WSN-BASED IEQ MONITORING SYSTEM: DATA ACQUISITION, PROCESSING, AND VISUALIZATION IN BUILT ENVIRONMENT

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ABSTRACT

This paper involves substantial research and development efforts that are necessary for the realization of highly versatile, scalable intelligent monitoring for concurrent and multi-layered environment data acquisition and monitoring in buildings. Thus, a new generation of Indoor Environment Quality (IEQ) monitoring system is presented, mainly in view of four IEQ parameters (illuminance, humidity, temperature, and pressure). Also, battery levels of the sensor nodes are dynamically monitored. This system was implemented at one office space as a "living-lab" in a selected sustainable office building in Tropics, whereby Wireless Sensor Networks (involving advanced wireless PV powered sensing nodes) and user interface development were conducted. Also, the implementation process of this IEQ monitoring system model was demonstrated. The outcome is expected for a multi-faceted use of collected benchmarking data relating to building stocks' environmental performance while meeting the objectives of a sustainable building operation regime.

Keywords: indoor environmental quality, user interface, environmental monitoring, wireless sensing network

1. INTRODUCTION

With space and resource constraints, a higher population density, and rising expectations from inhabitants, sustaining a quality living built environment that meets the needs and aspirations of a more diverse society is a key challenge. A number of innovative solutions are explored to address these long-term challenges which, if left unchecked, will result in serious physical, psychological, social problems such as physical illness, mental disorder, crime, slow public services and amenities, pollution, and energy wastage, and ultimately degrade inhabitants' well-being and increase dissatisfaction with public policies and their living environment. New buildings offer of course a field of opportunities to conceive, develop, implement, and test new sustainable and energy-efficient products and technologies. But the numerous existing building stocks represent undoubtedly the true challenge for improving the sustainability of the built environment. Thus, to achieve a higher level of living quality and sustainability (energy and resource efficiency) in the buildings sector, the consideration of the existing building stock is crucial. Toward this end, object-centered hardware developments (e.g. better thermal insulation of the building envelope, incorporation of efficient mechanical and electrical equipment, passive and active solar energy methods and devices) are important, but not sufficient. Specifically in the context of the existing building stock the intelligent (energetically and resourcially optimized) building operation is of utmost importance.

In this context, this paper involves substantial research and development efforts that are necessary for the realization of highly versatile, scalable intelligent monitoring for concurrent and multi-layered environment data acquisition in buildings. Thus, a new generation of Indoor Environment Quality (IEQ) monitoring system is presented, mainly in view of four IEQ parameters (illuminance, humidity, temperature, and pressure). Also, battery levels of the sensor nodes are dynamically monitored. This system was implemented at one office space as a “living-lab” in a selected sustainable office building in Tropics, whereby Wireless Sensor Networks (involving advanced wireless PV powered sensing nodes) and user interface development were conducted. Also, the implementation process of this IEQ monitoring system model was demonstrated. The outcome is expected for a multi-faceted use of collected benchmarking data relating to building stocks' environmental performance while meeting the objectives of a sustainable building operation regime.

2. BACKGROUND

There have been numerous past research and development efforts. However, most partially addressed certain aspects of the research effort's concerns, e.g. one reported mainly on the environmental data categories covered, and the other on the system architecture for monitoring of environmental data.

Diagnostics studies of various durations (from snap-shot measurements to multi-year monitoring) are frequently performed in the course of commissioning, litigation, and post occupancy studies. The cross-building energy monitoring has also a long research tradition and is currently becoming part of the commercial solutions for energy use optimization and system performance control (Krausmann and Haberl 2002; Gan et al. 2007; Mills 2010). Also, the design of appropriate data models to enable monitoring of performance metrics over the entire building lifecycle has been considered (O'Sullivan et al. 2004). Recent research activities highlight monitoring for intelligent commissioning (Plesser 2008; Piette et al. 2012).

The scope of most previous efforts in data acquisition and processing for existing building stocks is limited. There is a lack of truly comprehensive systems’ implementations. Wu and Noy (2011) demonstrated a wireless data set that monitors thermal and lighting systems operation in a laboratory building; how the retrospective data mining can be used to optimize building operation. Kordjamshidi (2011) used a combination of reference and monitored data to present a technique for energy labeling. Data from broadband access of homes were used to discuss simulation for optimization of metering information and energy management (Clarke et al. 2008). Jeong et al. (2011) tested the feasibility of wireless sensors for airflow modeling, and concluded that they were useful for model validation; but the sensors were expensive for residential solutions. Ha et al. (2012) reported that they could decrease configuration costs in their air quality study substantially by using a ZigBee sensor network. Oksa et al. (2011) describe in detailed requirements and methodology for building a wireless automated data acquisition system for small-scale buildings.

2.1 Previous efforts

In a previous research effort (Chien and Mahdavi 2011), we conducted a user survey (134 participants) and three focus group sessions (24 participants) to capture the views of the potential receivers of building monitoring information regarding the relative importance of different kinds of information and the modes and means of presenting and visualizing such information. We included two groups, namely building experts (system developers, designers, building operators, facility managers) and building users (occupants, guests). The main findings from this study were summarized as below.

2.1.1 Functional requirements

- "Experts" would require more comprehensive technical information from a building monitoring system. Such information includes indoor environmental information (concerning CO2 and VOC concentrations as well as illuminance, air velocity, and air change rates) and outdoor environmental information (including wind speed and direction as well as global irradiance).
- Non-expert users express more interest in information of general character, such as indoor air temperature and humidity, general outdoor weather conditions and outdoor temperature. Instead of detailed and comprehensive information levels, non-expert users should be provided with general and intuitively comprehensible information.
- A high level of interest in buildings' energy performance for both groups. A relevant question in this context may be the potential of user interfaces to not only provide energy use information, but also to moti-

vate users toward energy efficient behavior.

2.1.2 Cognitive design requirements

- The importance of interface design strategies that properly address mobile device usage for queries pertaining to building-related information.
- Advanced interface products that provide non-expert users with environmental information, must pay attention to the clarity of terms and navigational ease so that the interface of building monitoring system is easy to use and understand.
- The postures of the building monitoring user interface differ in view of user types. Potential users of sovereign posture application are typically advanced user types (i.e. building experts). On the other hand, Non-experts favor the user interfaces with a transient posture offering very short-term manipulation possibilities.
- The monitoring system interface should be available on a wide range of hardware devices, such that a convenient and ubiquitous access to building-related information is supported.
- It is important that the environmental information displayed in interface products is appropriate and effective for target user types. For example, the desired product should offer not only technical modes of information communication (such as charts and graphs), but also easily understandable elements such as icons and emotional pictorials and animations to present and visualize the environmental information.

3. PROTOTYPICAL REALIZATION

The observations analyzed in the previous section informed the resulting interface named as "WSN-based IEQ monitoring system" (see Figure 1). It serves as a user interface model for IEQ monitoring in a pilot living lab project. The end-users of this system are the building managers and research staffs (involving IEQ-related researches). In this section, firstly, the testbed infrastructure and system architecture are described. The design and implementation are then introduced.

Figure 1: Sample screenshot of the main page

3.1 Testbed description

To demonstrate the envisioned dynamic multilayered data acquisition and processing, an office in a new office building "CleanTech One" (completed in 2012) in Singapore was considered to conduct the prototypical realization under realistic conditions. This office (12.5m x 12.5m) is a living lab for building automation concepts (Eri@n test bed@ NTU) with thirty-two occupants (see Figure 2).

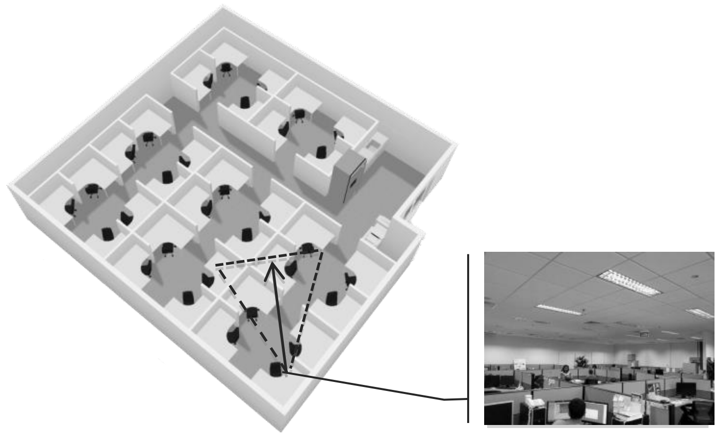


Figure 2: Schematic representation of the living testbed in CleanTech One building in Singapore

3.2 System architecture

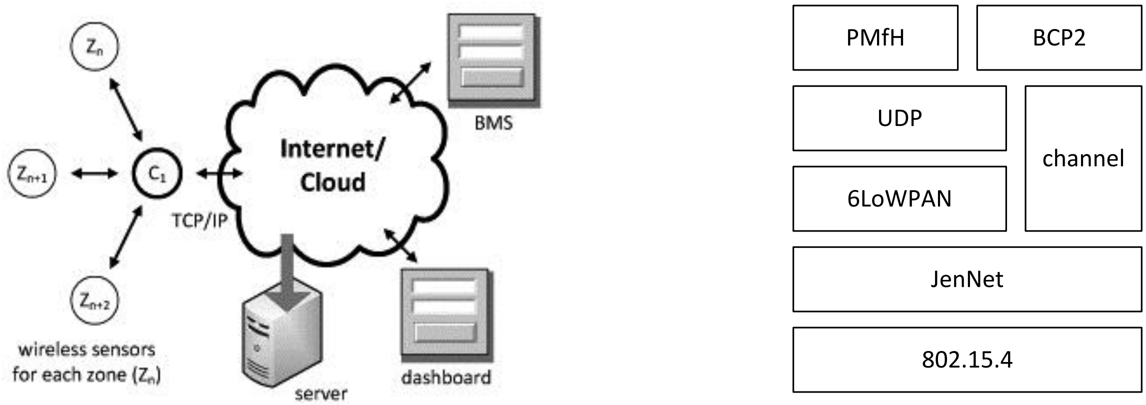
This Section is structured in three parts: the first part introduces the requirements which the distributed sensors need to provide. The next part gives a discussion on selection of technology and devices. Moreover, the actual networking structure and data acquisition framework is provided. Third, the operation of the sensor network is explained, and related to the intended research.

3.2.1 Monitoring System Requirements

The basic parameters for an IEQ management system needs are illuminance (brightness), temperature, humidity, and air pressure (Arens 2007; Edirisinghe et al. 2012). In addition, the data need to be provided reliably, frequently, and secure, i.e. an encrypted data exchange between the sensors and server at a sufficient monitoring rate is crucial. As buildings are rather static constructions, it can be assumed that no spontaneous or ad-hoc devices need to be integrated into the building monitoring network. Nevertheless, the opportunity of having wireless sensors makes installation as well as retrofitting convenient at a low-cost level. Based on the type and number of sensors, the nominal transmission distance, as well as the read-out rate an average power costs can be estimated (Li et al. 2011). That is, maintenance effort in terms exchanging batteries or complete modules (for reconfiguration) need to be avoided – particularly as low-cost deployment and operation is of high priority for accessing potential markets.

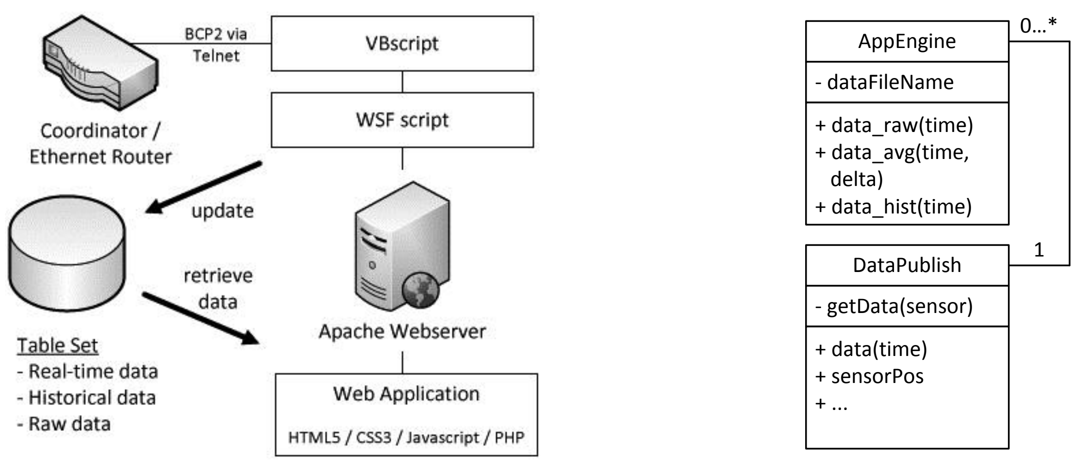
3.2.2 Device Selection and Network Structure

In order to meet those requirements, a sensor network in a star topology has been implemented in the selected testbed (see Figure 2). Figure 3 illustrates the structure of the complete network. The sensor modules (end points, EP) have both, a NFC interface (13.56 MHz) for commissioning, and a 805.15.4 radio module (2.4 GHz). The latter is for network access in order to do command and sensor data exchange with the coordinator (access point, AP) and eventually the database server and dashboard web application. Each sensor node (EP) has a solar cell with a light sensor. This allows harvesting of ambient light to extend the battery life. Moreover, the battery dimensions could be down-sized in order to save costs and space. In addition, a battery monitoring unit provides the actual voltage information so as to control/maintain a sufficient state of charge. As the system is operated in a test bedding environment for research purposes, data security at the air interface is of minor relevance. The preset selection of bands and the security keys are not fixed by BCPv2. However, security settings are generally possible via the NFC interface. (Here, authentication in order to prevent command and data manipulation, as well as data sniffing (privacy) is disabled. However, for a product release to market such security layers can be enabled, as they are part of the IPv6/6LoPAN protocol standard, too. For the moment, only safe data transmission routines are turned on, i.e. collision avoidance and packet data check sums are active as implemented in hardware in accordance to IEEE 802.15.4. As the BCPv2 protocol does not support commissioning, a NFC based configuration is used for out of band configuration. That is, the NFC interface allows configuration of each individual EP node such as transmission intervals, device numbers, and location settings. The settings are programmed by using a mobile device such as a cell phone with the NXP app Ease of Install (EoI). An Apache server accesses a MySQL database for updating with incoming sensor data, and retrieving data for web publishing via a dashboard with a web application (see Figure 4). The processing is mainly handled by Javascript, with a scheme as concluded in Figure 4(b). The telegrams are include a time stamp as well as a MAC address for identification. The web server / database has also a table with the matching sensor node positions (see Figure 5).



(a) (b)

Figure 3: (a) Sensor network structure with dashboard connection and SBM over internet, and (b) protocol stack with channel handling or IP access via 6LoWPAN.



(a) (b)

Figure 4: Sensor data acquisition via Ethernet link. (a) Technical implemenation; (b) Simplified UML (pseudo-) class diagram of the web application dashboard.

Time (2 byte)	*MAC adr.* (8 byte)	*State report* (n+1 bytes)

Figure 5: Telegram scheme for BCP messages (commands) and state reports (sensor data), with a minimum length of 12 bytes (with minimum effective payload of n=1).

3.2.3 Sensor Network Operation

The actual operation of the IEQ monitoring system can be separated into two sections: one is the sensor network with all the nodes (EPs), and coordinators (APs). This part essentially provides the data once accessed to the internet, as illustrated in Figure 3(a). The basic functionality of this part is already obvious from the explanations on network structure, and device features. The second part is the server and the BMS application, i.e. the IEQ monitoring and building control. Based on an Apache HTTP server, the APs are accessed and connected to the MySQL database system (see Figure 4). As the database gets a real-time update (period of 5 seconds), the server provides averaged data to the dashboard at every 15 minutes. This time interval can be modified at the server settings, the five second period of the EP data are set at each individual device with the NFC interface i.e. mobile app. Using a VPN (virtual private network) connection, the dashboard can be easily controlled from remote computers which only need a web browser.

As BCPv2 does not support ports for multiple applications, such as usual in IP-based networks, the concept of channels is implemented as an additional layer between JenNet and BCPv2. So, both applications, PMfH and BCP2, are accessible. The former is a PowerMatcher (for HAN / Home Area Network), and can be imagined as an invisible hand of software agents, leading an aggregated set of appliances to a common control objective (Kamphuis et al. 2007, Zach and Mahdavi 2012). The latter, BCP2, is another application layer protocol which runs on top of JenNet. The default protocol stack uses channels as ports do not exist in the IP less implementation. However, the integration of additional layers for 6LoWPAN (IPv6 over Low-Power Wireless Personal Area Networks) and UDP (User Datagram Protocol) , as shown in Figure 3(b), offers an easy extension (NXP 2013).

With such an open multi-layer test bed system, several research aspects can be easily addressed, and their cross-sensitivity can be studied. For instance, increasing the transmission interval from five to ten seconds will help to better achieve a sustainable operation of the end points. That is, a reduced transmission intervals implies a loss in precision, but considering long-term sustainability and reliability it actually improves the situation. A similar measure is operating the different EPs with best individual data transmission intervals, e.g. in order to account for the different ambient light conditions which highly influence the actually harvesting power. This could help to pertain proper sensor node operation.

3.3 Design and implementation

3.3.1 Design method

Design developments of this WSN-based IEQ monitoring dashboard involves two phases, namely concept design and detailed design. Concept design entails preparatory and exploratory design work in three goals: i) developing and validating the basic conceptual design of the interface model; ii) developing initial visual screens for this interface, iii) presenting the completed interface design as a key-screen prototype. In this early stage of design development, certain design concepts (including framework, key screens prototype, and navigation flow) were explored interactively via sketches, paper mockups, and wire-framing tools. In order to transform the above-mentioned requirements to concrete designs, initial prototyping (i.e. creation of user interface mockups) was conducted following a scenario-based design. Low-fidelity prototypes (e.g. paper prototypes) was created in initial iterations. Subsequently, high fidelity prototypes were used in later iteration cycles. In detailed design phase, a set of high-level requirements was developed to elaborate what the interface model must do and how the processing should flow. As applied to the later period of design development domain, a complete detailed design expanded from the conceptual design profiles was conducted.

Through an iterative process, the prototypes were evaluated (via expert reviews and focus groups) and further refined in each cycle. The target users for this user interface model are mainly the building managers and researchers (involving indoor environmental quality). The design approach followed a "design-evaluation-redesign" process involving users (Boehm 2007, Sharp et al. 2007). Throughout this phase, we applied usability methods (e.g. focus groups and interviews) to validate the conceptual design with help of scenarios, picture-driven animations, as well as the Wizard of Oz method.

3.3.2 Defining posture

Posture is a way of talking about how much attention a user will devote to interacting with a product, and how the product’s behaviors respond to the kind of attention a user will be devoting to it (Cooper et al., 2007). The end-users of this system are the building managers and research staffs (involving IEQ-related researches). According to our research effort in section 2.1.2, we concluded that the essential feature of the IEQ monitoring user interface is its long-term usage patterns. This kind of user interfaces with a sovereign posture must monopolize users' attention for long periods of time and offer very long-term manipulation possibilities. They must efficiently offer a set of comprehensive functionalities and allow the users to keep them up and running continuously while taking up the full screen.

3.3.3 Design requirements

To better portray the interface, user requirements generated from the user needs (based on expert reviews and focus groups) and scenarios with are described as follows (see Table 1).

Table 1: Design requirements generated from the user needs and scenarios

User need	Scenarios	Design requirements
Performance query via parameters	• Monitor IEQ performance using four environmental parameters such as illuminance, temperature, humidity, and air pressure • Check the battery level and charging state of the sensor nodes • Understand the performance trends in terms of spatial zoning and over differing periods of times (e.g. single point in time, daily, weekly, and monthly)	• Real-time info display of illuminance, temperature, humidity, and air pressure • Real-time info display of the battery level/charging state • Further info display comparing the selected performance trend for whole zones over differing spans of time
Performance query via micro-zoning	• Monitor critical IEQ performance based on the spatial zoning (i.e. Zone 1 to 5). Such info includes zone number, illuminance, and battery level. • Understand the performance trends in terms of parameters and over differing periods of times (e.g. single point in time, daily, weekly, and monthly)	• Use 3D geometry model to visually demonstrate the testbed and display critical IEQ info • Further info display comparing the performance trends of above-mentioned five parameters over differing spans of time
Navigation	• Switch between two query methods (i.e. queries via parameters and micro-zoning) easily. • Make learning and retaining of the required manipulation sequence easy	• Provide tailored shortcuts to allow the users to "jump" from one query mode to the other • Minimize the number of transitions amongst screens (pages) and keep consistency in the layout design

3.3.4 Design implementation

The sample screenshot of the dashboard main page is shown in Figure 1. Based on the expert reviews and focus group with users, two monitoring groups considered essential for the building users are implemented by means of the users' preferences and able to monitor the indoor environmental quality (IEQ) parameters. These monitoring groups include "Zones" (based on monitoring via spatial micro-zoning) and "Parameters" (encompassing monitoring via parameters). Both deployed monitoring groups have been integrated in this user interface model providing a "one-for-all" and consistent interface to unify the monitoring solutions to the environment. The dashboard allows the users to change their monitoring preferences to other parameter options (e.g., from “temperature” to “brightness”) and group (e.g., , “Zones” to “Parameters”group) in the midstream of manipulation.

i) “Zones” –“Zones” group info include primary info and context information extensions. Primary info, which is activated when the mouse hovers over the desired zone, provides the users with the desired zone label info (involving zone size, boundary, and location), illuminance (brightness), and battery energy level of the sensor node on the dashboard main page. The users can further inquire the context information of the desired zone via a corresponding information section (see Figure 6). The context information includes the indoor environmental quality parameters (i.e. temperature, illuminance (brightness), humidity, and air pressure) as well as the critical battery performance parameter (i.e. battery level) of the novel PV-based sensor nodes. Also, this monitoring group may be further specified via user-based definitions of temporal (timeline) extensions.

ii) “Parameters” –“Parameters” group offers an integrated monitoring view of this room in terms of indoor conditions (i.e., indoor environmental quality) (see Figure 7). Such parameters include temperature, illuminance (brightness), humidity, air pressure, and battery level of the PV-based sensor nodes. Also, this monitoring group may be further specified via user-based definitions of spatial (micro-zoning) and temporal (timeline) extensions.

Figure 6: Sample screenshot of “Zones” (based on monitoring via spatial micro-zoning)

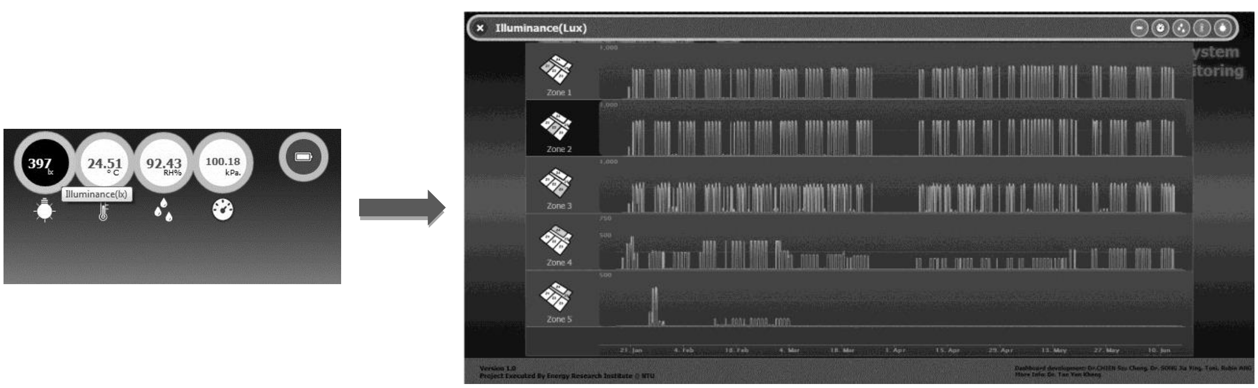


Figure 7: Sample screenshot of “Parameters” (encompassing monitoring via parameters)

4. CONCLUSION AND FUTURE WORK

The presented paper demonstrated the preliminary development of a WSN-based IEQ monitoring system. We first introduced the advanced compact PV powered sensor nodes and Wireless Sensor Network (WSN). Thereby, the hardware and requirement specification were considered. We then presented the development of a set of high-level user requirements to capture the core functionalities of desirable system models for IEQ monitoring. Lastly, we demonstrated the prototypical implementation of this IEQ monitoring system model. This system was implemented and evaluated at one test bed of a selected sustainable building in Tropics.

For future phases of this research, we will make an attempt to further articulate current effort toward a comprehensive WSN-based IEQ monitoring system for a selected office building. In addition, the systematic (long-term and high-resolution) data acquisition will be conducted for analyses on the means and patterns of such IEQ data. The outcome will serve as a solid basis for a multi-faceted use of collected benchmarking data relating to building stocks' environmental performance while meeting the objectives of a sustainable building operation regime.

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