Development of a Portable Wireless Sensor Network to Enhance Post-Occupancy Commissioning

Sarah Noye[1] Dr. Robin North Prof. David Fisk
PhD candidate Lecturer Professor
Laing O'Rourke Centre for System Engineering and Innovation
Imperial College London
London, UK

ABSTRACT

In many modern buildings, a performance gap between as-designed and as-operated energy consumption is observed. Through the building life cycle, different commissioning strategies can contribute to reducing this gap. However, before considering the implementation of in-use commissioning measures, it is important to ensure the initial realisation of the design performance. With growing energy challenges, commissioning needs to include energy performance, but the commissioning program usually gets compressed as its principal activities occur toward the end of projects. We propose to extend commissioning to a post-occupancy commissioning (PO-Cx) process. The feasibility of PO-Cx relies on the availability of a low-cost set of appropriate data. This paper presents the initial development phase of a pop-up monitoring^{TM} toolkit using a wireless sensor network system to perform commissioning during the initial year of occupation of a building. Initial results for a simple air conditioning case are presented showing the potential of the method.

INTRODUCTION

From initial design to building operation, various discrepancies can make realised energy consumption disappointing (Bordass et al. 2001; Menezes et al. 2012). Through the building life cycle, different commissioning strategies can contribute to remedying those discrepancies and to reducing the gap between as-designed and as-operated energy efficiency. Annex 40 (Visier 2004) of the International Energy Agency's Energy in Buildings and Communities Programme classifies commissioning processes into initial commissioning (I-Cx) for new buildings, retro commissioning (Retro-Cx) and re commissioning (Re-Cx) for existing buildings, and ongoing commissioning (O-Cx) for commissioning measures running continuously in contrast to the previous types that are all one-off processes.

O-Cx is increasingly recognised as an efficient energy saving measure (Djuric & Novakovic 2009; Keuhn & Mardikar 2013). However, before considering the implementation of O-Cx or other in-use commissioning measures, it is important to ensure the good realisation of the initial design performance. Some significant inefficiency could otherwise go unnoticed as most monitoring methods use 'normal operation' data as a baseline to detect performance degradation (Katipamula & Barambley 2005; Teyssedou et al. 2013). This design realisation check should happen during I-Cx in addition to compliance and 'health and safety' checks.

In the context of growing energy challenges, I-Cx needs to be extended to include energy performance. As the principal I-Cx activities occur toward the end of projects, where time is running out and money is running low, the commissioning program tends to get compressed (York 1988). The building is often delivered when 'practical completion' is reached, which means that, while the building is ready for occupation, there is rarely the opportunity to optimise its energy performance, and to account for variation between the as-designed occupancy pattern and as-operated.

To overcome these barriers the initial construction process needs to extend beyond handover into the early occupation of the building. In 1999, the Probe (post-occupancy review of buildings and their engineering) project looked at 16 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). This lead to the introduction of the Soft Landing framework (Way & Bordass 2007). Soft landing is based on

---

[1] Corresponding author: s.noye11@imperial.ac.uk

the Probe methodology and aims to keep members of the design and construction team involved in the first three years of the building's operation to facilitate a smoother transition between stakeholders and provide feedback to improve the building industry delivery of future projects. Probe and soft landing post-occupancy evaluations mainly use information from questionnaires to occupants and ready available data such as utility bills.

On the system operation side, Isakson et al. (2004) proposed to implement systematic reporting using the available building management system (BMS) data to perform seasonal commissioning. They developed a visualisation tool that enabled the identification of a significant number of problems, such as outdoor temperature sensor malfunction, or the ventilation system operating longer than expected at night. This method relies on the BMS system being fully functional. However since BMS requires all the other systems' commissioning to be completed, and is usually commissioned last, it is likely to have some deficiencies. Painter et al. (2012) used a sensor overlay with standalone data loggers to understand the behaviour of a naturally ventilated building and perform seasonal commissioning of its BMS system. The availability of this additional data provided insight on the building operation, but took an extensive time to collect and one of the authors' recommendation was to use wireless sensors to collect the data.

Indeed, the feasibility of post-occupancy performance evaluation relies on the availability of a low-cost set of appropriate data. The rapid evolution of wireless sensor network (WSN) technology is recognized to provide an opportunity for the building industry (Vähä et al. 2013), in particular for energy consumption reduction and system operation (Heller & Orthmann 2014). Among the identified benefits of WSN for building monitoring and control are fast installation, reduced disruption of building activity (Healy 2005; Jeong et al. 2008) and lower cost compared to wired systems (Kinter-Mayer 2005).

In this paper we propose to extend the I-Cx phase by introducing systematic post-occupancy commissioning (PO-Cx) of new and refurbished buildings. We describe a Portable Wireless Sensor Network (PWSN) system developed to perform pop-up monitoring^{TM} to support extended commissioning during the initial year of occupation of a building. The PWSN collects real-time data in addition to the existing BMS to support building fine-tuning and performance evaluation, taking advantage of the flexibility of wireless communication to reconfigure the monitoring system depending on PO-Cx needs. The system links together four categories of data often considered separately: occupant comfort, energy consumption, system operation and operation conditions

The following section describes PO-Cx and the requirements for a data gathering system to perform it on a common ventilation system. Pilot tests for the PWSN and their results are then described, before discussing the potential of PWSN for PO-Cx.

SYSTEM REQUIREMENTS

Post-occupancy commissioning framework

The first year of operation of a building has a strong bearing on its future operation as this is when Facility Management (FM) takes ownership of the building and learns how to operate its systems. If setting and control problems remain from I-Cx, there are risks that the system will be controlled manually to supress occupant complaints. This may result in conditioning loads running at maximum and even potentially working against each other. There is a missed opportunity during the liability period to move from a merely compliant building to a successful building. The main contractor is usually required to come back to repair defects and solve complaints if the client requires it. The resources allocated for that purpose could be turned into a building performance verification process, namely PO-Cx, which would result in reduced operation cost for the client and better referencing for the contractor.

The proposed scope of PO-Cx includes:

- Systematic performance checking
- Seasonal commissioning
- Solving occupant complaints
- In-use building evaluation

Performance checking consists of evaluating the energy efficiency of the building system to deliver indoor comfort. This can be done in several ways depending on the means available. It can range from benchmarking of simple performance metrics combined with data trend analysis to feeding back live data to design models to spot divergences.

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 practice, 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). Longer term monitoring could enable fine-tuning of the different intermediate loads of the building.

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.

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 problem and which ones come from the building usage. This would include comparison of the actual occupancy schedule with design assumptions and evaluate how well the occupants use the building.

Building data

To realise the tasks above mentioned requires extensive data. The different elements of data required to understand building operation performance are summed up in Figure 1. Part of this data would generally be available in new non-commercial buildings, but in a fragmented way.

System data is generally monitored by BMS. Its purpose is to manage operation and maintenance on a daily basis. It can be used to change the system's operation or to detect fault through alert messages. The available data is not used for long-term analysis and it might not be possible to do as the data is often not stored for more than a few weeks.

Energy data is available through utility meters, but while this general overview can give an interesting indication about the overall building operations, it cannot identify where inefficiencies come from. Sub-metering can then provide better temporal and spatial granularity and is required by the British building regulation for some facilities. The quality of the data obtained would typically depend on the design of the building services distribution network (especially gas and electricity).

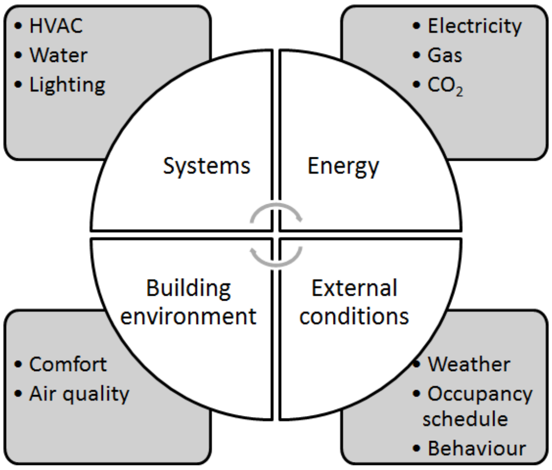

Figure 1. Relevant building data

It is technologically possible to integrate energy and BMS data but the hardware will usually have been obtained from different manufacturer which implies compatibility and integrity issues.

Comfort data would most likely be limited to one BMS temperature reading per heating/cooling zone and external condition to standard normalisation assumptions like yearly degree days for the weather.

Ventilation case

The intention is to apply PO-Cx to building systems in general including HVAC, water distribution and lighting. In the first instance, since HVAC is the biggest share of building energy consumption and air systems are the most challenging to measure, we will focus on ventilation systems. The following section presents the data requirements for PO-Cx of a common ventilation system.

Figure 2 represents the trial system considered in this study. It includes a room and an Air Handling Unit (AHU) with heat recovery. Table 1 summarise the data requirement for PO-Cx of the ventilation system from Figure 2. The typical values are considered in the UK context. Plant measurements are not considered here as we focus on the ventilation part of the system. Additionally BMS data would be more intensive for this part of the system, thus requiring less additional data. The weather data can be monitored on site or they can be imported from a suitable local weather source.

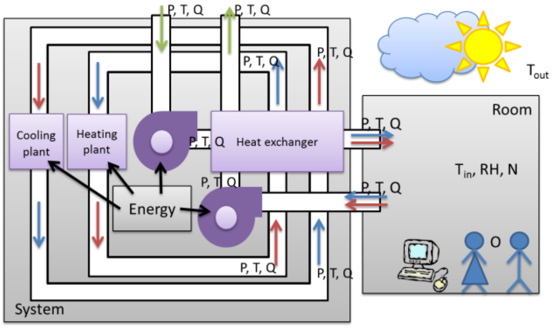

Figure 2. Single ventilation system with AHU

Table 1. Monitored parameters

	Parameters	Typical values
System	Temperature Pressure Flow rate Pipe temp.	-40 – 200°C 0 – 2500 Pa 0 – 50 m^3/s 0 – 80°C
Energy	Electrical power	NA
Building environment	Temperature Humidity Radiant temp. Air changes CO_2 level	10 – 30°C 40 – 70 % 0 – 40°C 0 – 60 /h 0 – 2000 ppm
External conditions	External temp. Occupancy	-12 – 32°C NA

Portable Wireless Sensor Network

A sensor network to perform PO-Cx needs to be low cost to limit the capital cost of the process. As the building will be in use and only a minimum of disruption is acceptable, the network would need to be easily deployable. Since the different PO-Cx tasks require more or less data for a more or less extended period of time, the system need to be scalable and flexible. Wireless sensor networks are a good way to achieve all of these objectives.

The authors have previously introduced the concept of a portable wireless sensor network that can be deployed during the first year of operation of a building to perform PO-Cx (Noye et al. 2013). As shown on Figure 3, this system is composed of a meshed network of wireless sensors that sends measurements to a gateway. The data can then be retrieve on site via a mobile device or off-site via a web server.

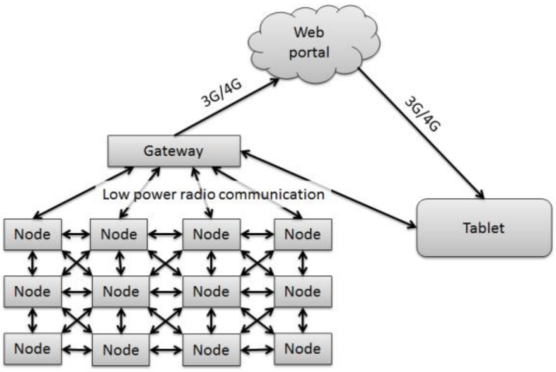

Figure 3. PWSN architecture (Noye et al. 2013)

The different sensing nodes considered to monitor the ventilation system from Figure 2 are summarised in Table 2.

Table 2. Node types description

	Sensors	Parameters	Location
1	Temperature	Temperature	Room
2	CO_2 Temperature Humidity	CO_2 level Temperature Humidity	Room
3	Radiant temp.	Radiant temp.	Room
4	Passive infra-red	Occupancy	Room
5	Temperature	Pipe temp.	System
6	Temperature CO_2 Humidity Air flow	Air temp. In/out CO_2 Air humidity Flow at vent	System
7	Current Voltage	Electric power	System

Nodes 1 to 5 are commercially available wireless solutions from a BMS manufacturer based on the Zigbee protocol. Node 6 and 7 are self-developed using the architecture showing in Figure 4.

The main development constraint is to find sensors that consume little energy as the nodes need to be deployable for several months with little intervention. In the following section some sensor are tested to assess their suitability for the PWSN.

EXPERIMENRAL METHODOLOGY

Sensor evaluation

To select a sensor for a specific application, it is necessary to consider the following factors: range, accuracy, precision, tolerance, linearity, sensitivity resolution sensitivity (Morris & Langari 2012). Experiments have been carried out with two types of air temperature sensors: 1) type-T thermocouples, and 2) capacitive temperature and humidity sensors integrated with a CO_2 sensor. Both sensor systems are low power, which make them suitable for WSN applications. The stated thermocouple theoretical accuracy is 0.5°C and the capacitive sensor's one is between 0.3 and 0.8°C over the temperature range considered.

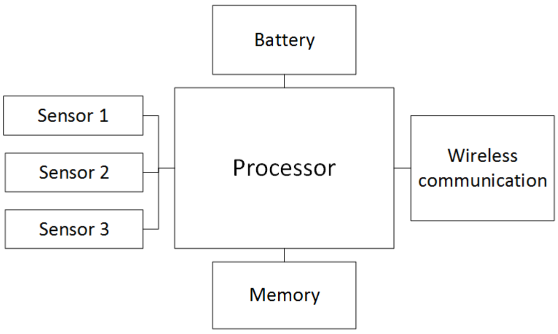

Figure 4. Schematic of self-developed nodes

The sensors have been placed in a SANYO MIR 253 incubator to provide a controlled test environment. The incubator accuracy is stated as +/- 0.2°C with an homogeneity of temperature repartition of +/- 0.5°C. The temperature is varied between 13 and 30°C in steps of 2°C between 19 and 27°C and in steps of 3°C for the rest. The temperature is left to stabilise between each step and then 5 min of data at that temperature is recorded.

Pilot case study

The same sensors are used to monitor temperature, humidity and CO_2 levels in a single office room of 14 m^2 floor area and 34.5 m^3 volume. The office comprises a desk on the window side and a meeting table on the door side (Figure 5). To regulate its thermal comfort, the occupant can open the window, turn on an electric heater or turn on a fan.

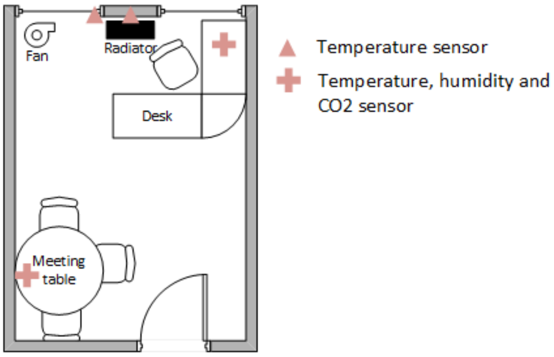

Figure 5. Case study floor plan and sensors location

A CO_2, humidity and temperature sensor has been placed on each table. Thermocouples have been placed on the window frame, on the wall behind the electric heater, and on the desk co-located with the CO_2 and capacitive sensor.

As a first test case, the different thermal control actions are performed in series of 10 minutes with 10 minutes break between each, starting with the window, then the heater, and finally the fan.

This controlled study was then supplemented by measurements taken for two days; one week day and one week-end day. The number of occupants and the thermal control actions have been recorded via a paper log.

RESULTS

Sensor evaluation

Figure 6 shows the median temperatures and the 95% confidence interval where all the measurements for each type of sensor are grouped against the 8 set points of the incubator. The red line represents the y=x equation and the brown line is the linear best fit considering all data points. The coefficient of linearity is close to one with a coefficient of determination $R^2=0.99$, showing the suitability of the selected sensors over the range of interest.

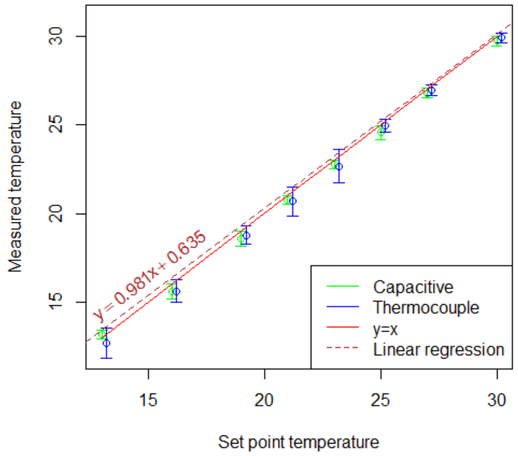

Figure 6. Median and two standard deviations error bars for the two types of sensors

Figure 7 shows the variability of all the tested sensors at 25°C. This particular set point has been chosen as there is less variability in the incubator temperature, probably due to the fact that the temperature elevated above the ambient temperature of the laboratory.

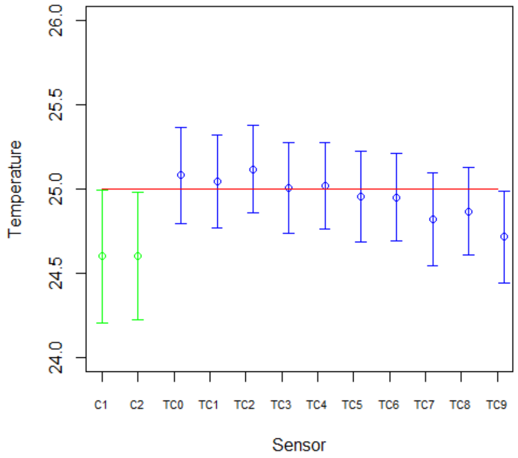

Figure 7. Median and two standard deviations error bars at 25°C

The capacitive sensors (C1 and C2) measure lower temperatures than the thermocouples (TC). This is expected as the temperature and humidity sensor is placed in a plastic enclosure which makes the diffusion of the air to the sensors slower than for the thermocouples which are directly exposed. The 5 min measurements were not long enough for the integrated sensor to assimilate a 2/3°C temperature gradient. Nevertheless, for the longer term monitoring, a good agreement between the capacitive and thermocouple readings was observed, as the temperature variations were slower. The capacitive sensor therefore appears to provide more stable measurements than the thermocouple, but cannot be used to detect fast changes in temperatures.

<u>Pilot case study</u>

Figure 8 shows parts of the data recorded during the activity test. As expected, the window opening provokes a drop of CO_2 and humidity as well as a drop of temperature on the sensor situated on the window frame, but not on the ones further from the window.

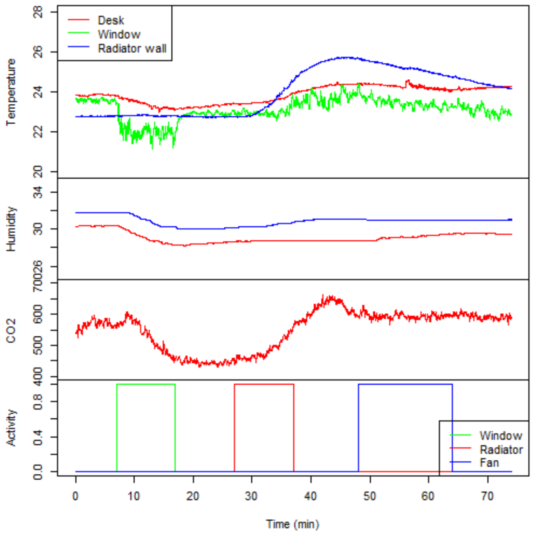

Figure 8. Temperature, humidity and CO_2 variation during ventilation, heating and cooling

The heating period can be detected from the temperature sensor placed on the wall. The delay between the start of the heating period and the increase of temperature detected comes from the warm up period of the electric heater.

The fan causes a slight decrease of CO_2 by mixing the CO_2 produced by the occupant at the desk with the rest of the room.

Figure 9 shows two days of monitoring of a single office. The first 24 hours represents a week day and the following a week-end day. None of the thermal control action has been used for the duration of this test. Only the CO_2 readings from the meeting table have been represented as this sensor gives very similar readings to those measured at the desk.

The CO_2 variations coincide with occupancy and the CO_2 concentration is stable when nobody is in the room. The window was not opened for the duration of this experiment and the temperature profile coincides with the rest of the room.

The temperature on the meeting table side of the room is between 0.5°C and 3.5°C above the desk side temperature with an average of 2.3°C. This difference can be explained by air leakage from the windows.

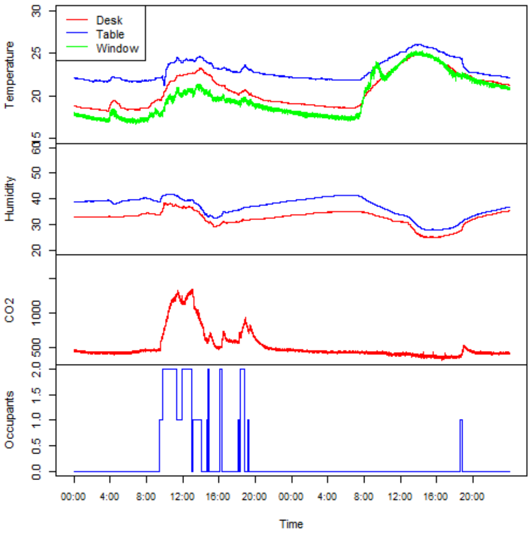

Figure 9. Single office monitoring

DISCUSSION

Experimental results

The thermocouples and CO_2, temperature and humidity sensors proved adequate for use in PWSN to perform PO-Cx. They require low power making them compatible with a long battery life for wireless nodes. They provide measurements close to the reference value over the desired range for building thermal application and are able to detect behavioural and physical events related to thermal comfort.

Also it can be observed that temperature profiles are significantly different around the room. The location of the temperature control sensor can therefore have a great influence on achieved thermal comfort and the ability of the sensor system to accurately capture to occupant experience. Using multiple temperature measurements to commission the BMS location can potentially contribute to improved occupant comfort.

Potential of PWSN for PO-Cx

Energy performance realisation is a growing challenge for the building industry. For financial reasons, clients want to get their buildings occupied as soon as possible, resulting in no time being allocated for overall building performance test during the construction period. It thus needs to be conducted after handover, when the building is already occupied. This presents additional challenges as minimum disruption of building normal operation would be required.

Performance evaluation and other PO-Cx tasks require additional data compared to normal building operation. WSN technologies offer the opportunity to collect data at a relatively low cost and with limited interference to the building activities. Current WSN technology can be found at around \$150 per node[2] and the prices are expected to drop in the future. Additionally the capital cost of the pop-up monitoring^{TM} system would be spread by the intention to reuse it on several projects. The main cost after hire costs, would then be installation and removal which would be kept to a minimum by the absence of wiring. The contractor would then only need to go on site if a problem needed special attention as the data would be available off-site.

The use of PWSN for PO-Cx also presents the advantage of keeping part of the design and construction team involved with the building. This can limit the loss of knowledge that normally happens at handover by allowing a transition period. In that perspective, PO-Cx can be considered as a complement to soft landing.

Performing PO-Cx at the beginning of the building life cycle is intended to improve the building energy efficiency at an early life cycle stage, but it also has the potential to improve results from other energy saving measures later on. Fault detection and diagnostic (FDD) and O-Cx would benefit from PO-Cx by getting a better starting point from which to detect performance degradation.

Finally, a PWSN toolkit could have other applications beyond PO-Cx. It could be used for other one-off commissioning process such as Re-Cx and Retro-Cx. In particular, in the case of a

---

[2] Around £90

refurbishment, the PWSN could enable understanding of the existing systems when documentation has been lost.

Practical challenges for PO-Cx implementation

This section discusses the practical challenges that need to be addressed for PO-Cx to be adopted by the building industry. The first challenge concerns how to incentivise PO-Cx. In the current product-based building services industry, the additional initial investment cost associated with PO-Cx is likely to be a barrier on the client side, even though it would result on long term saving through reduced energy bills. To facilitate PO-Cx adoption and energy saving measures in general, the building services industry would need to move from a product-based model to a service based industry. This change is likely to be driven by energy price increases. The emergence of this kind of delivery model can be seen in British public–private partnership (PPP) and private finance initiative (PFI) projects (Action 2002). PPP and PFI contracts incorporate substantial financial penalties if energy targets are not met, leading to the necessity of new tool such as a pop-up monitoring^{TM}.

Additionally recent evolution of building regulation, energy policy and certification schemes should lead to increasing demand for energy saving measures, but in practice their application is based on design intent. There is also a lack of means to control operating compliance of new buildings (Pan & Garmston 2012). Regulations and policies need to evolve to give a bigger weight operation in there scope.

Another challenge lies in the contractual arrangement around PO-Cx. First PWSN can provide a relatively low cost monitoring system as it can be redeployed from one building to the other. However the current practice is to bill measurement equipment on projects, and part of this equipment is generally lost when the projects ends. Secondly, once problems have been detected, means need to be allocated to solve them and provision need to be made to for this in advance or the contractor might choose to ignore problems that seem costly to fix.

Finally there is a challenge associated with data analysis. This process represents a significant cost of any monitoring measure. The need to build detailed models increases significantly the cost of PO-Cx. Thus it is important to develop analysis methods that can be relatively independent from the building and re-configurable to the demands of different projects. Another solution is to reuse models created at design stage.

CONCLUSION

The operation of new buildings is disappointing when compared to their brief and design. The liability period following handover could be used to improve the life cycle performance of buildings. Better initial performance could be set by performing post-occupancy commissioning (PO-Cx).

Technological advances have made access to more data for a lower cost possible using wireless sensor networks (WSN) and this should be used to have a better understanding of where inefficiencies come from regarding energy consumption to deliver comfort.

We have presented the requirements for a pop-up monitoring^{TM} toolkit to enable the realisation of PO-Cx. Initial sensor tests have been carried out showing the potential of the method. In the future, additional sensing parameters will be added to the study and challenges associated with wireless communication evaluated. The integration of such data with system and process models is also required.

ACKNOWLEDGMENTS

This research is supported through a Laing O’Rouke Studentship and the activities of the Laing O’Rourke Centre for Systems Engineering and Innovation at Imperial College London. The authors gratefully acknowledge the support of Laing O’Rourke and Crown House Technologies. The authors would also like to thank Dr Geoffrey Fowler for providing access to his laboratory facilities.

REFERENCES

Action, E., 2002. Energy efficiency in PPP/PFI contracts for further and higher education.

Bordass, B. et al., 2001. Assessing building performance in use 3: energy performance of the Probe buildings. *Building Research & Information*.

Cohen, R. et al., 2001. Assessing building performance in use 1: the Probe process. *Building Research & Information*, 29, pp.85–102.

Djuric, N. & Novakovic, V., 2009. Review of possibilities and necessities for building lifetime commissioning. *Renewable and Sustainable Energy Reviews*, 13(2), pp.486–492.

Healy, W.M., 2005. Lessons learned in wireless monitoring. *ASHRAE Journal*, 47, pp.54–60.

Heller, A. & Orthmann, C., 2014. Wireless technologies for the construction sector—Requirements, energy and cost efficiencies. *Energy and Buildings*, 73, pp.212–216.

Isakson, P., Wetterström, P. & Carling, P., 2004. BEMS-assisted seasonal functional performance testing in the initial commissioning of Kista Entré and Katsan. In *Proceedings of the Fourth International Conference for Enhanced Building Operations*.

Jeong, J.-W. et al., 2008. Feasibility of wireless measurements for semi-empirical multizone air flow model tuning. *Building and Environment*, 43, pp.1507–1520.

Katipamula, S. & Barambley, M.R., 2005. Methods for Fault Detection, Diagnostics, and Prognostics for Building Systems - A Review, Part I. *HVAC&R Research*, 11, pp.1–25.

Keuhn, P.L. & Mardikar, Y.M., 2013. Energy Conservation through Ongoing Commissioning. *Energy Engineering*, 110, pp.20–41.

Kinter-Mayer, M., 2005. Opportunities of Wireless Sensors and Controls for Building Operation. *Energy Engineering*, 102(5), pp.27–48.

Menezes, A.C. et al., 2012. Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap. *Applied Energy*, 97, pp.355–364.

Morris, A.S. & Langari, R., 2012. *Measurement and Instrumentation - Theory and Application* A. press, ed., Elviser.

Noye, S., Fisk, D. & North, R., 2013. Smart systems commissioning for energy efficient buildings. In *CIBSE Technical Symposium*.

Painter, B., Brown, N. & Cook, M.J., 2012. Practical application of a sensor overlay system for building monitoring and commissioning. *Energy and Buildings*, 48, pp.29–39.

Pan, W. & Garmston, H., 2012. Compliance with building energy regulations for new-build dwellings. *Energy*, 48, pp.11–22.

Sands, J., 2013. *BSRIA Guide: Seasonal commissioning* BSRIA, ed., The Lavenham Press.

Teyssedou, G., Zmeureanu, R. & Giguere, D., 2013. Benchmarking model for the ongoing commissioning of the refrigeration system of an indoor ice rink. *Automation in Construction*, 35, pp.229–237.

Vähä, P. et al., 2013. Extending automation of building construction — Survey on potential sensor technologies and robotic applications. *Automation in Construction*, 36, pp.168–178.

Visier, J.C., 2004. *Annex 40: Commissioning tools for improved energy performance*, International Energy Agency.

Way, M. & Bordass, B., 2007. Making feedback and post-occupancy evaluation routine 2: Soft laning - involving design and building teams in improving performance. *Building Research & Information*, 33, pp.353–360.

York, D., 1988. *Building Commissioning: Survey of Attitudes and Practices in Wisconsin*, Energy Centre of Wisconsin.