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A concept review of power line communication in building energy management systems for the small to medium sized non-domestic built environment

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ABSTRACT

To date, building energy management systems (BEMS) have been well established in the large scale non-domestic field as an energy saving technology, contributing towards sustainable future cities. They utilise complex control interfaces, with control signals passed through purpose built communication wiring. Estimated end-use energy savings, due to BEMS addition, can reach up to 50%, with associated financial savings for building users. The intelligent control, featured in BEMS, enables buildings to adapt; optimising operation based on up to date weather forecasts. Despite the positive savings for future sustainable cities, the additional wiring required and complex control interfaces have inhibited wide scale up take for small and medium sized commercial buildings. Retrofit installation is often time consuming, whilst efficient operation requires additional training for users. BEMS, based on wireless communication technology, are limited by radio-wave reception and therefore suffer in heavyweight constructions and larger premises (greater than 1000 sqm). Following review of available technologies, this paper investigates a novel strategy utilising power-line communication (PLC) for BEMS communication, for versatile applications in the small to medium sized non-domestic (SMSND) premises that make up future sustainable cities. The PLC strategy intends to send BEMS control signals via the established electrical wiring network. Before implementation of this concept, further work is required to overcome the more challenging aspects of PLC technology.

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1. Introduction

Worldwide, in 2011, the built environment accounted for 118EJ,[1] 34% of global energy consumption. 30EJ were consumed within service sector buildings, 26% of total built environment consumption [1]. Assessing the end-use energy demand in such buildings (Fig. 1), 33% of end-use energy was consumed through space heating and cooling, with a further 14% used on lighting. The demand for energy is projected to rise [2], putting extra stress on energy markets and the environment, yet the energy intensity (energy consumption divided by contribution to GDP) has not improved since the late 1980s, suggesting a lack of improvement in energy-efficiency [3]. To meet the UK government climate change targets (80% CO_2 reduction by 2050), energy-efficient measures, throughout the service sector built environment, are an essential feature in future cities [4].

In 2013, the UK commercial property market was worth approximately £717 billion, with 51% of organisations renting office space [5]. Industry wide, 74% of businesses had commissioned some level of energy-efficiency technology retrofit prior to 2014. Amongst large corporations nine out of ten had commissioned work; whilst only six out of ten SMEs had commissioned projects [6]. Fig. 2 charts the wide range of energy-efficient technologies commissioned during 2012/13.

1.1. Impact of user behaviour on building energy efficiency

Excessive end-use energy demand is commonly exacerbated due to improper occupancy operation. Of the top five technologies commissioned in 2012 and 2013 (Fig. 2), four of them relate to behavioural change or automating control away from the occupant. One 2013 study, assessing the difference between design and actual energy consumption, noted a 94% increase in actual consumption over designed consumption [7]. Assuming lights typically remain on throughout the working day, Garg [8] discovered occupancy sensors reduced lighting energy consumption by 20 to 25%. Intelligent control of the major energy consuming office elements provides excellent potential for energy savings.

The significant discrepancy between predicted and real building performance, shown in Fig. 3, is in part caused by both an underestimation of predicted values for building use and wasteful use of resources by occupants. Both of these “can mainly be attributed to misunderstanding and underestimating the important role that the occupants' energy use characteristics play in determining energy consumption levels” [10]. Occupant behaviour is one of the major factors contributing to excessive energy use during building operation [9,11], alongside effectiveness of services control and deviations from designed build quality. Linking energy optimization systems to forecasts of occupant energy demands and behaviours is identified as an area for future development in sustainable cities.

Given that the impact of users' behaviour on the operation and energy performance of buildings has been established, routes to reduce this impact must be explored. This includes attempts to effect conscious behavioural change in occupants (which can have limited or counter-productive results [12]) or to automate building services, transferring the responsibility of control away from occupants.

The field of building automation is not new; however as sensing, computing and actuating technologies have developed the scope of control has expanded. The use of more extensive sensor/actuator networks have made it more feasible to allow for automation taking precedence over occupant control, allowing for comfortable conditions to be maintained without wasteful behaviours from occupants. The ideal way to respond to occupants' needs is the subject of much research, but most studies confirm that greater automation in control can lead to significant energy saving. For example, studies have shown that the automation of lighting and appliance use – processes often left purely to occupant control - can reduce energy consumed by up to 21% [13], 22% [14], 25% [8], 34% [15] and 50% [16] respectively. The exact savings made depend heavily on the building of application and the level of responsiveness to occupant needs.

It is worth noting, that although building automation can significantly reduce energy use, research has also identified that occupant control can improve occupant perception of comfort [17]. For a building automation system to be accepted by occupants the comfort conditions maintained should be optimal.

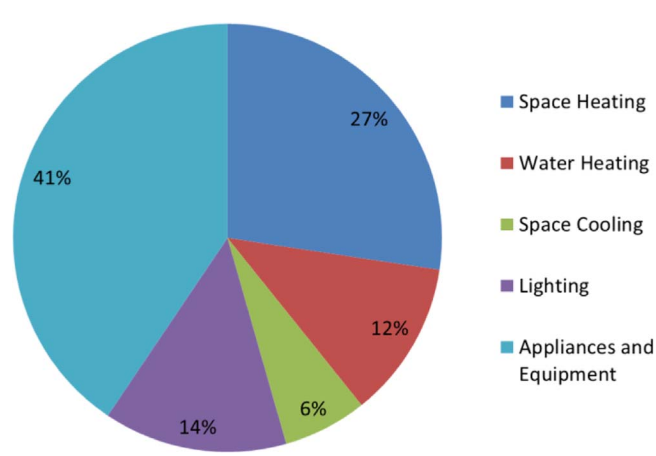

Fig. 1. Service-sector built environment end-use energy breakdown for 2011 [1].

[1] EJ is an exa joule, 10^{18} Joules. 1 EJ is equivalent to 23.9 Mtoe or 278 TW h.

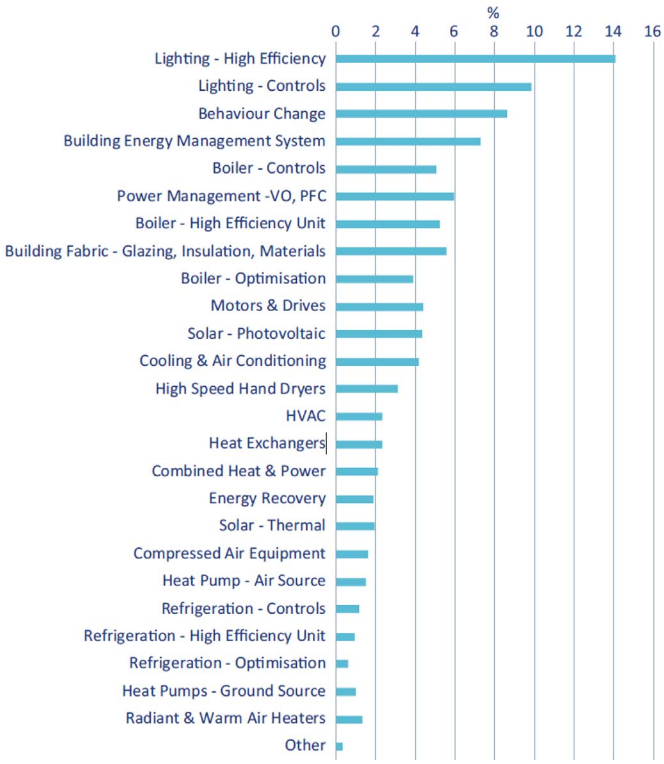

Fig. 2. Technologies commissioned in 2012/13 [6].

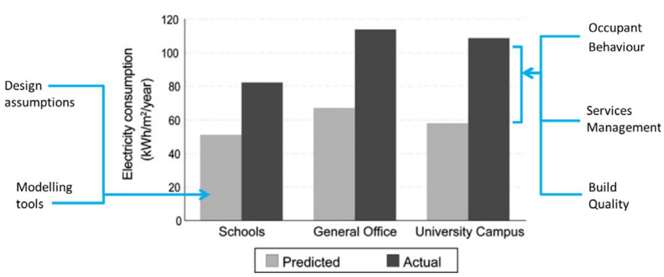

Fig. 3. Performance gap between designed and actual building use [9].

2. Building energy management systems

Since the 1970s the development of automated control systems to manage energy intense aspects within the built environment have been developed [18]. Building energy management systems (BEMS) seek to maintain occupant comfort in the controlled space, whilst minimising the energy consumption[19]. Central to each system developed are; the methods for specifying occupant comfort, and the energy-cost function [20], underpinning adaptive control that aims to design-out occupant behaviour from the energy efficiency equation.

2.1. Comfort metrics

The primary function of a BEMS is to maintain internal comfort for the building occupants. Internal comfort is made up of;

1. Thermal comfort,
2. Visual comfort,
3. Acoustic comfort,
4. And indoor air quality.

Thermal comfort is a function of occupant activity, indoor temperature, radiative solar-gain and humidity. Despite the

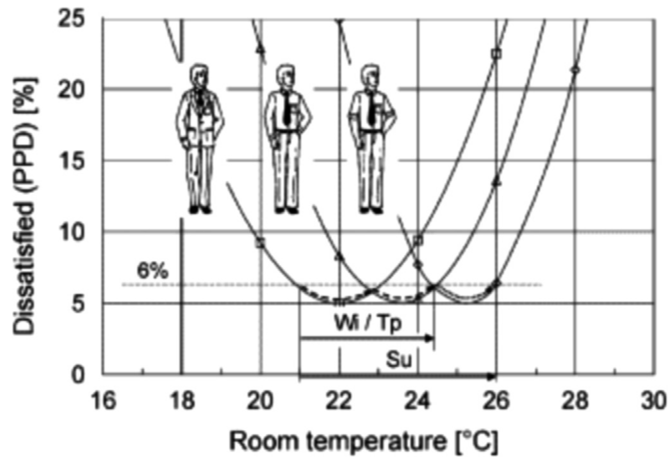

Fig. 4. Predicted Percentage of Dissatisfied (PPD) over various room temperatures and seasons (Winter/Transition Period and Summer) [22].

limitations, guidelines from CIBSE [21] uses a theoretical predicted percentage of dissatisfaction (PPD) to determine the thermal comfort region for different seasons. The curves in Fig. 4 chart the PPD of occupants depending on their level of dress. Taking an acceptable PPD level of 6% thermally comfortable room temperatures can be determined.

Comfortable levels of relative humidity (RH) lie between 40% and 70% [23]. Below 40% the dry air causes adverse health effects. Above 70% the high water content in the air can cause condensation on cool surfaces. By using psychometric charts it is possible to determine a comfortable range of humidity for respective room temperatures.

The PPD metric was developed from an alternative thermal comfort metric, the predictive mean vote (PMV) [21]. The PMV method was developed from a study conducted on Israeli soldiers under differing comfort conditions [24]. From these studies, under a range of steady state temperature conditions, an optional vote of +3 (too hot) to −3 (too cold) was available. Based on the subjects' votes, their level of dress and assumptions in air change and humidity a thermal balance relationship was developed to predict a group of subjects' thermal comfort. Further work investigating thermal comfort has led to the development of international standards such as ISO 7730 that map out acceptable human comfort to the majority of occupants depending on outdoor monthly mean temperatures [21]. Based on these standards, and depending on outdoor temperatures, human comfort temperatures range from 18.5 to 28.0 °C (based on 90% acceptable limits and a maximum outdoor mean temperature of 25 °C as shown in Fig. 5 [25]).

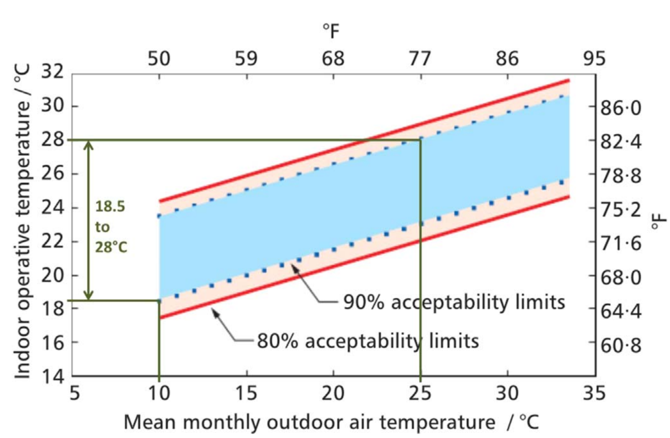

Fig. 5. Acceptable operative temperature ranges for naturally conditioned spaces [25].

Visual comfort is determined by illumination levels. For comfortable internal lighting, the daylight factor should be maintained between 2% and 5%. The daylight factor is calculated based on the supply of natural light, position of windows, depth of rooms and external obstacles. Where natural light is insufficient to meet the requirements, additional electric lighting is required to be provided. BEMS therefore optimise the use of natural light (without excessive solar gain), whilst ensuring sufficient lighting is supplied using the minimum amounts of energy. Lux sensors offer the main input for managing visual comfort.

Acoustic comfort is determined by the type, duration and volume of the surrounding soundscape [26]. In an office environment disturbances largely arise from excessive speech. Research suggests that buildings suffering from acoustic disturbance can account for up to 8% performance loss [27]. Further, in an office context acoustic privacy is desired to offer acoustic comfort [27]. Monitoring of acoustic comfort is achievable through sound level meters. However, since sources of acoustic disturbance are typically unconnected from the BEMS, controlling the soundscape is rarely possible. Where automatic windows or adjustable audio barriers/baffles exist, actuators can be integrated in an acoustic control system. BEMS connected to central personal address systems can be used to automatically adjust the volume of background noise to mask conversations, such as in restaurants.

Indoor air quality maintains acceptable levels of CO_2, avoids a build-up of smells and other unwanted gases. Air quality, governing ventilation rates, is typically measured by CO_2 sensors, where levels are maintained below 5000ppm for working environments [28]. The BEMS takes into account fabric infiltration rates, window openings and mechanical ventilation systems. Humidity levels influence perceived air quality; however improvements can be achieved through increased air changes. Comfortable air velocities in occupied spaces typically range from 0.1 to 0.3 m/s [29].

2.2. BEMS control strategies

BEMS control strategies dynamically optimise the energy-cost function and occupant comfort. Since both energy and comfort are dependant variables, multi-variant control and optimisation systems are required. Extensive research has been conducted into suitable methods, including *responsive*, *predictive* or *adaptive* multi-agent methods [30]. Various methods combine strategies to achieve optimum control throughout differing occupant behaviours and local climate conditions. Work by Dounis [30] thoroughly reviewed BEMS control strategies. Since the purpose of this paper is to introduce existing BEMS and the scope for integrating PLC a brief overview of BEMS control strategies has been presented.

For basic BEMS control a basic multivariate control hierarchy of; comfort first, and then energy is implemented [31]. Actuators are linked to control mechanical ventilation or automated windows, lighting networks, heating and cooling systems, and shading devices (where maximum luminance levels are included in the control strategy). Models featuring predictive elements look ahead using weather forecast data [32–34]. From the forecast, internal and external conditions can be pre-empted and energy consumption optimised. Second to the comfort optimiser will be an energy minimiser and associated cost function. An effective control system will:

- overcome non-linear estimations,
- make use of learning methods,
- distinguish between noise and required response (sometimes modelled results are impracticable or unrealistic or sensitive to noise/minor disturbances in the system) and,
- prioritise passive techniques.

Responsive heating control uses temperature switches allowing for on/off control. Within heating systems PID controllers control the temperature flow to rapidly and stably meet the determined set point. PID elements can be at risk from improper sizing, leading to slow or unstable set point delivery. PIR sensors coupled with lighting arrays are common responsive control to enable energy efficient management. The PIR sensors operate on a time-delay function to avoid disturbance in locations where activity is minimal.

To improve upon responsive control strategies *predictive* and *adaptive* control strategies have been developed. Typically, for adaptive control systems a model of the building is required to successfully tune the controller. Predictive systems assess weather forecast data to prepare the building system for future comfort disturbances. This is especially useful in buildings with high thermal inertia or where a passive night ventilation strategy is available. In these scenarios, when high temperature weather conditions are anticipated extra passive cooling can be predictively initiated.

Simplistic control is suitable for single-variant systems, however for multivariate systems, where comfort is a factor of multiple building systems, further advanced control mechanisms are required. This is required where metrics such as the PMV are used to define and control the internal thermal comfort, since the PMV is calculated from multiple non-linear inputs [35].

Fuzzy logic control (FLC), based on fuzzy set theory, enables automatic, black and white, processing to make human-like, grey, decisions using weightings and sliding scales [36]. Non-linear systems can be controlled without the typical trial-and-error process [37]. Rule sets, membership functions and weightings are created for each appliance being controlled. The rule sets determine the sensors and actuators associated with the appliance and their relationships [38]. Dounis [39] successfully used FLC to maintain PMV between -0.2 and $+0.2$ during peak summer design conditions.

Demand Control Ventilation (DCV) seeks to optimise between indoor air quality (IAQ) and energy consumption (Cooling/Heating loads). FLC has been used to control the window openings, CO_2 concentration and air temperatures [40]. Wang et al. [41] developed four PID functions to optimise IAQ using a DCV approach. The method used a gain scheduling approach to maintain robust control.

Work by Kolokotsa [42] evaluated the ability of fuzzy PID, fuzzy PD and adaptive fuzzy PD control methods to maintain internal comfort (IAQ, thermal and visual) whilst reducing energy demand. The purpose was to integrate users' preferences in a stable widely applicable model. The adaptive fuzzy PD provides the optimum comfort and energy reduction, however the non-adaptive fuzzy PD system is only marginally worse, satisfactorily maintaining human comfort and making energy savings. Energy savings of 25 to 30% were observed, using the fuzzy controller against standard ON/OFF control models.

Fuzzy PI logic control (FLC-PI) features the rule sets and membership functions of classic FLC coupled with crisp PI parameters. The fuzzy logic element benefits the complex multivariate nature of BEMS control; whilst appropriate sized PI elements improve the parametric response time [43]. The combination enables FLC to appropriately control first-order systems, as well as linear systems. Methods have been researched to develop FLC-PI strategies capable of appropriately controlling second-order and greater systems [44]. Typically an incremental controller, FLC-PI is governed by Eq. (1) where k is the sampling instance and $\Delta u(k)$ is the incremental change in controller output – as specified by the fuzzy rules.

$$u(k+1) = u(k) + \Delta u(k) \tag{1}$$

Fuzzy PID logic controllers are used to simplify complex control scenarios through linguistic programming. They are widely applicable; however they require a model of the building to specify suitable gains (D) and their boundaries. Work by Kolokotsa [45] applied fuzzy PID logic, in contrast with fuzzy P, fuzzy PI, fuzzy PD and adaptive fuzzy PD, to controlling the internal comfort of an intelligent building. The simulation based investigation developed fuzzy sets to control PMV, CO_2 levels and illuminance. The error from each system was calculated against given set points. In the case simulated, the fuzzy P offered the greatest energy savings and comfort conditions.

Adaptive fuzzy control was investigated [35] that avoids the need for building modelling or expert input to appropriately size and set FLC parameters. The method built upon typical fuzzy PID methods [46] with the addition of an adaptive network. The network was used to optimally size the integral and derivative components of PID system and increase stability. The adaptive FLC controlled the PMV, minimising the time variation of the error (Δe). In experimental testing, where PMV was initially set to minus one, the adaptive FLC developed coupled to a fan, took twenty minutes to reach a PMV of -0.2, and remained between 0.05 and -0.2 for the duration of the investigation. PMV disturbance through window opening was stabilised in fifteen minutes. Evidence from Kolokotsa [42] suggests adaptive PD FLC is capable of providing energy efficient comfort for intelligent buildings.

Where more advanced systems are required, *artificial neural networks* (ANNs) have been implemented in some BEMS control strategy research to better learn the system inputs and outputs, and assist in artificial control. ANNs are a collection of processing units that sum the inputs value by their weights and output the result. Across the ANNs they are trained to respond appropriately for any given building scenario. Asakawa [47] reviewed commercial ANNs for applications in air conditioning control. The system handled sensor inputs and calculated the PMV and components of the system. Further commercial systems reviewed were trained through human and sensor inputs to correct temperature settings in the air conditioning system.

Further integration of artificial intelligence has used *neural fuzzy systems* (NFS), implemented where the neural network takes initial inputs and weightings from the membership functions and rule sets in the FLC. Subsequently the ANN is trained from the system response and returns a modelled system representation for the FLC [47].

Further FLC based control systems include ANFIS (*Adaptive network-based fuzzy inference system*) [48], which was developed to provide a method for developing effective IF-THEN rule sets and an adaptive network. Making use of the rule-sets developed by Jang [48], Alcalá [49] developed a *genetic algorithm* to efficiently tune the FLCs for a BEMS. A weighted multi-criteria steady-state genetic algorithm (WMC-SSGA) was recommended, assuming trustworthy weights from a BEMS designer, to minimise solution finding time.

2.3. Energy cost function

The comfort metrics of a system are optimised in the BEMS energy cost function [50]. Hence, the implementation of an effective cost function that is stable, quick to solve and optimal in solution is a key requirement for any BEMS that features a predictive controller. Quadratic or linear programming (QP or LP) of the problems are optimised using convex optimisation methods to ensure the global minimum is always found. In LP control errors are minimised, instead of the quadratic value of the error. Weigh matrices are developed to influence the system preferences in the controller. Methods such as mean-level control, frequency response analysis and reference trajectory can be implemented for tuning of the system weightings [30]. Cost function constraints are required to denote the available optimisation and operational region.

Using FLC, Sierra [50] developed a LP cost function (Eq. (2)) for energy-efficient internal comfort that featured normalised parameters (f_n) and accompanying weights (w_n) for:

1. PMV
2. CO_2
3. Daylight contribution
4. Energy consumption for heating or cooling
5. Energy consumption for electric lighting

$$Cost\ F = w_1 f_1 + w_2 f_2 + w_3 f_3 + w_4 f_4 + w_5 f_5 \tag{2}$$

Initially weights were estimated and acceptable comfort limits set for each parameter. During simulation the weights were adapted based on user preferences. Results from the simulation conducted, where users' behaviour was simulated via random generators, maintained a cost function value beneath two throughout three winter design days; within the acceptable cost function range of zero to two.

Work by Figueiredo [20] utilised a simplified two parameter quadratic cost function purposing the reduction of energy consumption and the stability of the controlled system. Linear functions could alternatively be used however QP was favoured due to the additional flexibility available for complex scenarios; useful when considering multivariate optimisation as used in BEMS.

2.4. BEMS limitations

Studies of control systems and real buildings quantify the impacts of current building services systems' response to changing occupancy. Simulation will typically assume the building services respond properly to changing demand from occupants, which is not the case in practice. Typically, a poor response to occupant presence and behaviour shows systems wasting energy by running when occupants are not present.

Martani et al. demonstrate that, in real application, building services do not always follow actual occupant presence patterns [51]. Wi-Fi connections were used as an occupancy counting device in an educational building. Electricity use showed strong correlation with occupancy levels, while HVAC energy use did not. This shows the poor response of services systems to actual occupancy. The authors observed that “large common areas, such as studios, may be used by one person or a large number of people often with no alteration in the amount of energy supplied to the space”.

Masoso and Grobler's study of commercial buildings in a hot, dry climate showed more energy used during non-working hours than working hours [52]. This suggests that energy use is not properly linked to periods of occupancy and, once again, shows the need for more occupancy-centric control systems.

3. Case for BEMS in small and medium non-domestic premises

Despite the limitations, market research predicts that global building automation revenue will grow from $5.78 billion in 2013 to $7.28 billion in 2018 [53] making BEMS a central feature of sustainable future cities. A substantial proportion of this growth will be from the European Union where the market is growing at a rate of 19% per year [54], driven by increasingly demanding legislative and regulatory measures.

To date, BEMS installation has been favoured in large commercial buildings. The past few years have seen an emerging market in domestic intelligent thermostats, offering convenience and lower energy bills. Scope for BEMS benefits in the remaining building sectors, notably small to medium sized non-domestic (SMSND) premises, those with a total floor area of less than 1000 m^2, looks challenging yet necessary.

The SMSND building stock predominately consists of standalone retail and office buildings, but also includes small independent units within larger buildings such as, transport nodes and shopping centres. The diversity, low-concentration and flexibility of the building stock add risk and complexity to any solution. Any technological solution for SMSND buildings are required to be low cost, adaptable, easily installed and intuitively operable.

3.1. SMSND building energy data

Data analysis of energy consumption in the non-domestic sector has been the subject of a number of investigations. Three studies have been explored in this report to obtain an accurate cross section of the non-domestic sector. The studies examined are: Building Performance Institute Europe's (BPIE) 'Building's under the microscope' study [55], research conducted by Bruhns in 1999 [56] and the Carbon Reduction in Buildings (CaRB) project model [57].

Initial analysis was conducted using data [55] from the Building Performance Institute Europe (BPIE). In 2011, the BPIE conducted surveys and collated data to produce an approximation of building numbers, use and size in different countries. The data shows that 47% of the UK non-domestic sector consists of buildings with an area of less than 1000 m^2 (Fig. 6).

The data collected in this survey is missing crucial information, for example, only commercial offices are included, health centres and surgeries have been overlooked and only the sports facilities owned by local authorities are included. The stock can be represented using different units, causing difficulties when comparing different data sets. In the BPIE analysis, the stock appears to be expressed as buildings whereas the majority of analysis conducted in the UK uses hereditaments; the main unit used by the Valuation Office Agency (VOA).

Similar analysis was conducted by H Bruhns in 1999 based on data from 1993-4 [56]. Data was sourced from the Valuation Support Application, obtained from the VOA; which contained data for four bulk categories. The data covered approximately 70% of the non-domestic stock: retail, offices, factories and warehouses. The data was broken down into size bands, useful to size specific analysis, however, the data gathered is now twenty years old and therefore using this data alone incurs inaccuracies.

The Carbon Reduction in Buildings project has modelled energy consumption of the non-domestic building stock [57]. The CaRB model uses data from different sources including the Valuation Office Agency (VOA), government departments, trade associations, market research companies, tourist boards and the Census. The CaRB model provides mean floor area, number of buildings and an approximate energy usage for a range of non-domestic sectors. The model contains the most comprehensive and up to date set of data currently available for the UK SMSND building stock. Fig. 7 displays the main findings from the model.

The CaRB model does not contain information on the size distribution of hereditaments. To obtain an accurate indication of the size distribution, the CaRB model has been used in conjunction with the results of analysis conducted by Bruhns. The number of buildings has increased since 1994 however, to enable analysis; it has been assumed that the size distribution has remained the same. The data on number of premises from CaRB has been used with the size distributions from Bruhns to generate an updated SMSND building stock profile (Fig. 8).

The categories are based on the four bulk categories from the VSA data in Bruhns' analysis. For categories in the CaRB model which do not correspond to the four bulk categories from Bruhns, their results have been omitted from Fig. 8. The distribution can be represented by the number of premises or total floor area. The number of premises with a floor area of 1000 m^2 or less comprises 94% of the total stock. However, the floor area of these buildings is only 43% of the total floor area. The retail sector contains the highest proportion of hereditaments with a floor area of less than 1000 m^2 (Fig. 9).

The energy consumption of each sector has been estimated in the CaRB model and can be used to identify the most energy intensive sectors (Fig. 10). Based on the analysis, factories and workshops account for the largest share in SMSND building energy consumption. The shops (16%) and office (14%) sectors account for a smaller proportion of the total energy consumption than would be expected from the high number of hereditaments in these sectors (shops 39% and offices 27%). This indicates that there is a large quantity of small shops and offices which each have low energy consumption. The estimated energy consumption can be further broken down into electricity and gas consumption (Fig. 11).

The breakdown of gas and electricity (Fig. 11) gives an insight into the energy requirements for each sector. For example, the arts and leisure and health sectors have high gas consumption since heating is required constantly within the hospital wards and there is a high demand for hot water. The office sector has a higher electricity consumption caused by computer and lighting requirements. Shops require a significant amount of electricity when

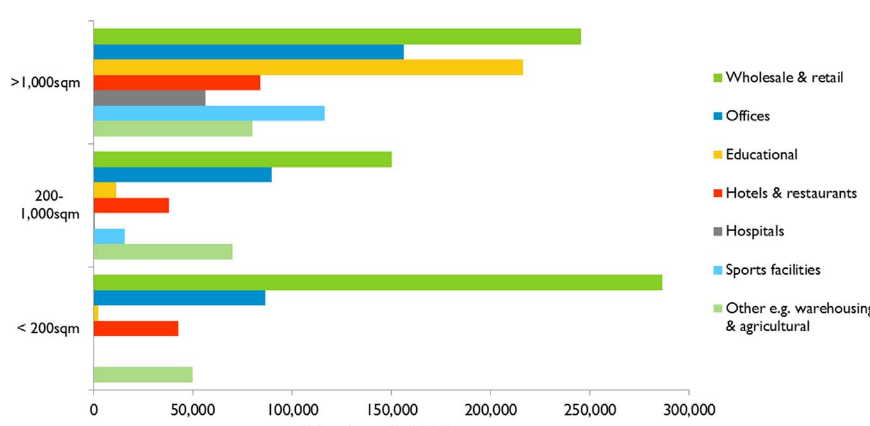

Fig. 6. Breakdown of non-domestic buildings in the UK by floor area from BPIE 'Europe's buildings under the Microscope' [55].

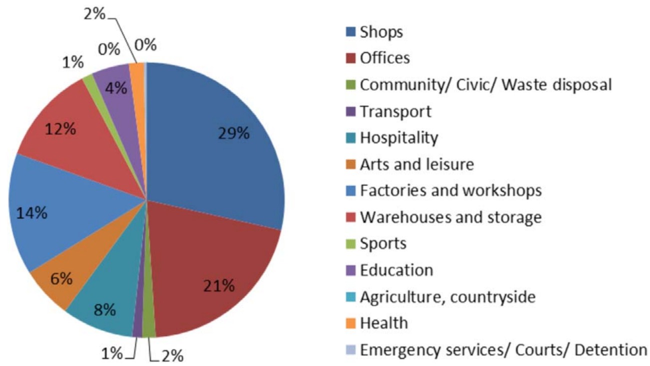

Fig. 7. Number of hereditaments in each category within the non-domestic sector from the CaRB model [57].

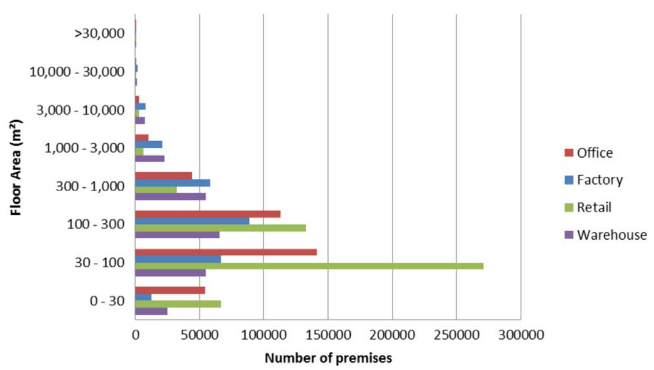

Fig. 8. Number of premises and the floor area band calculated using the CarB model and data from Bruhns' analysis in 1999 [56,57].

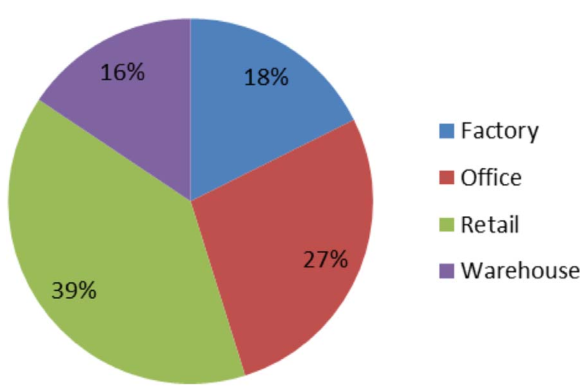

Fig. 9. The breakdown of number of hereditaments with a floor area of 1000 m^2 or less.

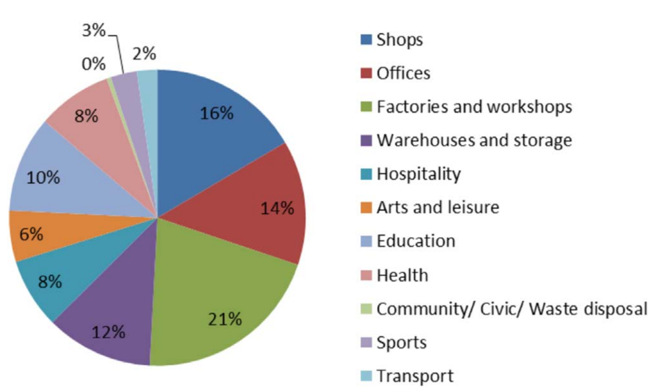

Fig. 10. The estimated energy consumption in each sector where data is available.

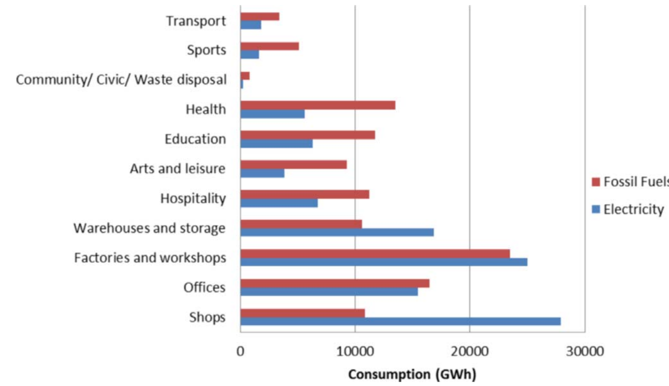

Fig. 11. Estimated electricity and gas consumption in each sector.

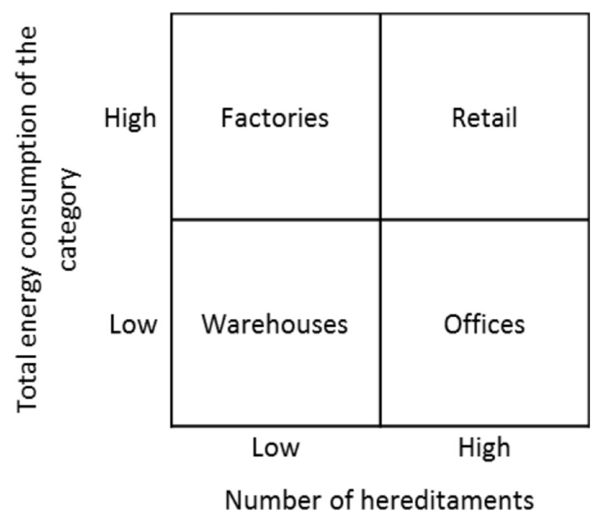

Fig. 12. Diagram showing basic trends in number of hereditaments and consumption of the four bulk categories.

compared to gas because of the lighting and air conditioning requirements.

Analysis of the number of hereditaments and total energy consumption of the bulk four categories shows some general trends as indicated in Fig. 12. The most significant opportunity for BEMS installation in the SMSND building sector is retail. There are a high number of hereditaments within the UK, and the sector has a high total energy; offering potential for significant savings through installation of appropriate controls.

4. Existing building energy management systems

The opportunity and challenges faced with offering BEMS for SMSND properties have been noted by previous industries. Companies specialising in high floor area, non-domestic BEMS have developed simplified versions for the SMSND building manager. This section introduces the main systems and discusses the methods used to overcome SMSND building challenges.

4.1. Existing BEMS

The world leaders in BEMS have traditionally targeted large non-domestic buildings due to the available capital of building occupiers and potential for energy savings on a large scale. Sixty companies specialising in systems, components and consultancy of BEMS were reviewed. Table 1 documents suppliers of complete BEMS for large non-domestic buildings. Table 2 displays the

Table 1
System suppliers to large non-domestic buildings.

Manufacturer	Control/ monitoring/ automation	New/Retrofit	Wired/ Wireless	Primary target market	Ref
Johnson controls	Monitoring and control	Mainly retrofit	Both	All building types, generally restricted to large buildings	[58]
Cylon Active Energy	Full systems including control, monitoring and building automation	Mainly retrofit	Both	Large buildings including: healthcare, pharmaceutical, education, offices, retail, hospitality and leisure, airports	[59]
Honeywell	Full systems including control, monitoring and building automation	Both	Both	All building types	[60]
Siemens	Full systems including control, monitoring and building automation	Both	Both	A combination of large and medium sized buildings including restaurants, medical, offices, retail shops and other commercial businesses	[61]
IBM	Full systems including control, monitoring and building automation	Both	Both	All building types	[62]
GridPoint	Full systems including control, monitoring and building automation	Both	Both	Range of building types from large commercial buildings to convenience store and airport small businesses	[63]
Schneider electric	Full systems including control, monitoring and building automation	Both	Both	Large and small buildings, all sectors	[64]
Elster EnergyICT	Monitoring - energy management	Both	Both	All types and sizes of building	[65]
EnerNOC	Monitoring - energy management	Both	Both	Primarily Commercial and industrial	[66]
Trend controls	Monitoring, controlling and automation	Both	Both	All building types and sizes	[67]
Clarke control	Monitoring, control and automation	Both	Wireless	Industrial and commercial sectors particularly the automotive industry	[68]
Ener-G controls	Monitoring, control and automation	Both	Both	Variety of building types including: Hotel, retail, manufacturing, Education, commercial offices, healthcare, warehouses	[69]
Imserv	Monitoring and control: monitoring utility meters, time, temperature, lighting and control devise via Modbus network interface, cloud base	Mainly retrofit	Wireless	A range of building types including: retail shops, outlet stores, schools, hotels, smaller offices, hospitals and manufacturing sites	[70]
Verisae	Mainly monitoring	Both	Wireless	Food industry/ retail	[71]
City Energy Solutions	Monitoring and control	Both	Wireless	No specific market - industrial, leisure, retail and education	[72]
Innotech	Monitoring and control	Both	Wireless	Range of building types	[73]
WEMS	Monitoring, control and automation	Both	Wireless	Large buildings, cinemas, retails, ed. campuses, data centres, telecommunication however extending into smaller buildings and residential buildings	[74]
Automated Logic	Monitoring	Both	Both	Range of building types from small residential buildings to large commercial and industrial buildings.	[75]

Table 2
System suppliers to small and medium sized non-domestic (SMSND) buildings.

Manufacturer	Control/ monitoring/automation	New/retrofit	Wired/wireless	Primary target market	Ref
Johnson Controls	Monitoring and control	Mainly retrofit	Both	All building types, generally restricted to large buildings	[76]
Honeywell	Full systems including control, monitoring and building automation	Both	Both	All building types	[60]
Siemens	Full systems including control, monitoring and building automation	Both	Both	A combination of large and medium sized buildings including restaurants, medical offices retail shops and other commercial businesses	[77]
IBM	Full systems including control, monitoring and building automation	Both	Both	All building types	[62]
GridPoint	Full systems including control, monitoring and building automation	Both	Both	Range of building types from large commercial buildings to convenience store and airport small businesses	[63]
Schneider electric	Full systems including control, monitoring and building automation	Both	Both	Large and small buildings, all sectors	[78]
Elster EnergyICT	Monitoring – energy management	Both	Both	All types and sizes of building	[65]
EnerNOC	Monitoring – energy management	Both	Both	Primarily Commercial and industrial buildings	[66]
Imserv	Monitoring and control	Mainly retrofit	Wireless	A range of building types including: retail shops, outlet stores, schools, hotels, smaller offices, hospitals and manufacturing sites	[70]
Verisae	Mainly monitoring	Both	Wireless	Food industry/retail	[71]
City Energy Solutions	Monitoring and control	Both	Wireless	No specific market – industrial, leisure, retail and education	[72]
Innotech UK	Monitoring and control	both	Wireless	Range of building types	[73]
WEMS	Control, monitoring and automation	Both	Wireless	Large buildings, cinemas, retails, ed. campuses, data centres, telecommunication however extending into smaller buildings and residential buildings	[74]
T-mac technologies	Primarily monitoring but offer a small control system	Both	Wireless	Primarily high street retail buildings, offices and residential	[79]
Enistic Energy Management Systems	Primarily energy monitoring with small scale control systems	Both	Wireless	Small facilities including offices, retail units and manufacturing facilities	[80]
SyxthSense	Monitoring, control and automation	Both	Both	All building types of any size including homes	[81]
VDA uk		Retrofit	Wireless	Primary market is hotels however cater for large residential houses.	[82]
Lennox group	Monitoring and control	both	Both	Mainly residential and commercial buildings	[83]

Table 3
Breakdown of BEMS suppliers to small and medium non-domestic premises.

	Number	Percentage
Companies who can supply a fully operational system	25	42%
Consultancy companies who can design a fully operational system	18	30%
Companies directly related to manufacture of components	11	18%
Companies providing software solutions and programming expertise	6	10%

commercial BEMS available for medium and small non-domestic buildings. A combination of wired (Ethernet cable) and wireless (WiFi or similar) technology typically constitutes the communication infrastructure.

4.2. Existing system analysis

Benefits for targeting SMSND buildings, with a lesser energy consumption, have been demonstrated above. A number of system suppliers and market research [84] have acknowledged the potential for energy saving through BEMS integration in these buildings [85]. An investigation into companies supplying and installing building controls has been undertaken. A total of sixty companies were identified and analysed, the breakdown is shown in the Table 3.

A number of trends were identified in the services offered by these companies in the following areas:

- Small and medium sized buildings
- The building services targeted
- Wireless devices
- New build and retrofit

The majority of companies target large buildings with energy intensive equipment. However, a third of the companies reviewed has identified the energy-saving case for SMSND buildings and have begun targeting these. Of the systems researched, many have been biased towards large domestic buildings instead of small office and retail buildings.

The companies supplying fully integrated systems typically focus on the building services using the most energy; such as space heating, air conditioning and lighting. There are a small number of companies that target total building management; including, for example, fire and security systems. An equal number of companies offer simple energy monitoring systems and strategies for building management installation.

Wireless devices are the most prevalent method of communication due to existing networking capacity and the disruption caused by installing wiring. Nevertheless, many large BEMS installers still offer fully wired options at the SMSND building level.

4.3. BEMS trends

A recent requirement, particularly for large businesses, is data availability causing an increase in demand for metering and monitoring technology to be included in the building controls; for example, the Carbon Reduction Commitment (CRC) scheme which requires regular energy consumption reporting [86]. The installation and management of meters and sub meters will also allow identification of areas with high energy consumption and highlight areas of potential improvement.

Building management technology is constantly evolving. Recently, installation of wireless devices and use of cloud-based data storage have both become popular [87]. The adoption of wireless technology has increased the flexibility and affordability of building controls systems, resulting in cheaper and more widely available systems. Wireless control systems are a relatively recent development in which components of the system transmit data using radio waves. This is particularly useful when fitting a BEMS to an existing building as reduced wiring and decreased disruption to the building result in lower cost to the client. However, there are some potential problems with this technology including signal range, interference from other technology, power source or battery requirements and, as with all wireless technology, security is an issue. Wireless systems require carefully designed system architecture and encrypted communication to avoid these problems [88].

Traditionally, control systems were typically accessible from within the building they were controlling, and often only from one computer. Using cloud technology for applications and data storage solves this problem, making the system accessible from any location. This allows facilities management staff and BEMS maintenance engineers to work on the system remotely resulting in quicker resolution of problems [87].

The growing dependency on wireless and cloud technology has increased the cyber threat to intelligent building systems. For future cities this is of particular concern when the control system incorporates fire and security. The cyber threat has led to an increase in security authentication and encryption technologies [89].

Individual controllers have been developed with increased functionality and the ability to control building systems without input from a central system [87]. This has caused a shift in the market as the BMS systems often only connected controllers and collected data, instead of operating systems. With the introduction of individual controllers the BMS market has adapted to enable use in a wider variety of building types and designs. This has shifted the market towards customised controls systems instead of generic off the shelf systems [87].

4.4. Communication limitations

Whilst modern control systems are beginning to feature wireless technology, functions such as intelligent lighting or HVAC control in non-domestic properties are still almost exclusively provided by systems requiring the installation of dedicated communications wiring throughout the building. This is in addition to, and often runs in parallel with, the standard mains power wiring, often taking the form of twisted-pair cabling. There is no industry-wide consensus on a suitable standard interface [90]. A survey of vendor websites shows that interfaces such as BACnet, LonWorks, ModBus, KNX, DALI and numerous proprietary variations are used, all of which require dedicated control wiring.

During the construction of a new building, the cost of installing this wiring may not be significant compared to the overall cost of the construction project. However, there are a vast number of buildings already in existence which would benefit from the installation of BEMS, therefore it is essential when designing a BEMS product to consider the retro-fit case closely. In many buildings, the cost and disruption [91] involved in installing new wiring throughout the building is actually prohibitive, leading to low take-up of these systems.

As an alternative to systems requiring control wires, several companies are marketing products which use radio transmissions for communication, employing, for example, Zigbee, EnOcean, Z-Wave or other proprietary protocols. These have the advantage that the need for control wiring is much reduced which lowers the installation cost and also saves copper, benefitting the environment by reducing raw material usage. However indoor radio networks frequently suffer from range and electromagnetic interference problems which limit their applicability [92,93]. This is a problem familiar to many users of'WiFi' products in residential applications, who commonly find that Internet access is problematic in certain areas of the house, depending on the location of the WiFi gateway or router, the proximity of neighbours' WiFi equipment and the operation of other household equipment such as microwave ovens. Performance can even vary with time of day. This performance degradation is frequently more noticeable in commercial buildings due to their size and construction – especially those with steel frames and thicker walls – particularly in older buildings [94]. For this reason, radio-based automation systems are generally offered for areas such as warehouses where there are few walls and where there is a regular 'grid' to operate with, e.g. lighting fixtures near the ceiling which can be equipped with radio transceivers. Alternatively they are aimed at up-market domestic settings rather than commercial buildings. In general, the parts of the radio spectrum commonly used for this short range communication are becoming more and more crowded, hence spectrum 'clutter' will lead to an increase in the likelihood of radio interference and performance problems.

In summary, both wired and wireless systems have significant disadvantages when it comes to retro-fitting BEMS into commercial buildings. As a result, the take-up of BEMS is still relatively low (7% of all commercial energy-saving initiatives in 2012/13 [6]), both in existing buildings and in many new buildings where cost is the major driver. Whilst specialist or 'high-end' buildings do sometimes have BEMS installed, the vast majority of 'standard' commercial buildings such as offices, retail properties etc. do not benefit from the reduced running costs and energy savings that BEMS can provide [95].

4.5. Power line communication

To move away from the existing limitations of communication technologies for BEMS a novel combination is proposed. Mains electrical wiring is an intrinsic part of existing buildings. By utilising these pre-installed wiring networks, installation costs and interruption to users can be minimised. It is proposed that by using power line communication (PLC) to transmit sensor and control signals, the limitations of wireless reach could be overcome. Fig. 13 demonstrates how sensors and appliances can be connected via a PLC network. By connecting the network to an Internet connection, operation and reconfiguration is possible via web-based user interfaces, as shown in Fig. 14. Although the concept has been trialled on lighting networks, further investigation into PLC technology for BEMS is discussed in the next section.

5. Power line communication technology review

5.1. History of PLC

The mains power wiring within a building is an often overlooked but fundamental part of the infrastructure, without which

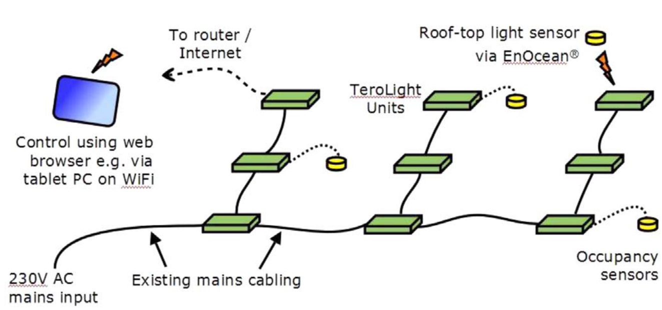

Fig. 13. TeroLight PLC Configuration.

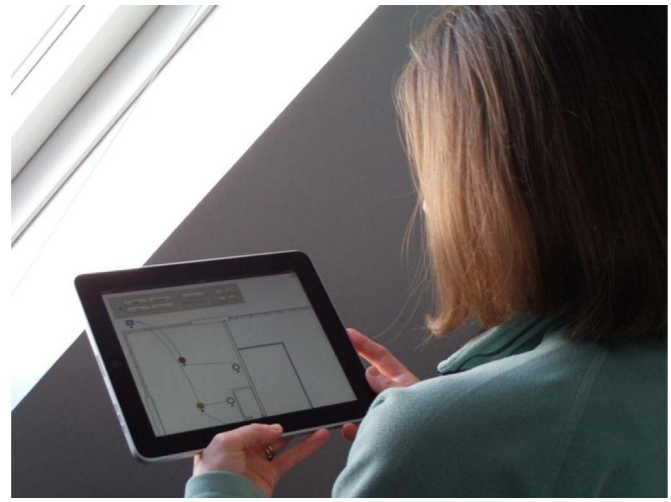

Fig. 14. Configuration of PLC network via a user interface.

virtually none of the building's systems can function. Wherever there is a need for heating, lighting or any mains appliance, there will be power lines. This situation will continue long into the future as there is, as yet, no satisfactory way to transmit significant electrical power wirelessly. The attraction of using this readily available wiring infrastructure to transmit information as well as power has been noted for many decades, primarily because it obviates the need to provide additional cables for carrying the communication signals.

The first applications of Power Line Communication (PLC) were of simple fault detection and correction by power generation companies, however systems for long range telemetry began to appear as early as 1922 [96]. Today, many power companies use PLC in so-called 'Smart Grids' [97], either for demand management or remote meter reading. This has prompted much commercial R&D in recent years to increase the range and reliability of PLC techniques and resulted in the roll-out in Europe of over 40 million PLC-enabled smart meters [98].

On a smaller scale, baby alarms and monitors using the power lines within homes have been commercially available for over 50 years [99]. Subsequent to their introduction, in order to satisfy a growing market for home automation, such as remote control of lights, the 'X10' protocol was developed in the 1970s [100]. However this was very simple, slow in operation and prone to electrical interference from the various mains-powered devices within the home – TV sets, vacuum cleaners etc. Over the years various improved offerings were made by a number of companies, e.g. Echelon Corporation, still being used in general within residential properties. These types of system were never widely deployed in commercial buildings due to performance limitations, despite several attempts to overcome the problems [101]. These failed attempts have resulted in the widespread assumption that PLC is not a suitable technology for automation and control in commercial buildings, evidenced by the lack of products in this space, whether modem devices or complete systems.

With the advent of the Internet and subsequent requirement for broadband data communications to every home and workplace there was a surge in interest in high bandwidth PLC, as opposed to the relatively low bandwidth required for building automation [96]. PLC was considered both for broadband provision to homes, which could have enabled power companies to provide Internet services as well as electrical power, and also for data networking within the home – collectively referred to as 'BPL' – Broadband over Power Line. BPL for delivering broadband to the home was largely superseded before it began, partly due to regulatory issues

[102] and partly due to rapid advancements in Digital Subscriber Line (DSL) and, latterly, optical fibre-based technology. Within the home itself, radio-based (WiFi) systems have become extremely common, however, as stated previously, these can suffer from range and interference problems, leaving 'dead spots' within the building [92,103]. This is when PLC can be effectively utilised, chiefly through the 'HomePlug' group of protocols, ratified in 2010 as standard 1901 by IEEE [104]. Many products compliant with this standard now exist for residential Local Area Networking, and are used in applications where WiFi has insufficient range especially, though not exclusively, in larger homes or older properties with thicker walls.

The success of HomePlug and the increasingly widespread deployment (especially in mainland Europe) of long-range PLC-based remote meter reading technology [98] have been made possible, at least in part, by the availability of affordable Digital Signal Processing and the resulting capability to provide, at low cost, some advanced communications methods which were previously economically viable only in the long-distance telecommunications field [105]. These factors mean that it is time to take a fresh look at whether PLC can be successful for building automation within commercial properties. If so, the disadvantages of both wired and wireless systems could be overcome simultaneously. A PLC-based system could enable low cost, low disruption installation whilst at the same time overcoming the range of issues suffered by radio systems.

5.2. PLC limitations

To create a successful PLC-based communication system, one which is scalable for use within commercial buildings, a number of technical limitations must be overcome. Mains cabling infrastructure was not designed to carry communications signals from any one part of a building to any other between multiple devices. Rather it was intended to carry electrical power at 50 or 60 Hz from a single power inlet to multiple electrical loads spread throughout the building, which can be connected or disconnected at any time. Using mains cabling for communication purposes has a number of implications.

The topology of the power network is highly variable between installations, depending on the size and type of building, and there can be many branches. The topology can also alter as electrical items are plugged into or unplugged from the network. The extended nature of the topology can give rise to signal 'fading', i.e. significant fluctuations in attenuation over time which are different at different signal frequencies [96,105].

The connected electrical equipment will include items such as fluorescent lighting, electric motors for lifts and other machinery, heaters, air conditioning units, IT equipment and many other appliances containing switched-mode AC-DC power supply circuits. These items present very low and time-varying impedances on the power lines [106,107], making the conditions for signal transmission very unpredictable; and again creating high attenuation at signal frequencies which are both time and frequency dependent. In addition, the electrical appliances inject electrical noise back onto the power cables, in the form of impulse noise and tonal interference at various frequencies, which can impede or prevent signal transmission [105]. Furthermore, sources external to the building may inject noise signals into the power cabling, which serves to exacerbate the situation.

Taken together, these factors of signal fading, noise and interference of various types create an extremely harsh transmission environment, increasing the probability that signals could suffer corruption during transmission. For the building control system, this can mean that messages, intended as instructions to operate the heating or lighting, are not received or are misinterpreted. Messages intended to relay information about the environment, such as light level, temperature or humidity may be lost, preventing the system from carrying out its functions properly, reducing building energy efficiency and creating a non-ideal working or living environment for the occupants. To some extent, as with any typical multi-layer communication system [108,109], intermittent signal loss can be mitigated by higher-level protocols (for example, hand-shaking and repetition of messages where they are not acknowledged) but even these methods will fail where the signal quality is too poor.

5.3. PLC innovations

The above problems must all therefore be addressed for PLC to be reliable enough for intelligent building automation purposes in future cities. A number of approaches to improve the reliability and robustness of PLC technology have been proposed at various times, much of this work concentrating on either Smart Grids, remote meter reading or on residential computer networking. One attempt to break in to the commercial building market involved a hybrid architecture including high power amplifiers and some dedicated twisted-pair cabling to bridge the PLC signals across 'troublesome' parts of the building [101]. Such systems are not in evidence today, indicating a lack of acceptance by the industry, probably due to erosion of the advantages of PLC, namely the need to install dedicated wiring as well as extra equipment.

Various configurations for noise filtering have been suggested [110–112]. Some systems have been implemented in products for residential use [113,114], however this is frequently impractical, depending on the application.

Use of multiple transmission frequencies for signal diversity provides a potential solution [115]. Building on this concept, rather than using just two spot-frequencies for narrow-band transmissions, spread-spectrum techniques borrowed from the radio communications world were tried [116], which used many frequencies across a wider signal bandwidth. Initially, this meant conventional spread-spectrum using frequency hopping or phase modulation. However, more recently, a number of spread-spectrum protocols have arisen which are based on *orthogonal frequency division multiplexing* (OFDM) [117,118]. This method of modulation is used in 3G mobile telephony and broadband DSL provision along copper telephone cables. On top of these advanced modulation techniques, various robust data communication protocols may be applied, such as forward error correction, data redundancy and mesh networking.

5.4. PLC approach for BEMS

One approach [119] for BEMS applications seeks to overcome the aforementioned PLC limitations of:

- High attenuation in the signal path – caused by low line impedances and multiple connected loads with low impedance which may also be time-varying,
- Conducted electrical noise – from nearby equipment of various types and frequencies,
- Signal distortion – due to line impedances and reactive loads producing unpredictable frequency responses, which may also be time-varying, and
- Frequency-selective fading – due to signal reflections causing multi-path effects, which again may be time-varying as the network topology changes.

To provide an electrical environment suitable for reliable PLC transmission, the approach [119] introduces two key factors:

Firstly, inexpensive filters are inserted at the input to each

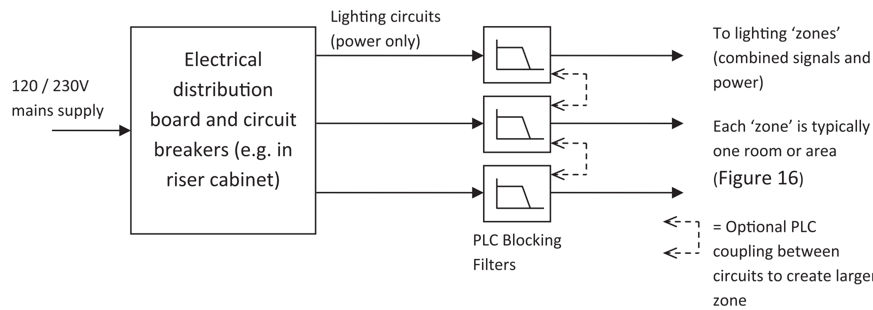

Fig. 15. Using filters to create zones.

lighting circuit (typically at the electrical distribution board) (see Fig. 15) which significantly reduce conducted noise at PLC frequencies. Because they also block PLC transmissions, this creates separate 'zones' for PLC transmission within the building, each zone typically encompassing a single room or area. This has several benefits:

- Noise and interference on each circuit are substantially reduced,
- the smaller size of the PLC transmission zones reduces the effect of signal fading and,
- the amount of network traffic at each PLC transceiver is also significantly reduced, thereby allowing lower bandwidth, hence simpler and more robust, transmission techniques to be employed.

Furthermore, the filters present relatively high load impedance at PLC frequencies looking into the lighting circuit. This means that the typical very low line impedance of the incoming power supply lines is no longer 'seen' by the PLC transceivers. In order to increase the size of the PLC transmission zones, each filter includes input/output ports which allow PLC signals (but not mains power) to be connected across several lighting circuits. For even larger networks, and to allow external access for monitoring and control, a second type of communications interface, e.g. Ethernet, is provided on certain units, designated as 'gateway units' – one per PLC zone (shown in Fig. 16).

Secondly, components within each control unit isolate the PLC transmissions from the connected loads, such as lights. This protects the PLC transmissions from the effect of low and time-varying load impedances, because the power wiring around each unit is effectively split into two regions – one for the connected loads, which may have low impedances, significant noise, etc., and one for PLC transmission. The PLC signals therefore experience much higher impedance, lower attenuation and lower noise than would otherwise be the case.

Practically, to enable the PLC architecture to be effectively implemented in BEMS applications the proposed solution utilises standard building wiring techniques and installation practices, avoiding excessive retrofit costs. The approach builds on the fact that, in many commercial buildings today, the wiring for lighting circuits increasingly uses multi-connection units or "marshalling boxes" to distribute electrical power to individual luminaires by means of pluggable connectors (Fig. 17). Typically these units are usually located above suspended ceilings and are distributed throughout the building. They contain no control, intelligence, communication, or networking capability.

The proposed solution replaces standard marshalling boxes with intelligent control units, each containing a PLC transceiver and multiple connectors for connecting to loads such as lights, heating, air-conditioning, etc. The units can control these loads, either directly or using relays, and also have inputs for sensors to detect temperature, light level or other parameters such as relative humidity or CO_2 level, as required. The units form a network, communicating with one another using PLC, which means that installing them requires only the same skills as installing the dumb marshalling boxes. There will typically be several units attached to each lighting circuit within the building.

The combination of PLC zone filtering and control unit isolation means that a transmission environment is maintained, suitable for high integrity robust PLC-based communications. Furthermore, the fact that the communications and control features are all provided in a lighting marshalling box format means that standard wiring and installation techniques can be used, which will be familiar to electricians and building owners alike, without specialist training.

The proposed solution therefore provides a low-cost, low-disruption method of providing robust networking suitable for building monitoring and control in cost-sensitive applications, such as small to medium commercial buildings.

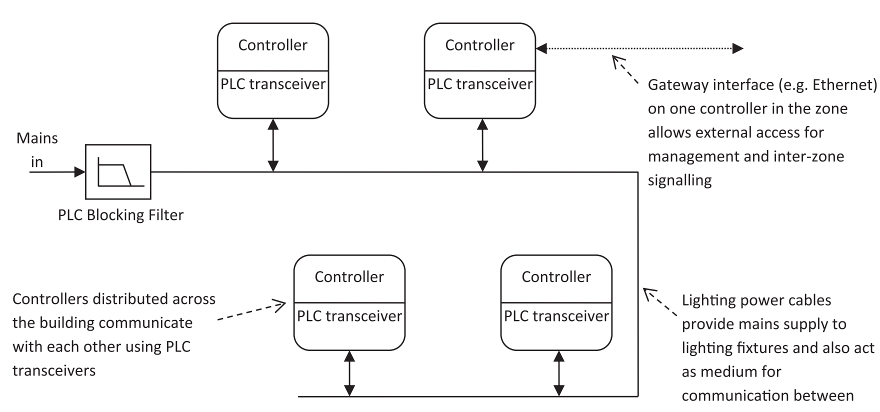

Fig. 16. A single communications zone.

Fig. 17. Example marshalling box.

5.5. PLC remarks

Whether one technique or another is appropriate and effective depends on the exact application and how it is implemented. This can make significant difference in achieving cost-effectiveness and customer acceptance of the solution. The challenges are great, however it is generally agreed that, if they can be overcome, the result will be an extremely elegant solution to the problem of providing a robust, low cost and low disruption communications path for commercial building automation in future sustainable cities.

The PLC approach discussed above has been developed through Innovate UK funding. The novel solution is subject to further field trial investigation through the oversight of University of Nottingham and the National Energy Foundation, at Costain PLC temporary site accommodation, Rotherham, UK and the National Energy Centre, Milton Keynes, UK. Whilst theoretically implemented and proven in a previous pilot study [120] the success of the approach will be judged based on the findings from the field trials, set for publication in 2017.

6. Conclusions and further work

The work presents the continuing need for BEMS within the commercial built environment of future sustainable cities; providing energy reduction in the greatest end-use energy demand sector. BEMS are especially applicable in non-domestic environments to overcome adverse occupancy effects between building design and use. To date extensive development of control strategies has been conducted, mostly utilising FLC of the PMV metric for internal thermal comfort.

Traditionally, BEMS have been implemented in large non-domestic buildings. A clear case has been made for implementation of BEMS technology in SMSND buildings, due to the extent of premises and their average energy consumption figures. A broad range of systems are available commercially. Sixty systems have been investigated and grouped into the size of building premises they service. Versatile systems, capable of satisfying the demands of differing premises are required to enable a strong economic argument for exploitation into the sector.

Most BEMS for smaller buildings rely on wireless based communication, however range limitations have been observed. To enable sufficient versatility for practical implementation in the SMSND building sector, a potential alternative communication technology, PLC, has been reviewed. This work has shown that there is scope for PLC utilisation in BEMS technology, targeted at SMSND buildings in future cities. Problems, however, such as signal quality and electrical noise must be mitigated before implementation can be practically considered.

6.1. Further work

Further investigation into PLC technology could further identify optimised approaches that overcome the limitations identified. Such areas that would be beneficial to investigate include:

- Comparison of performance of different modulation formats/ transmission techniques, to include the latest developments in meter reading technology, specifically investigating whether noticeable benefit is achieved in the more benign (post-filter) environment created, or whether the benefits of expensive or exotic new techniques are only marginal.
- Development of simplified mathematical models for predicting PLC transmission performance in built environment applications.
- Investigating a wider range of signals.
- Incorporating diagnosis of devices based on electrical signal – categorising in system to aid monitoring, analysis, control and maintenance of appliances.
- Research and development of alternative applications for a range of typical building wiring applications and building types.

Subject to the findings of the forth coming field trial, and in addition to the fundamental developments already listed, further work investigating wider applications where the proposed PLC approach could be employed would be beneficial. Applications where powerlines are present and monitoring and control is desired would be suitable for further investigation.

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