Monitoring the built environment: Developing a dynamic tool to optimise renewable energy use and energy efficiency at a community scale using GIS

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Abstract: Within the framework of the well-recognised need for a more sustainable future, a number of ambitious targets and energy policies has been set, regarding CO_2 emissions and energy savings. As buildings are responsible for the 40% of the global energy consumption, it is crucial to optimise the contribution from renewable energy resources in the built environment, as well as to use the energy in the most efficient way. It is therefore necessary to enable the ability of in-depth monitoring in the built environment, at a larger scale than an individual building.

This study investigates the role that monitoring can play with regards to encouraging renewable energy use and optimising energy efficiency in the built environment, by developing a dynamic tool that can be used both at an individual building level and at community level.

A bottom-up methodology will be presented that incrementally aggregates buildings into a community level tool using a set of case studies. The number of buildings included within the tool will be gradually increased to collate information about a live monitoring experience of multiple buildings, located on different sites in South Wales. Besides new ways to use monitoring in the context of sustainability, the conclusions of the study cover a variety of aspects related to the monitoring process, including choice of sensors and meters, data management (collection, transmission, storage and processing), availability by other stakeholders, choice of platform to manage the monitoring data, and cost-benefit analysis.

Keywords: retrofits, live building monitoring, community level, energy efficiency, renewable energy

Introduction

Energy use in built environment

Energy use in buildings is one of the most critical factors when aiming at mitigation of greenhouse gas emissions and global warming. 40% of the total energy consumption in European Union and approximately 36% of the greenhouse gas emissions are related to buildings (Departments of Business Energy & Industrial Strategy, 2017). The building sector is responsible for more than 40 percent of the European energy consumption but as stated in the IPCC WGIII Assessment report at the same time it offers the best technological opportunities to reduce energy consumption and greenhouse gas emissions.

The majority of the energy comes from fossil fuels, which leads to two major problems, the finite nature of fossil fuels and the air pollution caused from combustion, which is also related to climate change. A chain of impacts initiates from the energy consumption in built environment, which demands action in two general directions: Consume less energy and consume renewable energy as much as possible. In general, energy retrofits aim to improve the indoor environment, using less energy and renewable energy, and this study aim to quantify their efficiency.

Over 20 million houses exist in the UK and the annual replenishment rate is just 1%. Consequently, there is an increasing interest of the involved stakeholders on large scale retrofit programmes (Department of Energy and Climate Change, 2013). There is therefore a need for rapidly employed large scale retrofit programmes to take place which improve the housing stock, reduce emissions, create employment and improve quality of life and occupants' wellbeing whist being at an affordable level. Large scale retrofit programmes are planned and managed to be environmentally, economically and socially effective as possible.

In this context, an increasing attention has been drawn over the last decade, in building energy performance and its evaluation, specifically considering deeply retrofitted buildings (Turner & Frankel, 2008; Scofield, 2009; Fowler et al, 2010).

However, a "performance gap" is well recognised in relevant literature, indicating that retrofits as well as new buildings do not perform as expected. Dissatisfaction with the indoor air quality and with thermal comfort is common and the energy efficiency is not in the targeted level regardless of the new technology utilized and advanced systems installed (Menezes et al., 2012).

At present, however, technical systems in buildings are not usually monitored to confirm their performance or to check the energy efficiency of their operation. (Neumann and Jacob, 2008). Building performance is commonly specified and assessed in terms of desirable ranges of pertinent performance variables. Whereas building designs can be evaluated only based on virtual (e.g. simulation powered) monitoring of such variables, performance assessment of operating buildings should preferably rely on actual monitoring (Zach et al., 2014).

In this context, the need for large scale retrofit programmes is essential. Furthermore, there is a significant need to develop a systematic approach to evaluate the impact of the retrofit programmes. Aim of this paper is to introduce the concept of collating and visualising monitoring data from multiple buildings in a web-based platform. The scope of the present study is large scale domestic retrofit programmes.

Monitoring is the basis for improving

The famous quote from Lord Kelvin is more than valid when building performance is considered: "To monitor is to know. What can´t be measured can´t be improve either" (Wikiquote, 2018).
Here lies the importance of applying monitoring in large scale retrofits programmes.

To evaluate the actual outcome of a retrofit it is necessary to monitor the performance of the building both before and after the retrofit. To evaluate the performance of large scale retrofitting programmes, the methods used in individual buildings are no longer applicable and it is necessary to develop new tools, in order to collate and visualise the monitoring data, using a method applicable to a scale of hundreds of buildings.

The often significant discrepancy between the designed and real total energy use in buildings was recognized in IEA ECBCS Annex59-project "Total Energy Use in Buildings - Analysis and evaluation methods". In the annex the following six factors influencing building energy consumption were defined (Figure 1): (1) climate, (2) building envelope (windows, wall, roofs, etc.), (3) energy-using equipment and systems (building services), (4) operation and maintenance of the building and its systems, (5) occupant behaviour and activity, and (6) requirements for the indoor environment.

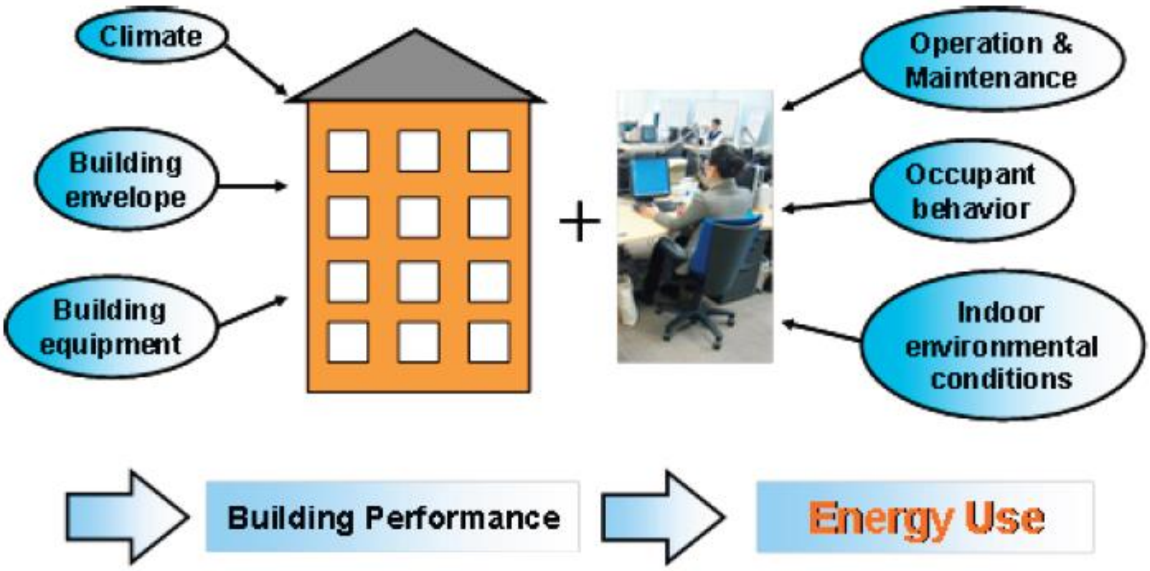

Figure 1. Six factors influencing total energy use in buildings (IEA, 2016)

According to the annex especially the latter three factors, related to human behaviour, can have an influence as great as or even greater than the former three. Therefore it is necessary to investigate all six factors together to understand building energy use data.

To monitor the energy use of one individual building, a monitoring system needs to be established. Besides energy meters and sensors used for data recording, a typical monitoring system should consist of data collection, data transfer and data processing (Figure 2). In the case of large scale monitoring, an additional step is to collate and visualise the monitoring data from multiple buildings.

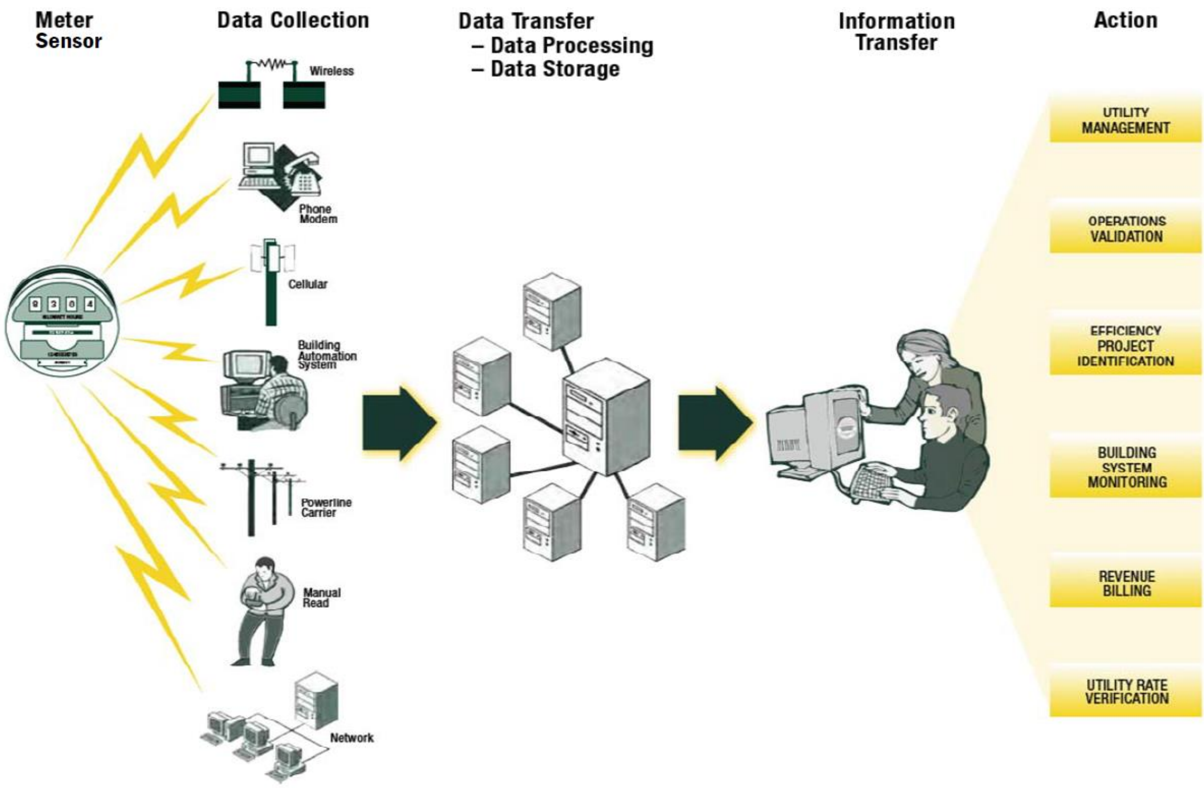

Figure 2. Basic elements of a monitoring system (IEA, 2013)

2. Background

The collation of large scale monitoring data is not common in literature. Only two relevant case studies were identified in literature, where large scale monitoring data were collated in one web-based platform. In both cases this platform is a Geographical Information System (GIS) based platform.

In the first case study, a GIS platform was used as support tool for developing a sustainable energy action plan in the municipality of Randazzo, which is situated at the northern foot of Volcano Etna (37°52'37"56 N; 14°57'1"80 E; altitude 765 m), 70 kilometers northwest of Catania (Gagliano, 2015).

The Randazzo study aimed to help local communities to make decisions for estimating and monitoring the energy consumption in buildings (residential, commercial, industrial), and to simulate effects of energy policies (the process is shown in Figure 3). The implementation of GIS platform was essentially used to give a mapping representation of the actual state of energy resources and demand, to develop sustainable energy policies. Large scale energy consumption data from multiple buildings is collated in a GIS database and is linked with the buildings' characteristic. Although, the energy consumption of the Randazzo municipality was calculated, using historical data from databases: the Regional Informative System for Environment and Energy, and the National Census database year 2001, 2006, and 2012 (Gagliano, 2015). Therefore, in the Randazzo study energy consumption data was provided by modelling and calculations, rather than monitoring. The scope of the Randazzo study includes mapping data from all kinds of buildings in the municipality. The aim of the Randazzo study is to use mapping representation in a GIS platform to develop sustainable policies.

The Randazzo study concludes that the adoption of a GIS-based platform proved to be a suitable support tool during the phase of elaboration of a Sustainable Energy Action Plan, as well as during the phase of realization. A further conclusion of the same study is that it is possible to propose such methodology for application in different geographical areas or context, such as to support energy policies at the urban level, or to make decisions for estimating and monitoring the energy consumption in residential, commercial or industrial buildings (Gagliano, 2015). Therefore, even if the Randazzo study is not focused on monitoring energy consumption, it is concludes that GIS platform is suitable for collate and visualising energy consumption monitored data.

The second project that uses GIS platform to collate and visualise monitoring data, is U-eco-city in Korea. U-Eco City is a research and development project initiated by the Korean government in 2008 (Shin, 2010). The project's objective is the monitoring and visualization of aggregated and real time states of various energy usages represented by location-based sensor data accrued from city to building scale. The system is not only used by energy management specialists but also by the general energy consumer.

In this context, a prototype energy monitoring system called EnerGIS was presented. It is a Web-based rich-internet application (RIA) integrating a 3D geospatial viewer based on the Google Earth platform and Google Maps components with additional data visualization modules. Combining city information model data from the database, power sensor data through sensor network, and environmental GIS data, it builds up its own monitoring database.

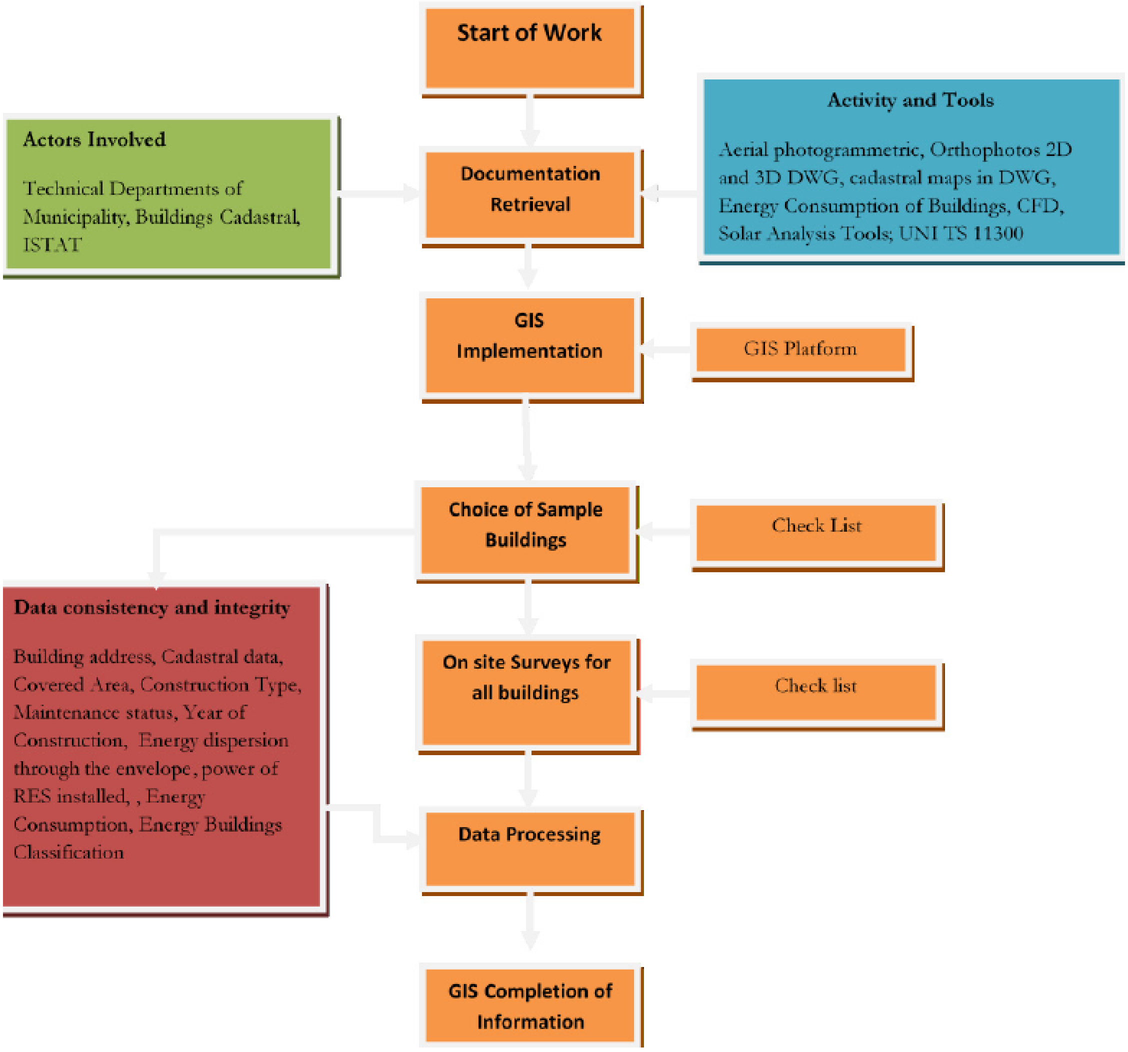

Figure 3. Stages of the process (Gagliano, 2015)

The main characteristics of the Korean project are:

- Web based platform
- Intuitive statistical data visualization
- Real-time based sensor data collection and data optimization
- Dynamic data loading and visualization
- Extensible city information

The research objectives:

- Optimized data structure model of urban environment
- Data optimization for 3D city representation
- Visualization strategy

This paper summarises the gains from designing the database structure to enhance system performance and to implement a customized middleware engine to optimize the visualization method, which is mainly based on a Level of Details strategy. In this process, significant knowledge was acquired for databases that manage large amounts of data that are continuously aggregated by time flow, and for a system architecture that represents an energy driven urban environment. Furthermore, the know-how for a web based management system was developed, which delivers sensor data, statistical data mining and diverse information visualization.

3. Methodology

A bottom-up methodology from one individual building to large scale

The proposed concept is to collate and visualise monitoring data from multiple retrofits in one single GIS-based platform using bottom-up approach. The case study of one individual dwelling (case study one) is used as a pilot case to define the framework for a replicable process, gradually adding monitoring data from multiple buildings into a single GIS-based platform.

The advantage of this accumulative approach is that different challenges will be revealed at each step of the upscaling and more easily solved due to gradually increasing the number of buildings.

Case study one will give a clear picture for the potential effectiveness and applicability of collating and visualising monitoring data into one platform, and the challenges related within each different scale of the process, while preparing the framework for future work.

Case study one

Case study one is a dwelling which was retrofitted as part of the SPECIFIC 2 LCBE Project, led by WSA at Cardiff University. This is a pre-1919, solid wall, end of a terrace house, which is owned by a social housing company, located in South Wales (Figure 4). The house was chosen as its layout is representative of the existing building stock in Wales, it has two storeys with a footprint of 36 m^2 (total floor area of 72m^2). The living room and kitchen are on the ground floor with two bedrooms and bathroom on the first floor. The house has a garden accessed from the rear façade plus a side gate from the street (Figure 4).

Figure 4 – Building envelope (SPECIFIC 2 LCBE Project)

As part of the SPECIFIC 2 LCBE Project, a semi-structured interview evaluating occupant behaviour and appliance and lighting use was carried out to assess the building performance before the retrofit. Geometric dimensions are presented in Figure 5 and properties of the building fabric are presented in Table 1.

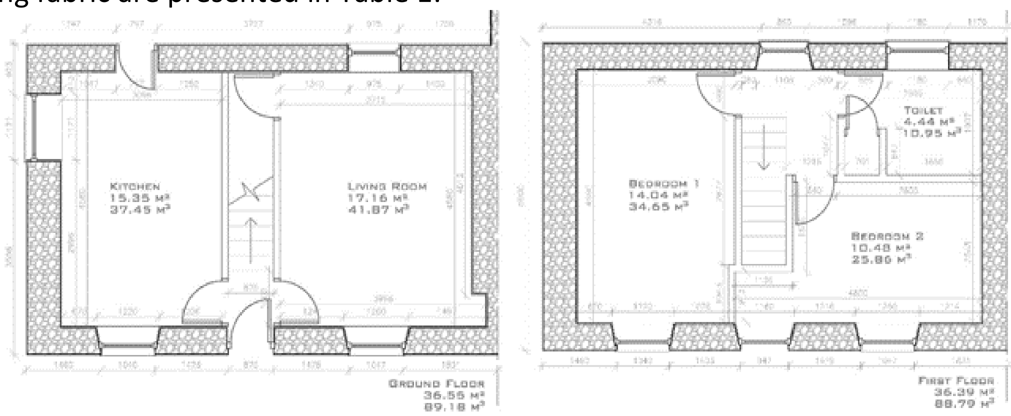

Figure 5 – Building's layout (SPECIFIC 2 LCBE Project)

Element	Measured U-value (W/m²K)*	Estimated U-value (W/m2K)**
External wall, East (50cm non-insulated solid wall + Spa dash)	1.45	-
External wall, West (50cm non-insulated solid wall)	1.50	-
External wall, South (70cm non-insulated solid wall + Spa dash)	1.30	-
Party wall, North (50cm non-insulated solid wall)	-	1.50
Loft	-	0.25
Ground floor	-	2.70
Window	-	2.20
Door	-	2.20

Table 1. Thermal properties of the building, (SPECIFIC 2 LCBE Project)
*Based on survey of property.
**Based on Energy Performance Certificate (EPC) data.

The building has a wet heating system fuelled by a gas combi boiler. Heating is set by occupants at 19°C which is boosted up to +30°C at times. Both the ground and the first floors are heated, the loft space is unheated. The Domestic Hot Water (DHW) is heated instantly by the combi gas boiler, which has a measured efficiency of 80%, the shower is electric. To ventilate the house, occupants use natural ventilation, controlling the opening of windows and trickle vents.

The retrofit which took place as part of the SPECIFIC 2 LCBE Project, included fitting internal and external wall insulation, TSC and MVHR installation, solar panels and battery installation.

Data collection

This paper will focus on the use monitoring data to be included in the web-based platform, an optimisation is needed to ensure two criteria: a) the monitoring data will be sufficient to lead to meaningful results, and b) the amount of data remains at a manageable level. Further data which add complexity to the system, without equally contributing to the results, are to be avoided.

The aim of the monitoring defines what data is meaningful. For the purpose of evaluating a retrofit it is essential to measure the building performance before and after the retrofit. To evaluate the building performance the following information is necessary:

Fabric: To evaluate the financial and environmental impact of fabric improvement, energy consumption is correlated with the U-values of the buildings. This data can help to compare between well and not insulated buildings, to quantify the impact of insulating interventions, and reveal performance problems in certain buildings. The size and the type of the building are also important for this evaluation. That type of data is characterized as static, since it remains unchanged with time. Regarding the case study one, this information is extracted from the survey, measurements and EPC data.

Energy consumption: Electricity and gas consumption are monitored. Majority of dwellings are connected in electricity and gas grid (Energy Consumption in the UK, 2017).

Regarding gas, which can be further broken down in heating space, heating domestic hot water (DHW), cooking and in some cases other appliances using gas as fuel. According to literature (Energy Consumption in the UK, 2017) energy consumption for heating space is the dominant factor (56%), second is domestic hot water (22%) and last is cooking with only 6%. Total gas consumption is sufficient for the comparative study before and after the retrofit. In the case of electricity, besides electricity consumption, there is electricity generation, as renewable energy systems installation is a common practice in retrofits. In order to simplify the system, total energy consumption may be used, without sub-metering. According to ASHRAE 14-2002 Guideline for measuring of energy and demand savings, 15-min interval is suggested to measure both the gas and electricity consumption.

Regarding case study one, gas and electricity consumption data is monitored using the monitoring system installed within the SPECIFIC 2 LCBE Project.

Environmental data: To evaluate the energy performance of a building, the energy consumption needs to be correlated with the indoor and outdoor environmental data. Representative aspects to describe thermal conditions are temperature and relative humidity. Solar irradiation, wind speed and wind direction are significant environmental data, but for simplifying the process those environmental data are not implemented into the platform, as the complexity added would be more than the contribution.

Regarding outdoors temperature and relative humidity, one option is to install a weather station (or a simplified form of one outdoor temperature/humidity probe) outside every building, and the second choice is to take outdoor data from the nearest available weather station. Regarding case study one, installing a probe in the building is feasible, but eventually, when applied in hundreds of buildings this will not be feasible. In that case, one weather may be installed for every neighbourhood, or data may be obtained from a local weather station, in case there is one.

Regarding indoor temperature and relative humidity, major spaces that are common in all houses are the bedrooms, living room, kitchen and bathroom. To simplify the system, one value per house is used as an indication of the indoor temperature and relative humidity. As a representative space is chosen the living room, as it is the most demanding space of the house regarding thermal comfort (CIBSE guide).

People: The number of residents is affecting the energy consumption, as the needs for space heating and for hot water are directly related with the number of residents. Occupancy related data can be altered without following a specific pattern. Regarding the case study one the information about the initial occupancy status is extracted from the survey contacted by the SPECIFIC 2 LCBE Project. Surveying at predefined times may be used to update the number of residents in future.

4. Results

This paper introduces the concept of collating the monitoring data from multiple building in one web-based platform. Case study one has resulted in a clearer picture of the needs for collating and visualising from multiple buildings, which are presented below as a series of steps:

The process from data recording to data visualisation

Step 1: Data recording

Data recording takes place exactly the same way as it would have been for monitoring one individual building. Gas and electricity meters were installed to measure gas and electricity consumption respectively, whilst a temperature/relative humidity sensor was placed in the living room and a temperature/relative humidity probe was placed outside the house. A PV system is installed on the roof of the dwelling, so an additional electricity meter was installed to monitor the generated electricity.

Step 2: Data transfer

As the main objective of this replicable process is to collate data from a large number of buildings, a manual method of data collection and transfer would not be efficient. An automated and remote method of collection and transfer is needed, to facilitate data transfer from a large number of buildings and from multiple sites. A web-based data transfer method is chosen, to ensure a remote and automated process. To enable the remote data transfer, the monitoring data needs to be collected and locally stored in a data logger. A data logger is installed in the dwelling and programmed to collect the monitoring data and to transfer it to a web-based platform. An internet connection is ensured to connect the local data logger with the web-based platform.

Step 3: Data pre-processing

The monitoring data is being collected and transferred as raw data. The format of the raw data depends on the type of the sensor, most likely a csv or an excel file. A pre-processing stage is needed to convert the raw data into a suitable for further processing format. Firstly, the file is to be converted to an excel spreadsheet in case it is generated as one, as this format is easily manageable for further processing. Secondly, certain calculations may be needed to convert raw data into meaningful information. For example, in case of measuring gas consumption with a pulse meter, the raw data is counts of pulses which is transformed to consumption units using simple functions.

In the case of one individual building this process is manually preformed, but this method is not efficient for managing monitoring data at large scale. This point is one of the technical challenges to be met.

Step 4: Data processing

The final step is to collate the monitoring data from multiple buildings in the same web-based platform. Processing the data may include different tasks depending on users questions, may be creating combined charts to compare different buildings, collating buildings with similar characteristics, creating daily profiles with regards to the time.

Step 5: Data visualising

Visualisation may vary depending on the objectives, might be a chart, a bar chart, or a coloured map to represent consumption level.

Classification of the challenges

Technical challenges.

The main challenge revealed is the need to automatically manage the monitoring data, at the pre-processing and processing stage. According to relevant literature (Shin, 2010) this challenge may be addressed by developing a middleware, a specialised software to facilitate the pre-processing data to implement it in a database.

An automated processing of the data is needed, after the implementation in the platform. Depending on the kind of data a different process is needed, to visualise the variation of a data set or the comparison between different datasets. The platform needs to provide the adequate visualisation techniques, to transform datasets into a graph or a bar chart. A necessary feature of the web-based platform is the flexibility to change the grouping of sites and the choice of data on demand. The adequate platform should provide the flexibility to investigate a variety of questions, by easily grouping different buildings based on their characteristics.

Financial challenges.

The development of a monitoring system includes the installation of the sensors as well as the equipment for data collection, for local data storage and for data transfer. The choice to monitor a large number of buildings instead of choosing individual case studies multiplies the number of monitoring systems to be installed. That causes a considerable cost, regarding equipment (mainly sensors and data loggers), as well as specialised personnel for the installation.

The process of upscaling is designed to upscale gradually, by doubling the number of buildings at each stage. The process of upscaling will be beneficial up to a certain extent, due to a certain extent. Beyond that extent the benefits will not be able to justify the additional cost. A cost-benefit analysis for each stage of upscaling is needed to quantify that extent. This can be investigated as part of future work.

An alternative solution to this challenge, is installing smart meters within the retrofitting programme. Smart meters collect and transfer the energy consumption data in a digital form, which reduces the cost, as there is no need for installing meters and a data collection/transfer system. In this case, an alternative solution regarding environmental data is needed. Weather stations may be installed for each neighbourhood, or data from existing weather station may be retrieved. Regarding the indoor temperature, the set point may be used as an indication, or smart meters with integrated sensor may be chosen.

Social / legal challenges.

A significant challenge that may arise, regarding privacy issues related with the energy data. Energy consumption data may be used for commercial purposes, it is considered as private data and the right to this data is legally protected. The consent of the tenants is necessary to use this data for research or energy management purposes.

A related challenge is that in the case of smart meters and PV installations the data is managed by companies. Suppliers or renewable installers may deny to share data.

5. Conclusions

The value of collating and visualising different types of related data

The value of collating different types of monitoring data (energy consumption, fabric, environmental, people) from multiple buildings is justified by the following benefits.

Firstly, the actual outcome of a retrofit programme will be validated. The impact of large scale retrofit programmes is essential to reduce energy consumption and carbon emissions in the built environment, but also a further effort is needed in order to verify that the outcome is close to the ideal (Newsham et al, 2009). The lack of this further effort might cause a significant 'credibility gap', as monitoring and assessing buildings post occupancy performance after the initial design and construction is not the common practice. Without this feedback, the actual efficiency of each intervention remains invalidated, a successful one would not stand out or an unsuccessful one might be repeated (Bordass et al., 2004).

Secondly, different types of monitoring data will be correlated in a holistic analysis. Literature shows that the actual result of the energy performance of a building is not matching the ideally expected one, as it was calculated through the design and the modelling process (Darby, 2008; Menezes et al., 2012). The combined study of all the related factors is aspired to shed light to this performance gap between the expected and the actual outcome. In addition, large scale monitoring data will contribute to further optimisation of the modelling process for planning future retrofit programmes.

Thirdly, the holistic analysis may contribute to the quantification of the social aspect of the retrofits. A main driver for retrofits is to fight fuel poverty and improve the indoor environment, including thermal comfort, air quality and lighting. This is a very important aspect of the retrofit, which may be indirectly evaluated, by relating the energy consumption with the indoor conditions before and after the retrofit.

Finally, collating monitoring data from multiply houses, eventually structures a network between houses at community level. In this network essential information is gathered, such as real-time data about energy usage and generation, related with the spatial and temporal factor. That infrastructure may have a major contribution to the recent discussion about the decentralisation of the energy system (van der Schoor et al., 2016). Based on this network, the applications may extend from monitoring to energy management at community level. Moreover, new potentials can be explored such as community shared renewables and energy storage units (van der Stelt et al., 2018).

6. Discussion and future work

The potential users

The significance of the proposed concept is evaluated with regards to the potential users. Moreover, the way forward to future work is depending on the potential users, as the focus of future work is depending on the type of potential users:

1. Public authorities or institutes, that implement large scale retrofitting programmes at municipal, regional or even national level. In this case the focus will be on evaluating the effectiveness of a programme and collecting data for future planning.
2. Energy suppliers and energy management companies. Real time monitoring of energy data related with spatiotemporal aspects may help balancing the network at community level. Real time monitoring may also contribute to dynamical tariffing system, based on the local demand and supply. Energy managements companies may implement community based approaches or social enterprises may take action in energy management at a local level. In this case, the focus will be on real-time data and balancing between energy production and demand at community level.
3. The tenants themselves may be the end users. In combination with dynamic tariffing system or local energy management, a user friendly application may inform the tenant about the energy consumption, the efficiency, the indoor/outdoor temperature and to suggest potential ways to reduce the bills and to optimise the energy usage. In this case, the focus will be on the end user.

The GIS-based platform

Future study aims to investigate the use a Geographical Information System (GIS) platform to collate and visualise the monitoring data, as it appears to have a number of benefits. In the last years, many studies have used GIS platforms for energy and environmental prediction models. In addition to facilitating a realistic representation, GIS provides an adequate platform for multilayer analysis. Further, the GIS platform has been valued for improving communication and collaboration in decision making, for effectively managing resources and improving the accessibility of information. Further, spatial mapping enables implementing more features in the platform, such as renewable sources or energy storage units. Therefore, GIS is recognised to be able to play a significant role as a platform for systematic approaches, integrating energy models and interactively linking them to real-world data (Gagliano et al, 2015).

A further benefit is that relating the data with the spatial aspect multiplies the potential for further analysis. Special areas of interest can be isolated and studied in detail. Space geomorphology may be related to environmental factors or influence the expected efficiency of the intervention. Fuel poverty issues may be analysed with regards to geosocial distribution of the population. Post occupancy studies may relate certain behaviour with spatial aspect. Many more spatial correlations with energy related data may arise depending on different approaches.

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References

ASHRAE's guideline 14-2002 for measurement of energy and demand savings: How to determine what was really saved by the retrofit.

Bordass T., Cohen R., Field J. (2004). Energy performance in non-domestic buildings: closing the credibility gap. In: Paper presented at the Building Performance Congress 2004, Frankfurt, Germany; 2004.

Darby S. (2008). Energy feedback in buildings: improving the infrastructure for demand reduction. Build Res Information; 36(5):499-508.

Fowler Kim M, Rauch EM, Henderson JW, Kora AR. (2010) Re-assessing green building performance: a post occupancy evaluation of 22 GSA buildings June 2010. September 2011. Prepared for the U.S. General Services Administration under Contract DE-AC05-76RLO1830 with Battelle Memorial Institute.

Gagliano A., Nocera F., D'Amico A., Spataru N. (2015). Geographical Information System as support tool for Sustainable Energy Action Plan, in: Energy Procedia 83; 310 – 319.

Kim S.A., Shin D., Choe Y., Seibert T, Walz P. (2012). Integrated energy monitoring and visualization system for Smart Green City development. Designing a spatial information integrated energy monitoring model in the context of massive data management on a web based platform. Automation in Construction 22 (2012) 51–59.

Menezes A.C., Cripps A., Bouchlaghem D., Richard B. (2012). Predicted vs. actual energy performance of non-domestic buildings: using post occupancy evaluation data to reduce the performance gap. Applied Energy, September 2012; 97:355-64.

Newsham G.R., Mancini S., Birt B.J. (2009). Do LEED-certified buildings save energy? Yes, but…. Energy Build 2009;41(8):897-905.

Neumann and Jacob . (2008). Guidelines for the Evaluation of Building Performance, Building EQ.

Scofield JH. (2009). A re-examination of the NBI LEED building energy consumption study. In: International energy program evaluation conference, Portland, OR; August 12-15; 2009.

Schoor T. et al. (2013). Energy Research & Social Science 13 (2016) 94–105.

Stelt V.., Tarek A., Wilfried v.S., (2018). Techno-economic analysis of household and community energy storage for residential prosumers with smart appliances, Applied Energy 209; 266–276.

Turner C., Frankel M. (2008). Energy performance of LEED for new construction buildings final report. White Salmon, WA: New Buildings Institute.

UK Housing Energy Fact File, Department of Energy and Climate Change, 2013.

2015 UK Greenhouse gas emissions, final figures, Department of Business, Energy & Industrial Strategy, 2017.

https://en.wikiquote.org/wiki/Talk:William_Thomson