Wireless sensing for the built environment: enabling innovation towards greener, healthier homes

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Abstract

Worldwide carbon reduction targets for the built environment are staggeringly ambitious. If they are to be achieved, orders of magnitude performance increases are required from HVAC systems, construction techniques and insulating materials. Given the limited understanding of many of the newer materials and techniques, objective measurement is fundamental to meeting these targets in time. This paper presents the case for a holistic approach to measurement within the built environment and shows how Wireless Sensor Networks (WSNs) are a prime candidate technology to support such an approach.

WSNs are readily *enablers of understanding* in domains characterised by spatio-temporal, multivariate complexity. Simple, portable and non-intrusive WSN systems, deployed for weeks or years, are powerful tools for empirical environmental and energy performance evaluation of occupied dwellings. Coupled with structured deployment processes and novel empirical evaluation metrics, WSNs enable, for old stock, focused actions towards reduced energy consumption, improved internal environment, lower maintenance costs and maintaining the cost viability of the building asset. They are equally valuable in the context of new builds, for generic and apportioned energy consumption evaluations against the delivered environmental quality and design expectations.

Keywords: WSN, Built Environment, Energy Performance, Occupant Comfort

1 Introduction

The industry's perception of wireless, embedded networked sensing systems (WSNs) as *reliable, available, usable* and *affordable* instruments is changing. To many, they are no longer the next wave in engineering and computing, but have become today's reality in assessment: be that of people, their well-being and actions, environments and their impact, machines and their performance. When widely adopted, this mighty technology, supported by miniature sensors, cheap computing power and recent advances in wireless communications, is likely to induce a new information revolution.

It is apparent that WSNs could have a significant role to play in the built environment. Understanding, assessing and controlling buildings may be the killer application for networked wireless sensing, which will enable the transit of this technology from research to wide adoption in a series of related industries. Applications of WSNs within the built environment industry have strong business cases (albeit made at present by the WSN community) derived from:

1. A relatively mature base of WSN off the shelf hardware which meets most of the requirements for measurement in the built environment.

2. Excellent economies of scale, commensurate with the size of the industry and thus promising a drastic reduction in commercial WSN systems costs.

3. Strong political drive and ambitious decarbonisation agendas which would clearly benefit from measurement and quantification: current carbon reduction targets are daunting for many national governments. In the UK for example, 80% reduction is envisaged before 2050 and an aspiration has been set for all new developments to be zero carbon by 2016 [4]. Achieving such targets with bounded investment implies the need for continuous insight into actual performance of new builds, that of refurbishments and also evidence-based evaluations of stock in general.

Within this context, the paper reports on the results obtained and insight gained so far by the authors during their ongoing collaboration towards:

- Demonstrating the usefulness and appropriateness of WSNs as tools for the built environment.

- Examining some of the conceptual and practical issues to be overcome by the computer science and modern built environment communities towards exploiting fully the power of wireless sensing systems and the data in which they collect.

- Establishing design and deployment guidelines for empirical buildings evaluation.

The paper is structured as follows: Section 2 discusses the need for sensing in the built environment, within the current political climate; Section 3 describes and evaluates the authors experience with WSN based assessment of residential buildings. Section 4 highlights some open research and practical issues uncovered during field deployments that will gain importance in the transition of WSN based systems from the research to the commercial domain. Finally, Section 5 concludes the paper.

2 Why sense the built environment?

The building and construction industry is practise driven and consequently less prone to reflection, dissemination of good practise and post-factum evaluation of its final products or their components. Evaluation of a building's performance, post-construction, is not commonly part of a building's construction and commissioning cycle. The inherent assumption is that a building, as constructed (and, following on, as occupied) will perform according to the design specification.

Although the number of studies carried out worldwide to empirically assess the performance of buildings is dwarfed by the number of buildings constructed, the findings overwhelmingly show that, when evaluated "as occupied" a building's carbon footprint: i) is heavily dependent on the occupants (with up to 200% energy consumption variations in identical residential buildings [5]) and ii) rarely aligns with design expectations of stock in general (usually performing worse) [9].

With reference to the residential sector in particular, the industry's over reliance on predictions from design models and estimations (based on nominal rather than actual performance of materials) thus: i) precludes the accurate quantification of a building stock's carbon footprint; ii) precludes evidence-based analysis of new builds and refurbishments value for money and the assessment of various technologies viability .

The sheer cost, scale and scope of the current decarbonisation exercise, its timeliness (one building needs to be refurbished every minute to meet UK carbon emission targets [7]) imposes rates of change far greater than those customary to the construction industry (renowned for its conservative attitudes [1]). This makes necessary rapid and accurate *feedback* on the real performance of new housing developments and refurbishments. A robust, evidence-based learning process, enabled by post construction and post occupancy monitoring, will: i) allow informed design and refurbishment choices which maximise the cost and performance benefits of using novel low carbon technologies, and ii) set realistic performance expectations from the use of both conventional and innovative building techniques, technologies and materials.

If deployed at large scale, Empirical Environmental and Energy Performance Evaluations (EEEPE) will: i) considerably enhance the industry's know-how on effective building decarbonisation; ii) enable energy benchmarking of occupied buildings and profiling the carbon footprint of real rather than modelled buildings; iii) identify mismatches between design expectations, building performance and occupant perceptions, thus drive design refinements and support informed techniques and material choices; iv) enable the apportionment of fabric, HVAC systems and occupant behaviour onto a building's energy profile, thus drive appropriate measures for energy reduction; v) support evidence based strategies for investment in both new builds and refurbishments.

The need for EEEPE is beginning to be recognised by various regulatory bodies (see guidance from the Homes and Communities Agency, UK [4]), although standards for this method of evaluation are yet to emerge.

Effective EEEPE is realised through continuous energy and environmental monitoring of a building over a set period of time (variable depending on the goals of the EEEPE) and inference of information from the data gathered, through data mining and / or statistical approaches.

Advances in wireless sensor networks (WSNs) allow for EEEPE to be deployed at relatively low cost per building, with minimal specialist infrastructure costs and minimal disruption to occupants. WSN systems can be designed to deliver a large variety of data types, but most commonly, EEEPE is concerned with accurate measurement of temperature, humidity, light, air quality, occupancy, energy and water consumption. This set of measurands could evaluate a building's performance in a holistic manner.

However, for EEEPE to become a widespread tool, a clear *definition of informational outputs* to be derived from the data is called for. At a practical level, to be successful beyond pilots, the need for and value added by EEEPE will need to be fully understood by the built environment practitioners.

3 Empirical evaluation of residential buildings—Experiences

Over the past two years, the authors team here (with 3 computer sciences researchers specialising in WSN design and one built environment practitioner experienced in asset management) have worked towards designing bespoke end-to-end, WSN based informational systems for EEEPE evaluation of residential buildings. They further deployed the instrumentation in 15 homes owned by Orbit Heart of England (OHE) Housing Association[1], gathering data equivalent to approximately 800 monitoring days. From the 15 deployments (performed with 4 identical sets of instrumentation), i) the first 3 (win-

[1]OHE own around 14000 properties in the Midlands, England, which are provided as social housing.

Figure 1: ArchRock Node(left) with integrated CO2 Module(right)

ter of 2008/2009) were *pilots*, aiming to evaluate the performance of the instruments against their technical specification (wireless network connectivity, yield, robustness, data quality and battery life); ii) the following 5 (winter of 2009/2010 and summer 2010) were used to *iteratively refine and validate* the systems and the deployment processes, define holistic and occupant driven metrics, and uncover operational issues (leading to a number of deployment policies) and iii) the most recent 7 deployments (winter 2010/2011) were used to validate the informational approaches developed and their ability to generate knowledge when used by built environment practitioners; these deployments were well aligned with OHE's operations.

Two WSN system usage scenarios were tested: i) routine winter performance evaluation and energy consumption / home "health" benchmarking and ii) investigation into causes for excessive energy consumption in some dwellings (following tenant reports). Both scenarios were supported by 2 weeks per home deployments, and the success of the WSN based EEEPE evaluation approach was measured based on:

1. The ability of the *instrument* to gather data of sufficient quality.
2. The ability of the *metrics* and associated *visualisations* to convey knowledge to building specialists.
3. The *match* between the knowledge inferred from the EEEPE and the surveyor's *subjective assessment* .

The instrumentation is built around the ArchRock system [8] and comprises of a number of sensing nodes, routers and a server. All nodes (based upon the TelosB platform [6]) sense temperature and humidity (battery powered) at 5 minute interval. Some nodes have an integrated CO2 gas sensing module (ELT B-530) to measure the air quality (5 minute sampling) and have been either battery powered (early work) or mains powered (later prototypes) (Figure 1). The nodes form a 6LoWPAN network based upon the IEEE 802.15.4 standard. Electricity usage is recorded via a meter-fitted Current Cost device [2] which has been interfaced to the server and records the power consumption every 6 seconds.

A typical deployment would include air quality nodes in the bedrooms and living rooms and a standard ArchRock

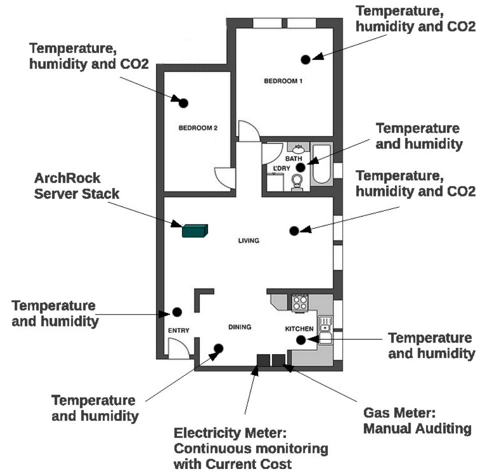

Figure 2: Typical Deployment

node in each of the other rooms / defined spaces (see Figure 2 for a typical apartment deployment). The largest deployment was 30 nodes per dwelling and the smallest was 10. An outdoor node was also deployed every time.

Several house and family archetypes were monitored, which had a variety of heating systems (air source, gas central heating, electric storage heaters and ground source heating).

3.1 Results and Evaluation

From an engineering and computer science viewpoint, the deployments were considered a success given:

- High data yield and excellent radio coverage—Yield averaged 95.1% over the whole set of deployments, with a minimum of 81.1% (due to a faulty router causing a system failure) and a maximum of 99.9% (achieved in 4 homes). 11 deployments were executed with a server per home, thus distances between neighbouring nodes were relatively short (10m or less). In 4 deployments, however, we successfully connected 2 neighbouring dwellings to a single server, maintaining a yield of 99%. This shows that instrumentation costs for large monitoring exercises (whole streets or geographically compact new built sites) can be contained by using few servers and dense networks of nodes.
- Satisfactory robustness of the instrumentation—The hardware (4 identical sets) survived with minor failures due to children playing with the nodes and breaking the connected CO_2 module and water damage on the outdoor nodes.
- Acceptable battery life—The nodes containing CO2 sensors had a battery life of approximately 10 days, whilst the rest lasted on average for 9-10 months. To eliminate the need for battery changes within

deployments, the CO2 nodes were adapted for mains power.

- High data quality—Few nodes delivered erroneous data, and this was always due to low battery levels; a range based filter was used during the pre-processing stage to clean the data.

- Low number of home interventions needed for maintaining the instrumentation—Only 3 deployments needed to be reconfigured.

Despite the excellent performance, the instrumentation, as deployed, had two drawbacks: i) high cost; ii) short shelf-life, as the Arch Rock components became obsolete after the first year of use, thus limiting the value of the instrumentation considerably.

3.1.1 Metrics and Visualisation

As opposed to many other WSN applications reported in the literature, in this work, designing and successfully deploying well performing data acquisitions systems is only a first step towards effective EEEPE. The following research question emerged once pilot deployments were performed and data was attempted to be analysed jointly (and independently) by our computer science and building specialists team:

What knowledge generation strategies are needed to bring meaning to environmental and energy data? In other words, a) what are the *metrics* and *processes* to be applied to monitoring data sets in order to bridge the data to information gap?; b) what *knowledge* is desired to be derived from the information?; and c) how should the information be *represented* to end-users to enable *decision-making*?

Given the wealth of data generated by monitoring systems and the relatively low informational content per data byte, *empirical metrics* are needed to convert *data* to *information*; the metrics should i) be easy to understand by building practitioners, ii) be weather and energy source independent, iii) be accompanied by easy to interpret visualisations, iv) integrate well with common surveying practise as well as observational and simulation-based assessment, v) function at several levels, from holistic to occupant focused assessments and from global evaluation to itemised apportioning of resources consumption; vi) enable knowledge generation by the user of the information (designers, contractors, asset managers, etc).

Based on their deployments experience, the authors propose that:

- *Energy/floor area/degree day* is an appropriate *holistic metric,* which allows for benchmarking as well as absolute evaluations. When coupled with an environmental quality metric (such as *Expected Comfort* or *Exposure* metrics [3]), and when applied to a large number of homes, this metric allows for: trends to be inferred; generic conclusions to be drawn regarding relative performance of specific types of heating systems and building archetypes; quantification of refurbishment effects; and qualification of occupant choices and behaviour impact on the homes' energy consumption. Examples of application for this metric are shown in Figure 3, for 14 homes. Whilst the number of deployments is yet too low to allow all the assessments above, note that for example, both properties featuring storage heaters have higher consumption than average consumers and exhibit low comfort levels. Home B is displaying high levels of comfort yet there is an extortionate amount of energy being used. It was found that the occupants left the heating on at all times and had the thermostat set high.

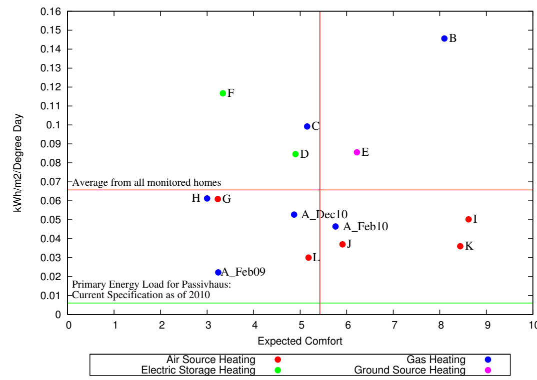

Figure 3: Comparing homes using energy and comfort

- *Holistic profiling* of a home should contain statistical information on Temperature, Humidity, Air Quality, Comfort and Energy; a "healthy, efficient home" template can be created as a baseline for evaluations, or, for new zero carbon buildings, the "passive house" design specification template can be used. Examples of holistic profiling are given in Figure 4. This easy to interpret visualisation not only allows for the "health" of a home to be assessed but also highlights the home's departure from ideal behaviour and points out its causes. Home B is very warm but is not perfectly comfortable. At the same time, it consumes considerable energy. House A_Dec10 on the other hand is in much better health, average temperature/humidity is as to be expected, carbon dioxide levels are low. The final spidergram shows expected values for a Passivehaus home. The home is comfortable in terms of temperature, humidity and air quality and the home is using a very low amount of energy.

The metrics and visualizations above have been derived iteratively through consultation with surveyors. In

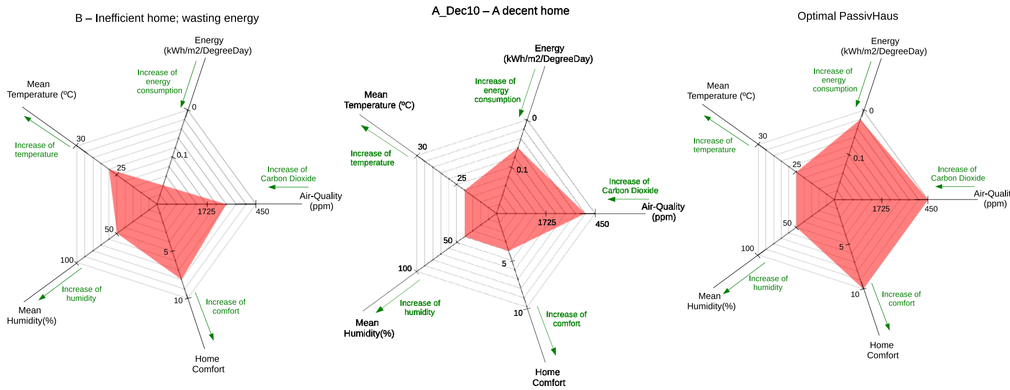

Figure 4: Spidergrams

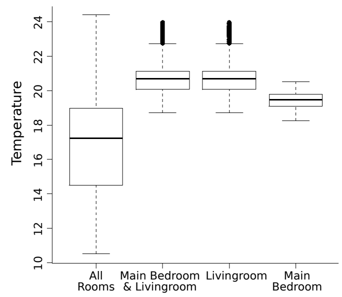

Figure 5: Multiple sensing point vs reduced sensing

their current form, they were deemed as fit for purpose. A further evaluation of the correctness of the information delivered by the metrics and their robustness was carried out. The study showed that:

- *Deployment density* can affect the information accuracy. Analysis of 6 deployments highlighted, for example, the need for sensors to be fitted in all rooms to enable accurate profiling. Figure 5 illustrates how measuring temperature in only some of the rooms would yield a poor estimate of the distribution of temperatures throughout the house.

- A *two weeks monitoring period* was found to be sufficient for holistic assessment and benchmarking. For new builds, a two year monitoring period is recommended to allow for both the building and the occupier to achieve stable performance and bedding-in respectively.

- The *Energy / unit area / degree day* and *Comfort* metrics appear to be robust with regard to deployment duration.

3.1.2 Matching surveyor subjective assessment

This evaluation exercise consisted in comparing and contrasting EEEPE reports on 4 properties as produced by qualified surveyors on the one hand and the authors on the other hand. The team's task was to provide evidence and confirm whether the heating systems in the selected homes were functioning as specified; if not, to identify the likely cause. The findings were delivered independently by the 2 teams, in a face to face meeting. The surveyors used observation, experience and predictive tools to assess and diagnose the homes. The authors used the metrics and visualizations above, together with in-house algorithms for heating energy apportionment. The two teams arrived at similar conclusions regarding the homes performance but the authors had the advantage of being able to rank the properties and quantify the energy wasted through heating system malfunctioning.

4 EEEPE beyond pilots—Generic findings and Open challenges

Besides the results obtained and evaluated in the previous section, insight was also gained by the team into a number of operational and deployment issues. These issues only became apparent once the transition of the monitoring instrumentation was made from the research domain (pilots) to its operational use within OHE. It was found that:

- A good understanding of *practical and procedural issues* is needed when deploying systems in occupied homes. As an outcome, stock owner procedures were developed for i) gaining access to properties, ii) communicating the purpose of measurement to occupants, iii) ensuring the systems are not tampered with and, iv) providing technical inductions to tenant liaison teams. It has become clear that "buy-in" for assessment needs to be secured from both tenants and tenant liaison staff, with the latter playing a critical role in EEEPE success.

- *Deployment and remedial protocols* needed to be established to minimise occupant disturbance. A deployment of 12 nodes and associated server now takes approximately one hour, which includes filling in bespoke proformas to gather relevant basic occupant and home information, audit meters and brief tenants on how to identify and report any system malfunction.

- The development of a *well organized deployment database*, was required to log observations, track deployments and allow the authors team to interact and plan remotely.

The work has also highlighted a variety of open challenges. They are listed below (organized into two categories), for the benefit of researchers and practitioners who intend to engage with the study and application of EEEPE. These questions (and probably more) will need to be fully answered before the built environment industry will fully adopt WSNs as empirical evaluation tools.

4.1 System design challenges

- *Who should be deploying and exploiting the WSN based systems: the computer scientists or the end-user?*
- *How does one design EEEPE systems, holistically, to respond to the diverse end-user base of contractors, surveyors, political bodies, occupants, building stock owners, etc?*
- *How low is the "low instrumentation cost" aimed at by the built environment industry to fully adopt EEEPE and how can systems be delivered within the given cost bracket?*
- *What level of hardware/software integration and automation is necessary to allow delivery to the end-user of the desired informational content in an acceptable form?*
- *What is the right balance between instrument flexibility (to allow diverse evaluation types), performance, battery life, integration level and cost?*

4.2 Deployment and operational issues

- *What are the operational costs associated with deployment of EEEPE and how could these costs be contained?*
- *What are the most effective approaches to tenant liaison in order to ensure tenant acceptance of monitoring systems?*
- *What are the direct benefits to tenants following EEEPE assessment and how should these be explained?*
- *What are the perceived barriers for EEEPE to become operational tools for classically trained, observation driven surveyors?*

5 Conclusions

The authors proposed and confirmed the hypothesis that WSNs: *i*) allow the built environment industry to reduce reliance on subjective surveyor's interpretation of a home environment or predictive energy consumption and performance models, *ii*) offer added value to compared with traditional evaluations and *iii*) enable a thorough analysis of the home's environment and energy consumption with little disruption to the occupant. The results of a sustained interdisciplinary research effort were presented, consisting on a validated approach to EEPE and associated instrumentation. Furthermore, remaining open challenges were listed, looking forward to the adoption of WSNs in the built environment.

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