hajdukiewicz et al. (2013) also use real-time data to calibrate CFD models aiming at understanding thermal comfort.

Beyond commercial applications, access to good building data can also contribute to better education and training, improved research quality and better tools for policy makers (Hamilton et al., 2015).

Occupancy

With the end goal of feeding real data to energy models, Mantha et al. (2015) inventory the following parameters to take into account for building energy monitoring:

- static parameters
  - primary building information
  - building materials
  - building orientation
  - building zones
- dynamic parameters
  - weather data
  - occupancy data
    - schedule information
    - occupant comfort information
    - occupancy characteristics
  - energy use
    - hot water
    - heating, ventilation, and air-conditioning
    - lighting
    - plug load
    - equipment data
  - water use

Most of those data have well established ways to be collected. However, occupancy is more complicated and is the subject of a lot of research. Occupancy is increasingly acknowledged as an important metric to monitor. It is widely used to implement demand-base control strategies or for security purposes. Occupancy can be evaluated using direct observations or surveys, but those methods are time and labour intensive. Using sensors is a cheaper way to access this information. Different sensing techniques have been investigated to sense occupancy, mostly for the purpose of demand driven controls. This includes passive infrared (PIR) motion detectors (Dodier et al., 2006, Caucheteux et al., 2013), video cameras

(Liu et al., 2013, Shih, 2014), RFID (Li et al., 2012), microphone (Kelly and Horn, 2015), Wi-Fi connections (Chen and Ahn, 2014, Martani et al., 2012), device-free localisation (Naghiyev et al., 2014), chair sensors (Labeodan et al., 2015), CO_2 (Emmerich and Persily, 2001) or a combination of those (Zhang et al., 2012, Lam et al., 2009, Ekwevugbe et al., 2013).

Among those methods CO_2 is of particular interest as it is related to the number of people present while preserving privacy. It has been widely used in the field of demand controlled ventilation (DCV) (Emmerich and Persily, 2001). However, it is difficult to give a direct relationship between the CO_2 concentration in the air and the precise number of occupants. Indeed, CO_2 concentrations also depend on room size, ventilation rate, exfiltrations, metabolic rate, and activity of the occupants (Naghiyev et al., 2014).

Divers models have been proposed to account for these factors. For example, Lawrance and Braun (2007) propose a model using mass conservation to predict CO_2 source generation in public spaces. The model shows good prediction with an 8 weeks learning period, but would only predict the occupants with an accuracy of $\pm$ 4 persons. Tuip et al. (2010) use the difference of CO_2 concentration between the supply and exhaust ducts to predict occupancy and obtained an accuracy of 1.9 occupants with 4 weeks training of the model. Requiring to a training period is acceptable for a long-term application like DCV or FDD, but would not be adapted for short-term deployment like building commissioning.

CO_2 sensors also present accuracy related problems (Fisk et al., 2006), which further complicate the implementation of physics-based models. This can be due to poor absolute calibration, calibration drifts or poor accuracy of the sensing technology. Another known drawback of CO_2 for occupancy sensing is its response time (Meyn et al., 2009), but this is a real limitation only for real-time controls. If the signal is not used in real time, it is possible to compensate for this during data processing. Research is needed to be able to sense occupancy without training or calibration of CO_2 sensors.

Data processing

With the increasing ease of getting almost limitless data, the new paradigm of 'big data' has appeared. It provides new opportunities, but new methodologies are needed to make use of these data. The following paragraph gives an overview of the solution under development.

Big data technologies are increasingly used to extract data from large data sets. Data mining is used to find relevant information in a data set. Yu et al. (2012) and Xiao and Fan (2014) use association rule mining to look though operational data. Domínguez et al. (2013) use data mining techniques on a campus energy monitoring system to detect faults. Yun and Won (2012) use a clustering method on humidity and temperature from a ZigBee wireless nodes associated with social media feedback to determine comfortable environmental condition as a control strategy for the HVAC system. Abreu et al. (2012) use pattern recognition for electrical consumption to help with behaviour change.

Machine learning uses algorithms that can predict outcomes based on data history. A type of machine learning commonly used with building data is Artificial Neural Networks (ANN). For example, Tuip et al. (2010) use ANN for FDD to correct expected energy consumption for weather and occupancy. Wang and Chen (2002) use ANN for DCV.

Sensor fusion is used to combine divers sensory data to reduce the uncertainty of information. It is used notably for occupancy detection (Ekwevugbe et al., 2012). Fuzzy logic is also used to take into account phenomenons that do not have a strict quantitative definition like comfort (Chu et al., 2005). Klein et al. (2012) use multi-agent system to coordinate occupants' behaviour, comfort and energy.

However, implementing those tools often require customisation to fit each different building and thus require specialist knowledge that is not necessarily present in the industry at the moment. Piette et al. (2001), Isakson and Eriksson (2004), and Raftery et al. (2011) look at ways to improve data visualisation tools to facilitate fast analysis of the data by FM teams.

2.5.3 Potential and challenges of WSN in buildings

Collecting data requires sensor and data acquisition technology. This section reviews the different methods available in the building context and how they are relevant for commissioning. Wireless sensor network technologies are discussed more in detail as the author identifies them to be the best candidate to assists with commissioning in a building in use.

Table 2.3: Comparison of different data acquisition techniques

System	Wired	Hand-held	Data logger	WSN
Pros	Reliable	Cheap, no set up	Cheap, limited set up	Real-time data
Cons	Wiring is expensive	Labour intensive	No live data	Higher hardware costs
Application	Long-term monitoring e.g. BMS	One-off measurement requiring direct intervention e.g. balancing	Short term measurement e.g. solve comfort problem in one room	Medium term measurements e.g. Seasonal commissioning

Comparison of different data acquisition strategies

There are three different options for collecting data for commissioning: the commissioning engineer can use hand-held, wired or wireless measurement tools (Table 2.3). Hand-held tools are appropriate for performance tests during pre-handover commissioning as the commissioning engineer is required to be on-site to alter settings or demonstrate the measurement. Jeong et al. (2008) compared hand-held, wired and WSN measurement for airflow model tuning of a residential building and concluded hand-held devices enable to get a good snapshot of the building behaviour for steady state applications. On the downside the risk of man-made errors is increased. Overall hand-held measurements are useful for one-off verification or balancing measurements when variation over time is not of interest.

Wired sensors usually collect data for the BMS or other permanent monitoring purpose. The extra cost of wired installation is justified by the fact that the sensors will stay in place for an extended period and the possibility to draw power from the main electrical supply. Wired measurements tend to be more reliable. For commissioning applications, the time frame is usually not long enough to justify specific installations, but existing monitoring facilities can be used to facilitate the process, especially in the case of seasonal Cx (Isakson et al., 2004), Re/Retro-Cx (Wang and Wang, 2002) and O-Cx (Feng et al., 2012) where the building's BMS is fully running.

Wireless measurements can be taken using standalone data loggers or wireless sensor networks (WSN). Standalone data logger presents the advantage to enable rapid measurement of the temporal behaviour of a variable. The measurement can be left in place

for as long as the battery and the memory of the device last. As an example, a simple temperature and humidity logger can last up to one year and take 32,510 measurements[3]. However, Painter et al. (2012), who used data loggers to perform commissioning in-use on a naturally ventilated building, report that this method is time consuming for large data collection, especially if intermediary analysis is needed, as the project required more data than initially anticipated. Standalone measurements are a good method for small-scale data collection when analysis can be done retrospectively.

Benefits of WSN measurements over other techniques include portability, flexibility, fast set up, time synchronisation, limited disruption for occupants and cost savings on installation time (Jeong et al., 2008) and the possibility to accommodate for changes in space use (Kintner-Meyer, 2005), which can balance the fact that the initial equipment cost is slightly higher than wired equivalents (Kintner-Meyer and Brambley, 2002) and that their communication can be less reliable. WSN require a bit more knowledge to install. However, they enable to access the data in real time like a wired system but with an easier and cheaper installation, as the communication and power do not require wiring. WSN can thus be a good option for medium-term deployment. They also present the advantage to give access to regions where power is not available or human presence could be a problem. For commissioning in use, WSN are the best way to obtain the dense data required. WSN in building application are further developed in the following sections.

Application of WSN in buildings

The concept of WSN first appeared in the 1960s (Iyengar and Brooks, 2005). It was used for military purpose and was enabled by the progress in radio transmission. The first commercial applications appeared in the years 2000-2002 (Wheeler, 2007). It is now employed in a variety of fields including environmental monitoring (Mainwaring et al., 2002), or divers fields of civil engineering such as structure health monitoring (Kim et al., 2007).

This new technology is also penetrating the building market and different communication protocols are in use. A comparison of some of those protocols is presented in Table 2.4. Wi-Fi is wildly used for mobile computing applications. It provides a high data rate, which results in high energy consumption (Kintner-Meyer, 2005). This does not make it suitable for sensor applications where battery life is a key concern and high data rate is

[3]http://www.lascarelectronics.com/

Table 2.4: Comparison of wireless protocols (Guo et al., 2010)

	Wi-Fi	**Bluetooth**	**ZigBee**
Bandwidth	Up to 54 Mbps	1 Mbps	250 kbps
Current draw (trans.)	400 mA	40 mA	30 mA
Current draw (standby)	20 mA	0.2 mA	$< 0.1\mu$A
Protocol stack Size	100 KB	100 KB	4-32 KB
Transmission range	1-100 m	1-10 m	1-100 m
Battery life	0.5 - 5 days	1-7 days	100-1,000 days
Network size	32 nodes	7 nodes	>64,000 nodes
Throughput	11,000 kb/s	720 kb/s	20-250 kb/s
Strength	High data rate	Interoperability, cable replacement	Long battery life, low cost
Application	Web, email, video	Cable replacement	Monitoring and control

not a requirement. Bluetooth and ZigBee achieve lower energy consumption and are more adapted to low data rates (Lee et al., 2007). Bluetooth is mostly used for wireless mouse and keyboard or phone headsets, but for WSN applications it would only achieve 1 week to 1 month of battery life when the practical requirement would be 3 to 5 years (Kintner-Meyer, 2005). IEEE 802.15.4 (IEEE 802.15.4, 2006) however was developed specifically for low data rate and low power applications (Kintner-Meyer, 2005).

Based on IEEE 802.15.4, the ZigBee Alliance developed a standard adding logic network, security and application software to provide safety and reliability for low data rate, low power applications (Kintner-Meyer, 2005). The original ZigBee standard was ratified in 2004. It was replaced by ZigBee pro in 2007. Improvements of ZigBee pro over ZigBee include an improved addressing and routing protocol, and asymmetric link detection (Wheeler, 2007). The software and hardware ecosystem around ZigBee, making it easy for non-wireless communication specialists to prototype WSN (Wheeler, 2007), contributed to the wide adoption of the protocol. ZigBee proposes a standardised implementation of IEEE 802.15.4, but ZigBee protocol remains proprietary meaning that ZigBee devices from different manufacturers cannot communicate between them. ZigBee is commonly used in the building context to form part of the BMS, either by interfacing with BACnet, the standard communication protocol for BMS, or through the Internet (Guo et al., 2010).

ZigBee is the most used wireless protocol for building wireless sensing applications, but

alternatives exist, such as 6lowWPAN (Grindvoll and Vermesan, 2012), Enocean[4], Modbus (Sun and Wang, 2011). Some companies also develop their own proprietary protocol (Kintner-Meyer and Brambley, 2002).

WSN applications to the building environment have been researched in the past 10 years. Most of this research aims at improving energy efficiency. The research was organised in four categories (Table 2.5). It was separated depending on whether the application was aimed at domestic or commercial buildings. In some cases, the research can apply to both, but in most cases they are differences due to the fact that the types of systems involved are different. A second distinction was made between 'commercial application' and 'research application'. Research on 'commercial applications' aims at improving existing services, while 'research applications' are about developing new initiatives that were not possible without the current technologies. Researchers are using either custom made nodes or commercially available alternatives to pursue this research.

Current commercial applications of WSN in buildings are mainly home automation, including comfort and safety, commercial buildings HVAC controls applications and, to a lesser extent, utility meter communication (Wheeler, 2007). The different applications of WSN in home automation include divers sensing and actuating systems, which aim at reducing energy consumption. WSN are progressively replacing traditional infrared systems that have the inconvenient to require line of sight (Dominguez et al., 2012). The use of wireless sensors enables to have more complex control of the house to provide energy conservation.

In commercial building the most widespread use of WSN is for HVAC controls and more specifically for controls retrofit purpose. The primary use of wireless sensors for building controls is the use of a wireless room temperature sensor that connects with the control system of the air-conditioning system (Will, 2004). Kintner-Meyer (2005) mentions the use of WSN over wired controls to implement an energy saving strategy that would not be economically viable considering the installation cost of new wired controls. WSN can be an alternative in any control strategy that does not require high frequency data. There are also a few references to potential use with smart meters (Kintner-Meyer and Brambley, 2002), but their implementation using protocols as ZigBee is more complicated

[4]https://www.enocean.com/

Table 2.5: Wireless Sensor Networks for building applications

Application	Wireless protocol	Nodes	Case study	Ref
Domestic building commercial application				
Home automation	Wi-Fi	Sensors and actuators for control systems	Mock-up house	Folea et al. (2012)
HVAC control	ZigBee	Transmitters and receivers	Four residential buildings	Li et al. (2009)
HVAC energy performance and walls moister	NA	Temperature, humidity, energy	Domestic building	Healy (2005)
HVAC control (cooling)	NA	PIR, temperature	Multi-zone domestic building (simulations)	Tachwali et al. (2007)
Home energy management	ZigBee	Lighting, temperature, humidity, etc.	Domestic building	Han and Lim (2010)
Energy management	ZigBee	Motion, temperature, light, relative humidity + optional sensors	Mix domestic and office test bed	Byun and Park (2011)
Smart power meters	ZigBee	Power and power outage	NA	Luan et al. (2009)
Home automation	ZigBee	Power and lighting controls and actuators	Domestic building	Shi (2014)
Smart home application	6LoWPAN	Sensor and actuators for home automation	NA	Serna et al. (2015)
Commercial building commercial application				
HVAC and lighting controls	IEEE 802.15.4 compliant	Actuators and sensors	Industrial assembly line, school, office building	Raimo (2006)
Control system	Proprietary Inovonics commercial mesh network	Temperature	Three office buildings	Kintner-Meyer and Brambley (2002), Kintner-Meyer (2005)
Close loop control	ZigBee	Sensors and actuators	NA	Mansano et al. (2014)
Building controls	NA	Temperature sensors and actuators	Simulations	Cao et al. (2010)
Lighting BMS	NA	Illuminance	Simulations	Mady et al. (2012)
Building environment and energy monitoring	ZigBee	Temperature, humidity, accelerometer, and light sensors	Office building	Wang et al. (2010)
Domestic building research application				
Calibrate airflow models	NA	Temperature, airflow, pressure	Small-scale residential building	Jeong et al. (2008)
Home automation	ZigBee	Window actuator	Three show rooms	Dominguez et al. (2012)
Biomedical home monitoring	ZigBee and Bluetooth	Ambient and body sensors	NA	Maciuca et al. (2013)
Platform to accelerate innovation in energy management	NA	Temperature, light, occupancy, energy meter	Residential and office buildings	Lim et al. (2014)
Enable passive house	ZigBee	Temperature, humidity, CO_2 and light	Homes (and office)	Daniel et al. (2009)
POE for domestic building	NA	NA	NA	Ozturk et al. (2012)
Integration of building information	IETF 6LoWPAN	Sensors, meters and actuators	Housing tower block	Ufuk Gökçe and Umut Gökçe (2014a)
Commercial building research application				
Validation of energetic models	ZigBee	Sensors for energy , climate and operating conditions measurements	Six floor university building	Aguilar et al. (2012)
Energy auditing	6LoWPAN	Energy meter, light sensor and vibration sensor	IT laboratory	Jiang et al. (2009)
Energy data disaggregation	ZigBee	Current	Test bed	Amaro et al. (2015)
Smart lighting control	IEEE 802.15.4 compliant	Ambient illuminance sensor	Living laboratory	Paulson et al. (2013)
Predictive modelling for lighting control	TelosB (IEEE 802.15.4 compliant)	Illuminance sensor	Research test bed building	Basu et al. (2014)
Occupancy based lighting controls	NA	Lighting and occupancy	Simulated office building	Pandharipande et al. (2014)
Energy monitoring	GPRS and MODBUS	Water, flow and energy meters	NA	Sun and Wang (2011)
Miscellaneous and electronic devices energy metering	6LoWPAN	Electricity meters	Office building	Brown et al. (2011)
Monitoring and control	ZigBee	Sensors and actuators	NA	Nanda et al. (2012)
Integration of different communication standards	ZigBee and 6LoWPAN	Temperature, light, humidity and energy meter	Office building	Grindvoll and Vermesan (2012)
Appliance power management	IEEE 802.15.4 compliant	Light, sound, temperature and power-line control	NA	Yeh et al. (2009)
Sub metering for energy benchmarks (retrofit project)	Wi-LEM (IEEE 802.15.4-compliant)	Temperature, humidity, CO_2, and power consumption	Office building	Woo and Gleason (2014)

because the different nodes of the network are much further apart than in a control type application. At the moment most commercial WSN applications are limited to providing similar services as wired systems (Wheeler, 2007).

The applications of WSN mentioned above consist in improving existing sensing application by making them easier and adding functionalities. In addition, WSN open the way for new opportunities that were previously not technically possible. Among those new applications is the use of real measurements to tune building models (Jeong et al., 2008, Aguilar et al., 2012), different levels of energy monitoring (Yeh et al., 2009, Sun and Wang, 2011, Brown et al., 2011, Lim et al., 2014, Woo and Gleason, 2014), including energy performance disintegration (Amaro et al., 2015), or integration with BIM (Ufuk Gökçe and Umut Gökçe, 2014b).

WSN are used for monitoring, but the flexibility of the system has not been exploited for troubleshooting. A few potential applications of WSN of interest relatively to the research gaps identified above and found in the literature are listed below:

- use of a temporary wireless tool-kit for building diagnostics (Kintner-Meyer and Brambley, 2002);
- WSN measurement to assist POE (Ozturk et al., 2012);
- WSN for initial commissioning and repurposing of the nodes during the life cycle (Heller and Orthmann, 2014).

However, none of them give any details about how this would be implemented. Research is needed to investigate how WSN could be used for troubleshooting buildings during I-Cx.

Barriers and future development of WSN

Despite the promising results of the studies mentioned above, WSN is still seldom used in practice. Healy and Jang (2008) identifies the following limitations to a broader use of WSN in the building industry:

- power management
- cost
- reliability

- ease of use and maintenance
- interoperability
- security

Beyond the technical challenges of WSN that are well researched (Akyildiz et al., 2002), those reflect the concern that need to be addressed for the decision makers to trust WSN and use them on their building projects. This section explains those challenges and how they are addressed in the literature.

Power management Power is one of the most important parameters to consider for WSN applications. For short-term measurement campaigns, the battery life needs to be at least equal to the deployment period. For long-term deployment, Healy and Jang (2008) suggest 3-5 years of battery would be necessary for wireless to be chosen over wired measurement. If those conditions are not fulfilled, the added maintenance cost will wave the benefits of the reduced installation cost as wireless equipment tend to have a higher initial cost.

The parameters that influence power consumption are duty cycle, data processing, wireless data transmission and data sensing power (Wang et al., 2011). Research is carried to create energy model to estimate nodes and networks power consumption (Halgamuge, Zukerman, Ramamohanarao and Vu, 2009, Wang et al., 2006), but current models tend to overestimate sensor battery life (Halgamuge, Zukerman, Ramamohanarao and Vu, 2009). In particular trade-off between battery and sampling frequency need to be made. Wang et al. (2011) looked at the energy consumption of wireless nodes for BMS applications. They concluded that the most important parameters to conserve battery for this type of application is the node warm up time, the time elapsed between the node wake up and measurement, and the energy consumption of the node in sleep mode. Because of the low data rate and low duty cycle, the other parameters have less impact on the final consumption. For control applications where high sampling frequency would be a barrier for the use of WSN, Mansano et al. (2014) propose to use virtual data to fill the gap between two measurements.

However, relatively long battery life is already possible. For example, Mainwaring et al. (2002) achieved 9-12 months of battery life using custom made hardware and software, and tight energy budgeting. This was for a habitat monitoring application where power is the

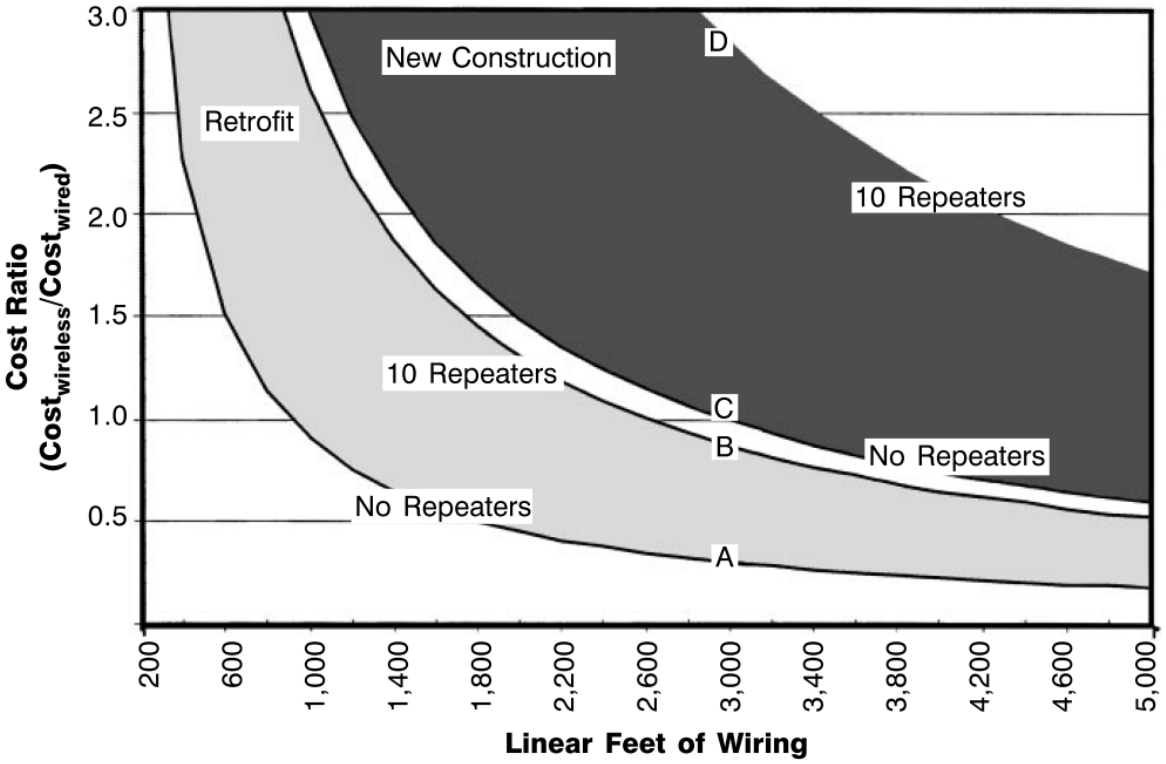


Figure 2.4: Competitiveness of wireless system versus wired system (Kintner-Meyer and Brambley, 2002). Point A: retrofit, no repeater, cost ratio 0.3; Point B: retrofit, high signal attenuation, cost ratio 0.9; Point C: new building, no repeater, cost ratio 1.0; Point D: new building, high signal attenuation, cost ratio 2.9

main limitation as no intervention is possible during the deployment.

In the future battery might be taken out of the equation by the possibility to harvest energy from the environment (e.g. radio frequency, light, temperature difference and vibrations) (Roth and Brodrick, 2008). In the meantime, in the building context, it is possible to access wired power fairly easily (Raimo, 2006, Healy and Jang, 2008). Doing this slightly reduces the flexibility of node location and increases the installation time, but power would already be available in most spaces that require monitoring and running cable within a space is much easier than drilling through walls to pass communication wires. In certain cases, this might be a good trade-off.

Cost Cost is also an important factor for penetration of WSN in the building industry. Compared with the use of wired sensors, WSN present decreased installation costs, but higher hardware costs and added maintenance costs to change batteries (Healy and Jang, 2008). Based on technology prices available in 2002, Kintner-Meyer and Brambley (2002) estimated the competitiveness of wireless over wired sensors (Figure 2.4). Comparing WSN cost to hand-held measurement or standalone data loggers, Jeong et al. (2008) concluded that cost of wireless systems needed to decrease before being worth choosing for gathering data to fine tune airflow models. However, with the intensification of use of WSN in buildings and capacitor price reduction law, the price of sensor nodes should go down.

The cost per sensor decreases with the number of sensors (Kintner-Meyer, 2005) as the receiver and repeater infrastructure, and initial site surveying costs are predominant compared to sensor nodes. Thus, WSN can allow more intense measurement without increasing costs (Kintner-Meyer, 2005). Additionally, increased drivers for energy efficiency will enable new incentive to fund getting additional data. As an example, Kintner-Meyer (2005) report 7 months pay back on a control retrofit project, which led to fixing faulty VAV boxes.

Reliability Healy and Jang (2008) identify the following parameters as influencing WSN reliability: accuracy, latency, fault tolerance, signal coverage and interferences. Accuracy is mainly dependent on the sensor and therefore not inherent to WSN, but noise can deteriorate the signal. However, disruption of digital signals will most likely result in a noticeable error. The only concern might be the necessity to use sensors with lower precision than wired system to trade-off with battery use. Latency of the system is likely to be higher than for wired system as data transmission needs to be delayed to preserve the battery. Because of this WSN might not be appropriate for time-critical applications.

Fault tolerance of the system refers to the ability of the system to heal itself in case of partial failure. Typically, mesh networks are more reliable and more flexible than stars or point-to-point networks as they are able to provide alternative communication routes in case of node failure (Healy and Jang, 2008).

Signal coverage depends on the transmission range between transceiver and receiver and is affected by transmission power, receiver sensitivity, antenna design, operating frequency,

building topology, and obstructions. Site surveys are typically carried out at installation to ensure good network coverage. Interferences come from disruptions by other radio frequency (RF) devices or activity that take place in the building.

To monitor signal strength of WSN systems, Jang and Healy (2010) list the following performance metrics: received signal strength indication (RSSI), link quality indicator (LQI), packet delivery rate (PDR), also found as transmission rate, and packet error rate (PER). RSSI and LQI are difficult to use for comparison between vendors since the unit is arbitrary (Healy and Jang, 2008). PDR and its opposite, PER, are more straightforward to use. As a metric, vendors tend to give the maximum distance between receiver and transmitter when they are in line of sight. This is not very useful in the building context where many obstacles are likely to be found on the communication path. Jang and Healy (2010) propose to use the maximum distance at which the PDR is 95% or more for a series of standard construction materials as a metric to give a better indication of the system's performance.

Several research projects have worked on evaluating how WSN preform in the build environment. Halgamuge, Chan and Mendis (2009a) looked at transmission on a one-floor building and observed three regions as defined in (Krishnamachari, 2005):

- a connected region for sensors up to 15m (transmission rate $> 90\%$)
- a transition region for sensors between 15 and 40m (transmission rate $> 60\%$)
- a disconnected region beyond 40m (transmission rate $< 60\%$)

However, this does not take into account the nature of the obstacles. Jang and Healy (2010) tested the performance of a WSN through different materials: gypsum boards and plywood do not affect the signal much, hollow concrete blocks induce a relative loss of signal strength, brick walls, composite doors, and metal panels considerably affect the signal. Transmission through different floors that are separated by concrete slabs is difficult (Daniel et al., 2009). Halgamuge, Chan and Mendis (2009b) propose to address this by placing the gateway on in the opposite building. Daniel et al. (2009)'s results for maximum transmission distance are reported in Table 2.6. Those results are all specific to a particular technology in a particular building and transmission analysis needs to be done on a case-by-case basis. Nevertheless, they give an indication of the density of nodes needed to obtain full coverage of a building.

Table 2.6: Connectivity test results (Daniel et al., 2009)

Obstruction	Maximum radio range
None	30 m
1 wall	18.9 m
2 wall	11.9 m
Wooden door	22.5 m
1 floor	4.6 m
PC system	22.8 m

In existing buildings, site surveys, consisting in evaluating transmission between receiver and transceiver in different locations, enable to choose appropriate node location. This can be done is a couple of hours with experience (Kintner-Meyer, 2005). For new buildings, modelling tools exist to predict transmission behaviour. Li et al. (2009) present a model to predict signal loss in domestic housing to account for floor, wall and interference impact on the transmission path. The model presented good result, but uncertainties are liked to the furniture and the buildings used to validate the model are fairly similar.

Ease of use To favour adoption of wireless in the building industry, WSN technologies need to be easy to deploy and maintain. Regarding maintenance, the main aspect is battery life, but also indication regarding node failure and battery level. Regarding deployment, the system needs to be easy to use by non-specialists. This includes easy installation, setting up and commissioning of the system (Wheeler, 2007). Guinard et al. (2009) designed a tool to help with network designs using building layout from the BIM. The tool is usable by non-specialists of wireless technologies.

On a broader perspective, there is a need to be able to develop custom applications with limited knowledge in RF transmission. Jang et al. (2008) proposed a system based on TinyOS to enable the end user to focus on his application. Jang et al. (2008) list temperature, relative humidity, light, carbon dioxide, carbon monoxide, power, smoke and occupancy as common sensors needing to be available. Healy (2005) also recommends availability of air and water flow and radiant energy. Time synchronisation is also a plus to facilitate data analysis (Healy, 2005).

Interoperability One of the main conditions for adoption of the WSN is its interoperability with other communication protocols and networks present in the build environment. The WSN needs to be able to export its data to other systems to make them useful. For monitoring and control data this can include interfacing with the existing wired BMS or with Internet protocols (Guo et al., 2010). To go one step further the ZigBee alliance and BACnet have worked on the possibility for ZigBee wireless nodes to behave as BACnet nodes (Martocci, 2008). This enables to extend an existing BMS system with wireless controls.

All the wireless protocols commonly used in building applications are proprietary. Even if nodes from different manufacturers use the same protocol, the nodes will not be able to be part of the same network. This limits the flexibility of possible applications. Dominguez et al. (2012), who worked on migrating for a legacy RF system to a ZigBee WSN for a home automation manufacturer, abandoned the idea to work with public application profiles because they were not adapted for their application. Technologically there is a need for a wider range of building sensors and/or for an open WSN protocol for building applications.

The latest form of interoperability required relates to data formats. This would enable independent software development of software for data analysis. Indeed, manufacturers might not be the best to develop the ad-hoc software. Jang et al. (2008) propose a database format to address this, but it is still too specific to the system that is implemented in their paper.

Security Building managers need to be sure the application is secure to convince them to use it. This includes preventing malevolent people to access the building information or even take control of it. The system itself would also need not to disrupt the operation of other systems (Healy and Jang, 2008).

2.6 Summary of literature gaps

New buildings do not perform as well as expected because most of the efforts to make them energy efficient are concentrated during the design and operational realisation is thus not taken into account. This also impacts the comfort performance.

HVAC systems require particular attention as they represent the biggest source of buildings' energy consumption and inadequate operation also results in poor thermal comfort and indoor air quality.

Research aiming at improving building operations is focused on existing buildings, but to achieve emission reduction targets the building services industry needs to be able to deliver new buildings with good energy and comfort performance.

Initial commissioning is a key process to achieve this, but in practise its scope is limited due to time pressure. Overcoming this problem has attracted little attention in the literature. A couple of studies point out the benefits of commissioning new buildings in-use, but lack strategies and tools to implement it.

The first step of implementing such strategies is to understand the type of faults that need to be addressed. Studies have been carried out to find out typical faults for existing buildings fault detection and diagnostics or as feedback for future designs, but those do not reflect the faults that can be fixed during commissioning to improve new building energy efficiency.

In the meantime, the development of sensor and computing technologies offers new opportunities regarding data collection and analysis in the built environment. WSN technologies can provide affordable and flexible data collection for medium term deployments. At the moment, WSN are used mostly for control purposes, but not for fault troubleshooting.

In the light of those gaps, this thesis aims at answering the following research questions:

- What are the barriers to including energy and comfort performance to initial building commissioning scope?
- What are the common faults that could be easily solved in newly handed-over buildings?
- What are the requirements for a WSN to troubleshoot those faults?
- What are the practical constraints associated with such a WSN?

- How can such a WSN contribute to troubleshooting newly installed systems?

To answer these questions, a system engineering approach is used by analysing the problems that prevent commissioning to deliver energy efficiency and comfort, developing requirements for a tool to solve them and verifying the developed solution meets the requirements. To understand why commissioning fails to close the performance gap, the process is analysed using professional literature review, semi-structured interviews and shadowing of commissioning professionals. This leads to the definition of a new type of service to extend the commissioning process to address energy and comfort. The type of energy and comfort related faults that commissioning traditionally fail to address is identified through semi-structured interviews and a small-scale survey. The list of faults that comes out of it is used to determine a series of measurement use cases needed to detect those faults. Those use cases are then used to specify the requirements for a data collection system, in particular the list of measurements needed, and analysis tools. A prototype is then developed and verified in a series of laboratory tests. The prototype is then used to demonstrate that it can realise the measurement use cases mentioned before, and thus the list of common faults identified. Those use cases are then integrated to more general strategies to demonstrate the suitability of the prototype to assist in commissioning for energy efficiency and occupants' comfort. Each step is described more in detail at the beginning of the relevant chapter.

Chapter 3

System requirements for post occupancy commissioning data acquisition

Building commissioning is a key process to close the energy gap, but has received only limited attention in the literature. With the final objective of providing good environment with an efficient energy consumption, this chapter seeks to answer the following questions:

- What is generally meant by 'commissioning'?
- To what extent do common practises allow commissioning of real buildings before handover?
- What are the likely residual faults left for post-occupancy commissioning?
- What are the data requirements of the post-occupancy commissioning phase?

This chapter aims at determining the requirements for a WSN that would contribute to improving building commissioning. Following the principles of systems engineering the starting point is to understand the needs of the system. First a critical review of the state of practise of the commissioning process is performed (Section 3.2). As a result the need for a post-occupancy commissioning process is explained (Section 3.3) before looking in detail at what common faults could be solved by such a process (Section 3.4). The data (Section 3.5) and architecture (Section 3.6) requirements of the wireless system are then established. This chapter starts by a discussion on methodological choices made to accomplish those tasks.

Table 3.1: Heathrow T2 commissioning site visits

Date	Person shadowed	Activity
24, 25, 26/04/13	Commissioning Manager Head Mechanical commissioning engineer	Cooling tower commissioning Demonstration of mechanical commissioning to clients
22/05/13	Electrical commissioning engineer	Test of backup battery
19/06/13	Mechanical commissioning engineer Water commissioning engineer	Balancing Water flushing
17/07/13	Commissioning manager - Documentation	Commissioning documentation
31/07/13	BMS commissioning engineers	BMS commissioning
16/10/13	Commissioning Manager	Problem solving
29/01/13	Commissioning Manager	Cause and effect testing on retail kitchen units

3.1 Methodology

3.1.1 Commissioning review

The first step towards establishing requirements for a WSN monitoring system is to understand the challenges and limitation of the current commissioning practises. This chapter first compares commissioning guidance in various countries. This includes codes, guidelines and standards produced to the attention of the construction sector. Two streams of commissioning guidance, by CIBSE in the UK and ASHRAE in the US, emerged from this review and are compared in more detail to better understand what the concept of commissioning means. This serves as a framework to interpret a number of site visits during active commissioning of a large project.

Guidance reflects good practises, but does not give a full picture of the practical implementation of commissioning. An interview with the commissioning manager of the case study used for sensor deployments (see Section 5.2 for details) was conducted to better understand the commissioning process. This is then complemented by shadowing and semi-structured interviews of commissioning professionals on a live commissioning site to be able to observe and understand the practical challenges commissioning is facing. This took place at the construction site of a new terminal at Heathrow airport. During the commissioning period a series of site visits took place. Each time different professionals were shadowed to observe different aspects of the system commissioning of the terminal (Table

3.1). Notes were taken both on anecdotes told by the different professionals and on-site observation made by the author. The most significant lessons from those visits were extracted and are presented in Section 3.2.2. The observations made could be considered as limited since they rely on observations made on only one construction site, but informal conversations with professional from various companies during conferences and other professional events confirm that the conclusions drawn are representative from the state of practise of commissioning for large commercial projects in the UK. This was deemed sufficient for the purpose of highlighting the challenges of using IT technologies for commissioning.

3.1.2 PO-Cx definition

The conclusions of the commissioning review lead to the design of two commissioning models: one representing the current commissioning process and a second one presenting a process to overcome the current limitations of commissioning in terms of realising energy efficiency of new buildings. These models are used to introduce the concept of post occupancy commissioning (PO-Cx) and explain how it could contribute to close the performance gap.

Indeed, commissioning engineers face a series of constraints that prevents the commissioning process to result in a building that is both comfortable and energy efficient. Few of those problems have sufficient importance to delay the handover. As a consequence a PO-Cx becomes inevitable if one wishes to deliver buildings fit for purpose.

3.1.3 Typical faults

After looking at the overall benefit of PO-Cx, the specific faults resulting in poor comfort and/or energy waste that could be solved by PO-Cx are identified. Experienced building professionals were consulted. The aim was to identify the common operating problems of new buildings and to understand whether better commissioning practises could have prevented them.

First, two semi-structured interviews were conducted to get a starting point to work from. Both interviewees were energy consultants to get the most general overview possible. The interviews were conducted in person in a semi-structured form (Robson, 2002). The interview guide and a synthesis of the interviews can be found in Appendix A. The

interviews were organised in two parts. The first part consisted in understanding the respondents' background and experience. The second part consisted in asking them to think about 5 to 10 faults that they would commonly encounter in their work and go through the different aspect of those faults, including their frequency, how to detect and fix them, at what stage of the construction process the fault originated and how it could have been avoided.

Those initial interviews were used to create an 'open source' document listing faults of interest for PO-Cx. This document was circulated to a small number of building services professionals for comments. Among the 11 people contacted, 6 answers were received. A copy of the document circulated can be found in Appendix A. Based on the feedback received a final fault list was established. This list is not exhaustive as the idea is to be able to detect common faults but also to detect other faults that might be related to a specific project. The list of faults established will serve as a base to specify the monitoring tool-kit and to illustrate its potential to assist PO-Cx (Chapter 5).

3.1.4 Requirements

Based on the faults identified, a list of measurements use cases is established. Those use cases serve as a base to build up the requirements of a monitoring system for PO-Cx. The system requirements are divided in two parts: the data requirements and the architecture requirements. The date requirements consist in determining which data are needed to address the use cases. The architecture requirements regroup the specification of the data acquisition system that will collect the data mentioned above.

3.2 Review of current commissioning practises and challenges

From a general point of view, commissioning is a process to guaranty performance and security of complex systems through a set of dead and live tests. It can address industrial plants like petrochemical plants or oil and gas platforms, aeroplanes, rockets, warships or building systems. With regard to commissioning, building services present two particularities: 1) being less critical than the others as it is possible to come back to make changes and remaining issues will not put people's lives in danger and 2) having to cope with higher

variation in operating conditions (weather and occupants).

This section aims at understanding why commissioning fails to deliver comfortable and energy-efficient buildings. The current state of practise is investigated. First, the different international practises are reviewed, with a special focus on the UK and the USA that represent the two main streams of practises. This is done primarily looking at commissioning guidelines. Practical commissioning challenges are then identified based on interviews and shadowing of commissioning professionals.

3.2.1 International commissioning practises and regulations

Overview of international commissioning

The notion of building commissioning appeared in the UK and the US is the late 1970s (Nakahara and Shimazu, 2007). The concept then expanded to other countries starting from the ones having strong industry connection with the former counties, like Honk Kong with the UK or Canada and Australia with the US. The original scope of commissioning was mainly setting HVAC systems to work through Testing, Balancing and Adjusting (TAB).

It is only in the past twenty years that the concept started to evolve towards a more integrated approached and that commissioning started to refer to coordinate testing and documentation of the whole building and its systems. The evolution can be perceived between the IEA annex 40 completed in 2004 that addressed 'Commissioning of Building HVAC Systems for Improved Energy Performance' and the annex 47 completed in 2010 addressing 'Cost-Effective Commissioning for Existing and Low Energy Buildings'.

Commissioning is then at the cross section of many competence fields as systems concerned are as varied as electrical systems, water systems, air systems, fire alarm systems, lifts, controls. The interconnection and overlapping of those systems as well as the versatility of building construction programmes require a thoughtful coordination. Therefore, numerous organisations have produced guidance based on good practise experience to promote commissioning and to help owners and contractors to implement successful commissioning management.

Table 3.2: Inventory of commissioning documentation in different countries

Country	Publication	Organisation	Original edition	Current edition
Canada	Commissioning Guide for New Buildings	Natural Resources Canada	2010	2010
	CSA Z320-11 - Building Commissioning Standard	Canadian Standard Association	2011	2011
France	Memento du commissionninement	COSTIC	2008	2008
Hong Kong	Building services branch testing and commissioning NO. 1 to 12	Building Services Branch Architectural Services Department	1990	2000-2002
	A practise guide to building commissioning Management for Hong Kong	HKBCxC	2006	2006
Japan	The guideline of building services commissioning process	SHASE	2005	2005
UK	Commissioning Codes:	CIBSE		
	A: Air distribution system		1996	2006
	B: Boilers		2002	2002
	C: Automatic controls		2001	2001
	L: Lighting		2003	2003
	M: Management		2003	2003
	R: Refrigerating system		2002	2002
	W: Water distribution System		2010	2010
USA	ASHRAE Guideline 0-2005: The Commissioning Process	ASHRAE	1989	2005
	ASHRAE Guideline 1.1-2007: HVAC&R technical requirements for the commissioning process		1989	2007
	California Commissioning Guide: New Buildings	California Commissioning Collaborative	2006	2006
	New Construction Building Commissioning Best Practice	Building Commissioning Association	2011	2011
	Model commissioning plans and guidelines specifications	PECI	1997	1998
	Procedural standards for WBCx of new construction	NEBB	1993	2009

Three types of documents are available to the industry: guidelines, codes and standards. The character of the content of the three types of documents can be similar. The difference lies in their level of legal authority. The aim of guidelines is to gather good practises. They have only an information purpose. Codes stand as law even if in the case of commissioning this is more of a code of conduct and is not enforced by governments. Standards have an ambition of normalisation of the process. Table 3.2 lists the main codes, standards and guidelines available at the moment in the different countries investigated in IEA Annex 47 (Ferretti and Choinière, 2010).

In the **UK**, the Charted Institute for Building Services Engineers (CIBSE), the professional body dedicated to building services, has been producing guidance for commissioning since 1988 (Nakahara and Shimazu, 2007). It consists of 7 guides addressing air distribution system, boilers, automatic controls, lighting, management, refrigerating system,and water distribution system. They have inspired the **Honk-Kong** commissioning approach. The government, through the Architectural Service Department, published a set of twelve booklets adapted from CIBSE commissioning codes. Those guidelines address the technical part of the commissioning process for distinct subsystems such as HVAC&R, Control and monitoring, steam boiler and calorifier, electrical installation, etc. The Hong Kong Building Commissioning Centre (HKBCxC) published in 2006 "A practise guide to building commissioning Management for Hong Kong" (Hong Kong Building Commissioning Centre, 2006) to address the management side of commissioning. The HKBCxC opened in 2004 to promote commissioning practise and some further management guidelines are in progress to address commissioning planning and commissioning requirements.

In the **USA** several institutions have published guidelines recognised by the industry. Some of them are listed in Table 3.2. It is not intended to draw an exhaustive list as Kjellman and al. made an inventory of 44 codes, guidelines, standards and manuals addressing commissioning (Kjellman et al., 1996). This is due to the federal structure of the country, as different states would support slightly different practises. The first two American guidelines were issued by ASHRAE, the equivalent of CIBSE in the US, in 1989. They have been updated several times since. One is addressing the management of the whole process, "ASHRAE Guideline 0-2005: The Commissioning Process" (Knebel and McBride, 2005) and the second one is specific to HVAC&R systems, 'ASHRAE Guideline 1.1-2007: HVAC&R technical requirements for the commissioning process"(Doerr, 2007). The other

guidelines cited are inspired from ASHRAE's one or mean to complete it, except for California that decided to produce their own guidance. ACG (ABC Commissioning Group, 2005), CACx (California commissioning collaborative, 2006), BCxA (Building Commissioning Association, 2011) are non-profit trade organisations whose missions are to develop commissioning and for some of them to deliver commissioning certification to individuals or companies. Their guidelines aim at promoting commissioning to the stakeholders of the building sector. They are particularly aimed at owners and project managers. They do not limit themselves to the commissioning process but also include some cost-benefit information. PECI (PECI, 2014) and NEBB are companies and their guidelines aim more specifically at the commissioning professional. They are a base for certification criteria and a toolbox as well.

Several countries are following the American commissioning model. Until recently, **Canada** was using the ASHRAE documentation, but in 2012 the Natural Resources Canada published a guideline for new buildings commissioning through CanmetENERGY, its energy technology organisation: "Commissioning Guide for New Buildings" (Natural Resources Canada, 2010) (Natural Resources Canada, 2010). The Canadian Standard Association also recently published a first Canadian commissioning standard: "CSA Z320-11 - Building Commissioning Standard" (Canadian Standard Association, 2011). This standard includes 200 Excel templates for commissioning documentation.

Australia does not have specific guidelines, but the Australian construction sector follows CIBSE codes and ASHRAE guidelines (Ferretti and Choinière, 2010) and commissioning in accordance with CIBSE and ASHRAE documentation is required to get Green Council's Green Stars certification.

In **Japan**, the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan (SHASE), in collaboration with the Building Services Commissioning Association (BSCA) issued "The guideline of building services commissioning process" in 2005. It is an adaptation from the PECI commissioning model.

In **Taiwan**, the commissioning procedure is adapted from ASHRAE guidelines. To encourage the construction of energy efficient buildings, the government requires all public projects over 50 million NTD (1.5 million USD) to obtain the Green Building Label to

deliver a construction permit. Commissioning and TAB are in the prerequisite to get this certification (Nakahara and Shimazu, 2007).

In **France**, the COSTIC (Comité Scientifique et Technique des Industries Climatiques) has produced a guideline aimed at French owners, 'le memento du commissionnement' (Cyssau, 2008). It has also published three technical guides for TAB specific to water systems, air systems, and controls and BMS as well as TAB checklists. The commissioning approach is embedded in the construction process, as the same actors are responsible for installation and commissioning tasks. This approach is the dominant one in Europe, excluding the UK, the commissioning philosophy being that the contractors are responsible to make sure they deliver.

According to Ferretti and Choinière (2010), **Finland** and the **Netherlands** are also in the process to issue commissioning documentation adapted to their building industry to promote the implementation of commissioning in their country. In **Norway** a guideline for HVAC commissioning was published in 2007 and is under revision (Ferretti and Choinière, 2010).

There are different commissioning approaches regarding the management of the process. Three approaches come out of this documentation: the 'UK approach', the 'US approach' and the 'European approach'. IEA Annex 40 classifies the different commissioning approaches as follows Visier (2004):

- **The commissioning authority approach**: The commissioning authority depends only from the client.
- **The embedded approach**: Commissioning tasks are performed by the usual stakeholder (e.g. the mechanical subcontractor sets to work the AHU he has installed).
- **The mixed approach**: Most of the tasks are performed by the usual stakeholder but a commissioning authority verifies they are effectively performed.

In this paradigm, the 'commissioning authority approach' would correspond to the USA, the 'embedded approach' to the 'European approach' and the 'mixed approach' to what is done in the UK if it is considered that the 'usual stakeholder' is the commissioning subcontractor managed by the main contractor and the independent authority is the client representative that would witness part of the commissioning. This classification seems

nevertheless a bit too simplistic as it only considers the management of the testing tasks and omits planning of the commissioning and the review of design commissionability. The next section gives further detail of the UK commissioning process since it is the focus of this research. It is then compared to ASHRAE's approach to understand the main differences. Not much information about the European approach was found in the documentation so it was left out.

UK vs. USA

The CIBSE and ASHRAE documentation are the inspiration source for most countries undertaking commissioning activities. This section aims at drawing the common point and the differences of the two approaches.

The CIBSE commissioning guides cited above are the main source of guidance regarding the commissioning process in the UK. CIBSE commissioning codes are high level guidance mostly addressed to project managers. They are complemented by a series of guides edited by BSRIA, which address the practical realisation of the commissioning tasks. It is divided in seven guides addressing commissioning management (Hawkins, 2010), commissioning planning (Deramchi and Hawkins, 2009), water systems (Parsloe, 2010) and their pre-commissioning (Brown et al., 2011), the commissioning of air systems (Parsloe, 2001), and recent guidance for Seasonal Commissioning (Sands, 2013). Following the different steps of RIBA plan of work (RIBA, 2013), BSRIA commissioning job book describes what commissioning related activities need to be carried out at each stage (Hawkins, 2010). Figure 3.1 summaries the main steps of commissioning in the construction cycle. The main tasks of the commissioning team include reviewing the design, planning the commissioning schedule, on-site checking and testing, and documenting commissioning. It is often conceived as a set of tests and certification that takes place between completion of systems installation and handover, but to optimise the process commissioning should be integrated to the project as early as possible, preferably during the design phase as part of the commissioning work consist in ensuring that the designed systems are commissionable.

As detailed in Section 2.1.2, UK energy related Building Regulations are found in approved document Part L - 'Conservation of Fuel and Power' (HMG, 2013). Part L requires a commissioning process to take place and cite CIBSE and BSRIA as recommended best practise. However, approved documents are not legally binding so a building can be de-

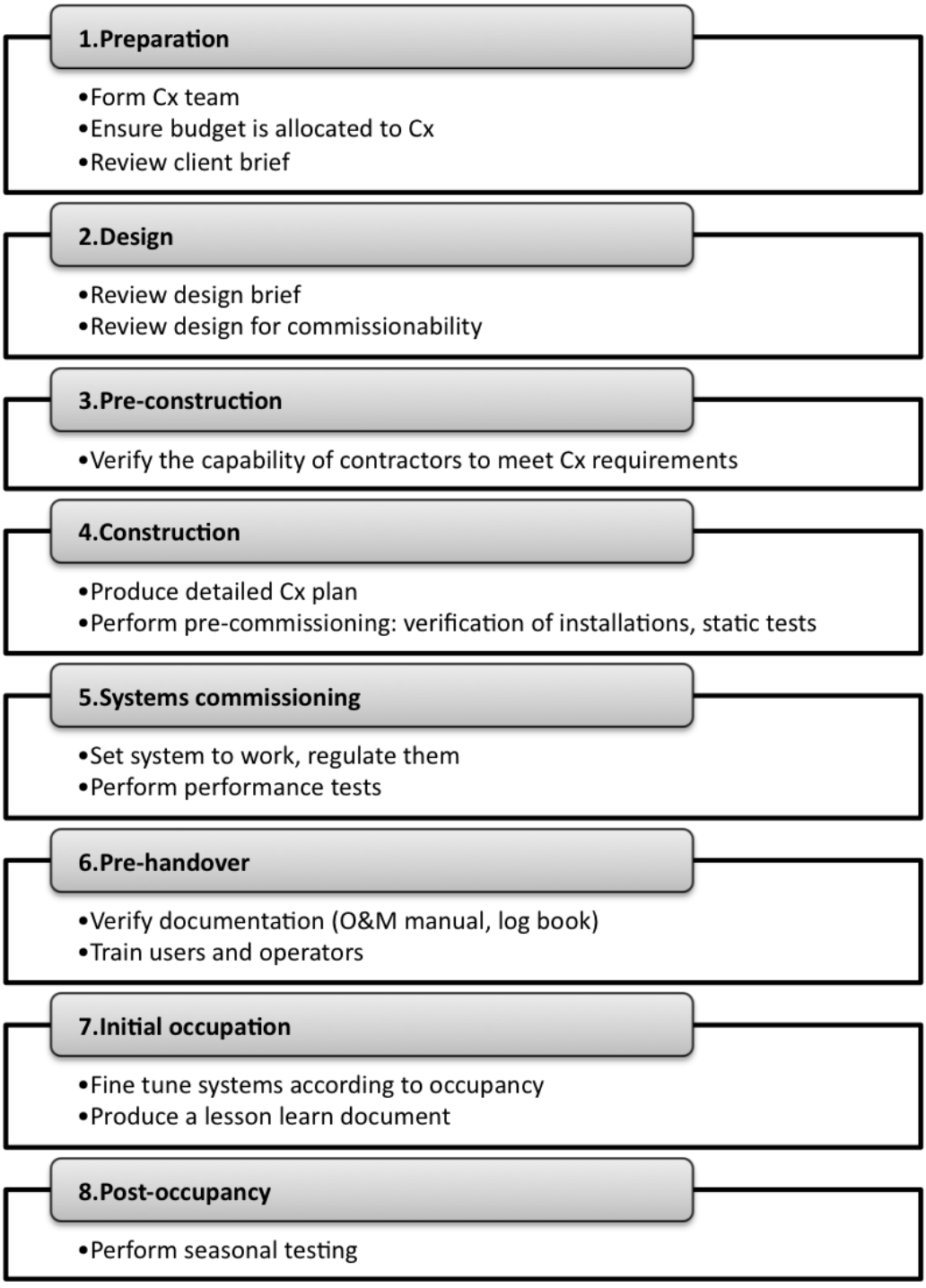


Figure 3.1: Main tasks of the commissioning process. Summary of (Hawkins, 2010)

clared compliant with the Building Regulations without following Part L and in any case the level of requirements from Part L is not sufficient to ensure a good level of commissioning. Indeed, it is possible for a building to comply with the regulations as long as someone signs off the commissioning documents with no guaranty how much work was really done. In addition, they are doubts that the regulations would be adequately enforced (Lau, 2014). Commissioning also represents 4 credits out of the 150 of the BREEAM certification scheme but surprisingly it is not in the list of pre-requisites for any level of certification and the requirements for the process are not very specific. It is thus mostly up to the client and the contractor to agree the level of commissioning that will take place on a project.

The ASHRAE commissioning documentation structure is articulated as follows. The commissioning management process is detailed in "ASHRAE Guideline 0-2005" (Knebel and McBride, 2005). Commissioning issues specific to HVAC&R are addressed in "ASHRAE Guideline 1.1-2007" (Doerr, 2007). Guidelines from the National Institute of Building Science (NIBS, 2006) cover the rest of the systems that need commissioning e.g. lighting, roofing, fire, envelope, plumbing, etc. The ASHRAE guides are written in a contractual manner. They aim at being incorporated in building contracts or at being absorbed by local building regulations. It is interesting to notice that having a commissioning process is a prerequisite for any LEED certification.

Despite the fact that both CIBSE and ASHRAE documentation address commissioning, comparing their respective approaches revels that they are some fundamental differences between both. Table 3.3 compares some essential aspects of each set of guidance.

The first interesting comparison point is the definition of commissioning given by both institutions. The definition from the British code emphasis the starting up function of commissioning that carry out the transition between the end of the installation and the operation of the building. The American definition favours the certification aspect of the process. This suggests that both commissioning processes do not have exactly the same scope. The first one focuses on the process when the second one focuses on the outcome.

The motivation for undertaking a commissioning procedure is also slightly different. The final objective of the process is to certify the conformity of the building in terms of

Table 3.3: CIBSE vs. ASHRAE

	CIBSE codes	**ASHRAE guidelines**
Country	UK	USA
Commissioning definition	"The advancement of an installation from the state of static completion to full working order to the specified requirements. It includes the setting to work of an installation, the regulation of the system and the fine tuning of the system."	"A quality-focused process for enhancing the delivery of a project. The process focuses upon verifying and documenting that the facility and all of its systems and assemblies are planned, designed, installed, tested, operated, and maintained to meet Owner's Requirements."
Target	'New-build and retrofit applications'	'New and renovation projects'
Reference document	Design Intent	Owner's Project Requirements
Objectives of commissioning	"Provide building occupiers with a safe, good quality, comfortable internal environment using heat and electrical energy efficiently and cost effectively"	"Its purpose is to reduce the cost of delivering construction projects and increase value to owners, occupants, and users"
Stakeholder requiring Cx	Building regulation, owner influence quality	Owner
Stakeholder managing the Cx process	Commissioning Management Organisation appointed by the main contractor	Commissioning Authority appointed by the owner
Process type	The commissioning authority does 100 % checks and partially demonstrates to client representative	Quality oriented process: "The Commissioning Authority [...] randomly samples the contractor's work to verify that it is achieving the Owner's Project Requirements."
Documentation format	Good managerial practises	Contractual layout

safety, regulation and performance requirements, but the performance of the US buildings is checked against the owner's project requirements, which correspond to the UK project's brief, whereas CIBSE codes require that the completed building operate according to the design intent. This suggests that the American process is more oriented towards the client's satisfaction, when the British process is focusing on making sure the systems work. However, looking only at the design intent means the design assumptions are not re-evaluated. It can also be noticed that CIBSE put the stress on providing quality indoor environment at optimised energy consumption when ASHRAE focus on costs reduction and owner interest. This can be explained by the nature of the documents, where ASHRAE follow a standardised contractual layout, the CIBSE codes are written as good practises.

As pointed out in the previous section, the responsibility repartition of the two processes is different. ASHRAE recommends the commissioning authority to be independent from the other contractors and to be appointed directly by the client. In the CIBSE approach, it is the responsibility of the main contractor or project manager. This creates different situations as the interest of the commissioning authorities are different. Also in the UK commissioning is required by the Building Regulations, even if the level of requirements is left to the owner, whereas it is up to the owner to require it in US. Also they might be local variation. For example, commissioning is required in the Californian Building Regulations. Finally, the scope of commissioning, despite the concordance of the main tasks such as planning, testing and documenting the process, presents some variation in the overall process. In the UK, the commissioning process comprises a systematic checking of the installations by different commissioning engineers whereas in the US each contractor is responsible for the quality checks of the work he has been doing. The commissioning process is then a quality control procedure testing random samples of the systems to check if the contractor did the work properly.

Most divergences can be attributed to a difference of scope between the UK and the US commissioning. Indeed, in the US, setting to work and balancing is the object of an independent process called Testing, Adjusting and Balancing (TAB). The commissioning is then the process of checking that installation and TAB have been done properly, whereas in the UK TAB is included in the commissioning process and the additional quality check is done by a client representative. This ground difference between both industries' organisation might come from the fact that the type of buildings in both counties tend to be

different as well as overall cultural differences.

3.2.2 Insights on real commissioning practises

Commissioning guidance is a good framework to understand the commissioning process. However, it only revels what should be done in theory. To fully understand commissioning it is necessary to look at what happens in practise.

Example of a commissioning process: a university case study

For that purpose, the commissioning of the case study used for proof of concept in Chapter 5 is used to illustrate a typical commissioning process. It is based on an interview with the commissioning manager of the project, which consists in a major refurbishment of a university building. The commissioning phase of this project took place between June and Dec 14. This section summarises information about the commissioning phase based on an interview with the commissioning engineer 30 October 2014.

According to the commissioning manager, the scope of the commissioning work is to bring the installed systems into operation, to prove that they have met the required standards and the design performance as laid down in the contract. As it is a refurbishment project, commissioning had to be done on all the new installation, but also on all the existing installations that were reused. The work was demonstrated to a professional inspector to prove that the level of performance laid in the contract was reached. The level of performance was defined in the contract using references to BSRIA guides, CIBSE codes and appropriate British Standards.

Commissioning can be done either with direct labour from the building services contractor or by employing specialist subcontractors for each specific task. On this project, due to the specific background and experience of the commissioning manager, he was able to do most of the supervision without hiring a third party. The hands-on work was subcontracted to a specialist company, which was responsible for the ventilation proportional balancing, chilled water and heating balancing. The original designer, the mechanical and electrical consultants and a water treatment consultant, all employed directly by the client, witnessed the different aspects of commissioning depending on their interests. People for the College's estate team also took part to witness activities when they were available.

One of the particularities of the commissioning for this project was that the client required 100% witnessing of the water treatment process, possibly because they had problems with water quality on previous projects. This means the specialist consultant had to be present for all the activities related to water treatment on each part of the system and produce detailed report of the work being done, in contrast to the common practise, which is to agree on the methodology with the client representative at each step, and then demonstrate that the expected results have been achieved once the work has been done to get the green light to move to the next step. 100% witnessing is not common, but it was not unique to this project. However, this meant that this phase of the commissioning process took more time than anticipated and resulted in less time available for energy-related commissioning.

The witnessing was less constraining for the rest of the commissioning tasks, which follow the more traditional pattern to present the results of the commissioning tasks to the client representative once they have been completed. In particular, for balancing the consultant once called on-site for witnessing would randomly sample part of the system to get it demonstrated. This includes first looking at AHU's traverses, and then grills and fan coil units (FCU). If it matches the commissioning readings that were submitted, the commissioning can carry on. The ventilation system was commissioned in the traditional way, with proportional balancing of the ventilation dampers. For the chilled water and the heating system they used pressure independent control valves (PICV). The PICV remove the need for traditional proportional balancing, thus considerably reducing the length of the process. All that is needed is to make sure the right valve is installed correctly on the right unit. This can be done by visual inspection and does not require skilled labour.

The next step was then to commission the BMS. Most of the sensing and actuating kits were already installed, as they would be needed for the mechanical and electrical commissioning (e.g. actuators to open and close valves). Electrical and mechanical commissioning needs to be cleared for the BMS commissioning to start. The work then consisted of testing point-to-point correspondence between sensors and software, performance of the BMS network and operation of the different control strategies.

The contractor engineers had several meetings with FM and the estate department to

make sure they are familiar with the installed systems and how they operate. According to the commissioning engineer it is in the best interest of the contractor to make sure FM is happy with the systems as otherwise they get called back on-site.

Like with most construction projects, the project had been running late and the time allocated to commissioning suffered as it got taken away to finish installation. On this project, the water treatment took a lot longer than anticipated, which impacted on all the commissioning planning. Normally each task is done on the whole building before moving to the next task. To try to recover time, the commissioning manager was planning to do the work on each FCUs one by one so that progress on the different tasks can be made in parallel. One of the challenges of the commissioning of this project was the fact that the building was still in operation. This has led the handover to be done in a piecemeal way. Some teaching rooms had to be handed over early and needed cooling, so not all parts of the systems were at the same level of advancement at the time of the interview. There was another small problem, but that took a long time to resolve, with the compressed air system of the laboratories. The consultant asked the contractor to demonstrate the actual flow rate of compressed air at the terminals and they add to develop a custom rig to do so.

For water balancing, the TA-Scope system from IMI Hydronic[1] was used. It consists in a series of wireless manometer that can be installed on the commissioning valves. The central unit then enable to have access to all the flow measurements at the same time through wireless and to centralise data for reporting. The commissioning engineer was satisfied with the systems. The described advantages are that it saves a lot of time by removing the need to go back and forth between the different valves. Since it is digitalised, the report can be done directly on the computer, which saves additional time to write the documentation. It also eliminates mistakes and the risk to lose measurements reports. It also eliminates the requirement for expertise, as there is a simple list of steps to follow to realise the balancing. The fact that the measurements are done wirelessly is seen as progress compared to the old digital meters that needed to be mains powered and resulted in long extension cables all over plant rooms. This shows the potential of new technology to improve the commissioning process.

[1] http://www.imi-hydronic.com/

Practical commissioning challenges

To understand better the challenges of the commissioning process a series of site visits to a live commissioning site were carries out. It involved shadowing and interviewing the commissioning engineers from the different building services fields. This resulted in first-hand observation of commissioning related issues as well as a synthesis of typical commissioning issues collected from the experience of the professionals shadowed.

The first observation gathered is that buildings are not designed to be easily commissioned. For that purpose, they would need to match the systems' architecture with the physical layout of the building, which is not often the case. Similarly, construction planning is usually not adapted to the requirements of commissioning as building structure is sequenced by areas from bottom to top, when the systems cover all the area. This means that the systems are handed over for commissioning in a less than ideal order, which makes the commissioning process inefficient.

To facilitate commissioning the construction process should follow the structure of the electrical network. It is the first element to be commissioned and no commissioning can be done beforehand, as all the other systems depend on power availability. One of the things that delays electrical commissioning is the need for the building to be watertight. As a result only partial power is usually available during commissioning and it can be taken out after having been on, which create problems with the BMS. Network is the other key element to perform commissioning as control of the actuator is necessary for most commissioning tasks.

There is usually a phase where commissioning specialists comment the design for commissionability, but the commissioning manager's feedback seems to be rarely taken into account. One of the explanations given was that designers and project managers do not understand commissioning and do not give it enough importance. As a result, projects tend to work better when manager and client understand the commissioning process. Final integration is difficult. Different engineers install and test the specialised systems but no one is really accountable for putting the different part of the systems together.

The commissioning measurements are relatively straightforward by themselves, but a lot of external factors can cause delays in the process:

- System installation is not completed on time or elements are missing (e.g. no power to test fans, no plug at the end of fan electrical cable, drain system not installed before flushing, BMS sensors missing...).
- Systems improperly installed (e.g. fans wired the wrong way around).
- Material and/or documentation needed for the tests not available (need not foreseen or equipment borrowed by other subcontractors), resulting in delay because of the time needed to find the equipment on-site (e.g. ladder, platform) or because of the time to go back and forth to the office (could be up of 30 min way and back from the furthers end of the construction site on such a big project as an airport terminal).
- Need to wait for a person with specific competences or accreditation to start the test (e.g. electrical power up, client witness). Causing delay because the person is busy somewhere else or bad synchronisation of breaks. For equipment installed by small subcontractors that are not on-site at all time this can mean several days of delay until they can send someone back.
- Previously commissioned system has been partly decommissioned by another subcontractor.
- The measurement points are not accessible (e.g. finish has been installed before commissioning was over, key to the plant room was lost) or require access equipment that is not necessarily available (e.g. ladder, platform lift...).
- The main mean used to get in touch with each other is cell phones with associated battery and reception problems.

All this results in a significant amount of time spent waiting for people and equipment or even postponing of commissioning activity until the problem can be sorted. Eventually due to accumulated delay coming from those mentioned issues, but also due to general delays in the construction planning, the commissioning plan often gets compressed to a minimum. The bigger the project is, the bigger the impact of those on overall delays is as they involve more complexity in the systems, a bigger spatial separation, and more workers to coordinate.

The fact that many parties are involved also has bearing on the efficiency of the process as it involves a lot of politics that add up to technical delays. When things do not work

well, subcontractors tend to send the responsibility back to each other rather than solving the problem. This is even worse when the project is led by a consortium, which is often the case for big projects for financial reasons, as the final responsibility gets diluted. This means that a lot of relational skills are involved in getting the subcontractors to complete the actions wanted. Also, a significant number of workers are freelance. Delays and deadline extensions create the risk of people leaving before the end of the project with the associate time loss of hiring and training a new person on the project.

The client does not always find the right balance regarding the type and amount of documentation he requires. To some extent, this has a strong bearing on the outcome of the commissioning process. As it requires people to sign out, it forces them to take responsibility and is also a good way for the client to follow the progress of the work. If not enough documentation is required, the risk is for part of the commissioning to be left out. However, if too much paperwork needs to be filed it takes time from the practical commissioning work.

Going through the last items of the 'snag' list is complicated. Since the deadline is likely to be passed, a significant part of the workforce would have moved to another job. Also, the building looks reasonably finished, so it becomes difficult to push the handover back. This tends to result in lowering of the final requirements (e.g. demonstrate that the system can deliver cooling instead of demonstrating it can run on automatic controls).

In particular, since the BMS is commissioned last, it tends not to be fully working when the system is handed over and a lot of things are still operated manually behind the scenes even if the building looks finished. One of the reasons is that there is a big gap between a mechanically and electrically commissioned system, and a fully automated control system, but there also tend to be a failure to recognise that some failure of the BMS system comes from bad commissioning of the other systems.

As a result of all the challenges mentioned in this section, the commissioning process tends to remain incomplete, which result in failure to deliver comfortable and energy efficient buildings.

3.3 The case for post-occupancy commissioning

3.3.1 Commissioning limitations

As demonstrated in the literature review, commissioning is a key process to ensure good realisation of building design. As a synthesis of Section 3.2, Figure 3.2 presents a model of the current Cx practise. In an attempt to overcome the current commissioning practise limitations, IEA Annex 40 commissioning definition is looked at:

> "Commissioning is a quality-oriented process for achieving, verifying and documenting whether the performance of a building's systems and assemblies meet defined objectives and criteria" (Visier, 2004).

The first step towards commissioning is thus to define the level of sophistication required in the verification of those objectives and criteria.

Five levels of verification were defined as shown in Figure 3.3 (Noye, North and Fisk, 2016). The first level consists in checking if the different elements of the system are installed where they are supposed to be. The second level consists in checking if those elements work as components. The third level consists in checking that the different elements are connected properly to form the system. The fourth level consists in verifying whether the system is capable of delivering the design. This is usually where commissioning stop as the compliance of the building with design and regulations is demonstrated. To account for comfort and energy performance in use a fifth level is needed. It consists in ensuring that the system's controls regulate the in-use system at the optimum performance throughout the year.

At present, commissioning is mainly aimed at certifying acceptable environmental conditions, health and safety, and design compliance. With the arising imperatives of preserving energy resources and reducing CO_2 emissions, commissioning needs to go towards addressing energy efficiency. However, the current state of commissioning practise presents many limitations that prevent it from optimising new building performance up to level 5. First due to overall typical delays experienced in construction projects, the basic scope of I-Cx might not be fully realised meaning that differences between as build and as designed might remain. In addition, as the current scope of commissioning is limited to certifying design compliance, design software and standard calculation methods are trusted to calculate flow rates deliver the appropriate comfort and energy cost. However, any type of

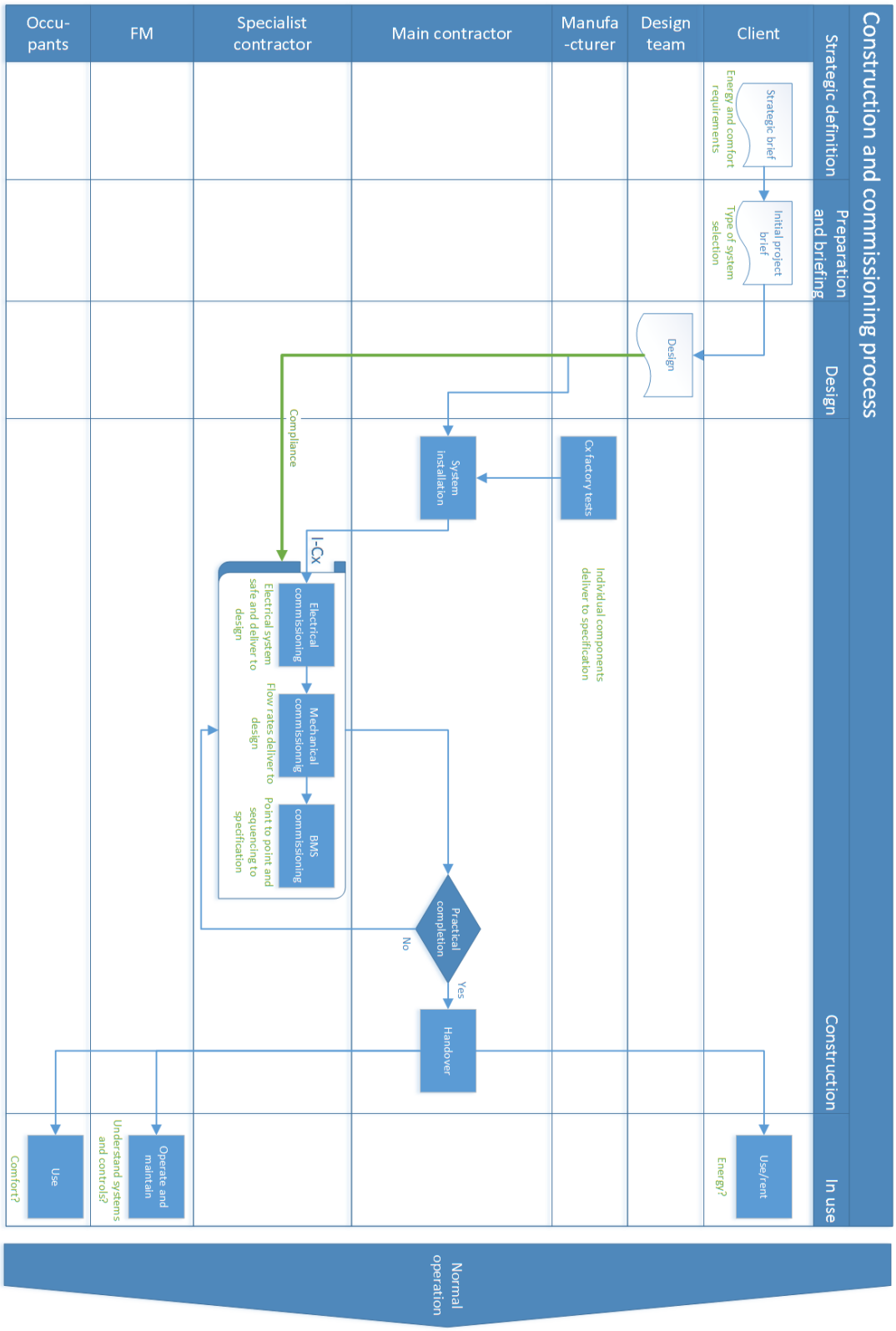


Figure 3.2: Traditional commissioning model

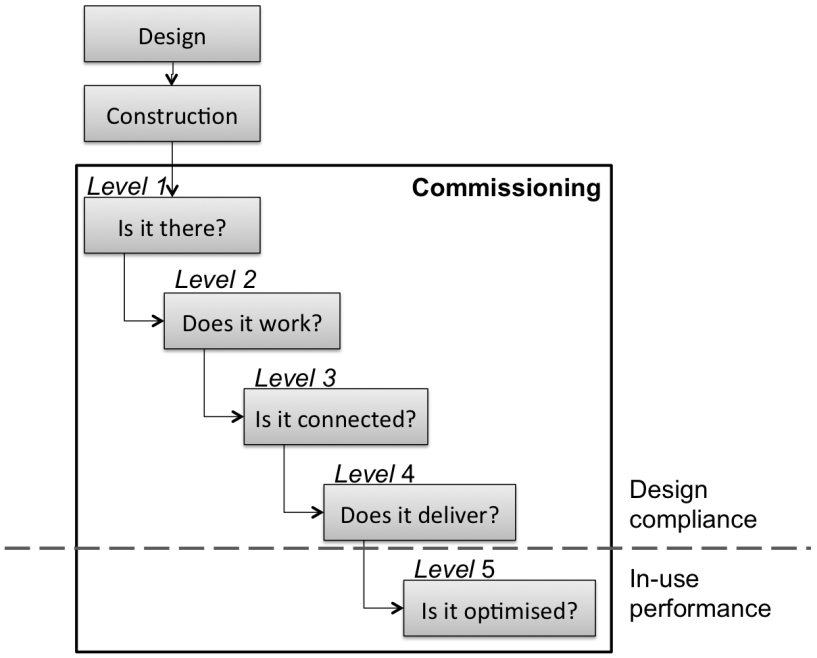


Figure 3.3: Commissioning levels (Noye, North and Fisk, 2016)

model presents limitations. This is especially true in the build environment where a lot of parameters come into play (Summerfield et al., 2011). This also assumes that real occupancy patterns and other unregulated loads will match standard design assumptions. The current scope of commissioning is also limited regarding seasonal commissioning. When it is included in the contracting requirement, it is often limited to testing only extreme load conditions on a very short time span resulting in potentially poor system performance when operating on smaller loads, which represent the most common operating conditions and having taken limited account of occupants influence or feedback.

3.3.2 PO-Cx scope

Since time pressure to sign off the building and get it occupied does not allow an increase in the scope of commissioning before the handover, resolution needs to happen after initial occupancy. It is unrealistic to hope that FM would take care of this as they are given limited budget and tend to put minimum complaints before energy efficiency. Since they would not have detailed knowledge of the design of the system, this tends to result in partial decommissioning of the systems. Additionally, the tools at their disposal are 'exception based', meaning they tend to detect performance degradation, but are not appropriate for

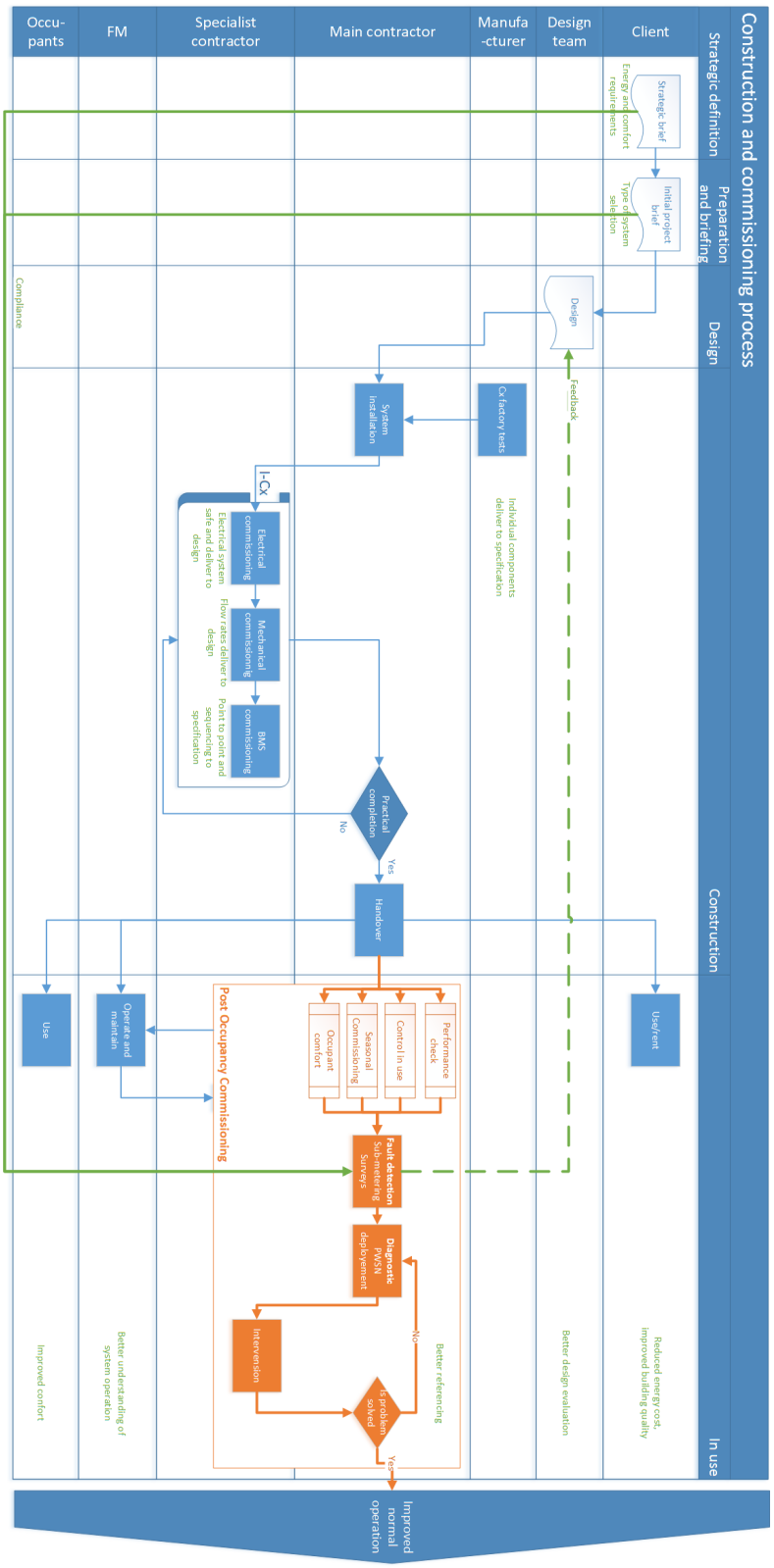


Figure 3.4: Commissioning model with PO-Cx

initial troubleshooting. Therefore, the introduction of a post-occupancy commissioning process that involves the contractor troubleshooting the building for energy and comfort efficiency during the first year of operation is proposed. As this service represents an additional initial investment for the client, the cost of the process should be kept as low as possible, even though energy savings and lower maintenance costs should be able to pay the investment back.

The first year of operation of a building has a strong bearing on its future operation, as this is when FM takes ownership of the building and learns how to operate its systems. The aim of PO-Cx is to fine-tune building in use and verify realisation of energy and comfort performance to overcome the limitation listed in the previous paragraphs and ensure compliance with the building brief (Figure 3.4). The main contractor is normally contractually liable for a 6-months to one-year period after the handover for any defect in the building. As new types of contract are emerging, where final energy consumption targets are established, usually with strong financial penalties if not met, this liability period could be turned into a more proactive performance verification process.

PO-Cx should benefit all the stakeholders. It should result in a better control of the energy bill for the client, in design evaluation to feedback in further projects, in insurance that FM properly understand how to operate the systems, in evaluation of the achieved comfort level for the occupants and ultimately in better referencing for the contractor.

The responsibility of PO-Cx will need to be clearly defined in the contract. The main contractor or its commissioning subcontractor would be responsible to carry out the investigation side, but clear boundaries need to be established regarding who pays for fixing the identified problems. The scope proposed for PO-Cx can be separated into four categories:

- Systematic performance checking of the different system including energy and comfort performance.
- Evaluate how the services and their controls operate in use.
- Performing seasonal commissioning on a more complete spectrum of operating conditions.
- Collecting occupants' feedback and solving complaints.

Performance checking consists in evaluating the overall energy efficiency of the building

and of the systems if appropriate sub-metering was installed. It can be completed by benchmarking either against other buildings or against expected performance.

Since building purposes often change between the original brief and handover, the PO-Cx period could also be used to evaluating the building-occupant interaction and evaluate which parts of the performance gap come from design and construction problems and which ones come from the building usage. This would include comparison of the actual occupancy schedule with design assumptions and evaluate how the occupants use the building.

Seasonal commissioning would normally be part of standard commissioning contract. It consists in fine-tuning heating and cooling loads to ensure settings are adapted to external climate. In practise, this is often done by choosing a cold winter day and a warm summer day to test extreme loads. This might not be representative to the average day of building operation and BSRIA recommend making provision for part-load commissioning as well (Sands, 2013), but there must be doubts that this ever gets done. Longer term monitoring could enable fine-tuning of the different intermediate loads of the building that represent the major part of building operations.

Solving occupant complaints would already be included in the liability contract, but the availability of easily deployable sensors to collect relevant data could reduce engineering time to solve the problem while providing a more efficient solution. It can be completed by a comfort survey like BUS.

3.3.3 Pop-up monitoring™

To perform PO-Cx, the main contractor, with the collaboration of FM and the client, would monitor the building for comfort, energy use and control. This would be done at a high level, making use of the existing data (energy and controls), and using questionnaires and users' complaints for comfort similarly to POE. When things do not work as expected, a pop-up monitoring™ system can be installed to troubleshoot the issues. Longer-term measurement capability would also be installed to preform seasonal commissioning on climate-sensitive systems.

To perform those tasks, data are required. Traditional commissioning measurement tools are mostly hand-held and thus require intensive labour to collect data, which can

be justified only if other forms of intervention from the same person is needed. In-use building data would then be provided by the BMS that is specified for the control of normal operations of the building. However, the BMS is not sufficient to preform PO-Cx for the following reasons:

- BMS is the last system to be commissioned, so it might not be ready in time for initial PO-Cx.
- Operational issues might come from bad specification or commissioning the BMS.
- The BMS is an exception-based system, optimised to detect performance degradation and not initial inefficiency.
- It is unlikely that the BMS specification would include sufficiently dense monitoring for PO-Cx.

The installation of a dense network of wired sensors to diagnose the causes of a problem that have yet to manifest themselves would be prohibitive. As demonstrated from the literature review (Section 2.5.3), WSN can be an interesting alternative to wired sensing in the built environment, especially when the objective is to take temporary measurements. For the use of PO-Cx, they present the advantages of being cheaper to install than wired sensors, while being able to provide real-time and synchronised data, which make the data easier to use than if using data-loggers. Their flexibility means the system can easily be calibrated and tested off-site. The two main concerns would then be reliability and power management, which make wireless systems less robust than wired solution. However, for the purpose of pop-up monitoring™ occasional data losses are acceptable as the process is less critical than boiler control, for example.

Wireless sensing can provide temporary data with limited labour time and has the potential to add to the tool-kit of the commissioning engineer. Some proposals have been made in this direction (Noye et al., 2013, Weekly et al., 2014). In the rest of this thesis, we investigate the potential of a portable wireless sensor network (PWSN) to improve initial building performance. The PWSN can be moved around the project to commission different zones. It can be used on a project until it is satisfactorily fine-tuned and then moved to another project. The fact that this pop-up monitoring™ tool-kit is reusable and wireless can achieve low cost monitoring by splitting the cost between projects and limiting installation and removal costs.

3.4 Typical faults remaining after handover

To provide adequate technological support for PO-Cx, it is important to have an idea of the type of problems that may be encountered after handover. Working with experienced professionals, the aim has been to derive a list of typical problems left after commissioning to serve as a starting point to specify the PWSN.

3.4.1 Initial interviews

The result of the initial interviews of the two experienced energy consultants can be found in Appendix A. Based on their experience with building issues, the interviewees were asked a series of questions about 10 faults that they either frequently encountered in building they audited or that had very bad energy/cost/comfort impact on the building.

Two aspects that were coming back a lot when talking about how to detect the faults, was the notion that a lot of problems occur in mild day as the systems have been designed and commissioned for peak loads. The second aspect is that looking at the behaviour of the half-hourly data profile gives a good idea to experienced energy consultant of the kind of problem the building might have.

3.4.2 New buildings operational faults list

Based on the interviews, the faults most relevant for PO-Cx were selected (see Section A.3). The selection criteria were to keep only faults that have a big impact on building operations (energy/comfort) and that can be fixed relatively easily by the contractor once the building is running. This means for example excluding design issues that would require a major retrofit (e.g. oversizing). Fault number 10 is not directly a building fault, it was, however, kept in the list, as it justifies the relevance of PO-Cx.

A number of senior CIBSE engineers have been closely associated with reducing the performance gap. The original fault list was circulated to them to authenticate it against their experience. Six replies were received. All respondents have more than 10 years of experience in the industry and have a wide range of background such as BMS, energy or M&E design consultants.

Table 3.4: Fault list

	Fault	Consequence	Detection	Fixing
1	Simultaneous heating and cooling of AHU or cassette systems	Energy used for nothing	High energy consumption on mild days	Re-commission the controls (dead band). Better interlock and alerts.
2	Operating schedule incorrectly set	10 to 12 hours of energy waste due to big base load at night + weekends	Half hourly energy data	Review time schedule against use of the system
3	Overcooling	Bad comfort, excessive energy use	Room temp. is much lower than outside temp. in summer	Increase deadband
4	Hunting of heating and cooling	Comfort and energy	BMS actuation history or plant room observation	Re-commission the controls (dead band)
5	Wrong boilers/ chillers sequencing resulting in more units used than needed	Wasted thermal energy	Boilers/chillers working together in mild conditions	Reset system to enable proper sequencing. Check proper sequence with manufacturer
6	Weather compensation control of boiler heating systems not set properly or overwritten	Wasted thermal energy from pipework	Noticing hot pipe in mild day or space temperature not following appropriate profile	Re-commission the controls
7	Fan inverter control not set up or set up too conservatively	High energy costs	Look at how much percent fans run in a mild day	Re-commission the controls
8	Failure to set installed smart controls (e.g. AC, lighting)	Systems running 24-7	Energy profiles do not look as expected	Involving the FM team
9	Poor commissioning including poor control set points, control logic, or balancing	Comfort not delivered and potential energy waste	Comfort complaint or BMS detection	Re-commissioning
10	Lack of performance monitoring and feedback	Energy not taken into account in building operations	Talking to building manager	Performance-based FM contracts. Trainings.

The respondents were positive the faults selected were representative of the type of faults new building would face and covered all the most common ones. A general comment that came up several times was that ideally those faults ought to be removed earlier in the construction process and in particular with a better design and operators' training. Most of the faults in the list come from poor control specification by the designers.

Except for the addition of chillers sequencing together with the boiler sequencing problems, no new faults were added by the respondents, but they provided useful clarifications for most of the faults. The final faults list can be found in Table 3.4. Each fault is associated with the consequences of the fault on energy and comfort, how it could be detected and what is required to fix it. This table is used as a base to specify the pop-up monitoring™ kit.

Some of the feedback about the faults is summarised in this paragraph. First it is interesting to note that the faults are not independent. For example, bad sequencing of boilers and chillers increase the risk of wasteful hunting as it results in 30 min cycles between 0 and 100 %. It becomes even more complicated when multiple sources are involved (e.g. solar + biomass + gas). It seems that weather compensation problems are less common than 10 years ago. It might be because most control software now gives guideline parameters that work for most cases. It is still a valid problem though. Regarding the need for more monitoring, it was argued that sub-metering need better specifications and that it often never gets commissioned. One of the respondents suggests that since FM generally does not know what to do with the data. Third parties could do the monitoring, however, it would risk diluting the responsibilities further. Overall all the respondents seem to agree that there is a need for better usability of controls. The 'smarter' the controls get the more likely they are not to be used properly.

3.5 Data requirements

Building on the type of faults the system needs to diagnose, this section establishes the data requirements for the PWSN.

3.5.1 Building data

This section is based on work presented at the International Conference for Enhanced Building Operation (Noye et al., 2014). To fully understand building operations and its

impact on comfort and energy consumption a set of building data need to be available. These data can be classified as follows:

- System data: valve positions, flow rates etc.,
- Energy data: heat, gas and electrical sub-metering,
- Building environment: comfort, air quality,
- External conditions: weather, occupancy.

In new commercial buildings only part of these data would normally be available through the BMS and the energy management system.

Energy data are available through utility meters, but while its general overview can give an indication about the overall building operations, it cannot identify where inefficiency comes from. Sub-metering can then provide better temporal and spatial granularity. However, it is often used to separate consumption between tenants rather than between systems, which would be more useful for building troubleshooting. According to the Building Regulations new buildings should have sub-metering but it is reported that this poorly enforced. The quality of the data obtained would typically depend on the design of the building services distribution network.

The BMS system primarily monitors the system metrics involved in the control of the system. This includes system pressure, valve and damper position, and temperature, etc. Its purpose is to manage daily operation and system maintenance tasks. The data are visualised by the FM team on demand (e.g. understand major failure of a plant) or is used to send alarm if the measurements deviate from normal operations.

In addition to the system data, the BMS would have one temperature reading per heating/cooling zone. This would normally be the only measurement related to occupants' comfort. It is complemented by occupants' complaints, but this is not an objective measure because complaints are not representative to everybody's feeling.

The BMS would also have an outdoor temperature sensor, which could be a useful way to account for weather influence, but in practise it is only used by the control algorithm to calculate the percentage of fresh air to intake and by other weather dependent controls. Instead of using local measured data, weather influence on performance is input using

Table 3.5: Additional faults linked to the PO-Cx scope

PO-Cx scope	Issue
SCx	Poor SCx
Control vs. occupants	Occupancy differ from FM schedule Unnecessary use of space conditioning
Occupants comfort	Poor thermal comfort Poor IAQ
Energy performance	Poor energy performance

standard normalisation assumptions (e.g. yearly degree days). Regarding occupancy, it is increasingly acknowledged to be a useful metric to optimise energy use, but is not yet widely implemented.

The fact that system data and energy data are available through different systems that are usually accessed by different people makes it difficult to do a crossed analysis. It is technologically possible to integrate energy and BMS data but the hardware will have usually been obtained from different manufacturers, which implies compatibility and integration issues. This comes from the fact that energy management and control systems were historically offered by different manufacturers. Also, the available data are not designed for advanced analysis. Regarding BMS data, they would normally not be kept more than a few weeks and data formats from either system are not made for easy use out of the dedicated software. Finally, they will normally not be enough data regarding comfort and occupancy.

3.5.2 Use-cases for PO-Cx

To refine the data needed for pop-up monitoring™ a series of measurements use cases is identified in this section. In addition to being able to identify the issues from Section 3.4 the pop-up monitoring™ system needs to support the four key tasks from PO-Cx. The additional faults to be considered are summarised in Table 3.5.

Poor seasonal commissioning refers to the lack of seasonal fine-tuning or its limitation to extreme loads. 'Control versus occupants' includes issues arising from divergences of the use of the building. Of particular interests is how the building gets occupied in practise and how this relates to the systems' operation and controls.

Regarding occupants comfort, the types of comfort issues related to HVAC systems are considered (Section 2.2.1). In particular: (1) thermal comfort includes high internal heat gain either from IT equipment or solar radiation or bad delivery from heating or cooling systems; (2) IAQ include lack of fresh air or build up of harmful components.

Energy performance evaluation should start by energy benchmarking and looking at energy time series from the data available in the energy management system. This then leads to further investigation to locate where the excessive consumption comes from. For that sub-metering can be used, mostly for electricity, as gas meters are difficult to install without turning off the system. Energy performance is also underlying in most of the issues that have been mentioned above and in Section 3.4.

Based on this and the faults identified in Section 3.4, the list of measurement use cases from Table 3.6 is identified. They are the use cases the pop-up monitoring™ system needs to realise in order to contribute to the detection of relevant faults during PO-Cx. Each use case is associated with the issues it is meant to help identify and with the measurements needed to realise the measurement function. The functions are organised in three groups depending on whether the associated faults impact mainly energy consumption, occupants' comfort, or both. It is interesting to note that most of the energy issues also impact comfort, suggesting that strategies of neglecting energy to focus on occupants' comfort might not necessarily yield such good results for the occupants.

3.5.3 Data requirement

This section summaries the measurement column of the use cases table (Table 3.6). The following list of measurements is the one that the pop-up monitoring™ system needs to include to be able to realise the use cases identified and ultimately to detect the faults from Tables 3.4 and 3.5:

- Room temperature
- Room radiant temperature
- Room relative humidity
- Room CO_2 levels

Table 3.6: PO-Cx use cases

	#	Function	Associated issues	Measurements
Comfort only	1	Assess thermal comfort	Poor thermal comfort; Solar radiation.	Temperature, radiant temperature, relative humidity
	2	Assess air changes and air pollution	Poor IAQ.	CO_2, airflow
Energy and Comfort	3	Assess ambient temperature	Overcooling; Poor commissioning (Control set points); Poor thermal comfort.	Temperature
	4	Assess levels of occupancy	Occupancy differs from FM schedule	CO_2
	5	Control conditioning mode (Heating/Cooling/Off)	Simultaneous heating and cooling; Hunting.	Pipe temperature, airflow temperature
	6	Compare heating/cooling load to weather conditions	Poor use of weather compensation control; Poor use of fan inverter control; Poor SCx.	5 + Outdoor temperature and airflow rates.
	7	Assess system balance	Poor commissioning (balancing).	Airflow rate
Energy only	8	Control equipment status (On/Off)	Equipment running out of hours; Failure to set smart controls; Wrong boiler sequencing.	Airflow rates, airflow temperatures
	9	Compare equipment use to occupancy	Unnecessary space conditioning	4+5+8

- Airflow
- Airflow temperature
- Airflow relative humidity
- Airflow CO_2 concentration
- Pipe temperature
- Current and voltage
- Outdoor temperature

Energy data for the energy management system should also be available. Access to the BMS data is also a plus as it enables to resolve problems in the controls faster. BMS data should, however, be considered as a bonus measurement set due to the potential difficulties to access it, but its accessibility could speed up the detection of BMS related problems.

3.6 Data acquisition system requirements

To measure the parameters listed at the end of the previous section a specific monitoring system for PO-Cx needs to be specified. This section addresses the system requirements for a pop-up monitoring™ system able to address the full range of PO-Cx needs. It is based on work published in BSERT (Noye, North and Fisk, 2016).

3.6.1 General design considerations

First a few general considerations regarding the pop-up system requirements are discussed. It serves as a base to develop the technical requirements that will follow.

A monitoring kit for PO-Cx first needs to be **affordable** as there is a limited amount of money that clients and contractors are willing to put into commissioning. Thus, the less individual elements of the system cost the more data points can be afforded. In addition, portability of the system means it can be reused on several projects making the equipment cost per project negligible.

A monitoring system for PO-Cx also needs to be **easily deployable** to limit the working time for installation and removal, and limit the level of specific knowledge needed for its installation and operation by being 'plug and play'. In particular, the sensing technique

should be non-intrusive. Needing to turn off systems or requiring a specialist technician would put off installation. Similarly, calibration and maintenance should be done off-site to limit intervention over the one-year period the sensors would stay on-site. As access is one of the challenges of Cx, ease to install sensors has potential to improve measurement location.

Wireless communication is a good way to fulfil the two previous requirements, as wiring the system would be prohibitively complicated and expensive. Wireless communication would need to be embedded within the system as building Wi-Fi might not be operational and in any case is not adapted to sensor node power limitations.

To keep the resources in terms of installation and removal of the nodes low, the sensor nodes need to be **self-powered**. The need for electrical wiring would substantially reduce the benefits of wireless communication in terms of cost and system flexibility. The challenge implied by self-powered system is battery life management. The target would be to reach one year of autonomy to coincide with the length of deployment.

The configuration of the system will need to adapt to variations of configuration and node number. The system thus needs to be **scalable**. The system then also needs to support several operating modes and facilitate simple reconfiguration of communication protocols and data acquisition. Identifying the optimal deployment configuration for different applications is then important to minimise costs and maximise performance.

Two types of analysis will be needs during PO-Cx. The first is live data visualisation to solve complaints or fine-tune subsystems on the spot. The second looks at historical time series to evaluate long-term system performance or do advance troubleshooting. Therefore, **flexibility** of the system and of the end user interface is required.

Finally, a fair level of **reliability** of the system should be demonstrated. It is one of potential users' main concerns, as partial data or data deterioration can lead to misleading information and limit energy savings.

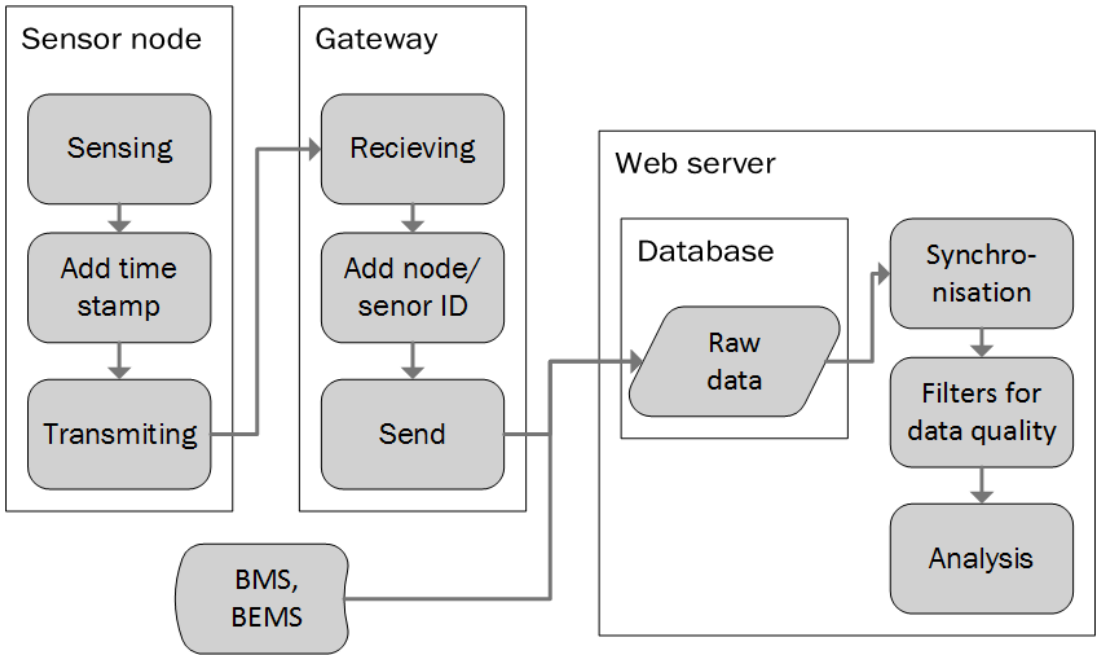


Figure 3.5: Data flow

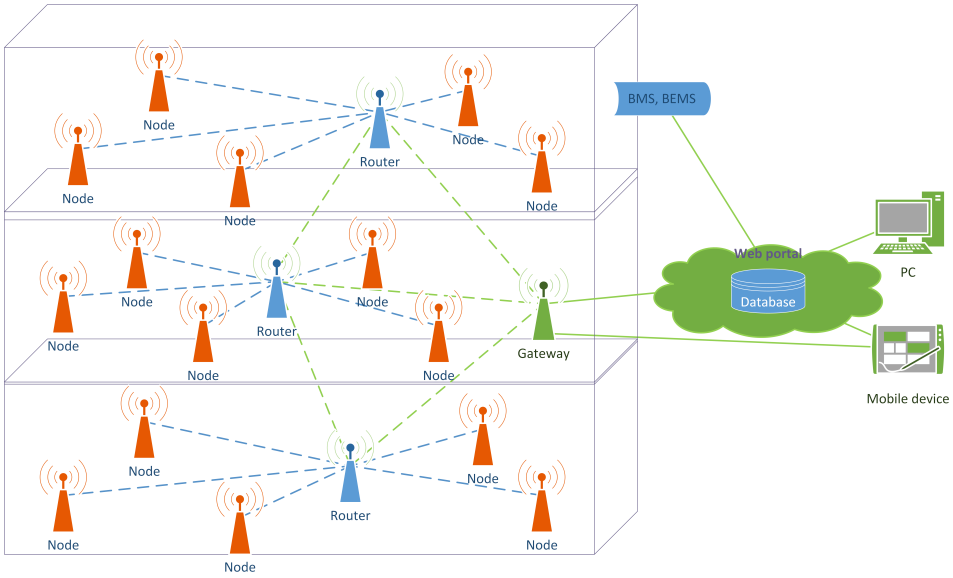


Figure 3.6: PWSN architecture

3.6.2 System architecture overview

In general, when developing a monitoring strategy compromises need to be made between a bespoke configuration and a more general approach. The bespoke system will require less hardware on a specific project but more time to transfer between projects. On the other hand, a general approach can be applied to any building, which results in more hardware and less specific data. Since there are a limited number of building physics measurements of interest and wireless nodes can easily be transferred from one application to the next, a PWSN combines both approaches. This section describes the architecture envisaged for the pop-up monitoring™ system.

Figure 3.5 shows the process flow of pop-up monitoring™. Figure 3.6 shows the proposed architecture of the PWSN. It is composed of four main elements: a mesh of wireless, self-powered nodes, a gateway, an on-site portable device and a back-end web portal. The wireless network communicates via radio band using a proprietary protocol. Several standards, such as ZigBee or 6LoWPAN, defined under IEEE 802.15.4 (IEEE 802.15.4, 2006) are suitable for building data collection due to their low-communication cost and low energy consumption. The selection of the bandwidth depends on the availability in the country it will be used[2].

The design must be able to accommodate wide separation of the different sensing nodes. Routers are used to form a mesh network and ensure wireless signal coverage of the whole building. Once the initial repeater network is installed, sensor nodes can then be installed anywhere in the building as the troubleshooting process requires. The network of routers can be installed just before or just after handover and cover all the building wirelessly. Through the routers the measurements are gathered by a gateway that pushes the data to an on-line server where they are stored for off-site analysis. Data transmission can also be triggered by a mobile device such as a smart phone or a tablet to view real-time data on-site.

3.6.3 Sensor network

Every wireless node is composed of a set of one or more sensors, a processor, some memory, a wireless communication interface and a power source. The Nyquist-Shannon sampling

[2]E.g. for ZigBee the allocated bandwidth is 2.4 GHz worldwide including the UK, 915 MHz in Americas and Australia and 868 MHz in Europe

theorem states that to reconstitute a signal from measurements the sampling frequency need to be at least twice as much as the maximum frequency of the signal observed. Over-sampling is necessary for non-periodic signals. CIBSE Guide H recommends using 10 times this maximum frequency (Warburton and Butcher, 2009). Sampling frequency of the measurements is chosen to be one sample per min as an initial assumption. This requirement will be completed later in the thesis based on lessons learn through the practical work (see Section 5.5.2). As stated in the previous section, it is useful to have relatively small nodes to have greater flexibility in their location. They need to be easy to attach and remove, so that each node's installation would not be more than a few minutes. All the sensing techniques need to be unintrusive to avoid disruption of normal operations.

The envisaged mesh network is able to adopt self-managed, self-healing networks. This makes the use of sensor networks much more practical and reliable than traditional point-to-point or star network as it reduces the configuration effort and minimise the data loss in case of node failure as well as enabling dynamic reconfiguration of the network when nodes are added or removed. The drawback of mesh networks is that they consume more power, as the nodes need to be 'listening' all the time. To counterbalance this a network of routers aiming at covering the building with some degree of redundancy can be installed once and powered from the mains. Since the location of the repeater is not conditioned by any sensing requirement, it would be easy to find a convenient access point to existing electrical infrastructure.

Once the repeaters ensure the wireless network is capable of covering the full building, sensor nodes can be installed where the measurements are needed and their data will be relayed to the gateway via the closest repeater. The sensor nodes can thus use power when they are sensing or transmitting data and be idle the rest of the time having negligible power consumption. As data transmission is the most power-consuming task, the data can be sent by batches (e.g. every 10 min for 1 min sampling frequency) to save battery further.

3.6.4 Gateway

The gateway is used to centralise the data from the all the sensor nodes installed in the building before sending them off for visualisation and analysis. For this the easiest solution is to use the building's existing Internet network. If this is not an option, either due to the

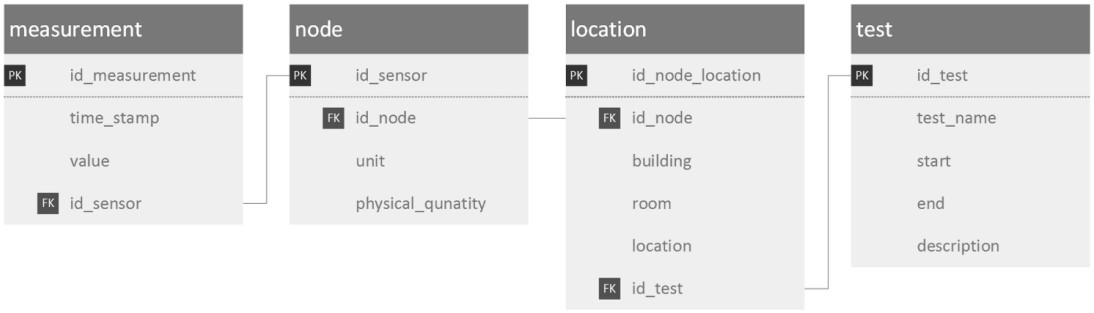


Figure 3.7: Database structure

way the network is administered or problems of authorisation, technology is available to transmit the data over 3G. The data can then be stored in an on-line server. Basic fault detection on the gateway algorithm should be able to send an alert if not enough data are transmitted. Because this relatively intensive data processing involved and the fact that as with the repeaters the gateway need to listen all the time not to lose data it will need to be plugged in the mains. As it can be located anywhere in the building, this is easy to achieve.

3.6.5 Data storage

The data are stored on an online server to be accessible on and off-site. The best way to store the vast amount of data generated is to use a relational database. Jang et al. (2008) propose a database structure based on the assumption that a sensor node can have up to 10 different sensors. This result is wasted storage for placeholders used when fewer sensors are used and can be a problem if a node having more sensors is used. Instead, it is proposed to use the structure presented in Figure 3.7. It does not make any assumptions on the number of sensors for each node by associating each measurement with its time stamp and sensor ID. The primary key in the table containing the measurements is obtained with an auto-increment function. The measurement ID is then also useful for debugging the systems, for example if the nodes lose synchronisation. Complementary data about the node and its location are stored in separate tables that are filled when the node is installed.

3.6.6 User interface and data processing

The user will have two types of needs regarding data access and analysis:

1. **Off-site**. Data need to be available off-site for detailed analysis and troubleshooting to save the commissioning engineer time consuming site visits.

2. **On-site**. Real-time data need to be available once the commissioning engineer is on-site to make sure of the latest status of the system.

For long-term storage, off-site processing and visualisation, the data are used out of the database. An analytic tool including time series visualisation, but as well more advanced analysis function need to be available with an easy to understand user interface. Once BIM use is widespread, the data could also be integrated in order to facilitate usage and transmission of information between stakeholders.

For real time, on-site visualisation, a portable device such as a tablet or even a phone is used. An application providing simple data visualisation and processing can be used. The latest data can be accessed in real time from the gateway and older historic data can be pulled from the database via Wi-Fi or 3G. The mobile device is also used for the commissioning of the WSN at installation (ensure nodes are connected, assign node ID with their location). Other functions of the mobile device could include access building documentation, entering nodes' location on a map, and potentially use augmented reality for data visualisation.

3.7 Summary

This chapter aimed at elaborating requirements for a portable wireless sensor network (PWSN) for post-occupancy commissioning (PO-Cx). The commissioning process was first examined in detail. It was found that the boundary of commissioning varies internationally and that existing guidance for commissioning states what should be done, but does not reflect what is likely to be done in practise. On-site problems observations suggest that the main limitations of commissioning are the lack of importance given to it by design consultants and project managers, impacting design for commissionability and construction for commissionability. If the actual measurements do not present particular technical difficulties, management of such an interdisciplinary process can prove difficult. There is also a lack of precise requirements for Cx in regulation and certification schemes that contribute to undermine the importance given to the process.

The accumulation of all these limitations means that there is a limited time to achieve a fully commissioned building before handover. In addition, some parameters of the building can only be tested once the building is in operation (occupancy and weather). Post-occupancy commissioning is essential for good energy performance and comfort. This would aim at troubleshooting the building and bringing it to a fully operational state by performing systematic performance checks, performing comprehensive seasonal commissioning, ensuring the building meets the need of the occupants, and ensuring that occupants and FM understand how the building operates.

To do this measured data are required. To understand what type of data would be necessary, typical building operating issues were investigated and a list of problems relevant to PO-Cx was established with the help of experienced professionals. It was found that a number of issues were direct consequences of design and could not easily be fixed after construction. Thus, PO-Cx does not remove the need for better feedback to design consultants, but a significant number of common energy and comfort related problems could be easily solved by a PO-Cx process.

The faults retained were used to develop a list of measurements use cases that are the starting point of the requirement for the PWSN. From this a shortlist of measurements of interest was selected. Those measurements aim at integrating together the four big categories of building data, which are system operations, energy metrics, environmental conditions and external conditions. These are normally monitored separately if at all.

It was argued that wireless sensing network was the best option to collect those data and a possible implementation of a PWSN was proposed. WSN are an interesting solution for PO-Cx and troubleshooting, as they are easy to install and remove, do not need specialist to install them and present a flexible measurement capability. This means that it is economical to monitor a variety of data depending on the needs of any building.

Chapter 4

Prototype development and verification

Based on the requirements laid out in Chapter 3, a PWSN system prototype has been implemented and tested. This chapter seeks to answer the following questions:

- How should a PWSN be configured to meet the proposed requirements?
- What practical constraints (e.g. battery life) remain?
- Should the PWSN be integrated to the BMS or be independent?
- How fit for purpose are commonly available sensors?
- How can CO_2 sensing for occupancy detection be simplified to fit with PO-Cx requirements?

This chapter starts by describing the system and justifying some choices made during the PWSN development (Section 4.2). The performance of the WSN system is then tested (Section 4.3), including the wireless communication and the characterisation of the sensors. In particular, Section 4.3.3 studies how CO_2 sensors can give insight on occupancy patterns. The lessons learned from the development and deployment of the PWSN are then discussed evaluating the readiness of the technology and feed future iterations of the system's design (Section 4.4). The chapter starts with an overview of the methodology used.

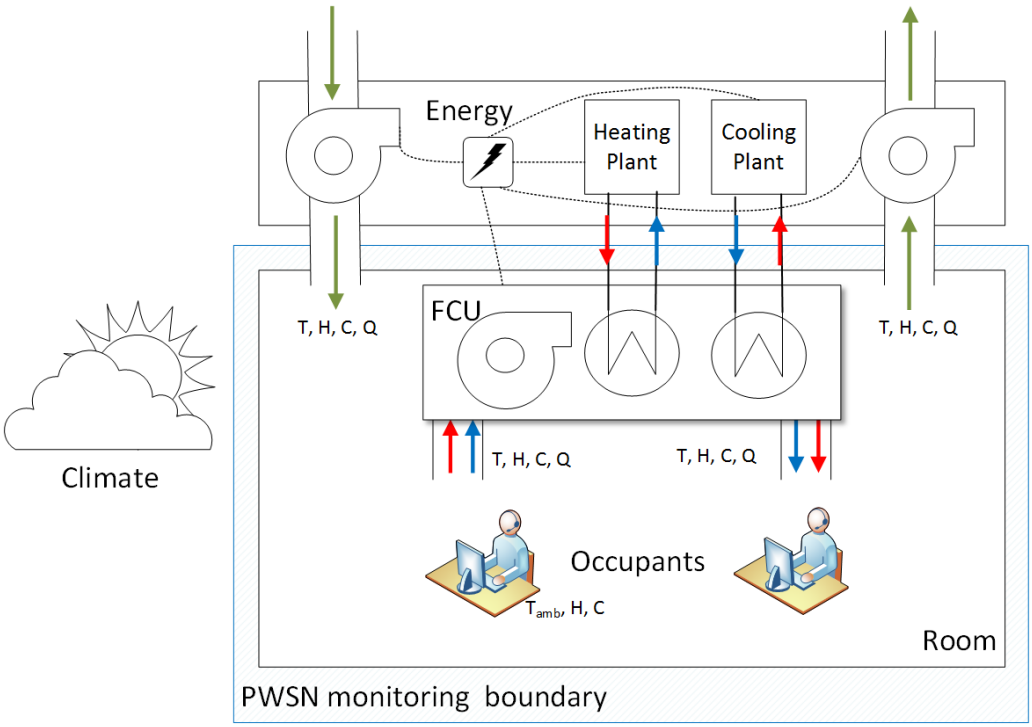


Figure 4.1: Air handling and PWSN monitoring boundaries

4.1 Methodology

4.1.1 Focus on air-handling

Ultimately PO-Cx should be able to address all the building systems, but in this thesis a FCU based system was chosen as the monitoring focus for a number of reasons:

- Most new commercial buildings that are complex enough to benefit financially from PO-Cx are mechanically ventilated.
- Even though the number of innovative naturally ventilated buildings is growing, mechanically ventilated buildings remain the biggest energy consumers.
- Air related measurements are more problematic than water flows, so air-based heating is more likely to result in waste that water-based heating.
- HVAC systems are challenging systems to commission as they are at the interface between the different technical competences needed for commissioning: water systems, air systems, electrical systems, and controls. This is especially true for FCU that are

a commonly installed systems.

The BMS system would present a pre-existing monitoring capability with the limitations presented in Chapter 3. However, the BMS mostly monitors the state of the plant and very few sensors are evaluating whether the system delivers in terms of comfort and energy sobriety. In addition, local operation of FCU and other room outlets have a big influence on the end energy consumption of the plants. For example, a single FCU being kept on in an office building could trigger a chiller to operate full load 24 hours. For these reasons, the monitoring prototype developed in this chapter will focus on what happens within the boundary defined on Figure 4.1. Figure 4.1 represents a typical air-conditioning system using a AHU for ventilation and a FCU for air-conditioning, but considering the definition of the boundaries, this can be extended to any type of ventilation-based system.

By defining these boundaries, the outputs of the systems are considered, in particulate how they affect the comfort of the occupants. The values taken into account are:

- Ambient conditions including:
  - Temperature
  - Radiant temperature
  - Relative humidity
  - Carbon dioxide concentration
- Fresh air supply, conditioned air supply, and exhaust conditions including:
  - Temperature
  - Relative humidity
  - Carbon dioxide concentration
  - Airflow
- FCU heating and cooling pipe temperature

Approaching the monitoring system in this way means that sensor nodes are easy to install since all the measurements of interests are physically accessible. If more detail about the system operation is needed, the information can be pulled out of the BMS system.

4.1.2 Development

Based on the system boundary defined in the previous section and the requirements established in Chapter 3, a prototype PWSN was developed. This prototype objective was to 1) test the practicality of a PWSN for PO-Cx, and to identify 2) the key functionalities and 3) the potential pitfall to consider towards the design of a commercial PWSN.

The prototype is also used in Chapter 5 to demonstrate the value WSN data can bring to a PO-Cx process and to set the requirements for an analytic tool to make a fast use of those data.

4.1.3 Monitoring system verification

Once the initial prototype was put together, its performance needed to be verified before using it for troubleshooting. The verification of the monitoring system is divided in two aspects. First its capacity to handled data, second the ability of the sensors to provide appropriate information.

Wireless transmission

To ensure the capacity of the system to handle data, the battery life cycle and the wireless transmission are looked at. The battery life estimation is based on current measurements using a multimeter and practical experience with the sensors.

One of the common concerns regarding wireless systems is the reliability of the communication, which tends to be lower than for wired systems. Data loss can be caused by interference, noise or insufficient transmission power. Power loss can also be responsible for missing data. As stated in Section 2.5.3, some metrics exist to assess the quality of the data link. Jang and Healy (2010) list the following:

- Received Signal Strength Indicator (RSSI)
- Link Quality Indicator (LQI)
- Packet Delivery Rate (PDR) and its opposite Packet Error Rate (PER)

RSSI and LQI have arbitrary units making it difficult to compare performance across manufacturers and are more adapted to evaluate environmental effect on a specific technology (Jang and Healy, 2010). They are often used as hardware is installed on most radio

device that enables instant access to the metrics. The interest for the user is to know how many packets were successfully received. Unfortunately RSSI and LQI are not directly correlated to this (Jang and Healy, 2010). At the most basic level, the PDR, which is expressed as the percentage of the number of packets received over the number of packets sent (Equation 4.1), is a good performance indicator as it is completely independent of the RF technology (Jang and Healy, 2010).

$$PDR = \frac{Packets\ received}{Packets\ send} * 100 \tag{4.1}$$

PDR calculation can be implemented in the network protocol, but the nodes from the prototype PWSN did not have embedded signal quality testing protocols. The simplest way to access the successful transmission of the system was then to compare the number of packets sent to the number of packets received.

Sensing verification

Calibration requirements To make a proper use of the PWSN, it is important that its sensors are adequately calibrated for their measurements application. The calibration procedure should be done in a specialist laboratory with adequate calibration equipment. Because of the wireless nature of the system, it can easily be taken back to the lab when recalibration is necessary. Examples of calibration procedures are given below for the different sensors.

- **Temperature** Temperature sensors can be calibrated in controlled air chambers, using liquid immersion bath, or infra red sources[1].

- **Humidity** Relative humidity calibration requires a controlled environment with uniformity and thermal stability. This can be achieved by salt baths or a two-pressure system (Schellenberg, 2001).

- **CO_2** CO_2 sensors can be calibrated using calibration gas at several concentration. However, the CO_2 sensors currently available tend not to be extremely accurate and need frequent recalibration (Fisk et al., 2006). Stum (2006) suggests that for the type of use of CO_2 sensors in buildings, relative calibration of the different sensors might be sufficient.

[1]BSRIA Temperature calibration https://www.bsria.co.uk/instrument/calibration/temperature/

Table 4.1: Sensors characterisation tests

Character-isation test	**Sensor**	**Overview**
Back-to-back testing	Temperature Humidity CO_2	Placing all the sensors measuring the same quantity in close geographical location in a space with slowly changing conditions
Wind tunnel	Airflow	Compare sensor reading to pitot tube readings at different airflow in a wind tunnel
Occupancy	CO_2	Compare CO_2 reading to real occupancy to develop a qualitative algorithm

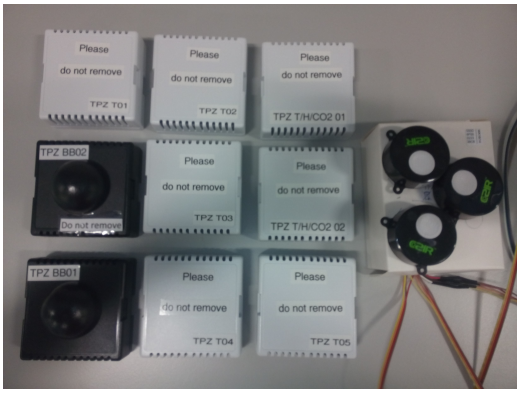


Figure 4.2: Back-to-back test - sensor set up

- **Airspeed** The calibration of a hot wire anemometer type of sensor requires a specially intended device as it must be able to precisely control air velocity, temperature and humidity (Pupyshev et al., 2004).

For the thesis due to the lack of appropriate equipment and since the prototype used readily available equipment, a simpler approach consisting in verifying the sensor reading against each other has been chosen and will be described below. The limitation of this method is that it is not possible to know the end to end accuracy of the devices as the accuracy given by the manufacturer only take the sensor into account (Stum, 2006). This is, however, not critical to demonstrate the feasibility of the PWSN.

Back-to-back testing To verify the level of confidence to give to the sensor reading from the PWSN, three series of tests have been carried out (Table 4.1). For the digital sensors (temperature, humidity, CO_2), which have specific characteristics from the manufacturer, a simple back-to-back test was performed to see how much variation could be observed

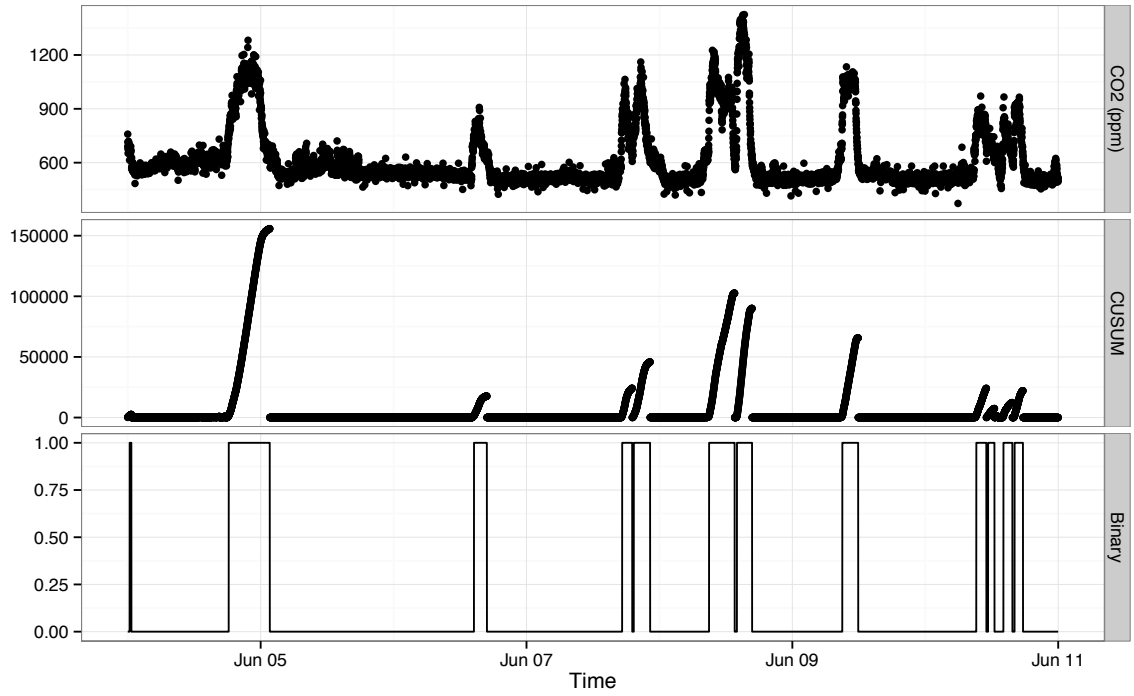


Figure 4.3: CO_2 measurement transformation by the O-CUSUM algorithm

from one sensor to the other. The back-to-back test consists in installing all the sensors measuring the same physical quantity close to each other on a laboratory bench (Figure 4.2). It is assumed that even though this is not a controlled environment, the quantity measured would vary slowly and be relatively uniform. The time series were then looked at to see whether they were significant variations between the sensors. Unless a significant variation between sensors relatively of their nominal accuracy is observed, it is assumed that they are calibrated well enough to perform PO-Cx.

Wind tunnel The air velocity sensors had to go through a more advance process as they are analogue sensors (meaning that they measure a voltage output not airflow directly) and the manufacturer did not give a precise calibration equation. However, a set of calibration data was obtained from the manufacture. To verify the validity of the calibration data, additional data were collected using a small blow-through wind tunnel.

Occupancy detection with CO_2 sensors

As explained in Section 2.5.2, CO_2 gives an indication of occupancy, but there is a number of parameters that influence the final CO_2 concentration, making it difficult to correlate CO_2 with a precise number of occupants. First, the rate of CO_2 generated by each person depends on a number of factors, the principals being activity and body size (Emmerich and Persily, 2001). This requires either a training period or the use of assumptions to relate the CO_2 generation rate to the number of occupants. Second, parameters from the building, such as ventilation rates and rooms volume, also affect the CO_2 concentration. At the simplest level, the CO_2 concentration can be determined by a zone mass balance (Equation 4.2) (Emmerich and Persily, 2001).

$$V \cdot \frac{dC}{dt} = G + Q \cdot C_{out} - Q \cdot C \tag{4.2}$$

where C is the concentration of CO_2 in the room, V the volume of the room, Q the ventilation rate, C_{out} the outdoor CO_2 concentration, and G the CO_2 generation rate. If the generation rate (e.g. number of occupants), the ventilation rate and the outdoor concentration are constant, a steady state concentration (C_{ss}) will be reached and the generation rate can be expressed as:

$$G = Q \cdot (C_{ss} - C_{out}) \tag{4.3}$$

This can then be used to calculate occupancy or ventilation requirements. However, the steady state will take time to reach. Build up and decay can be calculated by finding the transient solutions of Equation 4.2 with the appropriate boundary conditions. For the purpose of DCV, Wang and Jin (1998) propose to base control strategies on dynamic models (either using an incremental method based on past and current measurement or working with an exact solution of 4.2) to eliminate the delay of the steady-state model. This model, however, does not account for other parameters such as exfiltration or infiltration (Lawrance and Braun, 2007). Tuip et al. (2010) proposes to overcome this using artificial neural networks, but this requires a period of training against a data set of real occupancy.

All those factors mean that without training periods or detail building models it is difficult to know the exact number of occupants. Neither of those solutions is suitable for PO-Cx as they are too time and cost intensive for short-term measurements. Based on the

work that will be presented at CIBSE Technical Symposium 2016 (Noye, Keirstead and Angeloudis, 2016), a method using detection of the CO_2 variation as a qualitative indicator of real occupancy schedule is implemented. The method is independent of the building and occupants' characteristics and does not require accurate calibration of the CO_2 sensors.

CO_2 measurements provide a noisy signal that is difficult to process directly. Cumulative sum control charts (CUSUM) are used in signal processing for change detection in a noisy signal (Page, 1954). To decompose the CO_2 signal, a CUSUM algorithm as shown in Equation 4.4 - where S_n is the CUSUM series, (x_n) is the measured signal and $\bar{x}$ is the baseline of the signal - is used.

$$\begin{aligned} S_0 &= 0 \\ S_n &= max(0, S_{n-1} + x_n - \bar{x}) \end{aligned} \tag{4.4}$$

The algorithm measures how much the signal deviates from the expected baseline. The average value of the night CO_2 concentration was used for $\bar{x}$, as there would normally not be any occupancy during this period. Figure 4.3 shows how the CUSUM algorithm transforms a sample of CO_2 measurements. When the CUSUM values go up, it means the CO_2 concentration diverge significantly from the baseline value. When the CO_2 values are back to the baseline values, the CUSUM algorithm decreases. When this happens, the CUSUM value is reset to zero to be able to detect the next deviation. This means that the decoy period is included, which will tend to overestimate the end of occupation periods.

The CUSUM signal can then be transformed in a binary signal by filtering it with a threshold. In the binary signal, 0 means the CO_2 value is close to the baseline and 1 means the CO_2 value deviates significantly from the baseline. The height of the deviation can then be obtained by applying a maximum function to the original CO_2 signal on the intervals where the binary signal is 1. For convenience, this process will be called O-CUSUM for occupancy CUSUM.

This method has several limitations that need to be taken into account. First other sources of CO_2 generation can interfere. If plants or catering facilities are present, they can be responsible for the variation of the CO_2 measurements. Also, the algorithm should not be interpreted in the same way in different types of buildings, as the rate of CO_2 emitted by a person depends on its activity.

Table 4.2: Experimental design of controlled occupancy experiment

Test	Time	People	Door
1	7 - 7.30 am	1	closed
2	8 - 8.30 am	1	open
3	9 - 9.30 am	2	open
4	10 - 10.30 am	6	closed
5	11 - 11.30 am	2	closed
6	12 - 1.30 pm	30	closed
7	2 - 2:30 pm	6	open
8	3 - 3.30 pm	11	closed
9	4 - 4.30 pm	12	open
10	5 - 5.30 pm	3	closed
11	6 - 6.30 pm	2	closed
12	7 - 7.30 pm	0	open

First a pilot study was conducted over a week where regular occupancy counts were taken to ensure CO_2 could be paired with occupancy. There was then the need for a data set where the number of occupants was known at all times to justify how CO_2 variations reflect occupancy. A one-day experiment where occupancy was known at all time was conducted in the space used for the pop-up monitoring™ trial described in Chapter 5. The dimensions of the room are L10.71 m, W7.37m, H2.85 being about 225 m^3. The day was cut in 30 min time slots. Different levels of occupancy with the room's door closed or open have been tested and alternated with periods of non-occupancy to let the CO_2 level decease (Table 4.2). Occupants were asked to sit down to simulate the low activity of a group of students working or following a lecture. The last test is done without occupants to determine the CO_2 response to the door being opened. CO_2 and occupancy data were also collected for two days in a single office to see how the method transferred in another space. The CO_2 was collected with a wireless node and the occupancy was recorded manually by the occupant of the office.

4.1.4 Lesson learned from development and deployment

Starting from the particular observations made during the development of the PWSN prototype and its deployment (see details in Chapter 5), conclusions are drawn on the best option to implement future iterations of a PWSN. This then leads to generalised observations about the current status of WSN in the building industry, highlighting the

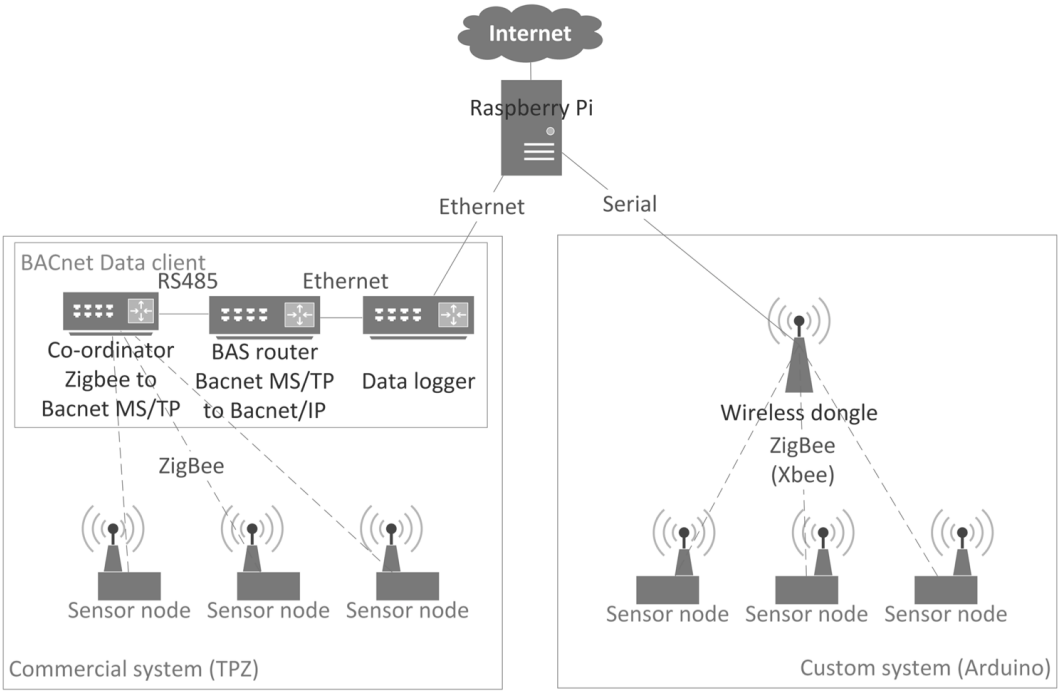


Figure 4.4: Prototype network architecture

current shortcomings and giving recommendation for future penetration in the industry.

4.2 Monitoring system description

This section describes the prototype PWSN developed to demonstrate the feasibility of pop-up monitoring™ for PO-Cx. It starts with a general overview of the system. The different components of the system are then described more in detail.

4.2.1 System overview

Although a growing number of BMS manufacturers provide wireless equipment, no system covering the full extent of measurements listed in Section 4.1 was found directly available on the market. This is seen as a direct consequence of the separation between control and energy monitoring systems. Therefore, it was decided to complement one of those systems with custom made nodes based on the open-source project Arduino[2].

[2]http://www.arduino.cc/

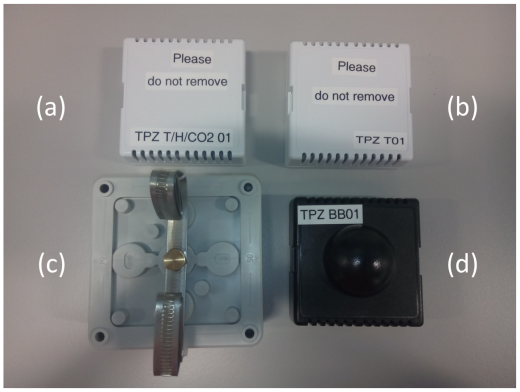


Figure 4.5: Commercial system nodes: (a) Ambient node, (b) Temperature node, (c) Pipe temperature node, (d) Radiant temperature node

Combining those systems resulted in an increase of equipment redundant function. The two networks could not intercommunicate. This complexity would need to be removed for commercial applications, but the resulting prototype was sufficient to demonstrate the benefit of pop-up monitoring™. This also enabled the comparison between two types of approach: PWSN as an extension of the BMS system or PWSN as a standalone system.

Figure 4.4 shows the realised prototype network architecture. It can be decomposed in three parts: the commercial system (that will also be called TPZ for Titan Products ZigBee), the custom-made system (that will also be called Arduino) and a Raspberry Pi. Raspberry Pis are small Linux computers that are used for example in robotics and can be easily embedded in mobile applications[3]. In this case it was used to integrate the two systems together. The Raspberry Pi collects data from both systems and converts it in the same format to be able to store it together in a database. The operation of each system is described in the following sections.

4.2.2 Commercial BMS system

The first subsystem is an off-the-shelf wireless network from the BMS manufacturer Titan Product Ltd[4]. It is using a proprietary protocol based on the ZigBee standard for wireless communication. This system is originally intended to easily refurbish existing BMS system. Therefore, the list of sensors offered is limited to typical BMS measurements.

[3]https://www.raspberrypi.org
[4]http://www.titanproducts.com/

Table 4.3: Control system sensor characteristics

Sensor	Accuracy	Operating range
Ambient temperature	+/- 0.5 °C	0 to 50 °C
Relative humidity	+/- 3 %	0 to 95 % non-condensing
CO_2	+/- 50 ppm + 2 % of reading	0 to 2000 ppm
Radiant temperature	+/- 0.5 °C	0 to 50 °C
Pipe temperature	+/- 0.5 °C	0 to 100 °C

Table 4.4: Cost of the commercial system elements

Equipment	Cost
Temperature node	£65
Ambient temperature, humidity and CO_2	£185
Radiant temperature	£75
Pipe temperature	£92
Repeater	£95
Coordinator	£150
Router and data logger	£800

From this system four types of nodes are used (Figure 4.5): single room temperature sensors; ambient sensor nodes including air temperature, relative humidity and CO_2[5]; black bulb radiant temperature nodes; and pipe temperature nodes using a contact temperature sensor. In the same range the manufacturer also proposes outdoor temperature, immersion temperature, duct temperature, passive infrared and light level sensors.

The sensor characteristics given by the manufacturer are summarised in Table 4.3. Their accuracy is not high, but they are typical of BMS sensors. As buildings that have a BMS system would normally have a high number of measurement nodes, high accuracy is traded off for low cost. Nevertheless, this level of accuracy gives a good idea of the physical quantities they measure and of their variations.

The nodes are powered with 3.6 V 2600 mAh lithium thionyl chloride batteries. The manufacturer claims up to 3 years of battery life at 15 min sampling intervals. In practice the battery of the TPZ system lasted between one year and a year and a half at 15 min

[5]through this thesis ppm represents part per millions as a volume fraction

sampling intervals. Surprisingly they did not seem to be a significant difference between the nodes sensing CO_2 and the others in term or battery life. The real battery life was less than the value stated by the manufacturer, but is still enough to perform PO-Cx. An on/off switch on the node to save battery when no measurement is taken would be a good way to extend battery life, as the nodes would not be used continuously during PO-Cx. At the moment the batteries needed to be removed to power the node off, which is likely not to be done in practice. In any case, having a few backup batteries available is a good way to avoid problems. They are about £5 each.

The sensor nodes form a star network around a coordinator. Self healing, meshed network can be achieved using repeaters. The maximum measurement frequency is 15 min. It is also possible to set thresholds to trigger additional measurements, but this was not used. The coordinator output data in BACnet MSTP[6] format, which is the standard BMS protocol for BMS systems. This can easily be integrated to an existing control system.

To be able to log the data, the BACnet MSTP needed to be converted to BACnet IP, as BACnet MSTP is not compatible with personal computers. The combination of a BACnet MSTP to IP router with a data logger was used as a data client. A Python script running on the Raspberry Pi pulls the data from the data-logger and sends them to a database.

Table 4.4 gives an idea of the price of the system at the time of its purchase in 2014. The price of the node is likely to decrease with the price of electronic components and increased production volumes.

4.2.3 Arduino and XBee based system

A non-intrusive way to measure airflow speed, temperature, relative humidity and CO_2 was still needed. A dedicated node was developed for this purpose (Figure 4.6). The sensing side was developed around Arduino boards. The wireless communication was obtained using XBee modules[7], a wireless radio proprietary protocol from Digi International designed for easy prototyping.

In addition to the Arduino board and the XBee module (Figure 4.7a), each node is

[6]Master Slave Token Passing
[7]http://www.digi.com/lp/xbee/

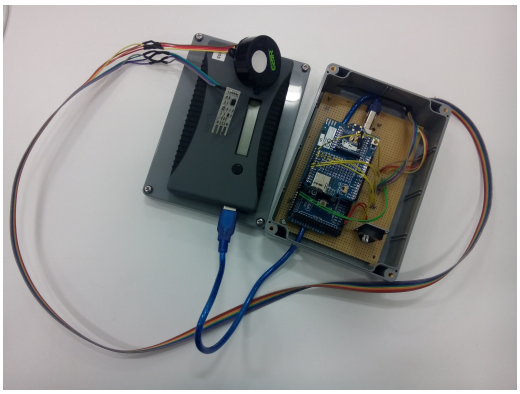


Figure 4.6: Arduino system ventilation node



(a) XBee module (b) X-Stick

Figure 4.7: XBee wireless communication. Source: www.digi.com

Table 4.5: Arduino system sensors characteristics

Sensor	Accuracy	Operating range	Power consumption
Air flow	NA	NA	20 - 40 mA
CO_2	+/- 50 ppm +/- 3 % of reading	0 to 2000 ppm	3.5 mW, 33 mA max
Temperature	+/- 0.75 °C between 10 and 50 °C	-25 to 55 °C	
Relative humidity	+/- 3 % between 20 and 55 °C	0 to 95 % RH	

Table 4.6: XBee ZigBee characteristics

Performance	
RF data rate	250 Kbps
Indoor range	40 m
Frequency band	2.4 GHz
Serial data rates	1200 bps - 1 Mbps
Operation temperature	-40 to +85 °C, 0-95 % humidity non-condensing
Supply voltage	2.1 -3.6 VDC
Transmit current	35 mA
Receive current	38 mA
Power-down current	<1 μ at 25 °C

composed of:

- a shield to interface with the XBee module and add an SD card back-up.
- a real time-clock (RTC) to get accurate time stamps[8].
- a COZIR™ [9] sensor, which measure temperature, relative humidity and CO_2. The CO_2 is measured using no-disruptive infrared sensing, while the temperature and humidity come from a capacitive sensor (data-sheets in Annex B). The sensor range of 0-2000 ppm as been chosen, as indoor CO_2 concentrations beyond 1550 ppm are considered to reflect poor indoor air quality (Braham et al., 2010).
- a 'wind sensor'[10] based on hot-wire anemometer measurement principle to measure air velocity.

The characteristics of the different sensors are summarised in Table 4.5.

[8]The internal clock of the Arduino board drift significantly over a day
[9]http://www.gassensing.co.uk/product/cozir-ambient/
[10]https://moderndevice.com/product/wind-sensor/

The wireless communication is achieved through XBee Series 2 ZB for ZigBee (Figure 4.7), a proprietary protocol based on the ZigBee standard. Some of its characteristics are summarised in Table 4.6. XBee modules can be set as coordinators, routers or end devices. To mimic the architecture of the commercial system, the sensor nodes are set to end devices, making them form a star network around the coordinator. This option is the most sensible as only the end devices mode enables to implement sleeping cycles when coordinators and routers need to be on at all times and can thus not be battery powered. Making use of the self-healing property would be feasible by using the router mode for repeater nodes. This was not implemented here as all the nodes were always within range of the coordinator, but it could have been easily achieved by implementing additional nodes on the same model but without the sensors components.

The power consumption of an Arduino mega is around 14 mA[11]. The RTC consumes 0.2 mA[12] and the SD card 12 mA[13]. This gives a base of about 65 mA including the XBee consumption (Table 4.6). Adding the sensors, each node's consumption peaks at about 150 mA. This was confirmed by measuring the node consumption with a multi-meter. Originally 9000 mAh Lithium Polymer batteries[14] were used, but due to problems with setting up the sleeping cycle and the fact that more data than strictly needed were taken for research purpose, they would drain in 2-3 days. The power consumption could easily be reduced by further design iterations on the node, for example by using a dedicated processor board instead of the Arduino board and better use of the XBee sleep cycles. As this would not have brought significant value to the proof of concept intended in this project, the nodes were powered from the mains when they had to be used for longer than a day. This still enabled a good idea of the advantages of WSN and they are examples in the literature that sufficient battery time can be achieved with careful node design (Mainwaring et al., 2002).

For the gateway, two options were considered. Digi offers a series of XBee programmable gateways that can be plugged directly in the network via Ethernet and cost around £90. This is the best option for a standalone system, as no further equipment is needed. The other option is to use a dongle that contains an XBee RF (Figure 4.7b) and send the

[11] As measured by divers users on dedicated forums e.g. http://forum.arduino.cc/index.php?topic=125344.0 Last accessed 24/02/16.

[12] http://datasheets.maximintegrated.com/en/ds/DS3231.pdf Last accessed 24/02/16.

[13] http://forum.arduino.cc/index.php?topic=149504.0 Last accessed 24/02/16.

[14] https://www.powertraveller.com/en/shop/portable-chargers/professional/minigorilla/

Table 4.7: Cost breakdown of the Arduino node prototype

	Cost inc. VAT (£)
Sensor	
Air movement sensor	£11
COZIR™	£118
Wireless communication	
XBee module	£12
SD and XBee shield	£20
SD card	£5
Processing	
Arduino board	£12
Real-time clock	£2
Power	
Battery	£100
Enclosure and fixtures	
ABS box	£12
Proto board	£3
Jumpers and wires	£0.4
Screws and nuts	£0.25
Total	£296

received data over the serial port of a computer, which amounts to about £80 including the RPi. Since it was easier to integrate it with the other system, as the RPi would handle the networking, the second option was selected. It also reduced the development time.

Table 4.7 presents the approximate breakdown of the cost of the custom node. This cost includes only the material components used to make the node for a small production. It does not take into account labour and shipment. However, bigger production would induce economies of scale as well in the material cost and in the labour time per node. The two major cost bearers are the CO_2 sensor and the battery. The CO_2 sensor is a relatively new technology and its cost has already been going down slightly during the project, and the company offers discounts on bulk orders. The battery needs can be scaled down by design iteration and thus be replaced by a less expensive battery. Marginally the SD card function was used for research purpose (see Section 4.3.1) and can be removed to save costs and most importantly battery life.

4.2.4 Data storage

Using a MySQL server, the database structure described in Section 3.6.5 was implemented. The database is stored on the Raspberry Pi and available on-line through SSH[15]. This solution was chosen to limit the software development necessary, but for a commercial application the database would more likely be stored on the server of the company. For backup and comparison purpose, the data from both systems were logged locally on SD cards, on each node for the Arduino nodes and on the data logger for the BMS compatible system.

4.2.5 Data analysis

For the purpose of this study, the data were analysed using the open platform statistical software R (R Development Core Team, 2015). In the context of a commercial application a custom front end with ad hoc function would need to be developed, but specific analytic needs need to be pinned down before being able to do this. This is one of the purposes of Chapter 5 and will be discussed in Section 5.5.

In this paragraph, the data cleaning process used is quickly commented. Assuming an ad hoc WSN developed for forensic purpose, those should be limited or even unnecessary. However, in practice the perfect system is rarely achieved and compromises need to be made. This also helps to outline the importance of the implementation of some feature in the WSN. First a filter was developed for the commercial system data. It is not clear whether the issue was coming from the TPZ system or from the data logger, but the time stamps of the data were the time where the data were pulled from the data logger instead of the time they were received. This resulted in a number or duplicated data since the data are updated every 15 min but a pulling attempt happens every minute. A function was also written to correct synchronisation problems that were of three types:

- The time stamp of the Arduino nodes had a few seconds of lag between each other's.
- Some time stamps shifted over time for the length of the experiments. The TPZ system shifted significantly during the six-month deployment.
- The measurements were not simultaneous.

[15] Secure Shell

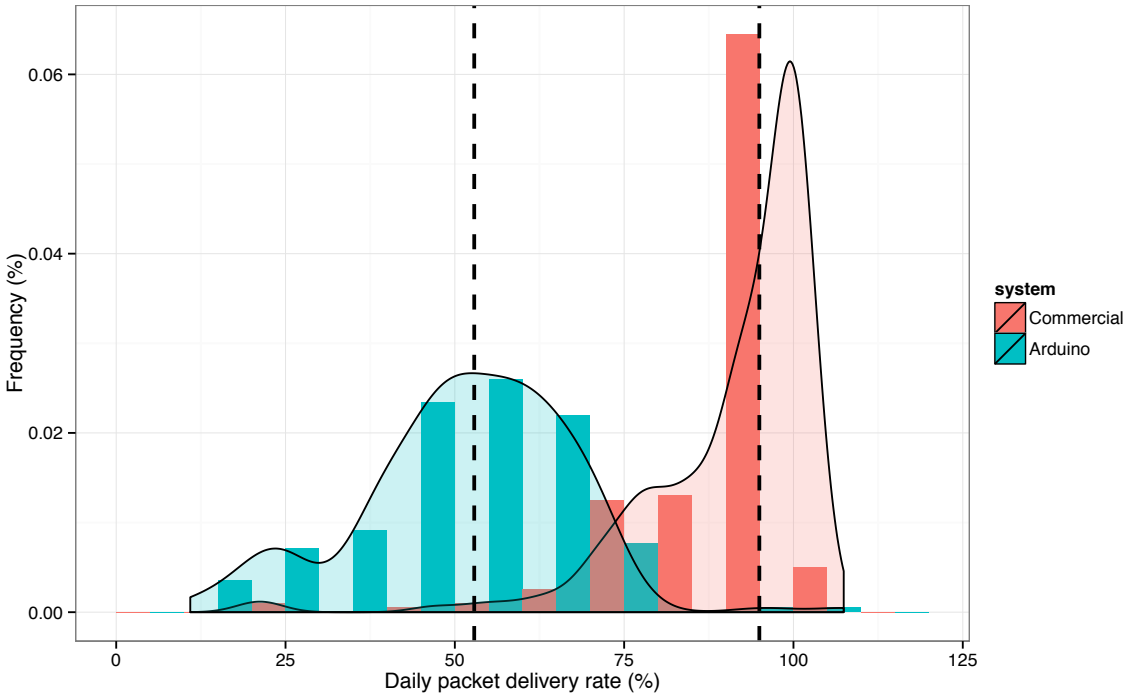


Figure 4.8: Daily PDR of Arduino and TPZ system

For ease of data analysis, the synchronisation process should be integrated in the communication protocol, rather than having to correct it a posteriori.

4.3 Monitoring system verification

This section describes the initial verification tests of the developed prototype. In a first time the performance of the wireless aspects of the system were evaluated. The characteristics of the sensors are then evaluated. The results are based on laboratory tests and the data collection on the teaching space described in Section 5.2.

4.3.1 Wireless transmission

Data transmission is an important indicator of the success of a wireless communication protocol. For the XBee nodes, it was possible to calculate the PDR directly as the data sent were backed up on a SD card on each node. Unfortunately it was not possible to do the same with the commercial system. The number of packets received was thus normalised by the total number of data expected daily knowing the transmission interval. As such it

is not purely an indicator of the wireless signal of the commercial system, but rather as the system as a whole. The PDR have been calculated based on the total of data sent and received each day.

Figure 4.8 shows the frequency of daily PDR calculated for the 6 months of data collection that will be described further in Chapter 5. The distribution of the PDR of the commercial system is centred on 53% of the expected data. Because of the way the PDR was calculated, it is not clear whether the missing data just did not get send or if there were lost in the wireless process. The low performance of the system comes from the simplicity of the communication protocol. As demonstrated by the Arduino system, which PDRs are centred on 95%, better performance can be easily achieved.

It is suspected that the commercial WSN has been developed by the BMS manufacturer to respond to the rising interest in WSN, but had not been optimised. Basic features like packet acknowledgement and battery level alarms would be an easy way to reduce data losses. However, despite the low delivery rate, the collected data could still be used for forensic purposes as will be demonstrated in the following chapter.

During the first few months of the data collection, the Arduino nodes were powered by a battery that would be changed almost daily. This was later replaced by a USB hub powered by the mains. Battery life could have been extended significantly by redesigning the node, but this was judged tangential to the main objectives of the chapter. Figure 4.9 represents the PDR repartition depending on the power source of the Arduino node. It can be noticed that the wireless transmission is more successful when the nodes are powered by the USB hub. It is not surprising as this power source is expected to be more stable. The battery-powered performance is still acceptable, but it has to be accepted that a battery-powered system is unlikely to rich 100 % transmission rate. The performance can be increased by adding acknowledgements to the communication protocol, however, a trade-off has to be made with the additional battery power this requires.

Ultimately, it will always be possible to find somewhere in a building where the wireless performance is poor due to high levels of interference (e.g. lift systems) but this is unlikely to be in occupied areas, which are the mains concern of PO-Cx. The interference levels in the test installation will be representative of the environment within an occupied space.

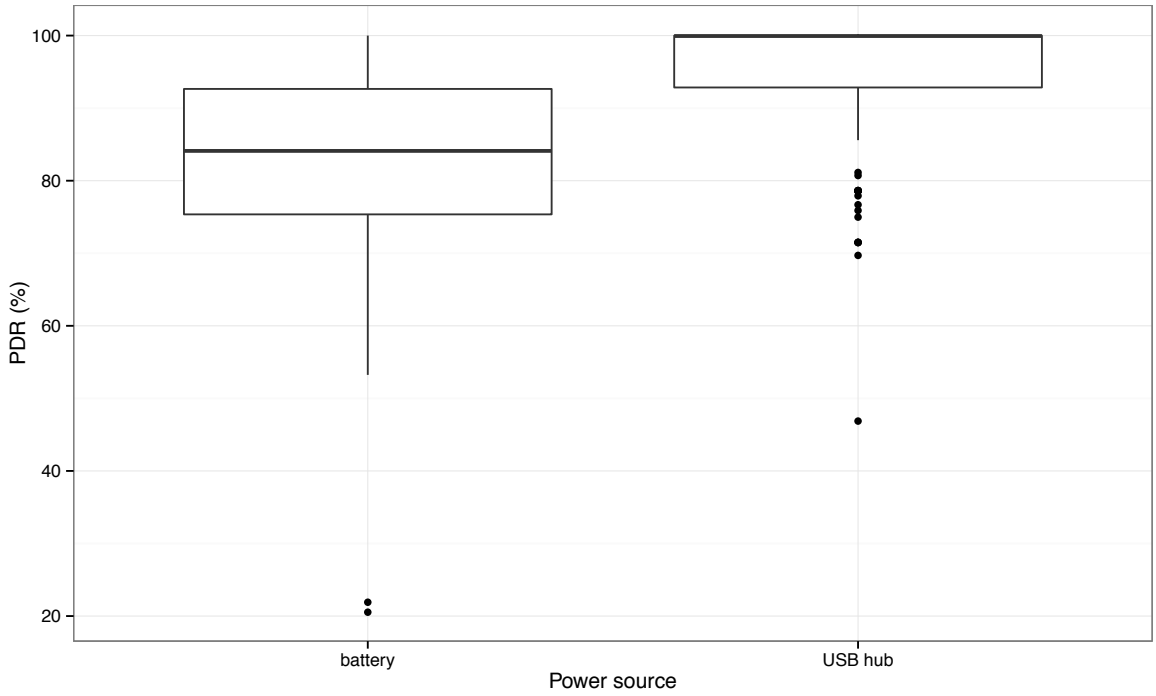


Figure 4.9: Wireless performance of the Arduino nodes in function of their power source

4.3.2 Sensors verification

In this section, the calibration of the different sensors used by each system is evaluated and appropriate verification tests carried out.

Back-to-back testing

For sensors that were bought calibrated directly from the manufacturer, a simple back-to-back testing was performed. The purpose of this test was to identify potential calibration problems and the extent of variation between the different sensors used. The temperature, humidity and CO_2 sensors were placed close to each other and left to record data for 3 days. It is assumed that the sensors are close enough that the physical quantity measured is the same for all the sensors and thus that the variation from one measurement to another only comes from the sensor. The detailed results of the tests can be found in Appendix C. The aspects relevant for this study are summarised in this section.

Temperature Within each system values are close to each other, but there is a gap between the TPZ and Arduino systems' measurements. The average temperature at each time t has been calculated for each system separately. For the Arduino system the dispersion around the average is ± 0.15 °C. For the TPZ system the dispersion ranges from - 0.25 to 0.15 °C. The variation from the average is independent of the temperature, so is only due to calibration bias and noise. The difference between the averages of two systems at each point in time has been averaged over the length of the test. The vertical offset between the systems is 0.32 °C. The graphs illustrating this can be found on Figure C.1 in Appendix C.

The overall variation of the sensors is within the ±0.5 °C accuracy of the TPZ sensors (see Table 4.3) and ±1 °C of the COZIR™ sensor (see Table 4.5). This means that the sensors are sufficiently calibrated and are suitable for PO-Cx. However, it must be noted that the temperature measured is likely to be a mix between air and radiant temperature since the temperature sensor is inside a plastic box. In the frame of calibration tests mentioned in Section 4.1.3, it would be interesting to characterise the responsiveness and sensitivity of the sensor nodes to air and radiant temperature.

Humidity The results for the humidity measurements are very similar to the one of the temperature test, therefore the same analysis method was used. The spread around the average for both systems is -1.5 to 1 %RH and the difference between the systems is 1.5 %RH (see Figure C.2 in Appendix C for more detail). Once more this is negligible compared to the 3 % accuracy of the sensor (Tables 4.3 and 4.5).

Carbon dioxide Looking at the time series of the CO_2 (see Figure C.3a in Appendix C), the three sensors from the Arduino system follow the same variations. However, one of the CO_2 sensors from the Arduino system is significantly off the other sensors and another one has slightly lower readings. This suggests the need to recalibrate those sensors. However, Stum (2006) argues that for CO_2 sensor relative calibration might be sufficient. For the TPZ sensors, the spread of the readings are within the 50 ppm accuracy stated (Table 4.3), which suggest acceptable calibration. The Arduino sensor the closest to the TPZ ones was thus used as reference. It is found that corrective constants of 383 and 78 ppm need to be applied respectively to the two other CO_2 sensors. From this point, this will be used to correct the CO_2 readings. Once the measurements were corrected the measurement dispersion of the Arduino system is ± 40 ppm and the difference between the two systems is 1.5 ppm.

The big difference observed between the sensors comes from the fact that the sensors have been reused from another project and the calibration had thus shifted. Overall CO_2 sensors are less stable than temperature sensors due to the more complex measurement method they use. Calibration problems are a known issue that tends to limit their use (Fisk et al., 2006). Precise calibration of the CO_2 sensors is difficult and requires specific laboratory facilities. However, it was shown that it is easy to perform relative calibration.

Air velocity

The air movement sensor from Modern Devices output analogue values, so a simple back-to-back test was not sufficient. Calibration data points provided on demand by the manufacturer and a test on a small wind tunnel have been used to derive a calibration equation for the sensors. The sensor works like a hot wire anemometer, meaning the output current depend on air speed and temperature. The details of the calibration tests can be found in Section C.2. The calibration obtained is sufficient for the purpose of the proof of concept of the PWSN, but for a commercial application the sensor would need a better calibration equation from the manufacturer. Using the same sensor principle and making it into a digital sensor might be the way forward.

4.3.3 Variations of CO_2 versus occupancy

Occupancy is one of the key parameters to evaluate the performance of building services against, as their primary objective is to deliver comfort to occupants. At design stage theoretical schedules are assumed to calculate loads and decide control sequences. However, real occupation of the building will most likely be different from the design assumptions. This can range from extended working hours, change of purpose of certain space, etc. Therefore minimum knowledge of real occupancy patterns is key for a complete post-occupancy commissioning process. This section is based on work accepted for CIBSE Technical Symposium 2016 (Noye, Keirstead and Angeloudis, 2016).

Preliminary observations

Figure 4.10 shows the recorded time series of the controlled occupancy experiment together with the state of the room's door. It can be seen that the spikes in CO_2 concentration and the occupancy record follow a similar pattern and that the more people are in the room,

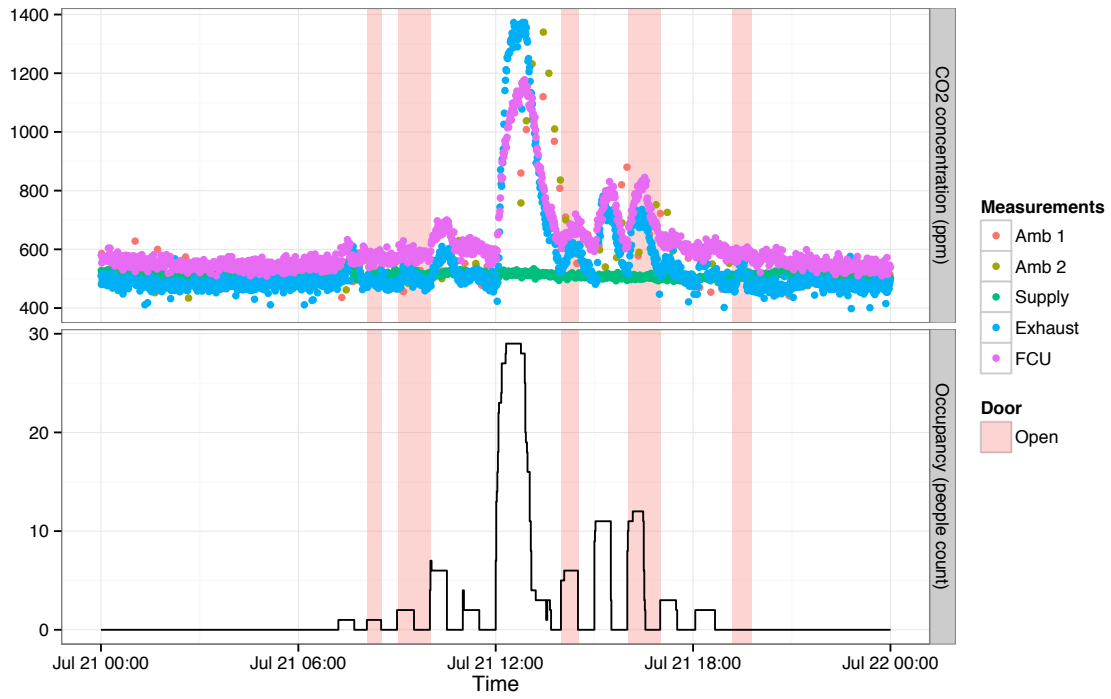


Figure 4.10: Time series of controlled occupancy test

the higher the level of the CO_2 peaks.

Looking at the different CO_2 sensors, the one placed at the supply grid does not show any variations as it measures the concentration in the intake air and is thus not useful for occupancy detection. All the other sensors present variation coherent with the occupancy variation. The two ambient sensors can be used when there is dense occupancy for long periods, but seem to miss the smaller groups of people, as measurements are not taken often enough. The sensor from the FCU could work, but the difference is more marked for small groups of people at the air exhaust. This is not surprising as it is where the air would be mixed the best. From now on, the data from the CO_2 sensor located at the exhausts is used.

Quantitative characterisation of CO_2-occupancy relationship

Using the O-CUSUM algorithm described in the method section, the starting and end time of the CO_2 deviations, and the maximum CO_2 concentration for each test described in Table 4.2 has been extracted. Except for test 2 (one occupant and door open), where the

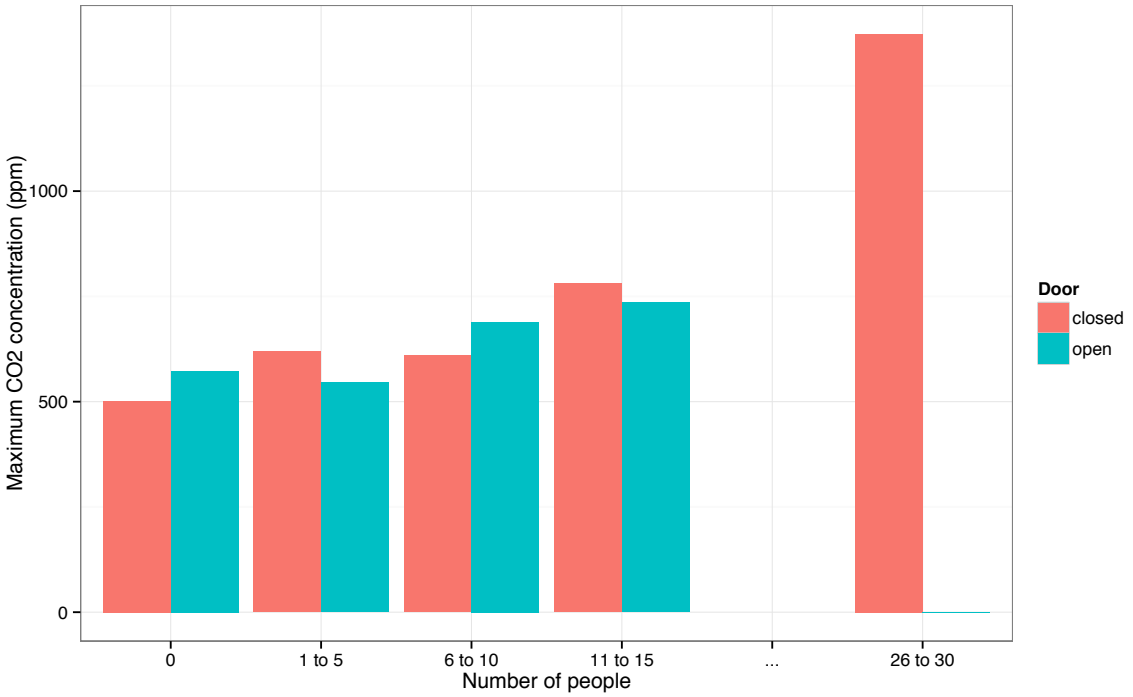


Figure 4.11: CO_2 concentration for the different test conditions

CO_2 level did not rise significantly enough, all the occupancy periods were detected. The delay between the beginning of the occupancy period and its detection by the O-CUSUM algorithm is found to be around 8 min, except for tests 7 and 10 where it was around 4 min. The delay comes from the combination of two factors which are the response time of the sensor and the mixing time of human-generated CO_2 until it raises significantly the CO_2 concentration in the space. The manufacturer gives a response time of 30s to 3 min for the sensor used. CO_2 mixing time depends on many factors such as ventilation rate and temperature, ventilation type and source location (Sherman and Walker, 2010). This time delay is negligible when looking at understanding occupancy patterns. The time for the CO_2 signal to go back to the baseline is more significant. For all tests above 6 persons, 30 min was not completely enough to go back to the baseline. For the tests with fewer people, between 22 and 27 min were needed. This needs to be taken into account when looking at the O-CUSUM's results.

For each level of occupancy, tests have been realised with the door closed or open to see whether it had an influence on the readings. Figure 4.11 shows the maximum CO_2

concentration grouped by occupancy levels for tests with the door open and closed. It can be seen that the maximum concentration of CO_2 is higher for increasing numbers of people. However, there is not a clear trend related to the state of the door. It can also be noted that the test with the open door and no occupants gives similar results that for a single occupant. The corridor leading to the teaching room not being ventilated, it is suspected that CO_2 builds up during the day and is sucked in the room when the door is open. This case of false positive is not likely to be a frequent case though as the change of the state of the door would normally be paired with a change of occupancy. However, this suggests the need to monitor adjacent spaces to evaluate the influence they have on each other.

Qualitative occupancy detection algorithm

As the CO_2 concentration variation can be related to people, it can be used as a proxy for occupancy. If it is not possible to infer the precise number of occupants, it is clear that more occupants generate more CO_2. Thus, four levels or occupancy are established: no occupancy, low occupancy, medium occupancy, and high occupancy. The levels are delimited by cutting in three equal intervals the range of CO_2 between the base line and the maximum measurement. For the case study measurements, when CO_2 is peaking between 505 and 812 ppm, it corresponds to low occupancy, between 812 and 1119 ppm to medium occupancy and between 1119 and 1425 ppm to high occupancy. This method presents the advantage to be easy to transfer from one building to the other, as it is independent from the building's characteristics such as volume, ventilation rate or airtightness.

The baseline for each day is taken for measurements before 7 am and after 23 pm when the building is closed and the only possible occupant is the security officer that would normally not stay long enough or come in often enough to significantly affect the night average. Recalculating the baseline each day enables to account for seasonal variations of the CO_2 level (Chevillard et al., 2002) and also accounts for potential drift in sensor calibration. In the case study the cleaners come at 7 am. In some buildings, they would come out of operating hours, which would then need to be taken into account while calculating the baseline.

During a pilot test, occupancy counts were taken every 1-2 hours during working hours for a week (Thu to Wed) to get a first idea of how CO_2 concentration responds to occupancy. Figure 4.12 shows the estimated occupancy for that week as calculated by the

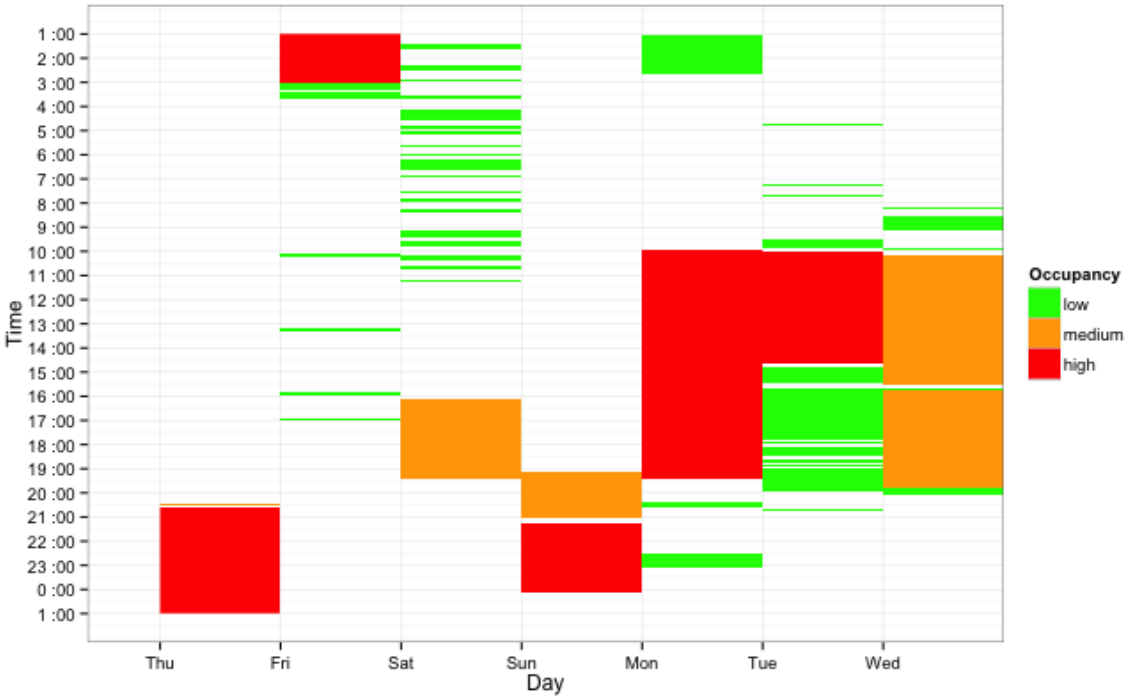


Figure 4.12: One week of occupancy carpet plot

O-CUSUM algorithm.

During that period, small group of students (1 to 5 persons) were using the room on and off on Thursday (e.g. 4 persons at 16:33), Friday (e.g. 1 person at 15:53) and Tuesday (e.g. 1 person at 15:34) afternoon. The room was used most of the day for a seminar Monday to Wednesday: Monday 9 am to 4 pm (20 to 30 persons observed), Tuesday 9 am to 12 pm (15 to 19 persons observed), and Wednesday 9 am to 5.30 pm (11 to 18 persons observed). More people attended the seminar on the first day. This reflects quite closely the idea displayed on Figure 4.12. The biggest deviation is the absence of occupancy detected during the day on Thursday. This is caused by the episode of high occupancy in the night of Thursday to Friday that contributed to a higher baseline. Higher baselines tend to mask smaller change when applying the O-CUSUM algorithm. This suggests the need to test daily baseline for anomalies. The detection of high occupancy at night suggests that some maintenance work took place that day.

A similar experiment was realised in a naturally ventilated single office room. It was

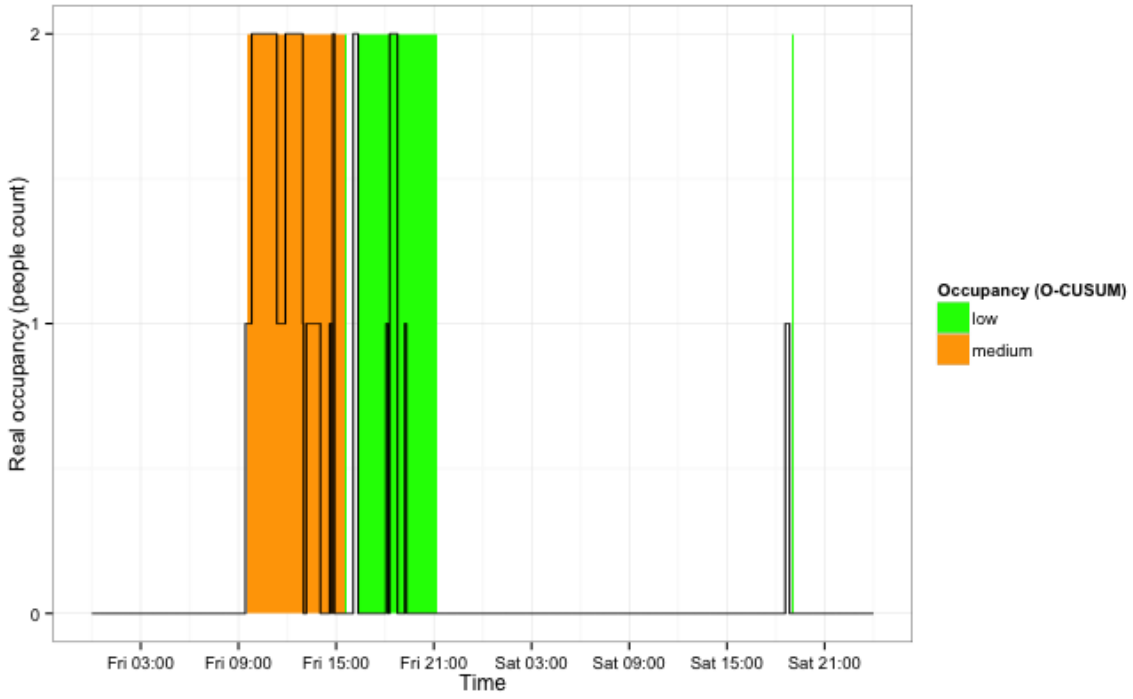


Figure 4.13: O-CUSUM vs. real occupancy in single office

instrumented with two ambient nodes. It was monitored for two days, a Friday and a Saturday, during which occupancy was manually recorded. Figure 4.13 shows a good agreement between the real occupancy and the period flagged as occupied by the algorithm. It even detects a very brief occupancy period on the Saturday. However, as with the other case, the end of occupancy is a bit over estimated.

Conclusion on CO_2 for occupancy detection

A method based on a signal processing algorithm has been developed to estimate real occupancy. A lot of models exist to infer occupancy from CO_2 measurements but since every building is specific they require training. A training period is not an option for pop-up monitoring™, however, variations of raw CO_2 signal can be translated into qualitative data. In addition, CO_2 calibration can be complicated and drift overtime. A method based on relative variations of the signal mean absolute calibration accuracy is not an issue. When most CO_2-based occupancy detection application using training and models focus on the

accuracy of the number of occupants, the O-CUSUM algorithm does not estimate the exact number of occupants. It only discriminates between different intensities of occupancy: none, low, medium, and high. This gives a sufficient insight for pop-up monitoring™.

The current implementation of the O-CUSUM tends to over estimate the length and intensity of the occupancy periods. When the CO_2 concentration does not go back close enough to the baseline between two groups of occupants, the occupancy will appear as one bloc. It still gives a valid insight on the 'on/off' occupancy, but can lead to show periods of high occupancy longer than they really are. The end of high occupancy periods also tends to be overestimated by about 30 minutes. This could be solved in the future by implementing more complex rules for resetting the CUSUM algorithm, as inflexions can be seen in the signal when the number of occupants changes. It could also be determined by adapting the mass balance model of Equation 4.2 to the case of a step generation function.

The method developed is most suited for mechanically ventilated buildings that will provide better air mixing. Further work is needed to evaluate the transferability of the method including evaluating the effect of window opening and testing it on larger spaces (e.g. open plan office, retail centre...) to see if it is sensitive enough and how the detection delay is affected.

4.4 Early questions raised by the PWSN development

Along the development process a few key learning on the current status of the state-of-the-art in wireless for building systems have been acquired. This raised a number of questions and considerations regarding future development of the PWSN. They are related in this section.

4.4.1 Why the BMS wireless system is not the best option for pop-up monitoring™

Looking through the wireless offer for building systems available on the market[16] no complete set of sensor suitable for troubleshooting has been found. There are either wireless nodes for very specific purposes that included only one, or too targeted measurements

[16] as of September 2013

and specialist analysis algorithms or BMS extension sensor nodes that were limited to system exception monitoring. One of those systems was used and even though it enables to collect the expected data, it does not seem like the ad hoc solution for building forensics.

First on the technical side, a series of problems were encountered while setting and deploying the commercial system:

- The first coordinator received could never be made to work and had to be replaced. The exact origin of the problem was unclear even after sending the device back to the manufacturer, but it was related to BACnet communication.
- The site survey function of the network commissioning software would indicate good connection even when the nodes were not powered. This makes installation difficult as it prevents verifying adequate sensor location before putting the WSN in service.
- Several pieces of hardware were necessary to translate the data in a usable format.
- Measurement frequency was limited to 15 min.
- PIR was originally considered in the list of measurement and a PIR sensor was procured with the rest of the TPZ system. However, this sensor is designed to be directly connected to a lighting system or other electric equipment to turn it on when the sensor is triggered. This proved to be incompatible with time series monitoring.

Those problems are not related to inherent limitations of wireless technology, but rather representative of the lack of penetration of the technology in the building industry.

In addition, the material is not done to be mobile. After 7 months of deployment one Ethernet cable became faulty and the power socket of the data logger had bad contact leading to regular data losses. The equipment is done to be installed once and be left in place. It is not robust enough to be moved regularly. PWSN equipment needs to be more resistant.

Most of those technical problems could be resolved by subcontracting the product realisation for PO-Cx to wireless specialists, but they would still be practical limitations, coming from the nature of BMS systems, to using an extension to the BMS system for pop-up monitoring™:

- The BMS system might not be fully functional even at the time the PO-Cx process starts.

- The FM team might be reluctant to give access to the BMS to a third party, such as the design consultant.
- BMS systems are not programmed to store data in the long term. The default setting is normally to keep data for 2-3 weeks.
- The analysis capability included in the BMS system is very limited and exporting data is not very conveniently implemented for intensive use.

Those constraints are harder to lift on the medium term as they come from the structure of the construction industry. In summary, a BMS compatible system is not an ideal solution for PO-Cx either with its current technical specification or from a practical point of view.

4.4.2 A standalone system is a better solution

It is also clear that integrating several specialised wireless systems together is not the solution. Even though, it can be a good option to address one-off specific monitoring needs, it would be an obstacle for generalised pop-up monitoring™. A few of the problem entailed are the following:

- Several systems mean more hardware equipment:
  - At the gateway level, it results in a non-compact gateway system, which is less easy to install and has more chances to result in hardware failure due to overheating.
  - More repeaters are also necessary to cover the full building wirelessly. Depending on the size of the building this can be a significant cost increase of the wireless system.
- It creates unnecessary complexity in software integration at the gateway level. In our case, a few days of data have been lost due to the code catching exceptions. It is not clear whether those were due to interferences between the systems or just general transmission problem, but it is clear that the need to write code for a WSN, which operation is not fully understood leads to complications and is better left to the WSN manufacturer. In any cases, system integration requires technical background that commissioning engineers would not be familiar with.

Developing the custom node took a bit of learning, in particular each new sensor represented a new learning curve, so a PWSN for commercial applications would need to

already integrate the full range of sensors needed for troubleshooting. The current design presents a few technical shortcomings, in particular regarding the battery life. The nodes would also be more flexible if they were a bit smaller. These problems could be easily resolved by subcontracting the next iteration of the node design to a specialist electronic company. The prototype nodes' cost is also too high as it is, but prototypes are always more expensive than the final product.

Despite the need for additional engineering work, the standalone system seems more appropriate than the BMS extensions systems. It has the potential to be plug-and-play without any knowledge in BMS related networking and give the possibility of independently and remotely accessing a rich data set to examine building performance. Having the party carrying the PO-Cx process having ownership of the data can significantly save both time and money.

4.4.3 The potential of PWSN

The installation time of the sensor nodes met expectations. For the BMS system it took about 10 min per node in average including installation of the gateway. There was no need to drill holes or make any kind of small work. The nodes were simply attached using zip ties. The zip ties also prevented from making any kind of damage in a newly decorated room and were a decisive factor to convince FM to support the project. However, if nothing is available to tie the nodes, they can also be attached using double sided tape or blue tack, or simply put on the furniture. The Arduino system was also installed easily, even though the need to hard-wire the node for power increased the installation time by about 5-10 min per nodes. On a full-building case for pop-up monitoring™, it is expected that an important number of nodes will be installed and moved around. This suggests that battery powered is the correct objective. It is also worth mentioning that there was no significant lag observed in the data transmission.

The prototype PWSN shows the promises of the technology for PO-Cx. It makes possible measurements that would otherwise be impractical or prohibitively expensive. Sensor devices can be installed fast with no intrusion for the occupants or interference with the building operation.

4.4.4 Next steps towards a generalised use of WSN in the building industry

Beyond the scope of PO-Cx and pop-up monitoring™, the possibilities offered by wireless technologies for building applications at the moment are limited by the offer on the market. Considering the potential benefit of wireless networks exhibited in the literature review (Section 2.5.3), this is a lost opportunity of the industry. This limitation is not so much a technical issue than a lack of proactive strategy in the industry.

The equipment on offer is scattered and scarce. Since integration of several systems is prohibitively complicated, there is the need for a major manufacturer to offer a comprehensive range of measurements. This could be done by the major BMS manufacturers, but as seen before this might limit the measurement application to turn existing sensor applications towards wireless rather than opening the door to new possibilities. The opportunity might lie in another sector that would break the codes of control oriented sensing.

Alternatively the problem could be solved by a standardised communication protocol that would allow devices from different manufacturers to join the same wireless network, in the same way that all modern BMS system equipment is based on BACnet. Current wireless standards in use in the industry remain proprietary even though they share common specifications. This could be done by using protocols compatible with the Internet of Things (Mainetti et al., 2011). In any case, this would require urgent attention from standard-setting bodies like ASHRAE.

The standardisation should not be limited to the wireless communication protocol, but should also extend to the data format. A standard data format would open the door to third-party applications and ensure a greater flexibility for the growing needs to optimize building operations.

In the future the power requirements of wireless nodes are only likely to decrease. This opens the possibility for sensors to harvest energy from their environment, removing the concern for battery lifetime. This is an interesting alternative since most of the measurements of interest are linked to thermal or mechanical equilibrium processes. Research is already on-going in this direction (Roth and Brodrick, 2008) and EnOcean[17] standard

[17] https://www.enocean.com

already offers a range of self-harvesting and wireless products such as lighting controls.

4.5 Summary

In this chapter a PWSN prototype to look into end uses of ventilation systems was developed and verification tests carried out. The final prototype is composed of two separate systems: a BMS compatible wireless system; and a custom system based on Arduino and XBee. Both systems are integrated with a Raspberry Pi and data are stored in a database available over the Internet making remote analysis easy.

Both subsystems have been tested for power and wireless transmission. They were both using more power than anticipated, to the point that the custom nodes needed to be plugged to the mains. However, the BMS system nodes proved that it is possible to achieve sufficient battery lifetime to perform PO-Cx without the needs to change batteries.

Regarding wireless transmission the BMS system performance was slightly disappointing but enough data are still collected to receive useful insight. The custom system performed well but at a high power cost. A compromise between a simple broadcast communication and a power intensive protocol needs to be implemented.

Characterisation tests have been performed for the different sensors. Digital sensors can be used out of the box, as the manufacturer calibration was satisfactory for the application. The CO_2 needed to go through a quick relative calibration process. Analogue sensors are more troublesome as they depend on the supplied voltage and are more sensitive to external conditions. In particular, the air movement sensor used did not have a pre-determined calibration equation. When possible, digital sensors should thus be preferred.

The requirements of PO-Cx do not allow for the implementation of models or training period for indirect measurements. Controlled condition tests have been used to develop a signal processing algorithm capable of giving quantitative indication of space use and use density based only on CO_2 variations.

Based on the issues encounter while deploying the prototype PWSN and installing it a series of lessons have emerged. Apart from a series of minor issues that are merely

engineering issues that are already in place is divers WSN, the main conclusion drawn is that for the purpose of PO-Cx a standalone system is far more convenient than one integrated with the existing BMS system.

Chapter 5

Trial of pop-up monitoring™ using a university case study

The PWSN system developed in the previous chapter is deployed on a case study for a proof of concept of PWSN for PO-Cx. Analytic strategies are implemented to demonstrate how the PWSN can contribute to improving the commissioning process. This chapter aims at answering the following questions:

- Is the PWSN data suitable for building troubleshooting?
- How can a PWSN contribute to PO-Cx?
- What is its benefit in addition to already available data?
- Based on practical experience, what are the key improvements to make to the PWSN?

Section 5.2 gives the details of the case study where the PWSN was deployed and overview of the data used for the study. The data analysis is then separated in two themes: Section 5.3 goes back to the use cases define in Chapter 3 and discuses how to implement them; Section 5.4 explores how PWSN can help to realise the different tasks from PO-Cx. Section 5.5 is a discussion of the results of the chapter. In particular it iterates on the requirements from Chapter 3 in the light of the analysis carried out in this chapter. The chapter starts by an overview of the methodology used in those sections.

5.1 Methodology

5.1.1 Case study

To investigate the possibilities and benefits of a PWSN for PO-Cx and establish analysis methodologies the PWSN was deployed for 6 months on a university teaching room. The client being the university where the PhD project was carried out and the contractor the sponsor of the PhD, it was possible to access design and operational data in addition to the data collected with the PWSN.

The chosen room had two main advantages for the deployment. The first one was that the systems in this room are exposed. Indeed, the ceiling is too low to have a suspended ceiling. This means that it is much easier to understand the systems and to test measurement points. The second advantage was that it does not have windows, removing air leakage and heat gain from the sun as possible causes of measurement variations. As a first approximation this made it easier to understand the sensor readings to develop analytical methods. This results in a slightly simplified case. To offset this, a few short-term measurements were taken in a semi-open-plan office with windows, but with much simpler systems, to see how the phenomenon neglected by the first case study affected sensor readings.

Regarding the duration of deployment of the sensor, one year would have been ideal, but due to time constraints the deployment was reduced to half a year. However, since the measurements ran from January to July, most of the seasonal variations have been covered. Additionally, PO-Cx analysis would be done along the way and a full year of data would not be available before the PO-Cx process is nearly over. As such 6 months of data is more representative of the type of data set the commissioning engineer would have to work with for PO-Cx. In addition to the data obtained by the PWSN, energy data, weather data and BMS data have been obtained from the building management team.

5.1.2 Use cases realisation

The data collected on the case study are used to implement the measurements use cases identified in Section 3.5.2. The demonstration that the PWSN is capable of implementing the use cases is meant to prove that the PWSN is able to detect the faults from Table 3.4

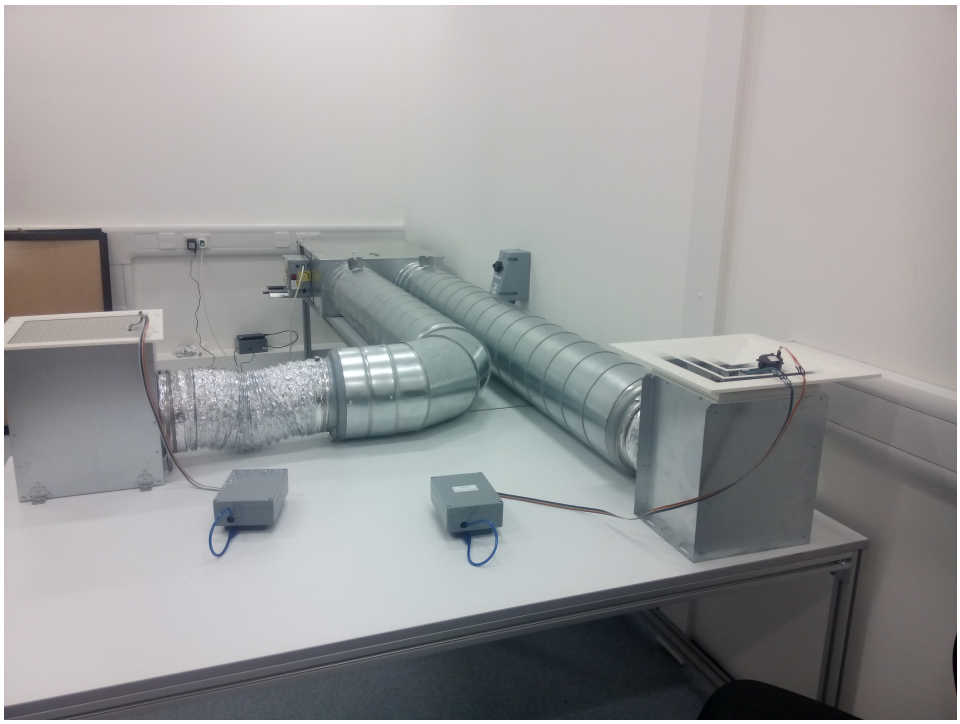


Figure 5.1: FCU test bed

if the right measurements are taken.

The use cases are classified in three categories depending on the complexity of the analytical method to obtain them from the sensor data: direct sensors reading, sensor transformation, multi-sensor integration. As in the previous chapter, the analysis carried out for this chapter was done using the statistical programming software R (R Development Core Team, 2015).

For the use cases related to the FCU and ventilation system, the data were collected on a laboratory FCU test bed (Figure 5.1). It is composed of a variable speed fan unit and two exhaust ducts and grills, in a similar way than it would be installed in an occupied space, but enabling manual control of the switch and the fan speed. The heating and cooling coils were not connected. For the rest of the use cases, the data collected in the teaching room as described in Section 5.2.2.

5.1.3 PWSN for PO-Cx

The potential applications of PWSN for PO-Cx are then looked at. The section is organised around the four scopes of post-occupancy commissioning identified in Section 3.3: energy performance, in-use performance, seasonal commissioning and occupants' satisfaction.

This section discusses general strategies to implement PO-Cx, and how the use cases defined before can be used to identify the faults listed in Section 3.4. This list of fault is used for the proof of concept, but the PWSN measurements should be able to implement additional use cases leading to the identification of further types of faults.

This section is based on two types of data. First the use cases from Table 3.6 are applied to the 6 months of data collected to show the type of information they provide when appropriate data is available. The faults that could not be illustrated based on the data collected on the test case are discussed based on the practical information given by the respondents of the interviews described in Section 3.4.1.

Regarding data analysis, in the cases where daily variation is relevant, the technique used to visualise the 6 months of data is to associate each data point with the number of its day in the year and then plot a trace for each day. Weekends and weekdays are discriminated by colour to differentiate between the two modes of operation.

For this Section most of the measurements are taken in the same room for the purpose of the feasibility demonstration. To perform PO-Cx on a whole building, energy data, occupants survey, and experience from the construction and commissioning phase would be used to determine where the additional data from the wireless sensor would be the more needed.

5.1.4 Discussion

Before the general discussion in Chapter 6, a discussion of the experimental results is presented in this chapter. It includes several related points including the advantage of additional PWSN data compared to existing data sources, an iteration on the requirements in the light of practical experience and a discussion on the requirements for the analytic capability necessary to exploit the PWSN data.

5.2 Case study description

This section describes the case study used for the demonstration of pop-up monitoring™. It starts by describing the general refurbishment project the cases study is part of. The specifics of its commissioning process are then described, before reviewing the data collected. Two complementary case studies are finally described at the end of the section.

5.2.1 Building and refurbishment description

The main case study and data collection used for the feasibility study of this research project is a teaching room from a freshly refurbished university building, namely the City and Guild building (C&G) of Imperial College London, a 28,585 m^2 building[1], which houses the Mechanical Engineering department. The refurbishment project was cut in four phases to allow the department to function during the construction work. The data collection took place between phases 2 and 3. The information about the project comes from construction documents[2] kindly provided by CHt[3] and a couple of guided site visits during construction of phase 2.

The refurbishment project was initiated as the current systems were getting old and the building was no longer fit for purpose. The project included new building facade and partitions, refurbishments of all the major services of the building, and additions of specific services for the laboratories (e.g. compressed air, safety cabinets, oxygen depletion monitoring). From the HVAC perspective, the major changes are the installation of four new chillers, new heat exchangers to interface between the campus's MTHW[4] and the building LTHW[5], new LTHW system, new AHUs and FCUs, and all the controls and distribution systems associated.

According to the design requirements, the heating of the building is provided by a LTHW secondary circuit (82/71 °C flow/return). The primary circuit is a MTHW supplied by the campus's CHP. Cooling is provided by four air cooled chillers (10/16 °C flow/return).

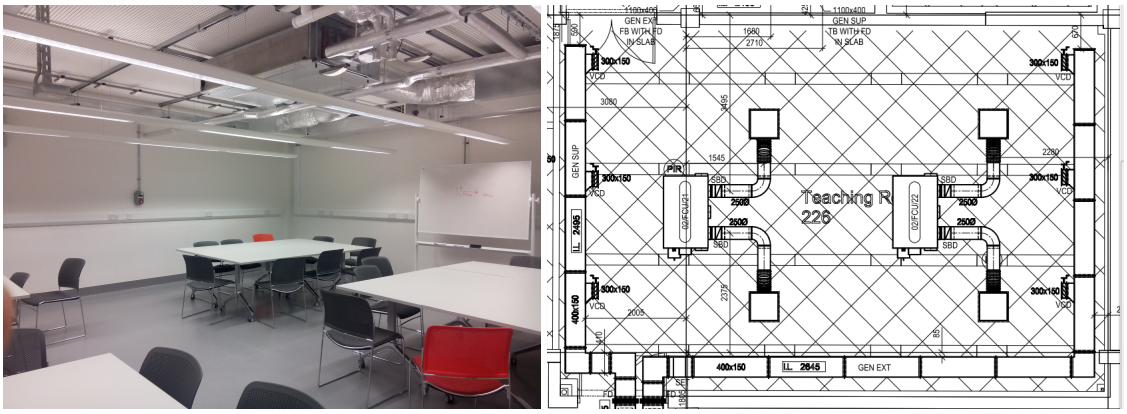
[1] usable floor area

[2] "Mechanical and Public Health Service Specification", TB+A, April 13; and "Specification for the Trend Building Energy Management System serving the Mechanical Services", Powell System Engineering Ltd, April 13.

[3] Crown House technologies, the building services branch of the contractor Laing O'Rourke

[4] medium temperature hot water

[5] low temperature hot water



(a) Layout (b) Schematic

Figure 5.2: Instrumented teaching room

The ventilation system is composed of several AHUs that supply different sections of the building. The design requirement is to provide 10 l/s/p of fresh air in teaching rooms, 20 l/s/p in cellular offices and 10 l/s/p in open plan offices based on 80 % occupancy. Fresh air is distributed at 20 °C at constant volume[6]. FCU are then conditioning the air based on 24 °C set point in summer and 21 °C in winter. All the systems are controlled centrally and are included to the College existing BMS.

The room used for measurements (Figure 5.2) is situated on the second floor of C&G. It has two entrance doors even though only one is in use. As mention in Section 5.1, it has exposed systems and does not have windows. The teaching room is supplied with fresh air by three ventilation grills (2.5 m/s) and the air is extracted via three other grills at the other end of the room. Two 172 l/s FCUs condition the air using the systems described above to provide heating and cooling.

The control logic of the system servicing the teaching room is described below. The FCUs operate based on a schedule. When they turn on in the morning, they run at maximum for 5 min. After that the fan speed is determined by temperature demand based on two proportional-integral (PI) loops with a 1 °C dead band and a temperature sensors in the return air duct. The FCU was to be set at 24 °C during commissioning[7]. Heating and

[6]Except in computer rooms that use VAV boxes

[7]There is no mention of it automatically switching to 21 °C in the winter so there is a chance this will be the yearly default.

Table 5.1: Summary of data available for the C&G case study analysis

Data source	Dates	Channels	Measurements interval
BMS data	20 Jan 15 - 22 July 15	13	15 min
Energy	1 Jan 14 - 30 June 15	7	1 hour
Schedule	15 Jan 15 - 12 July 15	NA	NA
Outdoor temperature	1 Jan 15 - 30 June 15	1	15 min
PWSN	21 Dec 14 - 20 Aug 15	28	1 and 15 min

cooling is provided on demand based on the FCU controller.

The AHU that provides fresh air and extract to the zone of interest is a double-decked external AHU with heat recovery. It is controlled by the FCU demand, thus having the same schedule. If the FCUs reach their maximum capacity, this set point will be automatically changed to assist the FCUs. The extract fan is set to work at 100% during its scheduled operation. For both the FCU and the AHU, a series of manual actuators enables to change the setting if necessary. According to the contract's requirements the AHU's set point is to be 20 °C. The control specification, which was issued the same month, states the set point was to be set to 19 °C at commissioning. After verification on the BMS, the actual set point was 18 °C. This illustrates the difficulty to have coherent and up-to-date documentation on large projects.

5.2.2 Data for PO-Cx

This section discusses the different sources of data that can be used for PO-Cx. The data considered are summarised in Table 5.1. Energy and BMS data from the building were sought, as this would normally be the starting point of PO-Cx to decide where to focus the additional measurement capability. Booking schedules of the teaching room have been provided by the building administration and are used to highlight the benefit of occupancy measurements. Weather data are used to evaluate the influence of external temperature in the building operation. Finally, data were collected using the PWSN prototype described in the previous chapter to show its benefit for PO-Cx.

Table 5.2: Summary of BMS data points

Data	Unit	Date
AHU		
Extract air pressure	Pa	20 Jan 15 - 22 July 15
Extract air temperature	°C	20 Jan 15 - 22 July 15
Supply air pressure	Pa	20 Jan 15 - 22 July 15
Supply air temperature	°C	20 Jan 15 - 22 July 15
Supply air temperature set point	°C	3 Feb 15 - 22 July 15
FCU 1		
Cooling valve	% open	30 Jan 15 - 15 Apr 15
Heating valve	% open	30 Jan 15 - 15 Apr 15
Supply temperature	°C	30 Jan 15 - 22 July 15
Extract temperature	°C	30 Jan 15 - 22 July 15
FCU 2		
Cooling valve	% open	30 Jan 15 - 15 Apr 15
Heating valve	% open	30 Jan 15 - 15 Apr 15
Supply temperature	°C	30 Jan 15 - 22 July 15
Extract temperature	°C	30 Jan 15 - 22 July 15

BMS data

BMS data for the room was obtained from ABEC[8], who subcontract the BMS operation for Imperial College London, in order to judge how easily it would be to incorporate it in a PWSN data collection. The data have been sent in several batches, 1 to 3 months at the time. Table 5.2 summarises the data points made available. They come from the AHU supplying and extracting air from the room, and from the two FCUs that condition the space. The BMS data are logged every 15 min.

Table 5.2 also summarises the period for which the data were given. It can be noticed that no data are available before the 30th Jan 15, even though the handover of the room took place beginning of December. This is because the new BMS points were not ready to be integrated before that date. This is evidence that the BMS commissioning extended after handover. The temperature set point is available only from February because it was forgotten in the first batch. The heating and cooling valves are not available after 15th April any more, as the control program was changed and no longer kept the recorded for these values.

[8]Automated Building & Energy Controls Limited

Including the BMS data to the database for analysis against the PWSN data proved troublesome. First the data were provided in files of no more than 1,000 rows, which represent about 10 days of data, probably due to the export limitation of the BMS software. This proved troublesome for the people sending the data, meaning that they were almost always sent later than promised, as the BMS people could not find time to do the tedious export. Second the data were provided in format less than ideal for automated treatment (.html, .txt). This required a bit of manual processing to be able to include in the database and much more effort than if the files were .csv for example.

The problems with the data related here are likely to be representative of the difficulty of combining BMS data with the PWSN. While it would be feasible to create a bespoke dataset as part of a research exercise, this fails the easy availability required of pop-up monitoring™. BMS are not currently designed to export data in a flexible format

Energy data

Data relative to the energy use of C&G were obtained from the energy and environmental team of the College's estate division. The total building energy is the sum of electrical, steam and MTHW. Electricity data were given for the current year and the previous year. These data represent cooling and other electrical use of the building. Electricity was logged in kWh every hour.

The electricity consumption of the C&G building is calculated from data from 7 transformers as follows:

$$E = Transformer\ T9 + Transformer\ T22 + Transformer\ T23 + Transformer\ T24 - Business\ School\ chiller - Business\ School\ riser - Faculty\ Building \quad (5.1)$$

Raw data for each energy meter was provided, to prevent anomalies due to data missing in one of the channels to go unnoticed. Each channel was provided in a separate Excel file that needed to be transformed and exported as .csv files to be used in R. For unknown reason the Faculty channel was given in a different format, which required additional preprocessing.

Transformer T23 was disconnection for a long period between April 14 and January 15 thus a big part of the data is unusable. Other small laps of data points needed to be discarded due to anomalies or period of missing data in the measurement. After the data cleaning process, only 47% of the data could be used.

The rest of the building energy consumption is divided between steam and MTHW provided by the college's CHP. The steam supplies the hot water service, some autoclaves, and a small amount of humidity control. The MTHW is responsible for the building heating. Those energy data were provided for the January-June 2015 period with a half-hour measurement frequency. To analyse with the electricity data, they were aggregated by hours. As with the electricity data, probably due to the construction work, the MTHW data were not available for the first half of January.

As for the BMS data, it was not straightforward to use the data from the energy management system. Standard format for the export file type, but as well for the time format would facilitate the comparison of data from different system. Although the possibility of exporting as .csv might have existed, but the person exporting the data might have chosen Excel being more familiar with it. Better training and conventions about data processing would be beneficial in an area where sensor data is everywhere.

Schedules

The room-booking schedule for the Spring and Summer term was provided by the administrative staff of the Mechanical Engineering Department. They only give a partial view of the real occupancy of the room as they only indicate times where people have requested the room. The schedule often do not include the number of people the room is booked for. Also people might decide to spontaneously use a room seeing it is free. However schedules give an insight on how much and when the room is used. This represents the occupancy data that would normally be consulted by FM in a case of occupancy related problems. The data were provided as screen shots from the room booking software (see Figure 5.9 page 173).

Weather data

The college estate department has a weather station on the roof of the Electrical Engineering building. For the purpose of this study they made available six months of outdoor

temperature logged every 15 min. Other weather variables were available, but only the temperature was used, as it is the parameter that has the most influence on building energy consumption and indoor comfort.

PWSN

Regarding the PWSN measurements, 15 wireless nodes were installed in the teaching room described before. They are listed in Table 5.3 and their location is shown on Figure 5.3. The 'Vent' sensors are placed at grills on the ventilation system (Figure 5.4a) to measure speed, temperature, relative humidity and CO_2 levels of the airflow. 'Temp', 'Ambient' and 'Radiant' nodes (Figure 5.4b) measure the ambient conditions of the room. The 'Pipe' nodes (Figure 5.4c) measure the temperature of the heating pipes. It was originally planned to also measure the temperature of the cooling pipes, but considering that the insulation of the cooling pipes had been one of the challenges during commissioning, authorisation was not given to install them. As this is likely to be the case in most buildings, another sensing solution would need to be identified. Measurements are logged every minute for the Arduino nodes and every 15 min for the TPZ nodes.

5.2.3 Semi-open plan office case study

A semi-open-plan office was used to look at the impact of solar radiation on the PWSN sensor readings. Radiant sensors and ambient sensors were placed by pairs, one on the window side, one on a shelve on the opposite side of the room. An addition, a sensor was placed on a desk beside the window, but in the shade.

5.3 Use cases demonstration

In this section, a demonstration of how the PWSN can address the use cases defined in Section 3.5.2 is presented. The different use cases have different levels of complexity. At the most basic level, all that is needed is to look at the time series of one sensor reading. However, most of the use cases require integration of several sensor readings or some extent of processing to access the desired information.

Table 5.3: List of nodes deployed

Node	Sensor	Location
Vent 01	Temperature, humidity, CO_2, Air velocity	Ventilation supply
Vent 02	Temperature, humidity, CO_2, Air velocity	Ventilation extract
Vent 03	Temperature, humidity, CO_2, Air velocity	FCU 1
Temp 1	Temperature	Left side - H 240 cm
Temp 2	Temperature	Right side - H 240 cm
Temp 3	Temperature	Left side - H 165 cm
Temp 4	Temperature	Drawer cabinet - H 75 cm
Ambient 1	Temperature, humidity, CO_2	Left side - H 160 cm
Ambient 2	Temperature, humidity, CO_2	Right side - H 170 cm
Radiant 1	Radiant temperature	Left side - H 170 cm
Radiant 2	Radiant temperature	Right side - H 160 cm
Pipe 1	Pipe temperature	FCU 2 - HW in flow
Pipe 2	Pipe temperature	FCU 2 - HW return flow
Pipe 3	Pipe temperature	FCU 1 - HW in flow
Pipe 4	Pipe temperature	FCU 1 - HW return flow

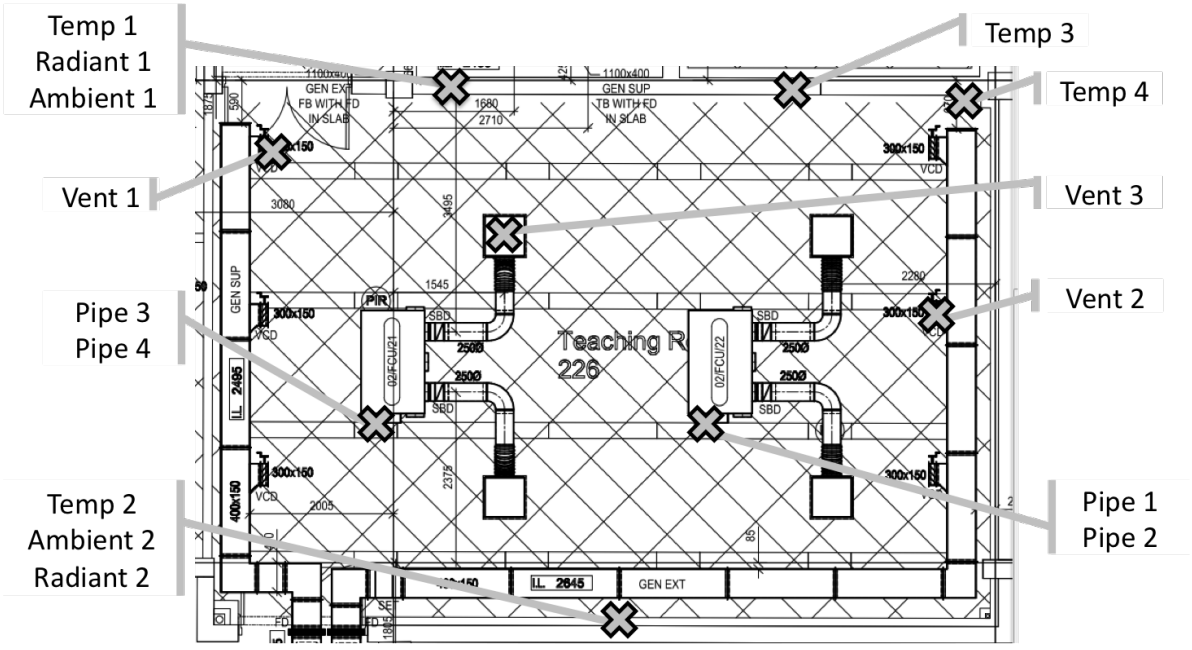
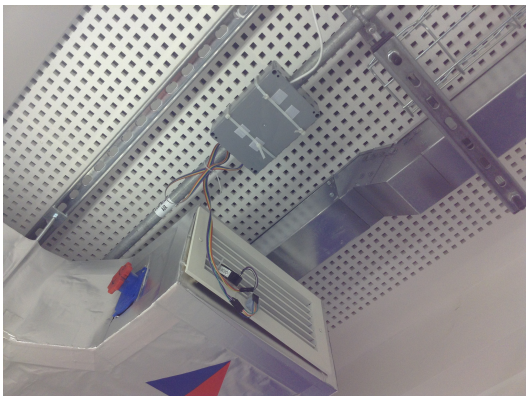
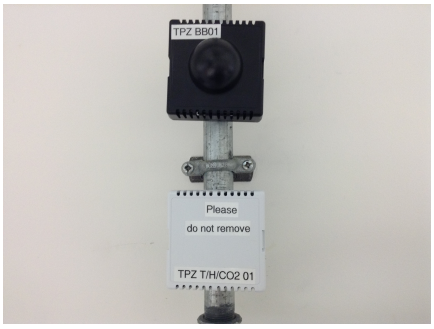


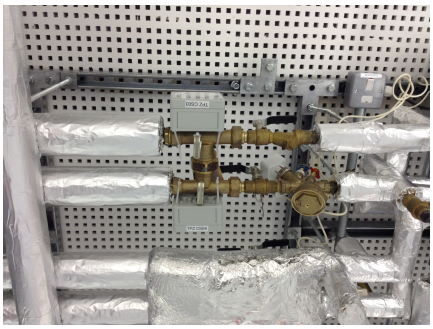
Figure 5.3: Measurements location in the case study room



(a) Vent node



(b) Radiant temperature, and temperature, CO_2 and humidity nodes



(c) Pipe temperature nodes

Figure 5.4: PWSN nodes as installed

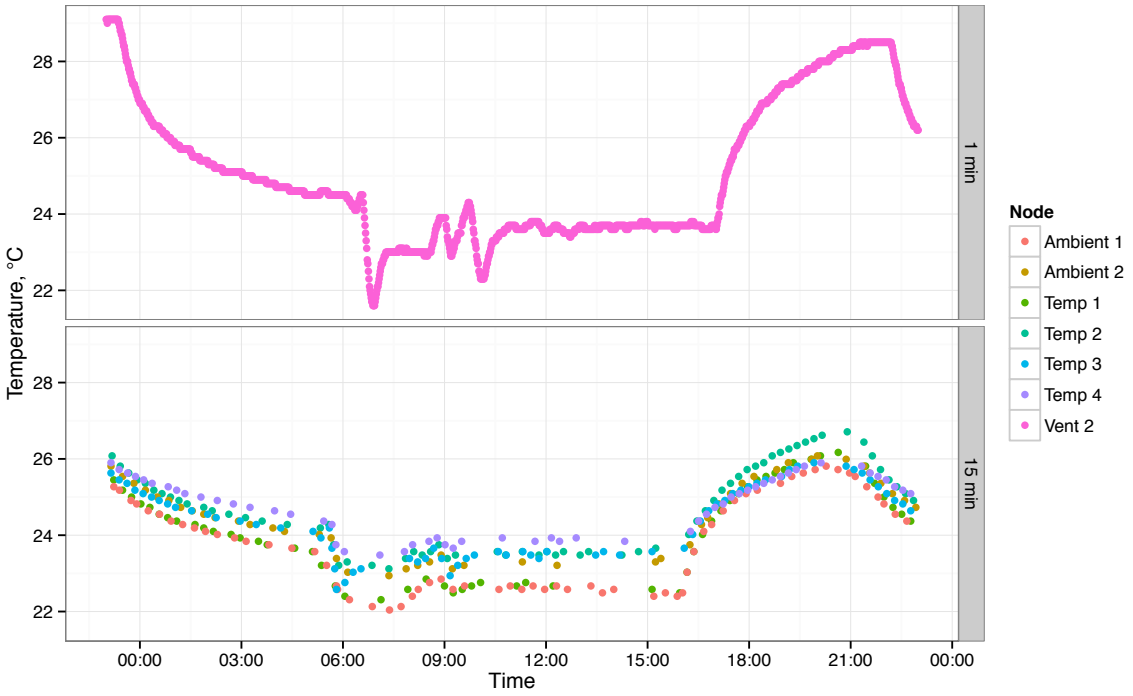


Figure 5.5: Ambient temperature

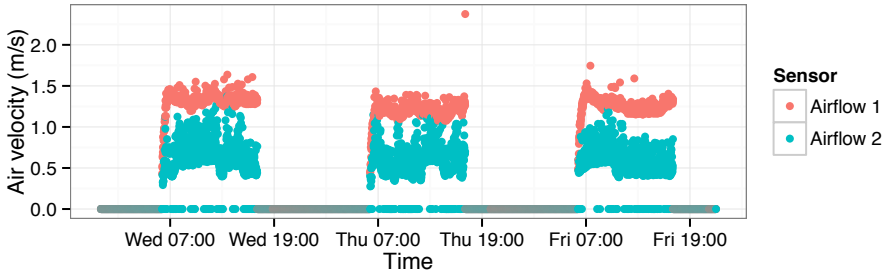
5.3.1 Direct sensors readings

Some sensor readings can be used directly and do not need any specific processing to realise the desired use case. It is the case of ambient temperature. Other use cases could work the same way but improved visualisation proposition are shown in the following sections. In any case looking at sensors' time series can give a quick overview of a situation.

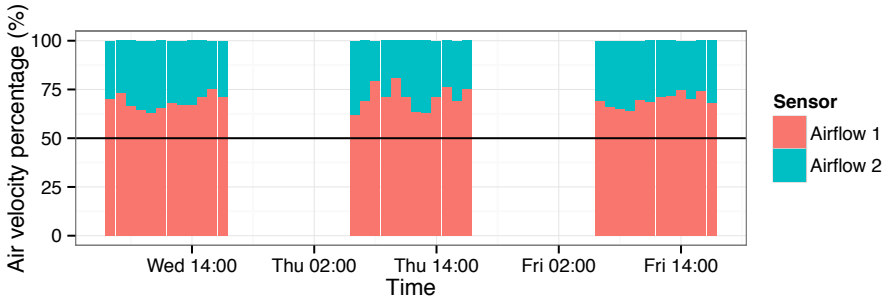
Assess ambient temperature

Figure 5.5 shows 24 hours of ambient temperature from the different nodes of the PWSN. This can give an indication of how the heating and cooling are operating. In this example, it can be seen that the room is being cooled down during operating hours and that the temperature rise significantly at night.

The different temperature nodes have been separated by sampling frequency. The 1 min interval measurements show that they are oscillations before the room reaches its set temperature. The phenomenon is some what masked in the 15 min data set, which



(a) Air velocity time series



(b) Percentage of air velocity

Figure 5.6: Balancing

could lead to overlook comfort issues. The response time of the temperature sensor would, however, be useful to determine the best measurement frequency. It must be noted that the difference between the different temperature comes from the sensors error and not form a significant variation of temperature in the room.

5.3.2 Sensor transformation

This section groups the use cases where the sensor readings require processing to obtain the desired information.

Assess system balance

The simplest level to look at the system balancing is to equip all the outlet of interest and compare the air velocity time series as illustrated in Figure 5.6a. To better visualise the balancing of the system, the air speeds are aggregated by hours and relative percentage are calculated and displayed as in Figure 5.6b. By plotting the line of the proportional balancing (50 % for 2, 33 % and 66 % for 3 outlets,...), it can be assessed in one glance

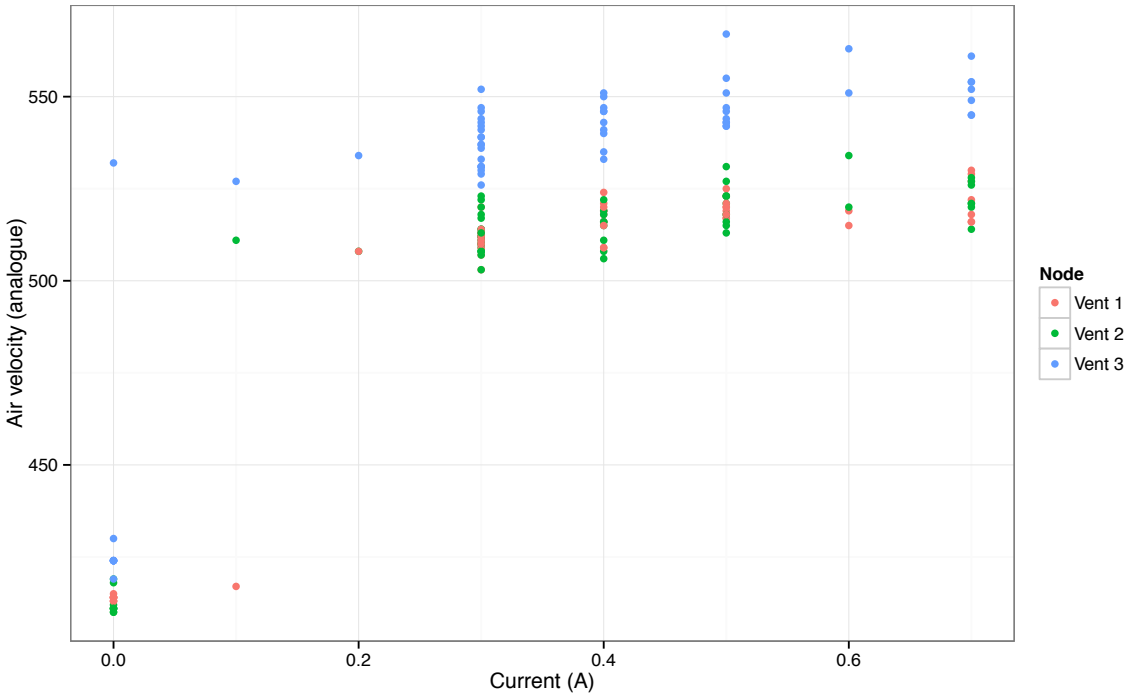


Figure 5.7: Air velocity in function of fan current

whether the system is properly balanced. The advantage of this technique is that accurate calibration is not an issue as long as the sensors have been calibrated relatively to each other. The data used for Figure 5.6 illustrate a typical example of an unbalanced system.

This result must, however, be taken with caution, as the difference between the branches might come for the sensor location on the grille as the velocity field in ventilation ducts is non-homogeneous. Guidance recommends taking several measurements at the grille depending on its size (Parsloe, 2001, Caré et al., 2014) and several sensors should be used if balancing problems are seriously suspected.

Control equipment status

The air movement sensor can also be used to know whether the ventilation system is running. When looking at the analogue values coming from the air velocity sensor, they seem to be a clear gap between low and high values. To confirm this the sensors were installed on the FCU test bed and the current of the fan was measured. The speed of the fan was slowly reduced from the maximum to the minimum where it is off. Figure 5.7 shows how

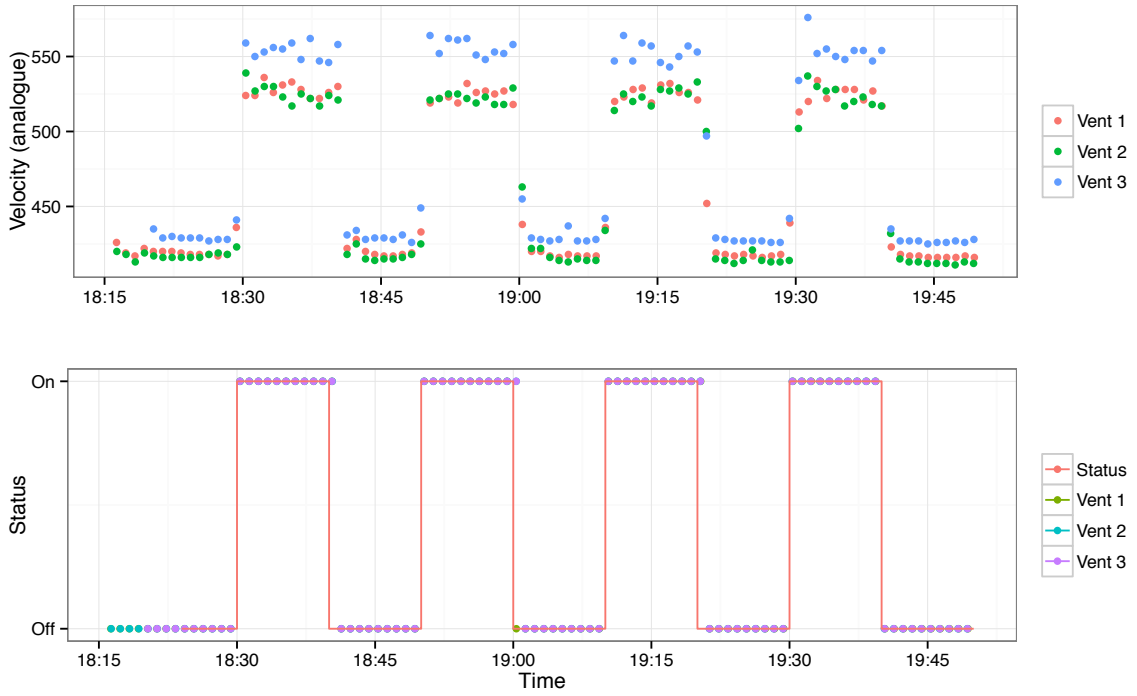


Figure 5.8: FCU on/off signal

the analogue air velocity readings as a function of the fan current. This illustrates clearly the gap between values where the fan is on and airflow is measured and the values where the fan is off.

The analogue value of the air movement sensor can then be used to know the operating schedule of the air systems. Based on Figure 5.7 and overall observation of the air velocity sensor's data, the threshold to discriminate between on and off status is chosen to be 450. The analogue reading from the air velocity sensor is then filtered to be 0 below this threshold corresponding to the system being off and 1 above corresponding to the system being on.

Using the same FCU test bed set up, the FCU was turned on and off at 10 min intervals (Figure 5.8). The red line shows the real on/off schedule of the experiment. It overlays perfectly with the outcome of the algorithm described above, proving that the threshold chosen for the air movement sensor is adequate.

Similar results could be obtained after converting the analogue value to airflow, but this way presents less heavy computation and removes the need for calibration.

Assess levels of occupancy

The outcome of the O-CUSUM algorithm as represented on Figure 4.12 page 146 can be used as realisation of the use case 'assess levels of occupancy'. When comparing it to Figure 5.9, which Monday, Tuesday and Wednesday correspond to the same week as Figure 4.12, it can be seen that Figure 4.12 gives much more information. The booking does not give any indication on how many people will attend an event and does not show exact occupation times. It also does not guarantee the room will actually be used and finally it does not account for casual use of the room.

5.3.3 Multi-sensor integration

For the rest of the use cases, several sensor data are integrated to access the information. This adds the necessity of good data synchronisation between the different nodes.

Assess thermal comfort

PMV is difficult to calculate as air velocity, clothing and metabolic rate of occupants are difficult to measure, plus it presents many limitations as described in Section 2.2.2. Therefore, the thermal comfort use case measurements are based on recommendations from CIBSE Knowledge Series: Comfort (Race, 2006), which is likely to be used by FM. Thermal comfort is deemed to be achieved if:

1. Relative humidity is between 40 and 70 %RH,
2. Radiant and air temperature are close to each other with radiant temperature slightly above air temperature,
3. Indoor air temperature is within comfortable range relatively to the outdoor temperature as determined by the adaptive model described in Annex D.

This can be completed by occupants survey to identify other comfort issues and a hand-held flow meter (e.g. hot wire anemometer) in case occupants complain about draft.

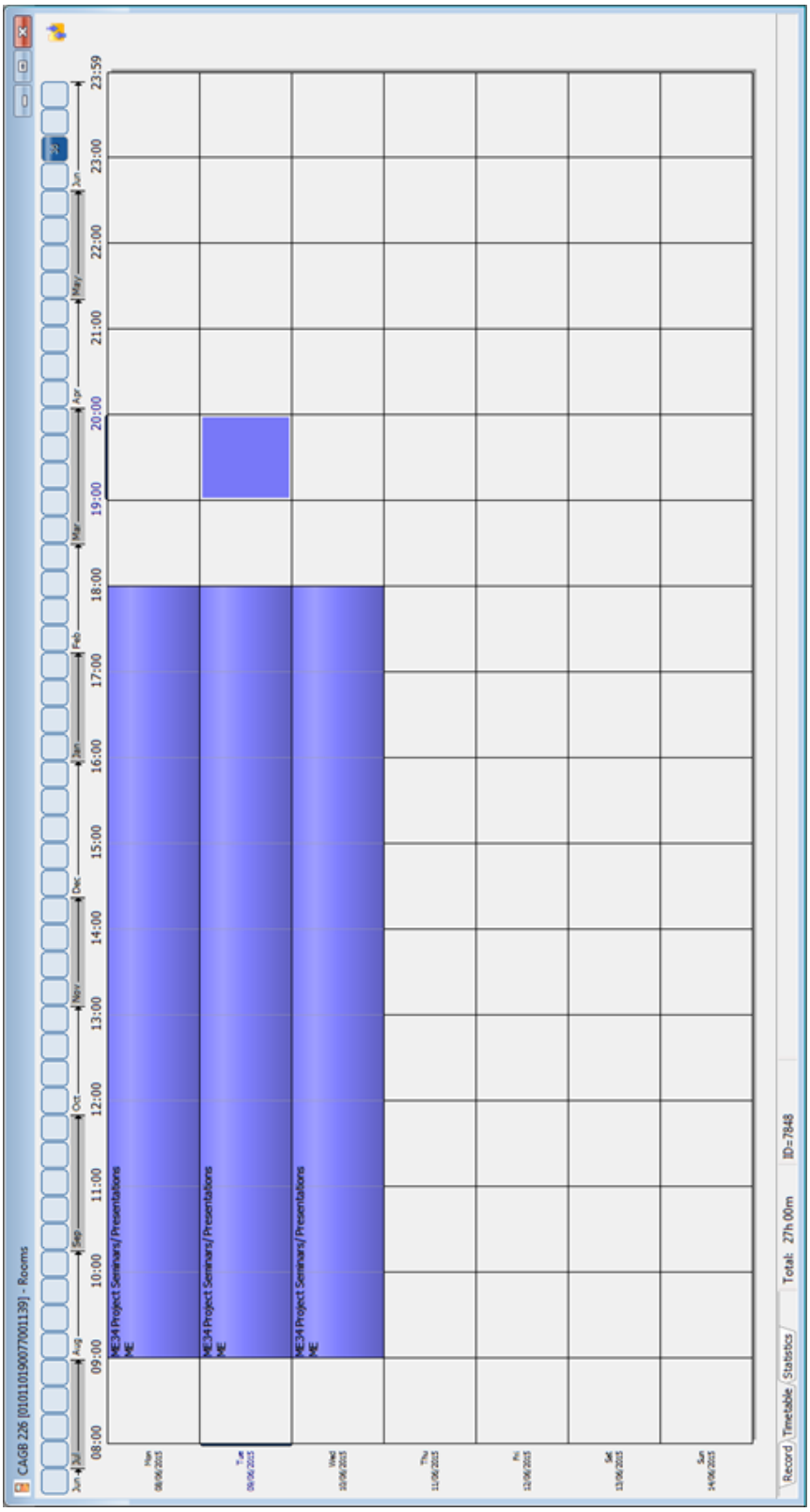
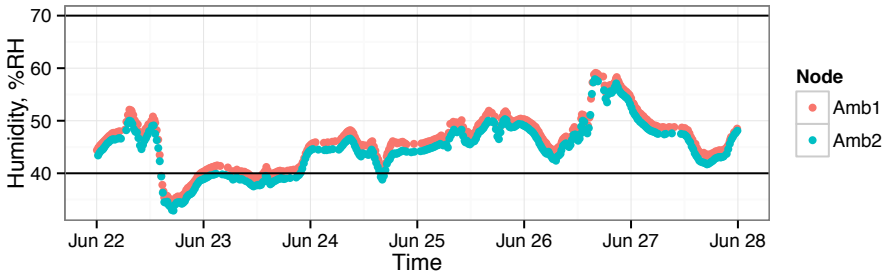
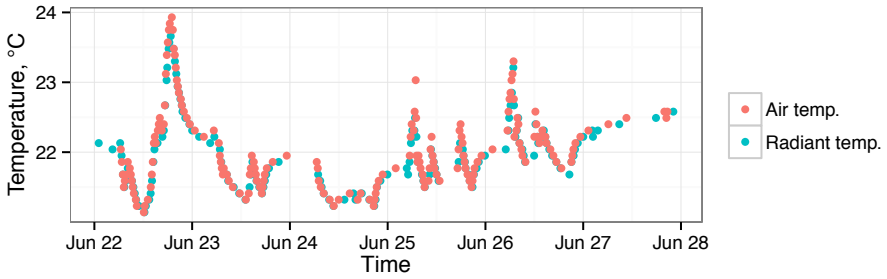


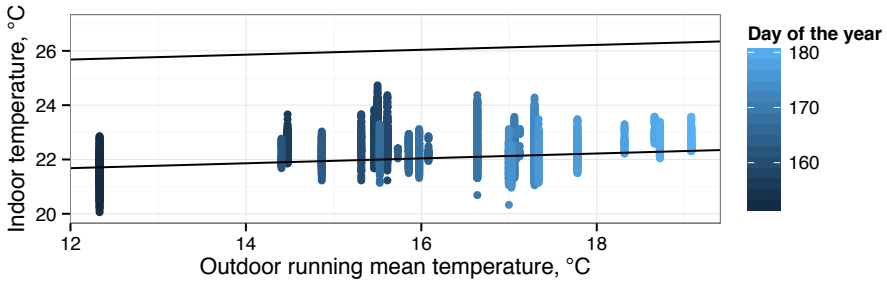
Figure 5.9: Room booking schedule



(a) Relative humidity



(b) Radiant and air temperature



(c) Air temperature comfort limit depending on outdoor temperature

Figure 5.10: Thermal comfort

Figure 5.10 illustrates the conditions listed above. Figure 5.10a shows one week of relative humidity readings relatively to the comfort range. Humidity is at the lower end of this range and even drops below one of the days. Figure 5.10b compares the air and the radiant temperature for the same week. Radiant temperature and air temperature are very close to each other, which in this case can be explained by the fact that there are no windows. Figure 5.10c shows one month of indoor temperature compared to running mean outdoor temperatures. Air temperature could be higher and still be comfortable. Thus, less cooling is needed.

Assess air change and air pollution

For this use case, there are two steps, both enabling to see if there is enough fresh air in the space. The first one consists in verifying that the carbon dioxide does not exceed the recommended level. This is done by comparing the CO_2 time series to a threshold. The second step is to look at the air changes. For the case study the requirement was 10 l/s/person at 80% of occupancy. This corresponds to 0.32 m^3/s. Since the fresh air is provided by three 13x28 cm x cm outlets, assuming the system is properly balanced, the air velocity measured by the sensor need to be around 2.9 m/s. As with the case of balancing, the location of the sensor needs to be taken into account when determining the tolerance of this measurement.

Compare equipment use to occupancy

Figure 5.11 shows how equipment status and occupancy can be combined to review the adequacy of control schedules relatively to occupancy. In an ideal scenario, the ventilation would be on mostly when the room is occupied and potentially at the beginning or end of the day to lower CO_2 and other pollutant levels.

5.4 PO-Cx troubleshooting with PWSN

This section discusses the practical use of PWSN for PO-Cx. It is organised around the four scopes of PO-Cx: energy performance, in-use performance, seasonal commissioning and occupants' satisfaction. Based on the use cases established in the previous section , the data collected, and the information obtained during the interviews, it is demonstrated how the faults identified in Tables 3.4 and 3.5 can be addressed by PO-Cx and pop-up monitoring™.

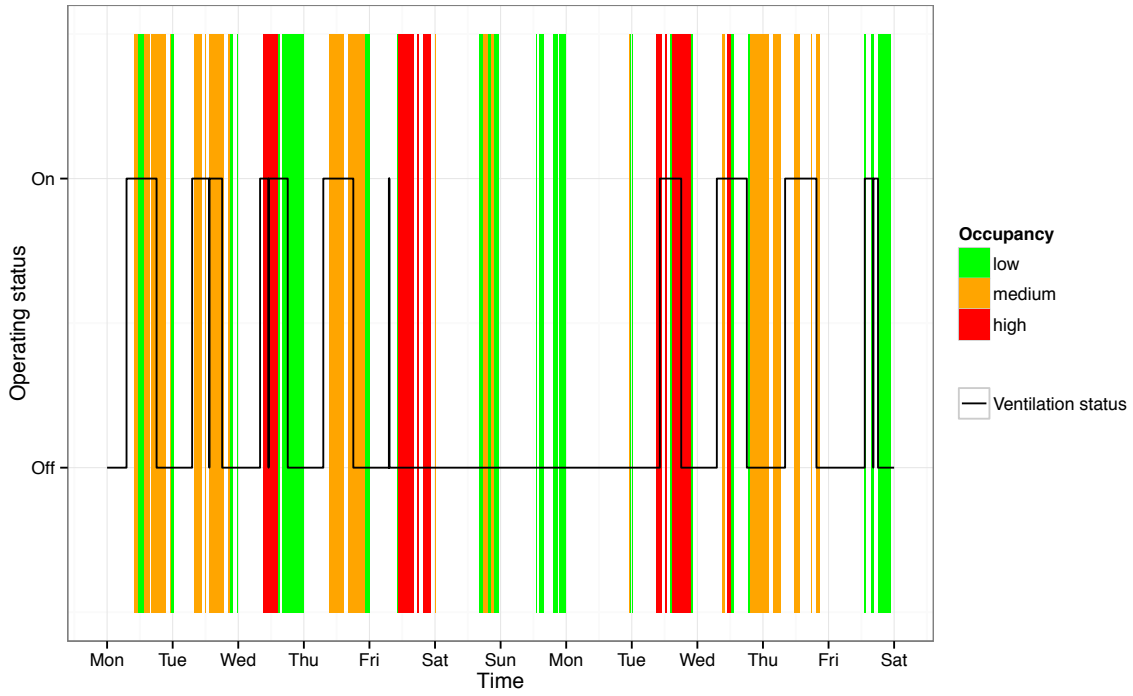


Figure 5.11: Occupancy vs. operating status

5.4.1 Energy performance

Energy performance is a high-level post-occupancy commissioning task. It makes little use of the PWSN data. Its objective is to identify how well the building is performing from an energy point of view. This knowledge helps identify how much of the rest of the tasks need to be performed and can also be a means to evaluate the benefit of the PO-Cx process.

The energy performance analysis uses data from the energy management system and makes use of the total energy consumption and potential sub-metering. A good use of these data would be benchmarking, but the available benchmarks require either one year of data (Cheshire, 2012) or system level sub-metering (Field, 2006) and is thus not adapted to PO-Cx. First, it is interesting to know how the total energy is divided between end uses. If the sub-metering does not allow for this information, the repartition of the different energy sources can give an insight. Figure 5.12 shows the monthly repartition of energy by energy sources for C&G. January was excluded as the data were not available for the full month.

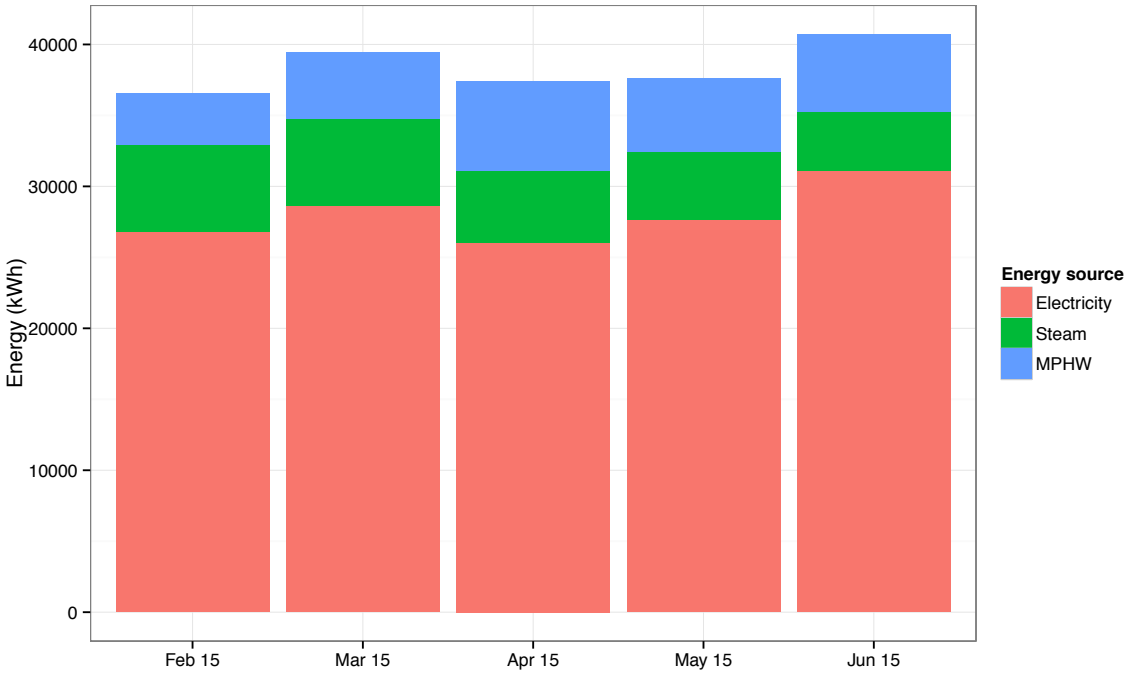


Figure 5.12: Monthly repartition of energy use by energy sources

Times series of the energy consumption are also a good option to gain insight of the overall building energy use. The facts to observe are:

- **Day load** How does it compare to the expected load (HVAC, hot water, lighting, lift, IT ...)?
- **Night load** Is it lower than the day load? Does it start and finish at the expected time? How does it compare to what is expected to be on at night?
- **Weekend load** Is it lower than the weekday load?

These observations give a high level overview of the energy performance of the building. It helps the contractor to understand how much energy should be used and could detect general issues such as equipment running 24/7. Bad system timers are a common problem. In the case of refurbishment, it can also give an insight on the efficiency improvement of energy-saving measures.

In the case of the C&G refurbishment project, a simple look at the electricity time series shows the electricity consumption is higher after refurbishment (968 kWh average before

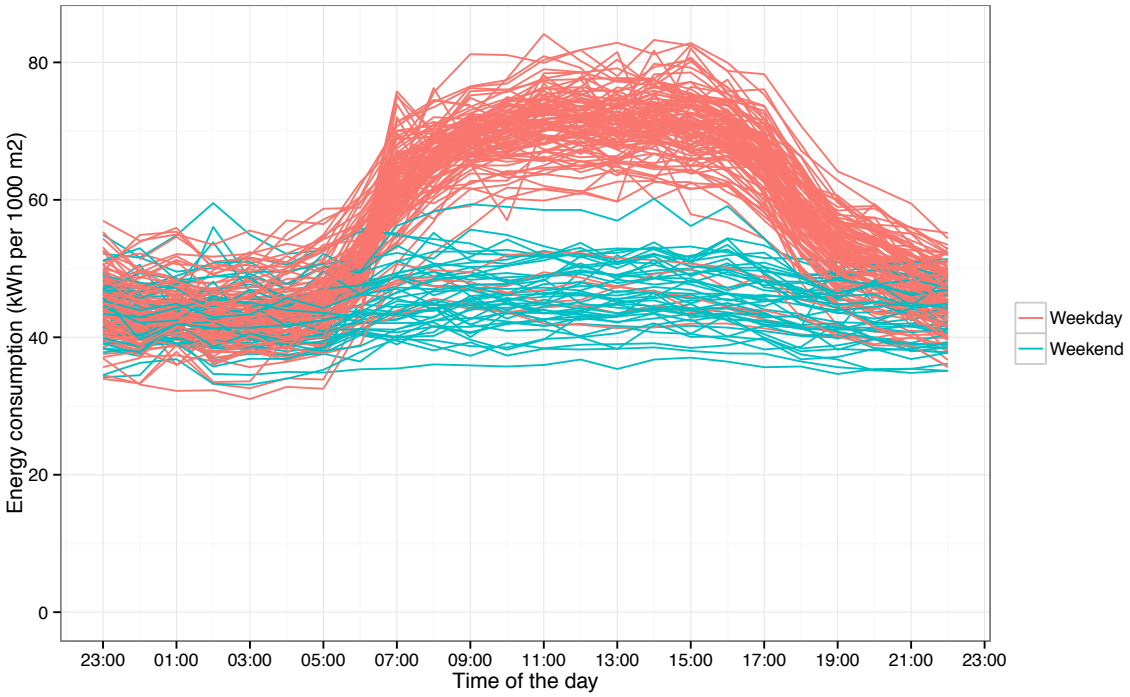


Figure 5.13: Case study building daily electrical consumption

versus 1085 kWh after for the same period of the year). This can be explained by the fact that they are now more services in the building. Figure 5.13 shows the daily building total energy consumption for six months. It can be seen that the night and weekend loads are lower than the weekdays day loads. However the base load is much higher than the 15 Watt maximum recommenced by CIBSE Guide F (Cheshire, 2012). The overall energy consumption in general is also higher than the benchmarks given by the same guide, that rapport to between 25 and 35 kWh per 1000 m^2 over an hour. This suggests the possibility to make significant energy savings.

It is thus important to have good quality energy data available. One-hour frequency is enough to get an overview of the building consumption, but half-hourly or quarter-hourly data might be of use for more detailed analysis.

5.4.2 In-use performance

This PO-Cx task consists in evaluating how the building really work and is the core of PO-Cx together with seasonal commissioning, which is described in the following section.

The comparison points are the building brief, building design as well as occupants' needs. The point is to make sure that the design intent is realised and that the building is fit for purpose. Problems that are detected can come from design, installation or commissioning flaws. Those problems often have direct impact on energy consumption and/or on occupants' satisfaction.

Building specifications

The first step of evaluating the building operating performance is to look at the building operation in comparison to the building intent. From the original intent to the final building a lot of divergence can appear due for example to wrong design assumptions, value engineering decisions, bad installation, wrong control set up or rushing of the commissioning process. To make sure the building meets its specifications the following things should be verified:

- Set points, in particular indoor temperatures
- Operating schedules of the different systems
- Smart control operation
- Air change and balancing

The most important thing to look at is how the controls operate, as this would point towards problems. Abnormal control behaviours would not necessarily mean that there is a BMS fault, but would be symptomatic of some sort of problem that can then be examined more in detail. Looking at the overall operation of the controls could prevent cases as described during interviews where smart systems were not used at all (Appendix A). Two examples of such occurrences were mentioned: 1) a building with advanced smart lighting systems that was used as a single switch to turn all the lights on at 7 am and off at 6 pm, 2) a building running ventilation 24-7 despite having an advanced BMS system. Those are extreme cases but were said to happen at divers degree in a lot of new buildings.

Figure 5.14 shows the operating time of the ventilation system in the case study room using the algorithm proposed for the use case 'Control equipment status' (see Section 5.3.2 page 170). A transparency factor has been added to be able to filter out misleading data due to the instability of the air velocity sensor. It can be seen that the ventilation system is operating from 7 am to 6 pm during the week and is not operating in the weekends as

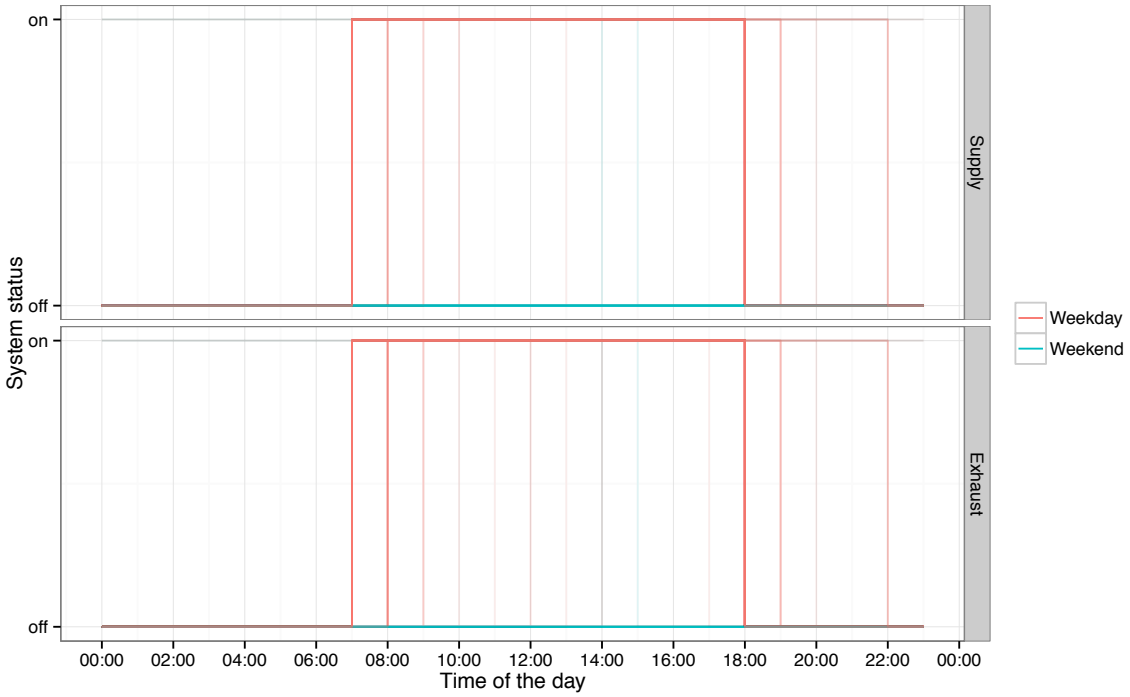


Figure 5.14: Air-conditioning system operations

expected from the controls specification. Similar results are obtained for the FCU, which confirms that FCU and ventilation are operating on the same schedule. This type of plot can help to easily detect which systems are operating when the energy performance step has revealed high loads at night, for example. This could be detected using the BMS. However, during one of the interviews it was reported that is was not uncommon for more systems to be on at night that is being shown in the BMS.

Figure 5.15 represents the daily ambient temperature variation cycles for the 6 months of measurements on the case study. The grey area represents the operating time of the system and thus the time when the ambient temperature is meant to be within the set point band. The BMS data show that the temperature set point was 24 °C for the whole 6 months even though the control specification said that the winter set point would be 21 °C. However, when the ventilation is off, the room temperatures are high. This is unlikely to be caused by the neighbouring zones as the room is surrounded by a corridor that opens on naturally ventilated offices in the other side. This suggests that the room rather needs cooling than heating, so it is not clear whether the absence of set point change is due to

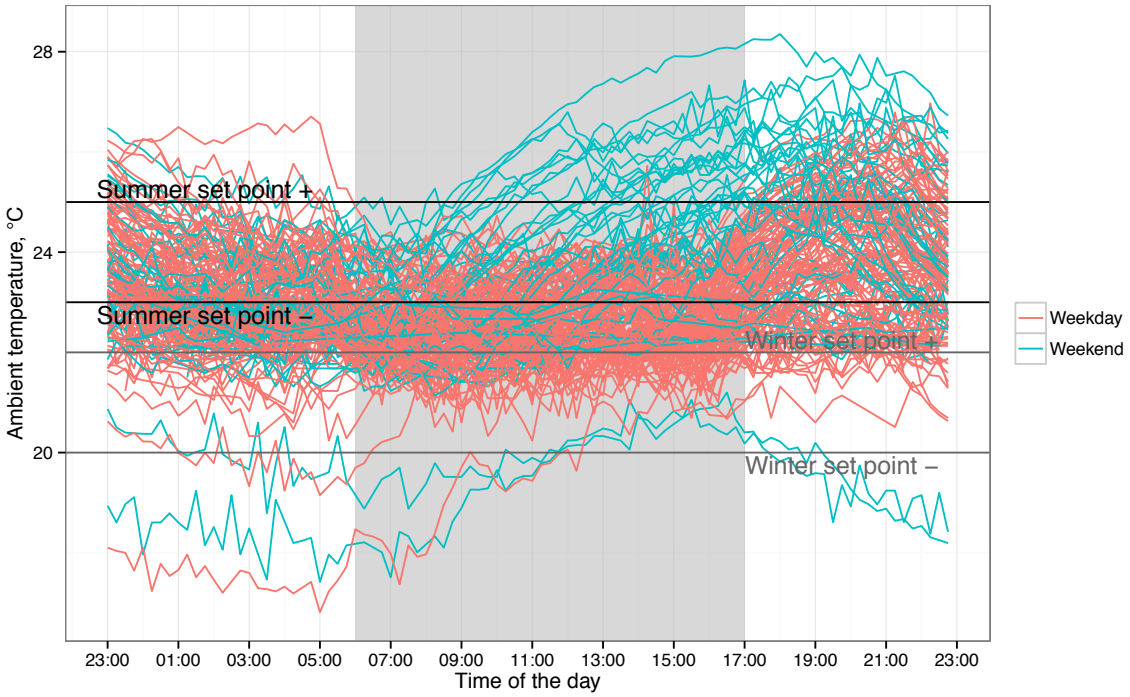


Figure 5.15: Ambient temperature daily variation

forgetfulness or to the realisation that 24 °C was a more sensible set point due to the warm nature of the room.

When comparing the week ambient temperature to the set points limits (24 °C ± 1 °C), the temperature band seem rather centred on 23 °C than 24. This could suggest a problem with the temperature sensor used for control. Either the location of the sensor could be inappropriate or the sensor could need to be recalibrated. However since the PWSN sensors are only accurate to ± 5 °C, this needs to be investigated further. Looking back at Figure 5.5 page 168 it can be seen that the system requires time to stabilise at the set point.

Example of common in use problems

Once general inspection of the building specification has been carried out (this can be done on a sample of the systems) some common issues might then be looked at depending on the system type and potential construction or commissioning related problems. As the faults discussed below could not be illustrated from the case study data, the discussion is

based on the content of the interviews.

Simultaneous heating and cooling, and hunting Cassette conditioning systems or chilled beams are reported to be wasteful if not controlled properly. A common occurrence, if the dead band is too narrow is that the unit will oscillate between heating and cooling without finding a stable operation point. This is commonly called hunting. It is not only wasting energy, but also has strong bearing on occupants comfort that risk to be alternatively too cold and/or too hot. The solution is often to set up a wider dead band. Heating fighting cooling also happens when heating is used to fight free cooling.

The other problem with this type of system is that within the same open office zone a unit would be in heating mode while another one would be cooling. This does not necessarily lead to discomfort like hunting, but the same level of comfort is likely to be achieved by both unites being off. The problem would come from bad control specification (all the unites should be controlled together) or override due to complaints. Simultaneous heating and cooling can also happen in AHU where both the heating and cooling coils are active at the same time, but this is less common.

Both problems can be detected in a similar way, but looking at the heating and cooling patterns of the systems using the use case 'Heating/cooling mode'. In the presence of hunting they would be a frequent variation between heating and cooling. For simultaneous heating and cooling, superposing the heating/cooling pattern from all the FCU in a space it can be seen that several modes are enabled at the same time.

Boilers and chillers sequencing Commercial buildings often have several boilers to cover the peak heating demand and have any combination of them working for smaller heating load. Interviews suggest it is a common thing that proper sequencing would be overwritten and never set back because of people complaining from cold or to cope with extreme weather conditions. Boilers sequencing might also have never been set properly. If excess energy use is noted on mild days, it is worth checking the BMS for boilers all defaulting to on for heating demand. Similar problems can happen when a building has several chillers.

Control strategy vs. occupants

The fact that the control strategy matches the design intent (see page 179) does not guarantee that the most efficient control strategy is used for the building. At the design stage, most control strategies will be based on a fixed schedule such at 7 am to 6 pm for heating, ventilation and air condition. Even when some sort of demand driven control is planned, it tends to be valued engineered out to go back to a more classic approach later in the project. PO-Cx is then an occasion to verify the validity of intended schedules compared to real building use. Systems might be running wastefully when nobody is using the space or comfort related issues might arise because of the building being used out of operating hours or at a higher density than accounted for during design (Noye, Keirstead and Angeloudis, 2016).

For the case study, looking at Figure 5.11 page 176 that illustrates the use case 'equipment use vs. occupancy', it can be seen that the room is occupied in the weekend days' afternoons. As it is a teaching room, it is only considered to be used during office hours, but students tend to use it for studying during weekends. It also tends to be used later than 6 pm. This does not match with the control schedule of the ventilation system.

Adjusting the control strategy for real occupancy will lower the probability for occupant complaints that easily lead to partial decommissioning of the systems once FM takes over.

5.4.3 Seasonal monitoring

In this section, the focus is on seasonal commissioning. The operation of the system is evaluated against the weather conditions to assess whether it is fine-tuned appropriately for its different loads. Seasonal commissioning when it is done tends to focus on a hot and a cold day. The use of a PWSN enables to look at the system operation in the entire spectrum of intermediary loads to be more representative of the systems' operation. It should be used in complement to the BMS data to ensure the system delivers the expected comfort levels.

Weather overview

The first step to carry seasonal commissioning is to understand the weather of the period that is looked at. Figure 5.16 shows the monthly variations of the daily average temper-

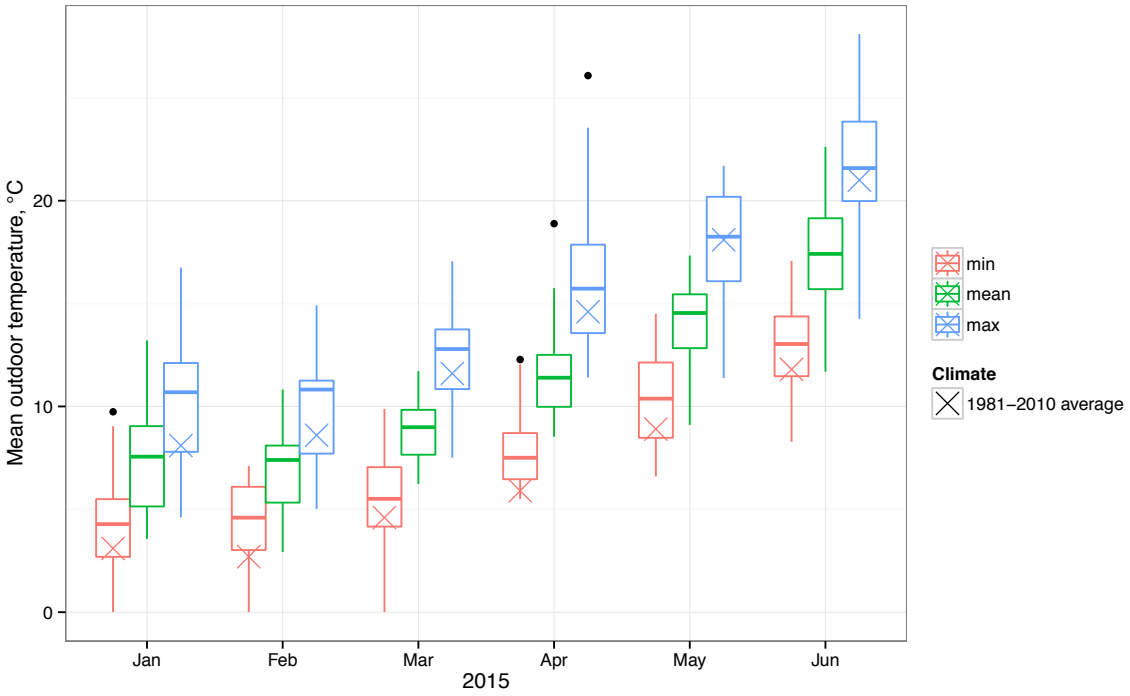


Figure 5.16: Weather summary during the data collection period (2015)

ature for the 6 months of the case study.The average of daily minimum and maximum temperature as calculated by the Met Office using the Greenwich Park weather station data from the 1981-2010 period has been overplayed for comparison[9].

The Met Office describes the temperatures from the first half of 2015 as 'fairly near average'[10]. As would be expected, January and February were relatively cold months and May and June were relatively hot. They were some days of April that were hotter than the normal seasonal variations.

Heating and cooling calculation are done based on cooling and heating degree days based on historical data over big regions of the UK (Day, 2006). With the acceleration of climate change, this guidance is likely to become rapidly obsolete. The first year of weather might not necessarily be representative of the climate for the building life cycle, but it will help to understand the response to the building to different types of weather.

[9]http://www.metoffice.gov.uk/public/weather/climate/gcpvh0xy5
[10]http://www.metoffice.gov.uk/climate/uk/summaries/2015/annual

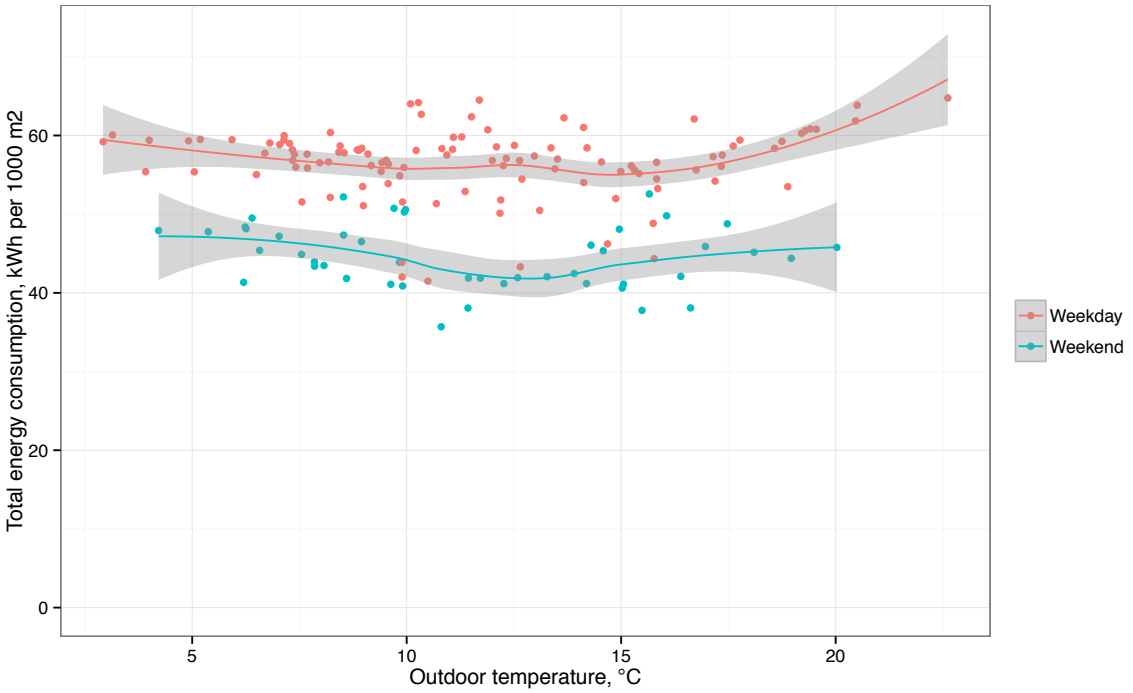


Figure 5.17: Energy use at the different outdoor temperature

Seasonal energy analysis

Once an overall idea of the weather is acquired the next step is to look at the energy consumption as a function of the outdoor temperature. In an optimised building, this should result in a V-shaped curve with energy consumption decreasing with increasing temperatures in the cold temperatures, corresponding to less heating being provided in milder days and energy increasing with increasing temperature in the high temperature corresponding to less cooling being provided in milder days. Such a V-shape indicates that the energy-saving measures to reduce the load in milder day are effective.

Other curve shapes can be signs of significant failure of the systems. If the curve is inverted, with high consumption in mild days and lower at more extreme temperatures there is likely to be hunting or simultaneous heating and cooling as described page 182. A rather flat curve indicates that load reduction controls are not set up properly as described in the following section.

Figure 5.17 shows the daily total energy consumption of C&G in function of the outdoor

temperature and is separated between weekdays and weekends. The V-shape is present, but the fact that the slope is steeper for warm temperatures means cooling uses more energy than heating. This suggests looking more into the cooling systems during PO-Cx as they are more savings to be made there. Also there seem to be a slight increase of energy in the mild days, suggesting some energy-saving measures might need to be fine-tuned. The fact that the weekend consumption curve also presents a V-shape when the heating and cooling are supposed to be off, also suggests further investigation, as the energy consumption is not expected to depend from the outdoor temperature.

Weather compensation and fan inverter

Two control systems that are used to reduce the load in mild condition have been reported being often badly set in the interviews. Weather compensation controls are used to improve the efficiency of heating systems. Without it the heating works on full load when heating is needed and then turn off. This can result in overheating and/or in the system running in on/off cycles. The weather compensation control will use an outdoor temperature sensor to adjust the load to the external condition, proportionally reducing the load for lower temperatures.

Fan inverters work similarly to improve the efficiency of the fans from cooling systems. Both controls are set up in the BMS as a proportional relation between load and outdoor temperature. They can be forgotten or set up too conservatively (e.g. only reducing the load from 100% to 90% for the milder days), which both result in energy waste, and possibly earlier failure of the equipment or comfort issues. Bad operation of those mechanisms can also come from unsuitable location of the outdoor temperature sensor.

Overcooling

Interviewees report that with the increasing use of IT and other electronic equipment, cooling has become dominant over heating. This means that a particular attention needs to be given to the cooling systems' operation. A first issue is cooling set points being set too low in the summer. A lot of buildings run at 21 °C when 24 °C would be an acceptable temperature and save significant energy. The other common issue that commonly leads to excessive cooling consumption is the fear of overheating due to IT and solar radiation. This leads FM to run cooling 24-7. A careful look at cooling schedules and how they impact

comfort can prevent energy waste.

5.4.4 Occupants' satisfaction

A lot of the issues addressed above can be uncovered through occupants' complaints, as they would affect comfort delivery. It is the case of schedule problems, overcooling, simultaneous heating and cooling, and bad commissioning, in particular bad seasonal commissioning. Resolving occupants' complaint is normally done by facility management, which might lead to control overwriting and its associated problems leading to partial decommissioning of the system and wasteful running. Early in the building life, it is better done by the contractor that will have a more detailed understanding of the systems. The systems can then be fine-tuned for comfort which will reduce the likelihood to default things 'on' later and make the building easier to operate.

The best approach is to actively seek to detect sources of discomfort by conducting occupants' surveys such as in soft landing (Way et al., 2009). The main source of occupants' complaint is thermal comfort related issues and in particular felt temperatures. Poor visual comfort, noisy environment and poor IAQ ought to be able to be investigated too, as well as general ergonomics of the building (e.g. lifts not operating logically, security access problems ...). The paragraph below gives a few examples of comfort related investigations.

Thermal comfort

According to the design set points, the temperature in the case study is a bit too cold (Figure 5.15 page 181), but it is interesting to evaluate the validity of the set point in function of more detailed criterion. For example, Figure 5.18 shows the use case 'thermal comfort' applied to the 6 months of data of the case study. The data points have been separated between times when the ventilation is 'on' (7 am to 6 pm on week days) and 'off'. The time the ventilation is on represents the scheduled occupancy during which the indoor temperature should be in the comfort range. In this case, it is actually confirmed that the air-conditioning could be run less cold. It can also be noted that when the room is used out of scheduled occupancy hours it is likely to be too warm. Three days are particularly cold. The temperature set point seems to have been lowered for that period and then put back to the original one after a few days.

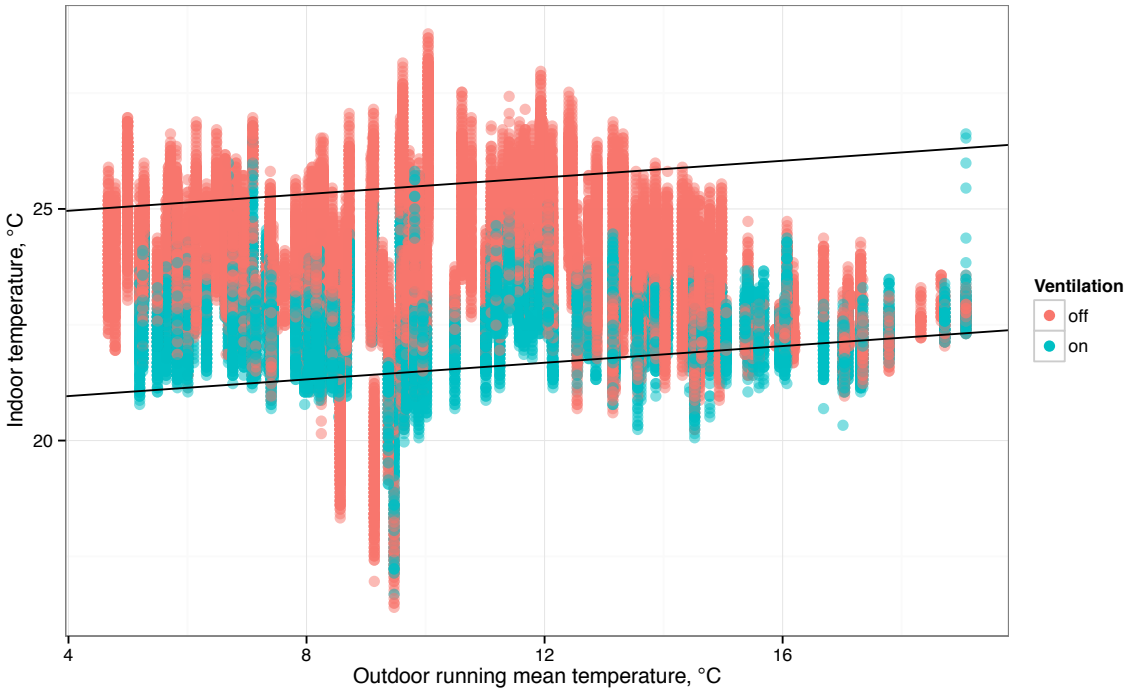


Figure 5.18: Comfortable indoor temperature and outdoor temperature

Figure 5.18 operation's schedule is based on the standard 7 am to 6 pm. However, as seen in the 'Control strategy vs. occupants' section page 183 this is not necessarily the best schedule compared to the building real use. The discrimination between on and off should be re-evaluated accordingly.

Figure 5.19 represents the daily variation of relative humidity in the case study as well as the recommended comfort range for the metric according to Race (2006) . It shows the room is too dry. This probably comes for the air-conditioning and the absence of windows. This means occupants should be consulted regarding the comfort of the space. If the occupants suffer from this, a humidifier might need to be added to the air-conditioning system.

Radiant temperature can be a big source of discomfort. The effect of radiant temperature could not be observed on the main case study as the room did not have widows. A few measurements were thus taken in the semi-open plan office described in Section 5.2.3. Figure 5.20 compares two days one that offers limited radiant temperature and thus a rather homogeneous temperature distribution in the room except for a brief peak around

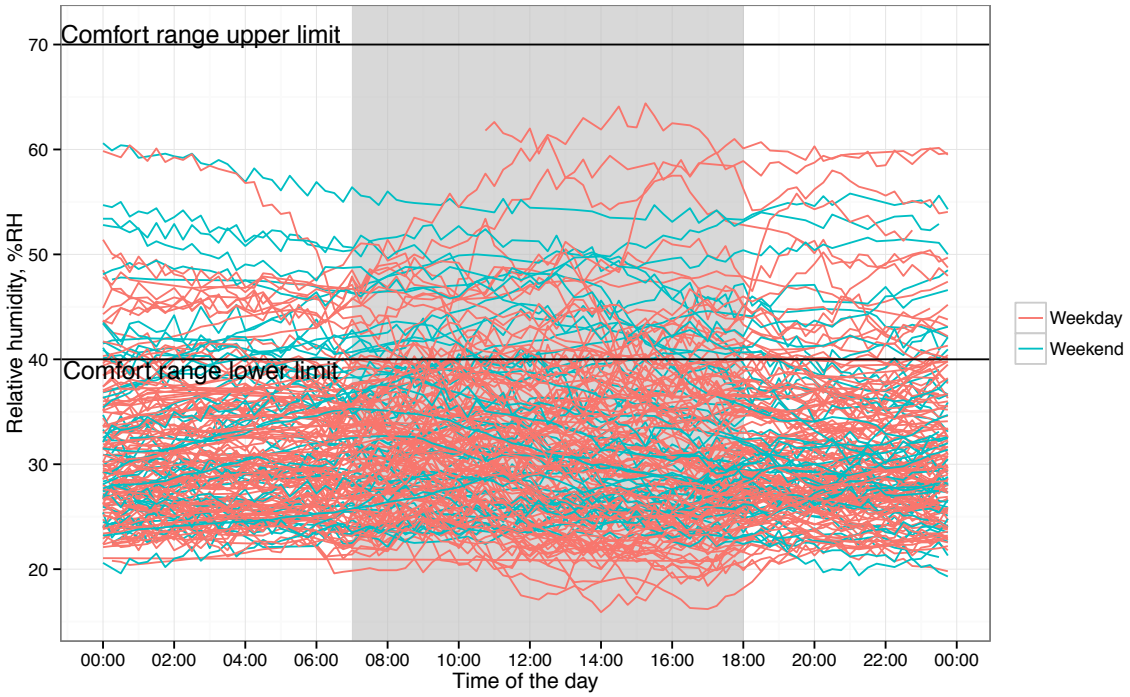


Figure 5.19: Relative humidity and comfort range

11 O'clock and a very sunny day where the radiant and ambient temperature behind the window were very high. The temperature on the desk was still low, which means a big difference was felt between the lower body in the shade and the upper body in the sun. Race (2006) this as a source of discomfort. It can also be noticed that there is a big difference of felt comfort between the different occupants of this office. This suggests increased difficulties to satisfy all the occupants. However, the discomfort could be detected from the ambient temperature sensor, probably because the sensor measures a mix of air and radiant temperature, so the radiant temperature sensor might not be a necessary part of the PWSN.

5.5 Assessment of pop-up monitoring™ potential

This section is a discussion on the results of this chapter and aims at assessing the potential of pop-up monitoring™. It first comes back on how PWSN can contribute to the PO-Cx process, before discussing relevant monitoring requirements based on lessons learned by the experimental use of the PWSN. Finally, the requirements for an analytical tool to support

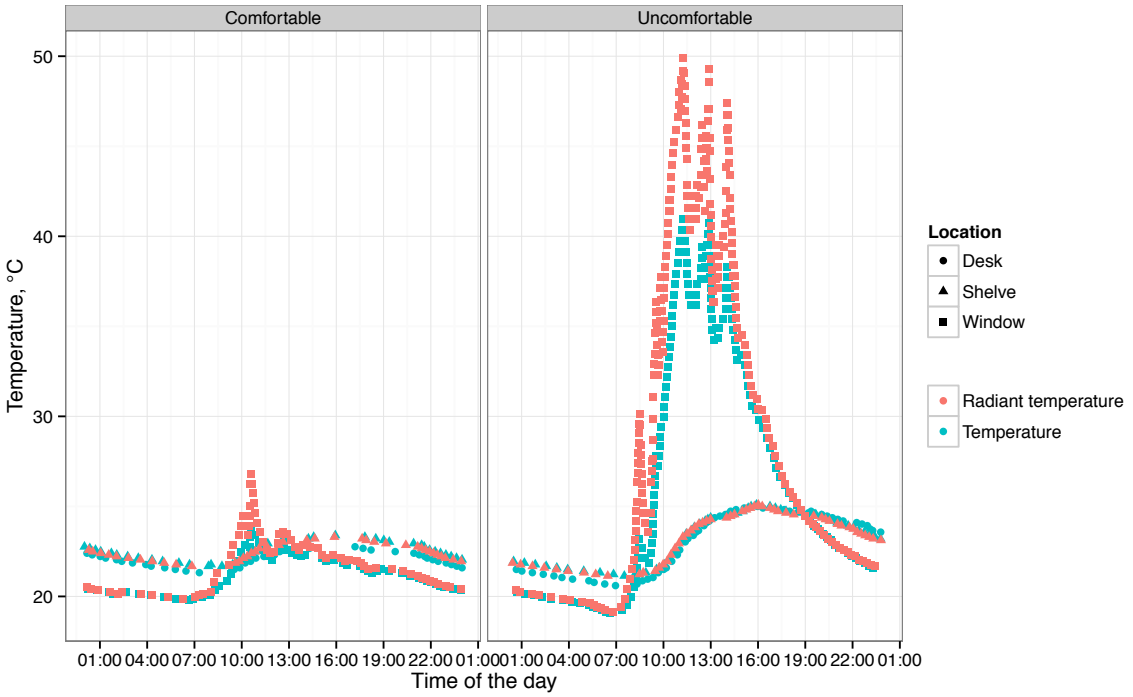


Figure 5.20: Application of radiant temperature sensing

the analysis of the PWSN data for PO-Cx are discussed.

5.5.1 Potential of PWSN for PO-Cx

The previous section has shown that PWSN data can help to diagnose new buildings' faults and to refine the understanding of how the systems work in practice. A few of the issues that would need to be resolved during a PO-Cx process have been presented. The PWSN would be able to contribute to the diagnostics of many more problems thanks to the flexibility of wireless technologies. As the pop-up monitoring™ kit focuses on the outcome of the system as a diagnostic staring point, the PO-Cx process could easily be adapted to any building even if the system and its potential faults have not been encountered before. The test case had open ceiling which would not be the case in most buildings. However the majority of the sensors were attached on part of the system that would normally be available. In any case the person in charge of installing the sensors would normally have authorisation to access the system even if it is concealed.

The engineers carrying on PO-Cx need to be able to have a general view of the build-

ing operations. Once a fault has been identified and specialist knowledge is required, a specialist engineer is called on-site to re-commission the responsible system.

The PWSN data should be used in complement to data collection systems installed for building management purpose. In particular, energy management data give an interesting overview of the building's performance and BMS data give access to details of the systems' operation that would be more difficult to access with the PWSN because installing temporary sensors would interfere with the system. It might be argued that some data collected by the PWSN are redundant with the ones from the BMS. However, the PWSN data allow much more flexibility by being able to be installed in different locations and can record data at a higher frequency. Since BMS sensors are a potential source of faults, this can help to identify BMS problems. When a discordance between the BMS and the PWSN are found, the engineer called for re-commissioning should then use a third measurement tool to make sure the problem does not come from the PWSN. Also, just after handover the BMS data might not be fully accessible, in which case this redundancy limits the delay in the PO-Cx process. A PWSN is thus a good tool to complement O&M monitoring systems for building forensic during PO-Cx.

5.5.2 Monitoring requirements

After the experience drawn from development, deployment and analysis of the data, the requirements of the PWSN are re-evaluated. This aims at closing the loop to improve the next iteration of the PWSN design. Regarding the configuration of the wireless sensor network in itself, time synchronisation between the different elements of the system is important to be able to make sense of the data. Simultaneous measurements would be a plus, but is not necessary. The frequency would need to be parametrisable through the commissioning software or the analytic software, in any case without the need to remove the nodes.

Regarding the sensor nodes, due to the facts that only the pipe temperature sensors could be installed and that the room monitored was in cooling mode most of the time, relevant data could not be collected to illustrate the FCU's heating and cooling modes. As a result 'Comparison of heating/cooling mode to weather conditions' could not be implemented either. Difficulties to install contact sensors on the cooling system is likely to be a recurring problem, which suggests the need for further research to find an alternative sensing solution (e.g. probe to insert in the commissioning valve).

The rest of the sensor nodes were satisfactory to perform the identified use cases. It is recommended to have a limited number of node types. A possibility would be to have, an ambient node including temperature, humidity and CO_2, and a ventilation node including temperature, humidity, CO_2 and air velocity. If the ambient node for the BMS system was not adapted to measure the ventilation system variable, the standalone system could be easily adapted to measure ambient parameters, to limit development complexity. Light and noise sensors could be added to the ambient node to include visual comfort and noise level to the scope of the PWSN measurements. The reason for having a limited amount of node is that the data that give the most useful information is not always the one that was considered before knowing the type of fault. Multiple data readings at the same location can also help to double-check the meaning of a reading. This means that individual nodes will be slightly more expensive, but that might be compensated by the lower design and production cost. This should also make the deployment of the node easier by saving the trouble of finding the node that has the exact set of measurements needed around the building or by needing to install several nodes at the same place. On the downside more sensors means more drain on the battery so it might be necessary to separate the ambient node in two (temperature, humidity, and CO_2 / noise and light). Radiant temperature was removed from the list of measurements, as it did not bring significant information over normal temperature sensors.

To help with battery life it is important to use the appropriate sampling frequency. For the PWSN prototype the measurement frequency was 15 min for the nodes from the commercial system and 1 min for the Arduino nodes. CO_2 changes quickly when occupants arrive in the room and the data is noisy due to the measurement technique. 15 min measurement intervals were not enough to give satisfying information for occupancy detection. 1 min is a more appropriate measurement frequency. However, for the ambient nodes where CO_2 is only used to look at the level of air quality 15 min intervals are sufficient. For air velocity measurements, getting a data point every 15 min would be sufficient. However, the measurements were rather unstable, so it is recommended taking a measure every minute and average it on 15 min. This enables to save transmission power and storage space compared to 1 min measurements intervals. Finally, temperature and relative humidity slow variation means that 15 min measurement interval is a good default value. It would be good to be able to increase the frequency for specific needs where a

Table 5.4: Recommended characteristic of the PWSN sensors

Parameter	Sensor	Unit	Range	Accuracy	Resolution
System operation					
Temperature (Heating)	Temperature	°C	0 - 100	± 0.5 °C	0.1
Air temperature	Temperature	°C	0 - 50	± 0.5 °C	0.1
Airflow	Velocity	m/s	0 - 5	± 3%	0.1
Indoor comfort					
Temperature	Temperature	°C	10 - 30	± 0.5 °C	0.1
Relative humidity	Humidity	%RH	0 - 95	± 3%	1
Operation condition					
Occupancy level	CO_2	ppm	0 - 2 000	± 3%	50

finer data resolution is needed to understand a phenomenon (e.g. comfort problems linked to system oscillations). However, response times of the sensor nodes need to be considered when sampling at higher frequency, as the time for the change in ambient conditions to be detected by the node might be greater than 1 min.

The specifications of the TPZ sensors were satisfying for the PWSN. The COZIR™ CO_2, temperature and humidity sensor was as well. The air velocity sensor is promising in terms of its energy consumption and the raw signal gave useful information, but it would require a better calibration guide from the manufacturer to make it easier to exploit for air velocity readings. For the measurements used in the project, Table 5.4 gives the recommended characteristics for the PWSN sensor based on the experience with the PWSN prototype.

5.5.3 Data analysis requirements

For the purpose of this research, the data analysis has been case specific. The full implementation should not assume that the commissioning engineer would have the coding competence to do so, even if he had time. For practical applications bespoke analytical software needs to be implemented, as the requirement for PO-Cx data analysis go beyond the possibility of industry-standard software. The requirements for such a tool have emerged from working with the PWSN prototype. They are described below:

- SQL user-friendly interface to import the data from the database.
- Possibility to easily plot time series of several data channels to give a quick overview of the measurements.

- Incorporation of a series of pre-defined use cases and visualisation function such as to obtain the figures from Section 5.4 in a few clicks.
- Possibility to define new functions to accommodate for other use cases that might be necessary on a specific project to be able to adapt to any problems that might arise. This might be offered as a service by the company providing the tool.
- Possibility to import and export data in comma separated format to easily include BMS and energy management in the analysis.
- Possibility to change some PWSN settings such as measurement frequency.
- Commissioning function to associate sensor ID and location (this might be implemented separately as an application for mobile devices and communicate directly to the database).

All this functionality should be intuitive and require limited training to be used.

5.6 Summary

In this chapter, 6 months of data collected on a case study teaching room are used to illustrate the possibility and advantages of using PWSN for PO-Cx. First the data have been used to implement analytic techniques to address the use cases established in Chapter 3. Then use of these data for practical PO-Cx problems has been illustrated.

The data collected by the PWSN prototype are able to give access to a wide range of information. Most of the use cases could be addressed with the sensor implemented and the ones that were not could be easily integrated in further design of the PWSN. Use case information can be obtained by simple plots of the sensory data or require transformation and combination of the sensors using simple signal processing. In any case, the information is presented visually for fast interpretation of the data.

The use cases have then been used to illustrate how the PWSN can be used to carry on the four processes of PO-Cx. *Energy efficiency* gives the big picture of the overall performance of the building and uses energy data currently available on most building projects. *In-use performance*, *Seasonal commissioning* and *Occupant's satisfaction* then investigate in detail where potential faults or inefficiency might lie. The investigation can be more or

less deepened depending on the energy study. It has been illustrated how the PWSN can detect faults and lead to more detail investigation. Once the cause of a fault is detected, the systems should be re-commissioned by an expert.

The results of the chapter have been discussed, in particular how the PWSN complement the BMS system in detecting and diagnosing system inefficiency. Based on the observations enabled by this research, a reflexive iteration on the requirements established in Chapter 3 was proposed, in particular, regarding measurement frequency and sensor specification. The key functionalities of bespoke software for PO-Cx analysis have been defined.

Chapter 6

On practical application of PWSN for post-occupancy commissioning

After demonstrating the use of PWSN for PO-Cx, this chapter aims at taking a step back and discuss the potential of PO-Cx and the possible application of the PWSN explored in this thesis. In Section 6.1, the benefit of PO-Cx is reaffirmed based on the work carried out and the current limitations for its implementation are discussed. Section 6.2 discusses the capacity of a PWSN for the realisation of PO-Cx. Section 6.3 briefly explores the other potential uses that could be made of a commercial PWSN. Section 6.4 explores the research possibilities open by this work.

6.1 PO-Cx perspectives

By taking place once the pressure to finish off the building and get it occupied has been lifted, post occupancy commissioning has the opportunity to include energy performance realisation in the building process. The primary objective of PO-Cx is to understand and reduce the gap between the design and operation of the building, but by ensuring initial energy performance is satisfactory, PO-Cx also impact the life cycle energy of the building by providing a better baseline for FM to work from. This can also make other energy-saving measures, such as FDD or on-going commissioning, more efficient by providing a better baseline to measure performance degradation. PO-Cx also enables to extend the involvement of the design and construction team on the project. This creates the opportunity for more dialogue with the FM team that should enable them to understand the systems they operate better. It can also limit the loss of knowledge that normally happens

at handover.

Implementing sound technical procedures for PO-Cx will not be sufficient to make it a standard procedure in the building services industry. In the current status quo, adoption of PO-Cx as a standard practice is seen as difficult as it requires additional time and capital investment. However, with the increasing concern for energy efficiency and potentially the increase in energy prices, processes such as PO-Cx are likely to be more demanded to assist reaching energy and CO_2 emission reduction targets. Some transformations are already appearing in the form of energy performance contracts where the contractor commits to deliver a building respecting fixed energy targets. On this type of contract the financial penalties for not meeting the targets are so important that the contractor cannot afford not to meet them. The emergence of this kind of delivery model can be seen in British public-private partnership (PPP) and private finance initiative (PFI) projects (Energy Action, 2002). In parallel, a paradigm shift has started for the building services industry from product-based to service-based (Robinson et al., 2015). Business models where the contractor sells a service (e.g. heat and power) instead of a product (e.g. CHP plant) are emerging. The efficient running of the system then becomes more critical as the benefit margin depends on the running cost of the system.

In addition, regulatory incentives are needed to encourage the adoption of PO-Cx. Recent evolution of building regulations, energy policies and certification schemes have led to an increased demand for energy-efficient buildings, but if this has affected new building design positively, more controls need to be done once the building is operating, as new buildings tend not to comply with the regulation (Pan and Garmston, 2012). The new policy asking for NZE buildings will also require new verification processes such as PO-Cx to be successful. Regulations and policies need to evolve to give a bigger weight to operations in their scope. At the moment commissioning is required by Part L of the building regulations, but there is no minimum requirements regarding the quality of the process. In the same way, BREEAM and LEED simply require a commissioning process to take place. This could be limited to ticking a few boxes and signing a paper off. More detail about the quality of commissioning need to be included in regulation and other green building incentives before implementing PO-Cx or there is a risk for the initial commissioning process to be done even less and rely too much on PO-Cx to solve all the problems.

For smooth realisation of PO-Cx, it will be very important to have a contractual framework to clearly define the responsibilities of the different stakeholders. The first question is what are the tasks to be carried out and by whom. The contractor would be responsible to install the monitoring system and look at its data, but they need to be some sort of involvement of the FM team to have lasting benefit from the process. Secondly, once problems have been detected, means need to be allocated to solve them. Who pays for fixing problems needs to be clearly defined as well. If the problem was a construction or commissioning problem, the contractor would obviously be responsible for it, but if the problem comes from differences in use by occupants or unexpected weather conditions, it can be more problematic. Necessary skills and training will also need to be carefully laid out.

In its current form PO-Cx is mostly aimed at new mechanically ventilated commercial buildings. Those are the type of projects that make the most sense to apply PO-Cx to, as each project consumes a significant amount of energy and has potential for the energy savings to pay back for the extra cost of the PO-Cx process faster. However, smart naturally ventilated buildings have been gaining increasing interest due to their low energy consumption. Bordass, Cohen, Standeven and Leaman (2001a) list the 4 following issues as typically preventing successful natural ventilation design:

1. Issues of responsibility for installation and commissioning: is it the responsibility of the structure or of the systems teams?
2. Difficulty to get the controls to work
3. Poor reliability of novel components
4. Insufficient understanding of occupants' perception and lack of manual override

PO-Cx could help with (2) and (4). The method developed here would need to be adapted, but a PO-Cx process for naturally ventilated buildings could improve the delivered comfort of such buildings.

6.2 PWSN perspectives

Performing PO-Cx requires access to data. Monitoring data typically available in modern buildings such as BMS and energy monitoring are able to point out when something is wrong (e.g. excessive energy consumption at night), but will not be able to diagnose the

cause of the problem. And that is if the system is fully commissioned once the building is handed over. PO-Cx presents additional constraints compared to traditional commissioning measurements as the building is being used and the measurement cannot disturb its normal operation. WSN technologies offer the opportunity to collect data that the cost of wiring sensors would make prohibitive and with limited interference to the building activities. The PWSN could fit in a rolling suitcase and be installed seamlessly with only a bag full of zip-ties or double sided tap and possibly a ladder. The installation requires little specific skills and can be done without interfering with the systems' operation since it mostly measures the outcomes of the systems. It has been shown that the PWSN could have an acceptable battery life and transmission rate.

Since the WSN infrastructure enables access to the data on-line, the contractor would need to come to site only when a problem to solve has been confirmed or could even delegate the on-site observation to the FM team. This represents considerable cost savings compared to traditional energy auditing methods. Using PWSN for Cx has the potential to move the process away from box ticking. Box ticking can lead to a lack of reflection on how the system is really working. The use of PWSN can help to look more into what is really working or most importantly what is not.

Since the PWSN measures the outcome of the buildings' systems, it can be fitted to any mechanically ventilated building and the associated analytic tools can be adapted to different types of systems without major redesign for each project. The focus on energy and comfort enables to assess the general performance of the building in contrast to the specifics of the systems. The measurement of real data is also a good way to make weather and occupancy adjustments for energy performance contracts and potentially to compare design energy models like EPC to real energy consumption. The PWSN measurements can also be used to identify the need for additional tests, such as the airtightness test realised in PROBE (Cohen et al., 2001). If the system is working as expected, but more heating than expected has to be supplied, this can suggest air leakage.

For PO-Cx with PWSN to be efficient, it is important to make sure the energy data are available early on to be able to start with the big picture as well as to be able to evaluate seasonal variations. Comfort surveys should be carried on a seasonal basis. Comfort and energy information then serve as a basis to decide where to install the PWSN nodes. Some

kit can also be installed based on the results of the commissioning process and known remaining 'snags'.

Based on the cost of the prototype, the cost per node would be between £100 and £300. The final cost is expected to be at the lower end of this range, as prototypes tend to be more expensive than the final product. Considering the results regarding wireless transmission distance in buildings presented in the literature (Section 2.5.3 page 70) a repeater would be needed every 10 - 20 meters depending on the number of partitions. The number of sensing nodes needed would also depend on the building layout. The cost of the gateway, which for a standalone system would be between £80-£150, need to be added to this.

To lighten the burden of PWSN's capital cost on the project further, the lack of permanent wiring means it can easily be used on several projects. However, the current practice is to bill measurement equipment on projects. As a result, part of this equipment is generally lost when the project ends. Alternative measures have to be instated to make sure the equipment is recovered at the end of the project in prevision for the next one. This could be through an internal inventory procedure or it could be that the measurement equipment is rented from a specific company or an institution like BSRIA that would then also be able to do maintenance work on it between uses. In the later configuration, it means that the hire cost can be charged directly to project and contractors might be more inclined to use the PWSN in this scenario. The main cost related to the use of the PWSN after hire/equipment costs would then be installation and removal that would be kept to a minimum by the absence of wiring.

The total cost of the PO-Cx process would be composed of four components: 1) the cost of the PWSN, than considering the discussion of the previous paragraph is not likely to be the biggest cost, 2) the labour time to install and remove the PWSN, which is minimised by the wireless aspect of the system, 3) the labour time to analysing the data, and 4) the cost of fixing the identified problems. (3) and (4) are likely to have the strongest bearing on the cost of the PO-Cx process, but should be compensated by lower energy bill and maintenance costs.

6.3 Other applications of PWSN in the construction industry

The use of PWSN to troubleshoot building performance presents the advantage to have access to more data in a more integrated way, compared to traditional auditing methods that would consist in time consuming site survey and eventual use of data-loggers. The forensic capability of PWSN could be used for other energy efficiency oriented process. This naturally includes POE and soft landing, which aims are partially aligned with PO-Cx. PWSN can help to gain more information faster and could lead to increasing awareness of the need of design for commissionnablity.

The use of the PWSN has been focused on new buildings, because it should be easier to close the gap when all the design information is still around and part of the original team is still mobilised, but a similar approach could be used for other types of commissioning such as Re-Cx and Retro-Cx. In the context of on-going commissioning, the FM team could have a certain number of nodes they move around regularly to ensure the building performance does not deteriorate. It could also be a tool for energy auditors.

For a slightly different purpose that would require a different set of analytic tools, PWSN could be used to survey existing system before a retrofitting construction project. In the case where part of the original plans have been lost, deploying the PWSN could enable to obtain the characteristics of complex systems. The potential diversity of uses the PWSN leads to reinforce the importance of a standard output format for its data for easy adaptation of the data use.

6.4 Future work

Through this research, several leads for further investigation have been uncovered. A first area of further research would be to understand better the energy performance gap. Despite being commonly acknowledged, little quantifiable data on this matter is available in the literature. As direct correspondence between design and operation cannot be directly established, it would be useful to clarify the causes of discrepancy to better take them into account during the design process. One step in this direction could be to use a PWSN to measure the real value of the assumptions used in energy models such as EPC (e.g.

weather, occupancy ...) to complement metering data and see how the results compare. Doing so on a number of buildings could enable to understand common limitations of the models and lead to improvements of those models. PWSN could also be used to evaluate the impact of energy policies and other incentives to improve energy efficiency.

The commissioning process also requires further research. At the moment, commissioning is based on good practices. It would be useful to have more theory, on the technical and managerial level, on what results in the best outcome of the commissioning process. Commissioning represents an extra investment of money and time at a moment where the owner wishes to get the building occupied as soon as possible. Better evidence of the benefit of initial commissioning and the consequence of bad commissioning is also needed to convince clients and contractors of its importance and help the research area gain more attention. Such evidence could also contribute to shaping policies and regulations resulting in a higher quality of commissioning. Some studies have been done in the US (Mills, 2009), but limited and inconsistent data have been found for other countries.

To be able to fully take advantage of the potential of PWSN the prototype could be developed further. The first step would be implementing and testing the recommendation from the present research as well as integrating light and noise measurements. Finding an ad hoc sensing technique for cooling coil temperature would also be part of this process. Little has been found in the literature regarding the impact of response time and calibration on building monitoring and would be worth investigating. It would also be worth investigating the possibility to make the sensor node harvest energy from their environment to remove the battery constraint and increase deployment flexibility. Another area of interest would be to add behaviour related measurements to the PWSN to better understand the use occupants have of the building.

Another aspect that could be investigated further is the processing of the data. First, it would be interesting to look into the particular challenges associated with real-time data analysis and to development the proper analytic capability for fast diagnostic and use of the big amount of data potentially generated. At the moment most of the analysis would be visual and based on the experience of the commissioning engineer, but semi-automated processes could be implemented to point towards some of the most common faults and help to decision-making for PO-Cx. Implementing an analytical tool box that is as indepen-

dent as possible of the building and that can easily be reconfigured is key to the success of PWSN. Indeed, the need to building specific detailed models is very costly. However, using the measured data to feed and fine-tune pre-existing design models could lead to better building operations. PWSN data could also be used to develop detailed benchmarks by adding precision to occupancy and weather adjustment or by adding a comfort component to existing benchmarks.

The possibility to access virtually any data also raises some questions on data management. In the last decade, the cost of numeric storage has been going down constantly, but with the intensification of the virtual economy and the energy intensity of data centres this might not last. Looking at which data need to be kept, for how long, and what is the energetic impact of this data then becomes critical.

Based on the PWSN implemented for this research, further research to lead to the adoption of PO-Cx in the building industry, would include carrying out PO-Cx on a whole building in partnership with the contractor to evaluate both the energy, comfort and cost benefit of the process, evaluate more precisely the cost of the PO-Cx process and the reception of the concept in the different contractors' teams. This could be the occasion to develop rigorous procedures for PO-Cx. Decision trees based on the measurements of useful key performance indicators (KPI) could lead to the PO-Cx evaluation to be done by less skilled people, since at the end of the present research reasonable experience with building systems would be needed to decide where and when to place sensors. It would also be interesting to see how PO-Cx generalises itself between different types of buildings (office, retail, hospitality, mechanically ventilated domestic buildings...) as well as on naturally ventilated buildings.

With the increasing use of BIM in the building industry, ways to integrate the PWSN data and analysis in BIM could also be explored. Finally, as pointed out in Section 6.3 further research could investigate the benefit of PWSN for other purposes than PO-Cx such as soft landing and POE, re-commissioning, retro-commissioning and energy auditing, or inspection of existing systems before refurbishment.

Chapter 7

Conclusion

7.1 Conclusions

The commissioning process has not had the attention it deserves in building services literature. Indeed, poor commissioning practices contribute to the performance gap between design and operation of green buildings. It has been shown that the constraints on the current commissioning process are too strong to increase its scope to energy and comfort efficiency.

In addition, many problems would only reveal themselves once the building is fully in function and occupied. Thus, systematic implementation of a post-occupancy commissioning (PO-Cx) process needs to be introduced. After handover, the main contractor and the commissioning engineer need to review the operating building for energy and comfort performance in order to close the performance gap.

To understand the source of the performance gap, the main faults responsible for energy waste and discomfort at an early stage of the building life have been identified based on interviews and feedback from experts. Based on this, a set of use case problems to be solved by PO-Cx was identified.

Unfortunately, current monitoring systems are not designed to cope with this type of process, but are only designed for exception monitoring. To offset this, an ad hoc portable wireless sensor network (PWSN) was specified and developed based on the real world constraints of commissioning. The use of wireless technologies can provide additional and

temporary monitoring capabilities tailored for PO-Cx at a low hardware cost.

The practicality of the PWSN has been verified on a case study and lead to conclude that a PO-Cx process assisted by PWSN measurements is functional and can contribute to reducing the performance gap by ensuring proper tuning of the systems and their control and by identifying the sources of discrepancies. In particular, wireless communication is a key feature to enable easy and non-intrusive data collection.

The data have demonstrated that the PWSN provides relevant data for building troubleshooting with little need for calibration. In particular, looking at signal variation of CO_2 can give quantitative information about occupants' presence. Access to flexible temporary data provides forensic capabilities to review new buildings' operation as soon as they get occupied.

The implementation of the PWSN is not straightforward and fundamental requirements for a commercially viable PWSN are identified. This includes the need for the system to be independent from other monitoring systems such as the BMS whose specifications are incompatible with building troubleshooting.

Overall PWSN presents a cost effective opportunity to deliver the post occupancy commissioning process that is necessary to close the gap between as-designed and as operated building energy efficiency. PWSN is a key technology to improve the delivery of new buildings and open the way for a better understanding of the performance gap.

7.2 Summary of contributions

The contributions made in this thesis are listed below:

1. In-depth analysis of the UK commissioning process, its limitations and its potential and how it relates to other commissioning practices in other parts of the world;

2. Proposition of the concept of post-occupancy commissioning to overcome the energy performance gap between as-designed and as-operated buildings and to include energy and comfort as critical to commissioning success;

3. Identification of the type of faults affecting buildings' energy and comfort in their early life cycle as priority targets for PO-Cx;

4. Development and testing of a PWSN for post-occupancy commissioning, and requirements for a commercially viable PWSN;

5. Development of analysis techniques and strategies to troubleshoot buildings with medium-term PWSN deployments, in particular regarding the detection of occupancy;

6. Demonstration of the feasibility and benefits of PWSN for PO-Cx.

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Appendix A

Typical faults - Interviews

A.1 Interview guide

Welcome and introduction

1. Thank you for accepting to take part in this interview.
2. I am looking into commissioning of non-domestic buildings and how extending the process after handover could lead to better building delivery. I want to get a better idea of the problems that need to be solved at the beginning of a building's occupancy.
3. Your answers will remain anonymous and will be used to support my PhD work.
4. Can I record the interview? It is only for me to be able to go back to it if I don't manage to take everything in my notes.

Respondent

1. What is the title of your job?
2. How would you briefly describe what you do?
3. On what aspect of the building do you specialise? Eg: a. Energy b. Boiler c. BMS...
4. How many years of experience do you have in doing this kind of work?
5. What stage of the building life are you most focused on? a. Design b. Construction c. Commissioning d. Maintenance

Typical faults

I am now going to move to questions about the faults you often encounter. I am particularly interested in faults occurring in new buildings.

1. Can you think of the 5 to 10 most common faults you would solve in the first year after handover?
2. Looking back at those faults (If it is not clear from initial description):
   (a) What is the system/sub-system/component affected?
   (b) Why is the fault important?
   (c) Is the fault frequent?
   (d) What are the symptoms that enable its detection? Is it easy to detect?
   (e) How can it be fixed? Is it easy to fix (time/cost)?
   (f) What stage of the construction process originated the fault? i. Design ii. Construction iii. Commissioning iv. Maintenance v. User vi. Control software vii. Control algorithm
3. Rank the mentioned faults by importance
4. Rank the mentioned faults by frequency
5. How could those faults be avoided in future buildings?
6. Are there any other comments you would like to add?

Thank you for your time and telling them how they can find out more about the research and the results of the interviews.

A.2 Initial interview results

This section summarises the interviews that were used as a basis of the open fault document. Both respondents were experienced energy consultants and active members of professional organisations aiming at improving the state of practice.

Respondent 1 was heading the energy consultancy part of the business he just left. It

Table A.1: Summary of respondent 1 answers

Fault	Consequence	Frequency	Detection	Fixing	Origin	Avoiding it
Failure to use AC smart control system.	AC running 24-7.	Not often so extreme, but at variant degrees very frequent.	Energy usage profile does not look as expected.	Technically easy. Require the management team's will.	Briefing/Cx/initial operation and FM authority structure.	Give suitable authority and importance to handover and Cx.
Failure to use smart lighting control system.	All lights on 6am-11pm.	Not often so extreme, but at variant degrees very frequent.	Energy usage profiles do not look as expected.	Technically easy. Require the management team's will.	Briefing/Cx/initial operation and FM authority structure.	Give suitable authority and importance to handover and Cx.
Lighting control system user interface valued engineered out.	System set up conservatively since difficult to make changes.	Relatively rare, but sometime important control elements are removed.	From lighting profiles.	Difficult to fix.	Cost reduction. Value engineering.	Make sure energy management features are not removed.
Fighting/hunting of heating/cooling.	Comfort issues for hunting.	Quite frequent between the two.	Not easy. Hunting: BMS actuation history. Fighting: high energy in mild days.	Recommission the controls.	Energy management system not/no longer properly Cx. Lack of seasonal Cx.	Decent Cx. Management and some form of performance analysis.
Excessive out of hours/night energy use.	High energy and cost.	Universal.	Energy profile analysis or/and night surveys	Review time schedules against use of systems.	Lack of maintenance and control review procedure.	Implement maintenance and control review procedure.
Wrong boilers sequencing (all boilers operating together).	Wasting thermal energy.	Getting rarer.	Boilers are working together in mild conditions.	Reset system to enable proper sequencing.	Poorly set up or manual override (all boilers turned on at pick load).	Seasonal review of controls every 6 months should be in the maintenance program.
Weather compensation controller (boiler systems) overwritten or never set properly.	Wasted energy from pipe heat losses. Difficult to control resulting in comfort problems.	Definitely a common thing	By noticing that the pipes are hot on mild days or looking at slope setting in the BMS.	Re-Cx controls	Feature disabled in a cold day and not put back or not properly commissioned	Cx. Avoid/forbid overwriting. Alarm if it is overwritten.
Fan inverter controls not set up.	High energy and costs.	Nearly universal, at least quite frequent.	Look at percentage of fan power on a mild day.	Re-commission controls.	Control set up conservatively or not commissioned.	Proper fan Cx procedures.
Unused thermal wheel.	High energy and costs.	Fairly rare	Switched off and brand new in 3 yo building.	Re-Cx	Un-Cx or motivation of the FM team.	Maybe an alarm or just Cx.

consisted in compliance certification of energy schemes (e.g. EPBD, EPC, CRC Energy Efficiency Scheme,...) and energy management consultancy (e.g. help to get funding from renewable heat incentive scheme, advising on feasibility studies). He is mostly working on operations and commissioning of existing building even though he also has experience with design. He has experience with all buildings services, but mostly AC since it is the biggest energy consumer. He has about 35 years of experience in the field.

Respondent 2 has 30 years of experience in troubleshooting bad operating energy performance of buildings. He is now also using his experience to educate the industry to avoid typical bad performance problems through teaching and writing.

The approach of respondent 1 was to start from relevant examples he had witnessed to get towards more general comments, when respondent 2 started from general problems categories to then give specific illustrations. Their answers are summarised in Tables A.1 and A.2[1,2] respectively. All the faults listed result in huge loss of money (capital investment and running costs) and energy.

Some faults mentioned are difficult to solve without major refurbishment (e.g. oversizing) or can hardly be solved at all (e.g. overcomplexity). Most of those faults result from poor design decisions. On the other hand, some of those faults could be easily solved by a PO-Cx process (Section A.3). They serve as basis to the open fault document.

A.3 Building Faults Open Document

[1](*) The percentages were given as an indication and don't rest on precise calculation.
[2](**) Not possible to fill with interview answers.

Building Faults Open Document

For my PhD thesis, I am exploring the possibility of using wireless sensor networks to troubleshoot building during the first year of occupancy as an extension of the commissioning process. Based on interviews with practising engineers, I came up with the following list of typical problems that could be solved relatively easily right after initial occupancy and that would prevent excessive energy use and/or discomfort.

I would be interested in your feedback on this list based on your experience. Feel free to:

- Change the order of the faults according to the importance you give them.
- Add faults you think are missing. Remove faults that seem marginal.
- Make any comment you feel appropriate.

	Fault	Consequence	Detection	Fixing	Any comments
1	Simultaneous heating and cooling of AHU or cassette systems	Energy used for nothing	High energy consumption in mild days.	Re-commission the controls	
2	Schedules incorrectly set	10 to 12 hours of energy waste due to big base load at night	Half-hourly energy data	Review time schedule against use of the system	
3	Overcooling	Bad comfort. Excessive energy use	Room temperature is much lower than outside temperature in summer	Higher temperature set points in summer	
4	Hunting of heating and cooling	Comfort and energy	BMS actuation history	Re-commission the controls	
5	Wrong boiler sequencing resulting in more boilers used than needed	Wasted thermal energy	Boilers working together in mild conditions	Reset system to enable proper sequencing	
6	Weather compensation control of boiler heating system not set properly or overwritten	Wasted thermal energy from pipework	Noticing hot pipe in mild day or review BMS settings	Re-commission the controls	
7	Fan inverter control not set up or set up too conservatively	High energy costs	Look at how much percent fans run in a mild day	Re-commission the controls	
8	Failure to set installed smart controls (e.g. AC, lighting)	Systems running 24-7.	Energy profiles don't look as expected	Involving the FM team	
9	Poor commissioning including poor control set points and poor balancing	Comfort not delivered and potential energy waste	Comfort complaint or BMS detection	Re-commissioning	
10	Lack of performance monitoring and feedback	Energy not taken into account in building operation	Talking to building manager	Performance-based FM contracts. Trainings.	

In order to anonymise the answers, please tell me what you do:

- Job title Click here to enter text.
- Area of expertise (eg. BMS, Energy…) Click here to enter text.
- Years of experience ☐ Less than 5 ☐ 5 to 10 ☐more than 10

Thank you for your time. Please send back to Sarah Noye, s.noye11@imperial.ac.uk. I would be happy to let you see the final form of this table if you are interested.

If you want to find out more about my research, here are a few publications:

- Noye, S., Fisk, D. and North, R. 2013. Smart systems commissioning for energy efficient buildings. *CIBSE Technical Symposium* (2013).
- Noye, S., North, R. and Fisk, D. 2014. Development of a Portable Wireless Sensor Network to Enhance Post-Occupancy Commissioning. *Proceedings of the 14th International Conference for Enhanced Building Operations* (Beijing, China, Sep. 2014).

Table A.2: Summary of respondent 2 answers

Fault	System	Consequence	Frequency	Detection	Fixing	Origin	Avoiding it
Simultaneous heating and cooling	AHU Cassette system	Energy used for nothing.	Common. Very common.	Feel duct temperature or BMS. Walking around or BMS.	Re-Cx controls.	Cx problem. Badly specified controls	Better training. Better feedback to FM.
Overheating in deep plan buildings	Air-conditioning and lighting.	24-hour operation of cooling plant.	Common to office buildings	High AC load.	Change IT and occupants' behaviour.	IT on 24-7. Blinds down, lights on.	External shading. FM and IT co-operation.
Big base load at night	AC, pumps, chiller, etc.	10-12 hours of wasted energy.	30%+ of the buildings.	Half-hourly energy data.	Shut systems at night.	Management issues	Use energy data tools.
Poorly designed systems	Wrong sizing. Poor ductwork etc. Control too complex.	System won't work	Control tweak 30%. Need retrofit 10%.	NA	Control: replace a few elements. Other: retrofit.	Design.	Better design.
Poorly commissioned systems	Bad set points or control setting. Poor air/water flows.	High energy use, poor operation, poor comfort.	70% of systems are running poorly commissioned.	Energy consultant asking questions.	Re-Cx.	Cx.	Better Cx.
Poor management of systems	Controls, AHU, boiler, etc.	System runs badly or all the time.	NA**	NA	NA	Occupants and FM don't grasp systems. No use of data feedback.	Better training.
Over-complexity of systems and controls	BMS. Heat pumps and other energy-saving plants.	Poor comfort. Plant unused.	NA	NA	Review the design. Re-Cx can help, but limited impact.	Designer put too much kit. FM unable to run it.	Use natural ventilation when possible.
Oversized plants	Boilers, air handling, fan, pumps, etc.	High energy & maintenance. Poor performance.	75% of building services may be oversized.	NA	Retrofit, but not likely to be done.	Design.	Training designers. Sizing method. CIBSE guidance.
Lack of performance monitoring and feedback	Energy, plants and comfort.	Performance of the building is unknown.	NA	NA	NA	Nobody looks at the data. Not enough sub-metering.	Enforce regulations. Performance-based FM contracts.
Overcooling	Comfort and energy.	AC running colder than needed.	NA	NA	24 °C is acceptable in the summer.	Control strategy. Temp. set points.	NA

Appendix B

Sensors specification

This annex presents the data sheets of the sensors used to the ventilation node. The air velocity sensor did not have a data sheet.

COZIR™

Ultra Low Power Carbon Dioxide Sensor

COZIR is an ultra low power (3.5mW[4]), high performance CO_2 sensor, ideally suited for battery operation and portable instruments. Based on patented IR LED and Detector technology and innovative optical designs, COZIR is the lowest power NDIR sensor available. Optional temperature and humidity sensing are available. COZIR is a third generation product from Gas Sensing Solutions Ltd – leaders in IR LED CO_2 sensing.

With measurement ranges of 0-2000ppm, 0-5000ppm and 0-1% the **COZIR Ambient** Sensor is suitable for applications such as Building Control and Horticulture.

- Ultra-low Power 3.5mW
- Measurement ranges from 0 to 1%
- Low noise measurement (<10ppm)
- 3.3V supply.
- Peak current only 33mA.
- Optional Temperature and Humidity Output



COZIR™ Ambient Sensor

Specifications

General Performance	
Warm-up Time	< 10s. 1.2 secs to first reading.
Operating Conditions	0°C to 50°C (Standard) -25°C to 55°C (Extended range) 0 to 95% RH, non-condensing
Recommended Storage	-30°C to +70°C
CO2 Measurement	
Sensing Method	Non-dispersive infrared (NDIR) absorption Patented Gold-plated optics Patented Solid-state source and detector
Sample Method	Diffusion
Measurement Range	0-2000ppm, 0-5000ppm, 0-1%
Accuracy	±50 ppm +/- 3% of reading[1]
Calibration	Autocalibration[6]
Non Linearity	< 1% of FS
Pressure Dependence	0.13% of reading per mm Hg in normal atmospheric conditions.
Operating Pressure Range	950 mbar to 1050 mbar[2]
Response Time	30 secs to 3 mins (Configurable via filter type and application)[3] Reading refreshed twice per second.[3]

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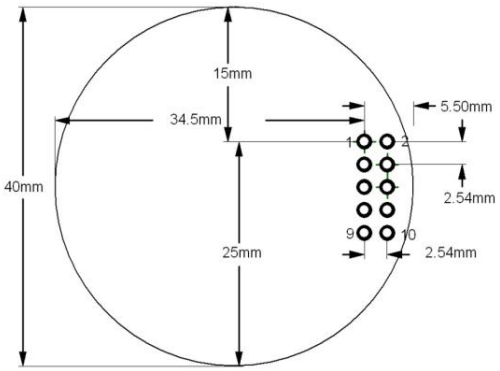
Electrical/ Mechanical	
Power Input	3.25 to 5.5V. (3.3V recommended). Peak Current 33mA[4]. Average Current <1.5mA[4].
Power Consumption	3.5 mW[4]

Dimensions and Wiring Connections

2x5 0.1" header. view from underside (connector side)



Note that the drawing shows details of the PCB inside the sensor casing. The outside dimension of the sensor casing is 43mm.

Function	Pin #	Pin #	Function
GND	**1**	**2**	N/C
+3.3V	**3**	**4**	N/C
Sensor Rx (in)	**5**	**6**	N/C
Sensor Tx (out)	**7**	**8**	Nitrogen Zero
Analogue O/P	**9**	**10**	Fresh Air Zero

Pin 2 should not be connected. Pins 4 and 6 do not require connection and are internally connected to GND.

The zeroing options are for hardware zeroing (both active low). These functions can also be implemented by sending a serial command (recommended).

Typical connections for digital interface are GND, 3.3V, Rx and Tx. Note that the Vh for the serial Tx line will be 3V regardless of the supply voltage.

The analog (voltage) output is available only when specified. Otherwise, N/C.

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Temperature & Humidity Measurement[5] Optional Temperature and Humidity sensor (only available as digital output)	
Sensing Method	Humidity: Capacitive Temperature: Bandgap
Measurement Range	-25 to +55 °C 0 to 95% RH
Resolution	0.08 °C 0.08% RH
Absolute Accuracy[5]	+/- 1 °C 0°C to 55°C. +/- 3% RH 20°C to 55°C. +/- 2 °C over the full temperature range. +/- 5% RH over the full temperature range.
Repeatability	+/- 0.1 °C +/- 0.1 % RH

Note 1: All measurements are at STP unless otherwise stated.
Note 2: External Pressure calibration required.
Note 3: User Configurable Filter Response.
Note 4: Power measurements for standard CO2 sensor with 2 readings per second. Temperature and humidity measurements increase the power consumption.
Note 5: Temperature and Humidity derived from Sensirion SHT21 chip. Please request data sheet for full details.
Note 6: Autocalibration is enabled by default on COZIR-A (after Nov 2012). For correct operation, the sensor must experience fresh air once every week. For details request the application note "COZIR Autocalibration".

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Datasheet SHT21

Humidity and Temperature Sensor

- Fully calibrated
- Digital output, I²C interface
- Low power consumption
- Excellent long term stability
- DFN type package – reflow solderable



Product Summary

SHT21, the new humidity and temperature sensor of Sensirion is about to set new standards in terms of size and intelligence: Embedded in a reflow solderable Dual Flat No leads (DFN) package of 3 x 3mm foot print and 1.1mm height it provides calibrated, linearized signals in digital, true I²C format.

With a completely new designed CMOSens® chip, a reworked capacitive type humidity sensor and an improved band gap temperature sensor the performance has been lifted even beyond the outstanding level of the previous sensor generation (SHT1x and SHT7x). For example, measures have been taken to stabilize the behavior at high humidity levels.

Every sensor is individually calibrated and tested. Lot identification is printed on the sensor and an electronic identification code is stored on the chip – which can be read out by command. Furthermore, the resolution of SHT21 can be changed by command (8/12bit up to 12/14bit for RH/T), low battery can be detected and a checksum helps to improve communication reliability.

With made improvements and the miniaturization of the sensor the performance-to-price ratio has been improved – and eventually, any device should benefit from the cutting edge energy saving operation mode. For testing SHT21 a new evaluation Kit EK-H4 is available.

Dimensions

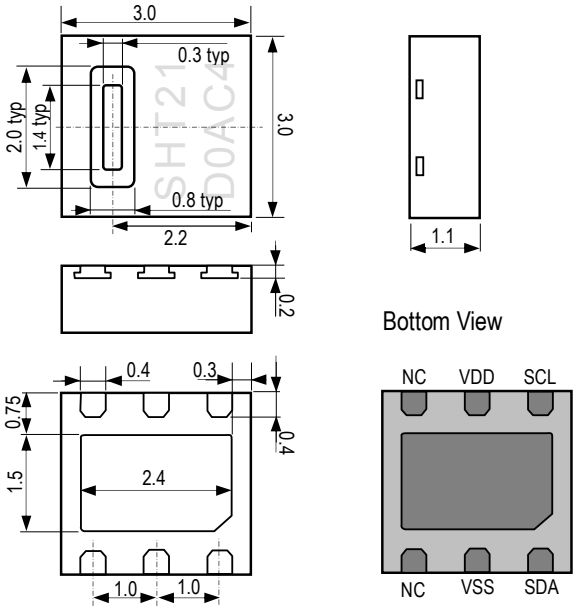


Figure 1: Drawing of SHT21 sensor package, dimensions are given in mm (1mm = 0.039inch), tolerances are ±0.1mm. NC and die pad (center pad) are internally connected to VSS. They may be left floating. VSS = GND, SDA = DATA. Numbering of E/O pads starts at lower right corner (indicated by notch in die pad) and goes clockwise (compare Table 2).

Sensor Chip

SHT21 features a generation 4C CMOSens® chip. Besides the capacitive relative humidity sensor and the band gap temperature sensor, the chip contains an amplifier, A/D converter, OTP memory and a digital processing unit.

Material Contents

While the sensor itself is made of Silicon the sensors' housing consists of a plated Cu lead-frame and green epoxy-based mold compound. The device is fully RoHS and WEEE compliant, e.g. free of Pb, Cd and Hg.

Additional Information and Evaluation Kits

Additional information such as Application Notes is available from the web page www.sensirion.com/sht21. For more information please contact Sensirion via info@sensirion.com.

For SHT21 two Evaluation Kits are available: EK-H4, a four-channel device with Viewer Software, that also serves for data-logging, and a simple EK-H5 directly connecting one sensor via USB port to a computer.

Sensor Performance

Relative Humidity

Parameter	Condition	min	typ	max	Units
Resolution [1]	12 bit		0.04		%RH
	8 bit		0.7		%RH
Accuracy tolerance [2]	typ		±2.0		%RH
	max		see Figure 2		%RH
Repeatability			±0.1		%RH
Hysteresis			±1		%RH
Nonlinearity			<0.1		%RH
Response time [3]	τ 63%		8		s
Operating Range	extended [4]	0		100	%RH
Long Term Drift [5]	normal		< 0.5		%RH/yr

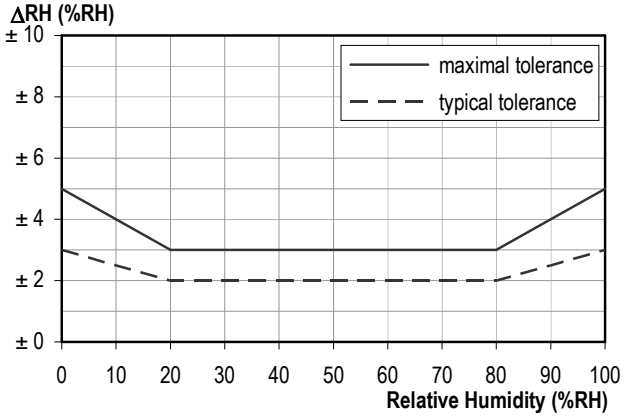


Figure 2 Typical and maximal tolerance at 25°C for relative humidity. For extensive information see Users Guide, Sect. 1.2.

Temperature

Parameter	Condition	min	typ	max	Units
Resolution [1]	14 bit		0.01		°C
	12 bit		0.04		°C
Accuracy tolerance [2]	typ		±0.3		°C
	max		see Figure 3		°C
Repeatability			±0.1		°C
Operating Range	extended [4]	-40		125	°C
		-40		257	°F
Response Time [7]	τ 63%	5		30	s
Long Term Drift			< 0.04		°C/yr

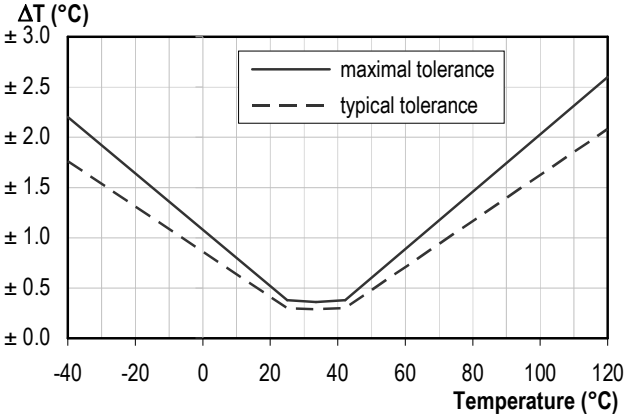


Figure 3 Maximal tolerance for temperature sensor in °C.

Electrical Specification

Parameter	Conditions	min	typ	max	Units
Supply Voltage, VDD		2.1	3.0	3.6	V
Supply Current, IDD [6]	sleep mode	-	0.15	0.4	µA
	measuring	270	300	330	µA
Power Dissipation [6]	sleep mode	-	0.5	1.2	µW
	measuring	0.8	0.9	1.0	mW
	average 8bit	-	3.2	-	µW
Heater	VDD = 3.0 V	5.5mW, ΔT = + 0.5-1.5°C			
Communication	digital 2-wire interface, true I²C protocol				

Table 1 Electrical specification. For absolute maximum values see Section 4.1 of Users Guide.

Packaging Information

Sensor Type	Packaging	Quantity	Order Number
SHT21	Tape & Reel	400	1-100707-01
	Tape & Reel	1500	1-100645-01
	Tape & Reel	5000	1-100694-01

This datasheet is subject to change and may be amended without prior notice.

[1] Default measurement resolution is 14bit (temperature) / 12bit (humidity). It can be reduced to 12/8bit, 11/11bit or 13/10bit by command to user register.

[2] Accuracies are tested at Outgoing Quality Control at 25°C (77°F) and 3.0V. Values exclude hysteresis and long term drift and are applicable to non-condensing environments only.

[3] Time for achieving 63% of a step function, valid at 25°C and 1m/s airflow.

[4] Normal operating range: 0-80%RH, beyond this limit sensor may read a reversible offset with slow kinetics (<3%RH after 200hours at 90%RH). For more details please see Section 1.1 of the Users Guide.

[5] Value may be higher in environments with vaporized solvents, out-gassing tapes, adhesives, packaging materials, etc. For more details please refer to Handling Instructions.

[6] Min and max values of Supply Current and Power Dissipation are based on fixed VDD = 3.0V and T<60°C. The average value is based on one 8bit measurement per second.

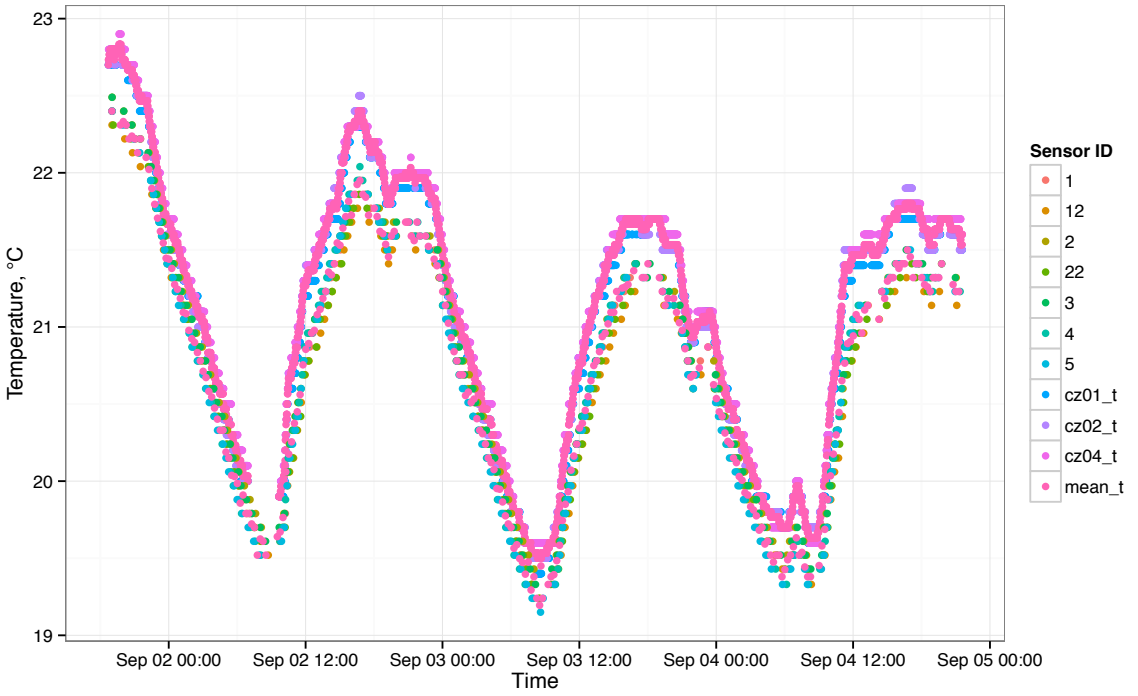
[7] Response time depends on heat conductivity of sensor substrate.

Appendix C

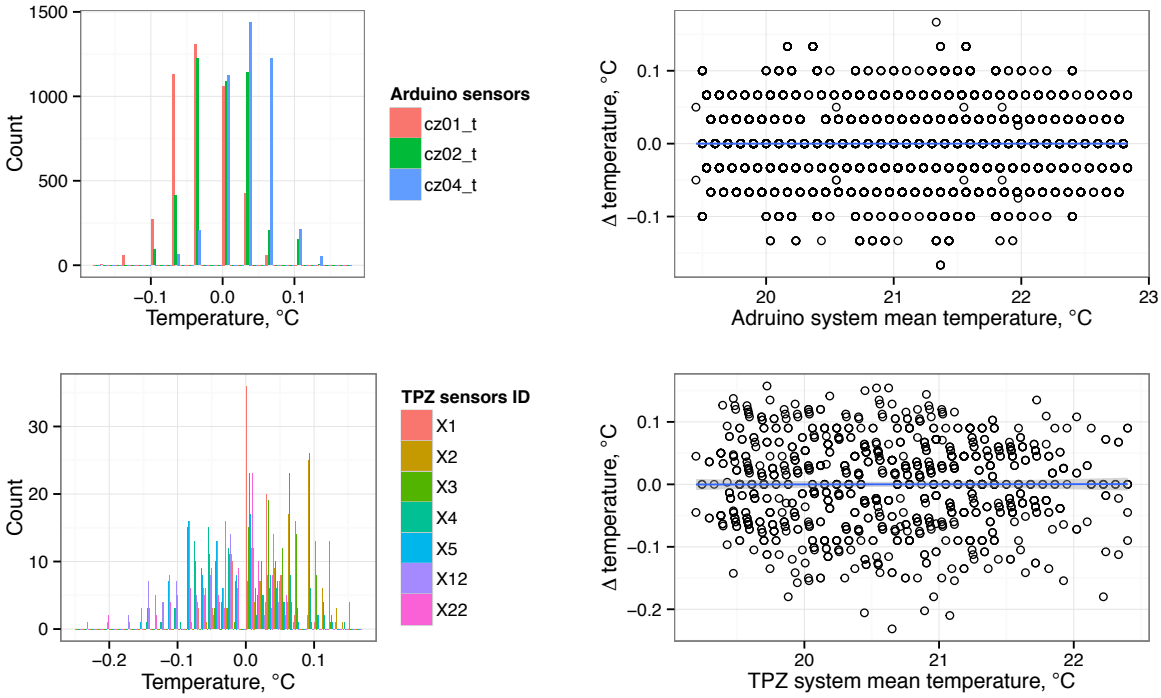
Sensor verification tests

C.1 Back-to-back testing

This section shows the graphs from the back-to-back tests described in Section 4.3.2. Figure C.1, C.2, C.3 show the data for the temperature, relative humidity and CO_2 measurements respectively. For each figure, the sub-figure (a) shows the time series of the test. This figure gives a first idea of the behaviour of the sensor. The upper part of sub-figure (b) shows the repartition of the measurements taken for each Arduino system's sensors on the left and the deviation of the measurements compared to the temperature on the right. The lower part of the figure show the same thing to the TPZ system.

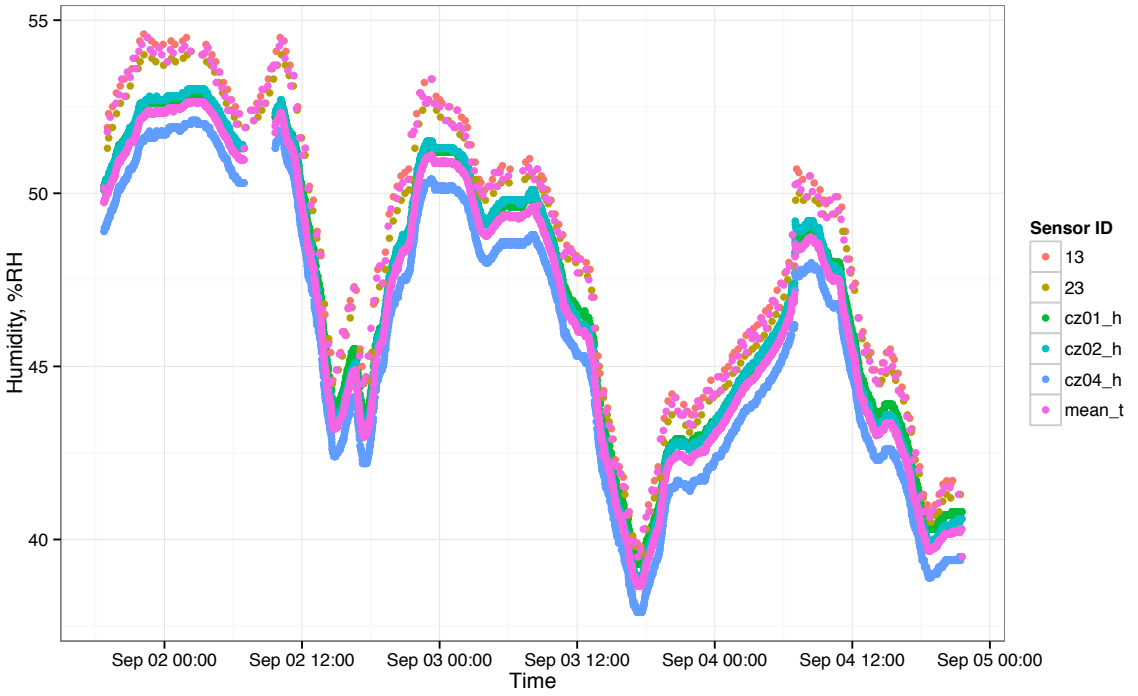


(a) Time series

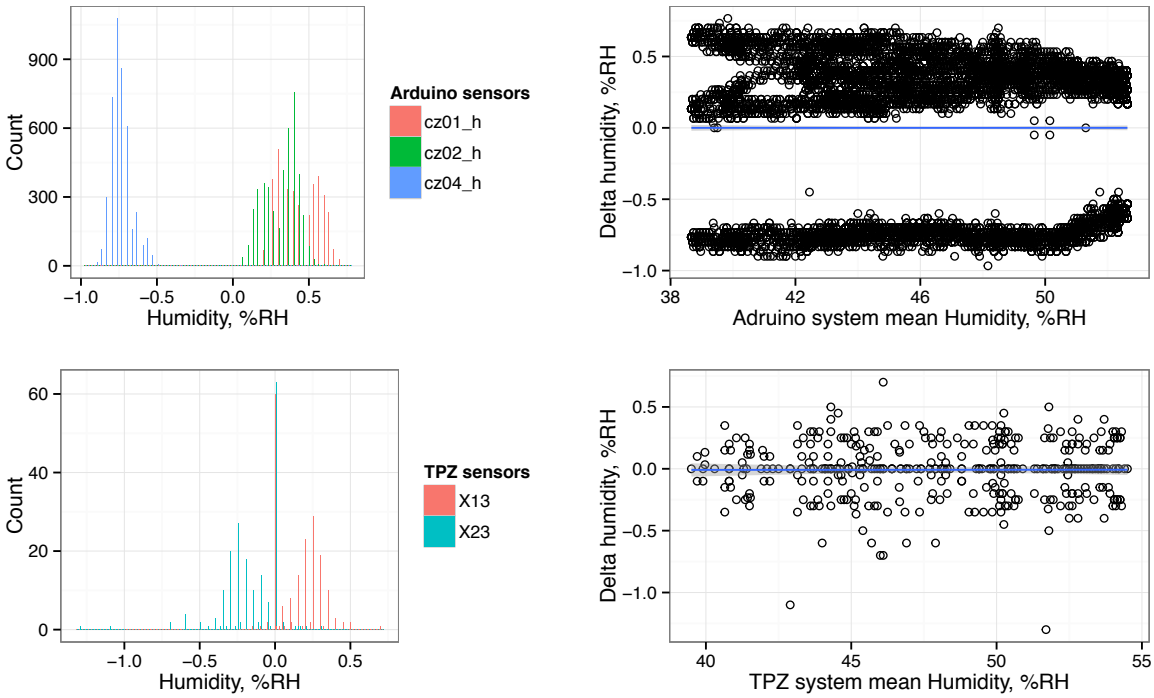


(b) Δ Temperature

Figure C.1: Temperature back-to-back test

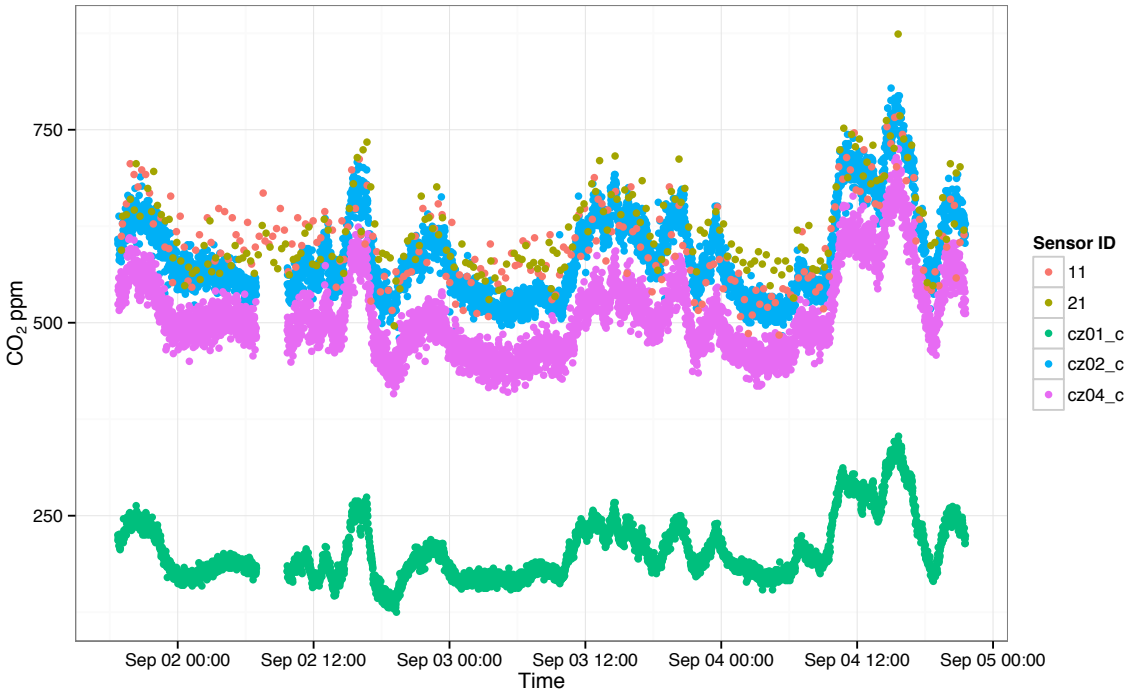


(a) Time series

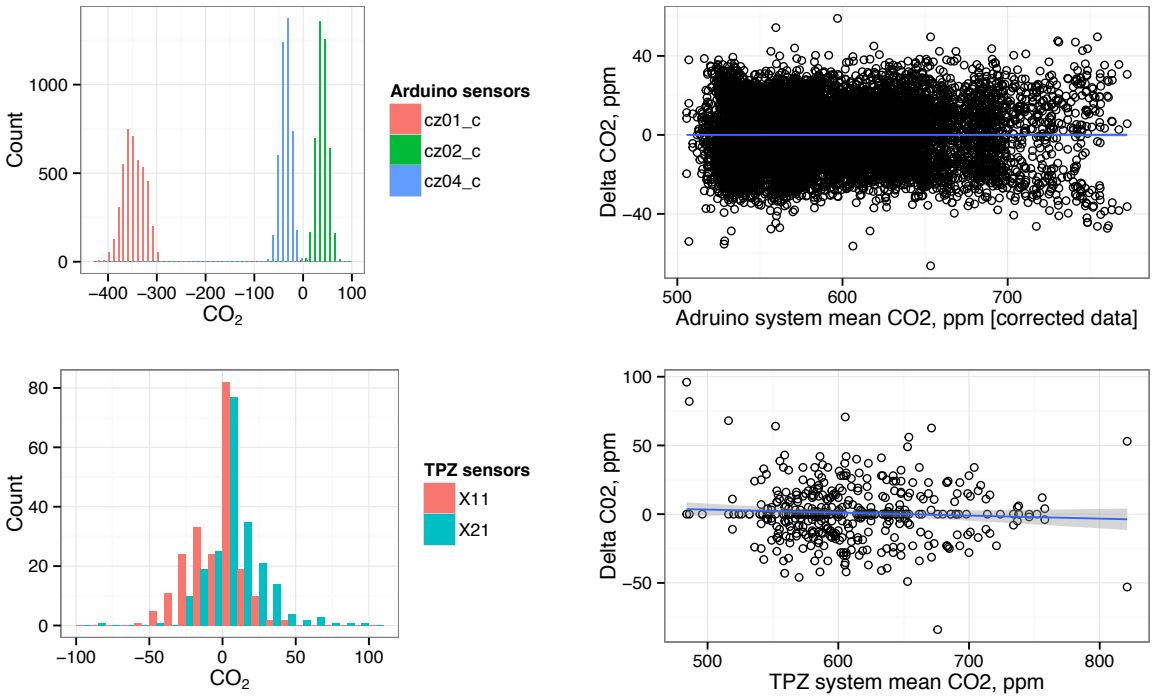


(b) Δ humidity

Figure C.2: Humidity back-to-back test



(a) Time series



(b) Δ CO_2

Figure C.3: CO_2 back-to-back test

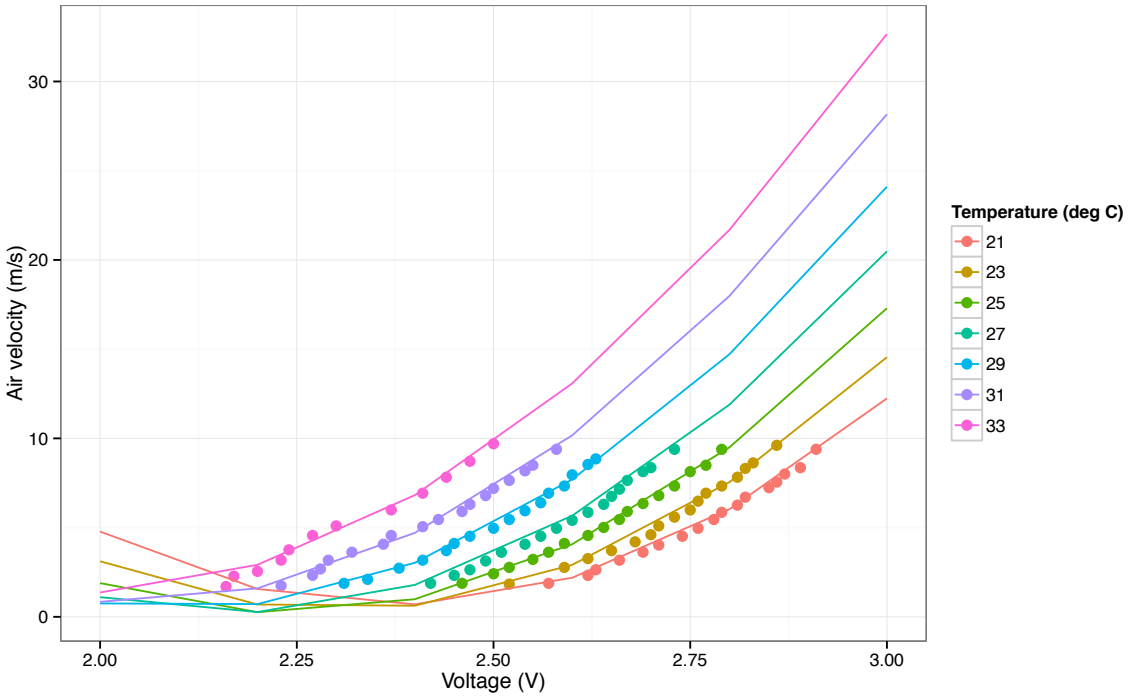


Figure C.4: Air velocity sensor regression

C.2 Air velocity sensor calibration verification

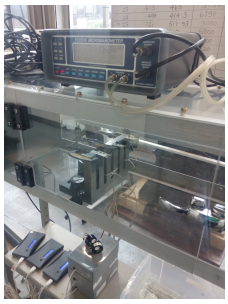
The sensor used for air velocity works on the same principle as a hot wire anemometer. It is an analogue sensor and the manufacturer does not provide a calibration equation to convert the sensor's voltage to air velocity. The output voltage depends on airspeed and temperature.

On request, the sensor manufacturer, Modern Device, provided some calibration data where the sensor output voltages and associated air velocities were recorded at different temperatures (21 to 33 °C). The spreadsheet contained 366 points with airspeeds between 1.5 and 21.5 m/s.

Those data were used to fit a linear model using temperature and airspeed as explanatory variables using the method outlined in (Crawley, 2015). The model worked well, but was less precise at the lower values, which are the ones of interest for air-conditioning fan speeds, so the model was fitted only with data points whose airspeed was inferior to 10 m/s to improve accuracy in lower values. The results of the model are shown on Figure C.4.



(a) Wind tunnel



(b) Air flow sensor set up

Figure C.5: Wind tunnel set up for calibration verification experiment

To validate the model obtained from Modern Device's data, the sensors used for the Arduino nodes were put in a small blow-through wind tunnel (FigureC.5). The air velocity was increased in steps from zero to 5 m/s every 15 min. A macromanometer connected to a pitot tube is used to serve as reference.

Figure C.6 shows the points measured in the wind tunnel test versus the data provided by Modern device. First it can be seen that all values below 2.2 V correspond to no airflow. Second the collected values fit the shape of the curve but there is a bit of dispersion.

The calibration function used in the thesis is based on the model described above and return 0 m/s for any voltage below 2.2V. The resultant function is not extremely accurate even though it gives a good order of magnitude. The reason better accuracy could not be obtained are the following:

- The measurements do not have a high precision, which means that one data point for each temperature/airspeed combination is not enough to properly calibrate the sensor.

- For the PWSN prototype, the sensors were powered from the Arduino board. The internal power of the board can vary. It was measured to correct the voltage reading of the sensor, but the error of this measurement adds up to the error of the sensor.

- Each sensor seems to respond a bit differently. Better accuracy could be obtained by calibrating the sensor individually by that would not fit with the PO-Cx requirements.

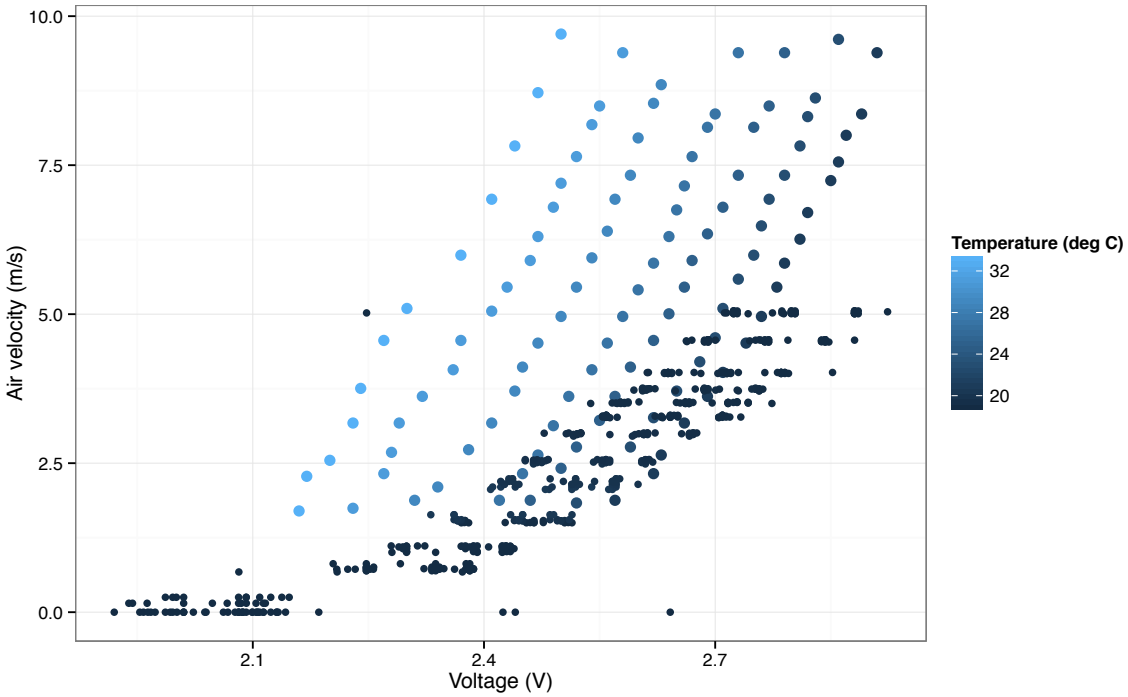


Figure C.6: Wind tunnel data compared to regression function

The air velocity sensors present good characteristics for wireless sensor networks (size, energy consumption), but this comes with a trade-off in accuracy.

Appendix D

Comfort adaptive model

Based on (Nicol and Humphreys, 2007), CIBSE Guide A (Braham et al., 2010) proposes the following calculations to establish the comfortable temperature band as a function of outdoor temperature of the previous days using the running mean outdoor temperature, θ_{rm}. It is a weighted average of past days' outdoor temperature with a higher coefficient for the more recent days as in Equation D.1 where α_{rm} is a coefficient between 0 and 1 and $\theta_e(i)$ is the average outdoor temperature of day i. Each day the influence of past temperature is attenuated.

$$\theta_{rm} = (1 - \alpha_{rm})[\theta_{e(d-1)} + \alpha_{rm}\theta_{e(d-2)} + \alpha_{rm}^2\theta_{e(d-3)} \ldots] \tag{D.1}$$

To be more practical D.1 is simplified as D.2

$$\theta_{rm(n)} = (1 - \alpha_{rm}) \cdot \theta_{e(d-1)} + \alpha_{rm} \cdot \theta_{rm(n-1)} \tag{D.2}$$

For the UK, 0.8 has been found to be an appropriate value for α_{rm} (Braham et al., 2010). The comfort temperature limits for a mechanically ventilated building are then defined by Equation D.3 for the upper limit and Equation D.4 for the lower limits (Braham et al., 2010). Another set of limits exists for free running buildings.

$$\theta_{com} = 0.09 \cdot \theta_{rm} + 24.6 \tag{D.3}$$

$$\theta_{com} = 0.09 \cdot \theta_{rm} + 20.6 \tag{D.4}$$

Appendix E

List of publications

The work presented in this thesis has been the object of several peer-reviewed publications.

- Noye, S., Fisk, D. and North, R. (2013), Smart systems commissioning for energy efficient buildings, in CIBSE Technical Symposium 2013, Liverpool, UK.
- Noye, S., North, R. and Fisk, D. (2014), Development of a portable wireless sensor network to enhance Post-Occupancy commissioning, in Proceedings of the 14th International Conference for Enhanced Building Operations, Energy Systems Laboratory, Beijing, China.
- Loh, C. F., Acha, S., Noye, S. and Shah, N. (2015), Retail building thermal efficiency improvement through an enhanced Re-Commissioning framework, in 'ASHRAE annual conference', Atlanta, GA, USA.
- Noye, S., North, R. and Fisk, D. (2016), Smart systems commissioning for energy efficient buildings, Building Services Engineering Research and Technology, 37(2),194-204.
- Noye, S., Keirstead, J. and Angeloudis, P. (2016), Practical use of CO2 sensors for early life cycle energy and comfort performance, in CIBSE technical Symposium 2016, Edinburgh. [Accepted]
- Lord S. F., Noye S., Ure J. W., Tennant M., Fisk D. J. (submitted), A Review of Building Commissioning Regulation: Efficiency Lost in Efficacy? Building Research & Information. [Submitted]