Holistic energy efficient design approach to sustainable building using monitored energy management system

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Abstract. Building sector focuses on surpassing challenges linked to energy efficiency and mitigation measures related to greenhouse gas emissions, in consequence, it needs to improve building performance in the interest of decreasing impact over environment. Buildings with reduced long-term operating cost, environmental-friendly and moderate construction costs can be achieved only by multi-object optimization and cross-disciplinary analysis, embodying a holistic approach. Following the main principles of the holistic sustainable design approach, the paper presents a sustainable experimental modular laboratory involving various strategy in regard with sustainable building, as resource, cost and material efficiency, health and well-being, environmentally conscious design, life cycle design, modular design, reusable/recyclable element, environment-friendly demolition method, safety design, consideration of life cycle cost, materials cost and waste disposal cost. Besides the installation of renewable energy sources and conservation of energy, the holistic construction of laboratory included also an integrated design with consideration for technology, operation and maintenance, which involved the implementation of a monitored energy management system. The system provides an accurate overview of the building's performance during operational phase. Although the monitoring is still in an incipient phase, recordings showed promising results regarding the behaviour of recycled-PET thermal wadding used for insulation and indoor comfort conditions.

1. Introduction

The concept of Concurrent Engineering (CE) has become a significant topic in the research community for more than two decades, representing a holistic manner of designing, developing and providing a created good [1]. „When trying to solve design problems, designers are primarily concerned with the functionalities and aesthetics of a product. Holistic design goes beyond that; it considers human moments in context and incorporates all aspects of the ecosystem in which a product is employed. It is

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about designing an experience holistically where 'the whole is considered more than the sum of its parts [...]'. Holistic design takes into account the person, the device, the moment, the ethnographic environment, the physical space as well as human behaviour and psychology, i.e. thinking, attitudes, emotions, motivations, abilities, triggers etc., and aims to deliver an optimal experience. At times the entire experience (with a product or brand) is not limited to digital devices but is a mix of digital, real-world brick-and-mortar, and human-to-human interactions" [2]. „*Holistic* design is to *see* and *think* of the world in two broad dimensions – as *interconnected* and *evolving* systems" [3]. Consequently, a holistic approach incorporates all aspects and items of the ecosystem in which the product is engaged.

While in other industries, such as aerospace, automotive or information technology (IT), CE is well implemented and proficient, due to intricate and unique nature of the projects, multiple blends of materials and components, as well as varied building activities, construction has always been characterised rather by taylorism. The complexity of the projects and hence, of the construction supply chains, the large number of stakeholders involved in a construction project, the strikingly uncertain planning environment, all lead to the conclusion that if the focus is drawn to individual construction standardized, construction processes are not appropriate [4]. In consequence, complex project planning techniques are required to be implemented in construction industry, in order to take into consideration the construction project environment. The building sector struggles challenges in reducing it's environmental impact and therefore, it needs to improve building performance in the interest of cutting down the dependence to fossil fuels and the greenhouse gas (GHG) emissions. Toward properly engage in these issues, construction industry needs augmented building design methodologies. Adopting a sequential approach, where the design stages are undertaken independently and successively is a common practice today, in building design, but making unalterable variable selection in the incipient phase of design process, reduces drastically the ability to find optimal solutions in the end [5]. As a result, multi-object optimization and cross-disciplinary analysis, embodying a holistic approach, are imperative in building sector in order to meet important sustainability objectives like reducing GHG emissions, energy use, cost effectiveness, structural strength, usability, increasing human comfort with respect to thermic, acoustic, visual comfort and indoor air quality, while simultaneously being heedful of concerns regarding integration of aesthetics and emotional needs of the user engaged in the building's enjoyment.

2. Holistic synergy approach in buildings' life cycle

A sustainable project has to uphold the triple bottom lines (TBL) factors, specifically social, financial (economic) and environmental (ecological) factors [6]. The TBL principles are named the „3Ps" also, which implies „People, Profit and Planet", meaning that a project is sustainable when it is engaged in people's needs, at a feasible financial level (or by bringing profit) and, at the same time, with care for the environment and the use of natural resources. Nonetheless, a holistic project addresses all the factors above integrating them in an optimization process, emphasizing a multidimensional approach which requires a multi-disciplinary team whereby participants are brought together to determine how downstream issues may be affected by design decisions [1]. A holistic concept for sustainable building design should consider various strategies and criteria in regard with the TBL factors [7]. Figure 1 shows a holistic scheme for sustainable building design representing this concept.

A construction project though, includes, besides the design phase, also a pre-design (inception / conceptual) phase, a construction phase, an operational phase and a demolition/deconstruction phase [8], [9], [10], [11], [12]. A holistic synergy approach in building's life cycle involves stakeholders across all five project's phases in an endeavour of optimizing simultaneously the factors related to building's project.

From the literature review [13], the economic values of sustainable construction have received the most attention so far by the current body of knowledge, which requires for more research in the environmental and social perspective of construction. Also, methodologically speaking, case study appears to be the most practiced research method, while quantitative research and experimental research are, by comparison, limited. The present work aims to explore various project factors in a holistic energy efficient design approach to sustainable building and use of renewable energy sources through an experimental modular laboratory hereinafter referred to as Experimentarium.

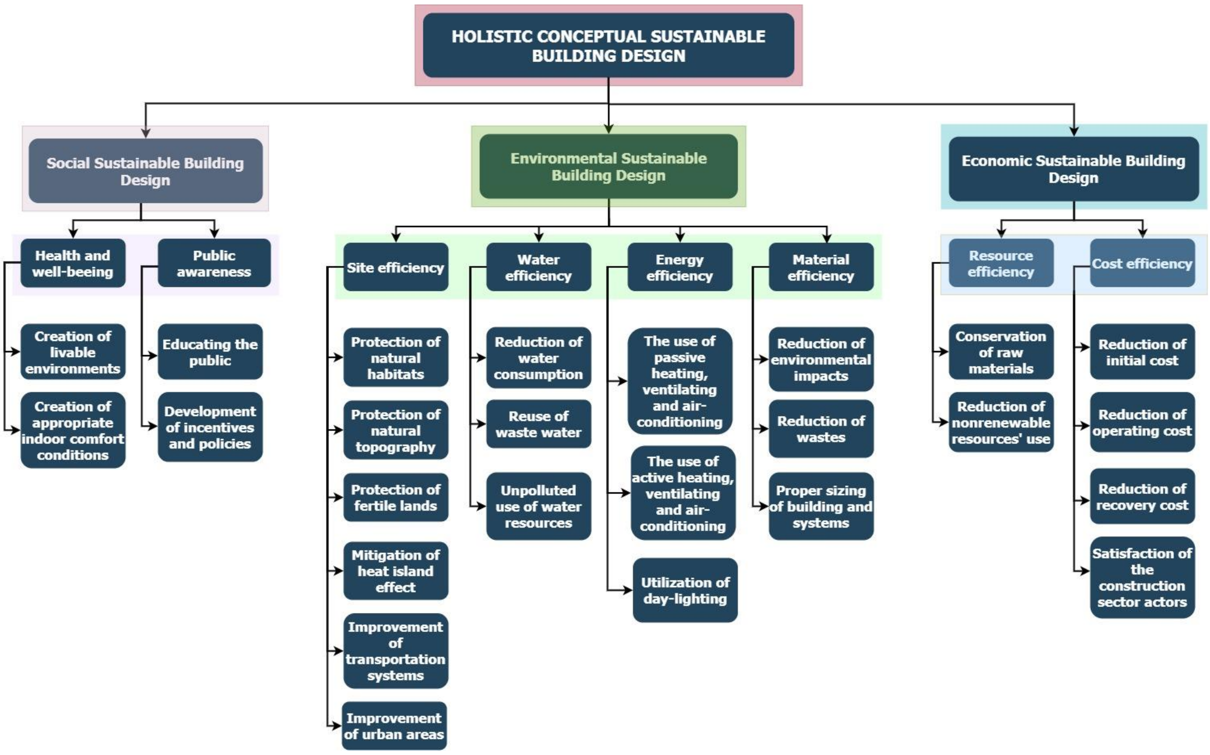

Figure 1. Holistic conceptual scheme for sustainable building design (based on [7]).

3. Holistic approach design of Experimentarium

With careful planning, we can frame buildings with reduced long-term operating cost, diminish the impact on environment while controlling the building aesthetics, functionality and construction costs. A sustainable holistic designed building can save 43% more energy than a building of comparable size [14]. The achievement of energy-efficient buildings demands an integrated design with consideration for technology, operation and maintenance, climate and occupant behaviour [15]. Following the main principles of the holistic sustainable design approach previously discussed in this work, an ecological experimental modular laboratory design is presented.

3.1 Selection of structural system and materials

Experimentarium (figure 2) is a steel structure located in Timisoara, Romania (soil design acceleration a_g = 0,2g (moderated seismicity), characteristic value of the snow load on the ground s_k = 1,5 kN/m^2), designed using cold formed steel profiles (S350 GD+Z). The selection of structural system and materials was based in regard with constituent factors of each principle of sustainable building: resource efficiency, cost efficiency, material efficiency, site efficiency, health and well-being. The load-bearing structure was steel designed, as the construction site is located in an earthquake region and on account of the sustainable attribute of steel, being a durable material, which can be reused and recycled repeatedly, without losing its properties. Using lightweight steel solutions also ensures reduced foundation costs, reduced erection time, while fabrication in a safe environment off-site drives to diminished complications on-site and a safe and healthy work environment in the construction phase. Furthermore, steel offers a flexible structural system for modular spatial design and facilitates deconstruction and future reuse of the components, in relation with the principle of the life cycle design and conservation of resources.

The main characteristics of the structure are: 5 m long span, 5 m long bay, 6.95 m ridge height, 3.80 m eave height (on the south side), 6.10 m eave height (on the north side) for two stories. The façades have openings on the south, east and west side. The access door is located on the west side of the façade. The interior access to the second storey is ensured by a 1 m × 1 m scuttle. The foundations, which are precast wedge foundations, were designed for quick installation, are recoverable, easily handled at the

End-of-Life and designed for reuse [16], in regard to ecology preservation, waste generation assessment, environmentally conscious design, life cycle design, modular and standardized design, reusable/recyclable element, environment-friendly demolition method, waste recycling and reuse, security consideration, safety design, working conditions, consideration of life cycle cost, materials cost and waste disposal cost.

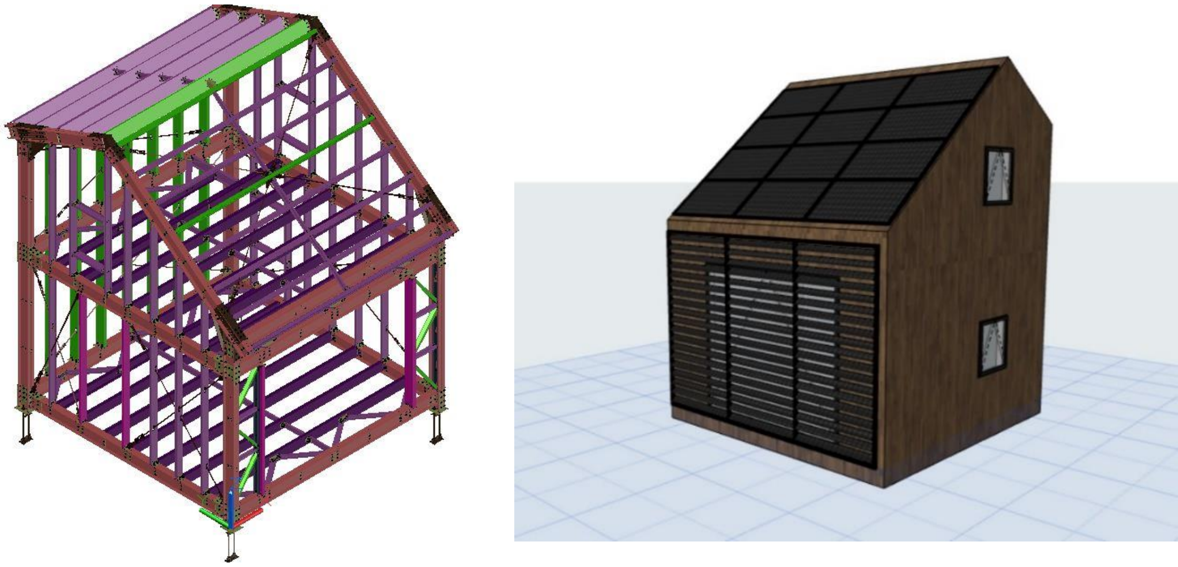

Figure 2. The steel structure (left) and 3D render of Experimentarium (right).

The roof pitch on the south side of Experimentarium was designed for 42°, in order to achieve an optimal performance of a roof-mounted solar energy system.

The structure is suitable for different envelope configurations. The thermal insulation of the laboratory was realized using thermal insulation wadding produced with polyester fibres made from the recycling of post-consumer PET bottles. Recycled-PET thermal wadding has both thermal and acoustic insulation properties, being also a breathable material, while the product's physical features remain unchanged over time [17]. Since recycled-PET thermal wadding is manufactured entirely with polyester obtained from post-consumer PET bottles ensures a refrain of CO2 emissions. No chemical or other textile agents are used in the production process, which means that the recycled-PET thermal wadding contains no harmful substances for human health [18], [19]. At the End-of-life of the building, thermal wadding produced with post-consumer PET bottles is 100% suitable for recycling, leading to the circularity of the material. The thermal insulation wadding, as all the other material used in the construction of the experimental laboratory, could be produced locally, reducing the cost value of the materials along with the cost and emissions related to transportation.

3.2 Strengthening a reduced operational cost in addition to appropriate indoor comfort conditions

On the south side of the building, Experimentarium has a 3.30×2.80 m glass curtain, which ensures natural light on the first floor and passive solar heating during daylighting. Good daylighting design can reduce electricity use, improves standards of visual comfort, users' comfort and health [20]. The artificial light demand is ensured by LEDs light sources. Passive cooling of the first floor is provided by external photo-voltaic shading lamellae. The glazing of the glass curtain represents a triple insulated glazing 40 mm with argon filling (U_g – value: 0.6 W/m^{2}K) and secures a high thermal resistance per unit area.

An important renewable energy system in the laboratory design was considered the twelve 250 W polycrystalline cell panels. The estimated amount of solar energy produced on site was 1269 kWh/year with a potential production under ideal conditions of 3427,29 kWh/year [17]. Another important renewable energy system designed for the experimental laboratory and planned to be installed is a

1 kWh vertical wind turbine, which, along with the photovoltaic panels will induce a significant decrease in the operational cost of Experimentarium. The laboratory is not connected to national grid, all the electricity needed coming from the renewable energy system.
The design of passive heating and cooling systems, the integration of renewable energy systems, the use of daylighting are aspects simultaneously optimized with consideration of sustainable factors as life cycle cost, capital budget, finance plan, energy consumption, provision of facilities, life cycle design, environmentally conscious design, proper sizing of buildings and systems.

3.3 Integrating technology in building design
Providing a suitable inner environment, in consonance with the building's functions is the primary function of building. A holistic construction of energy efficient buildings regards not only the installation of renewable energy sources and conservation of energy, but requires an integrated design that considers also technology, operation and maintenance. The envelope of a building has a critical impact on building's behaviour in operational phase. In order to have a genuine overview of the building's performance during operational phase, the design of Experimentarium included a monitored energy management system. The electric power distribution implemented in the experimental model is a direct current (DC) grid and is similar to a "smart nanogrid" (SN). The model integrates (i) two type of renewable sources of energy (wind and solar), (ii) the elements for conversion and storage of the electrical energy, and (iii) the distributed control and energy management through a SCADA system. Because it is proposed for residential application, common electrical appliances are used and adapted for DC supply.

3.3.1. Architecture of the SN
The architecture of the SN, presented in Figure 3, has a configuration consisting of two DC busses: a high voltage DC bus (HVDC) with a value of 350 V and a low voltage DC bus (LVDC) with a level of 24 V. Also, a standard alternating current (AC) bus with a voltage of $230V_{RMS}$ is implemented for AC loads and as a backup solution.

For harvesting the wind energy, a 1 kW vertical wind turbine coupled through a gearbox with a synchronous generator (SG) will be installed. The electrical power provided by the SG is injected into the HVDC bus using a diode bridge (DB) rectifier. To control the amount of electrical power, the SG has separate excitation supplied from the LVDC bus through a DC-DC converter which controls the excitation current. The solar energy is converted into electrical energy using twelve, 250 Wp, photovoltaic panels connected to the LVDC bus through a maximum power point tracking (MPPT) charge controller. The energy storage is composed of four 12 V/220 Ah Valve Regulated Lead-Acid Gel Batteries, specially designed for small residential photovoltaic system.

The batteries can store 10 kWh of electrical energy which, for a usual house, is enough for 2-3 days of operation without recharging. The batteries are connected to the LVDC bus for avoiding the high voltage DC requirements. The connection between the HVDC bus and LVDC bus is done through a bidirectional hybrid switched capacitors converter (BHSC) [21].

The BHSC converter has capabilities of high ratio voltage conversion with high efficiency and low cost. The connection to the AC grid is done through a hybrid inverter which has the DC output connected into the LVDC bus. Also, the AC loads are supplied by the hybrid inverter and, through a diode bridge rectifier, it can be used as a backup solution for the HVDC bus. A SCADA system supervises and controls the entire flow of electrical energy and ensures the data acquisition of all parameters.

3.3.2. Management of the nanogrid
The implemented SN uses a decentralized control, based on the voltage of the two DC busses and the power through the BHSC converter and the hybrid inverter. The hybrid inverter offers two modes of operating: on-grid (connected to the national grid) and off-grid (insulated from national grid).

In the on-grid mode, if there is not enough power produced by the renewable sources and the batteries are at a low level, the hybrid invert will supply power from the AC grid and delivers it to the loads and recharge the batteries. In the other case, when more power is produced and it is not required by the loads, the hybrid inverter can deliver the extra power into the national grid.

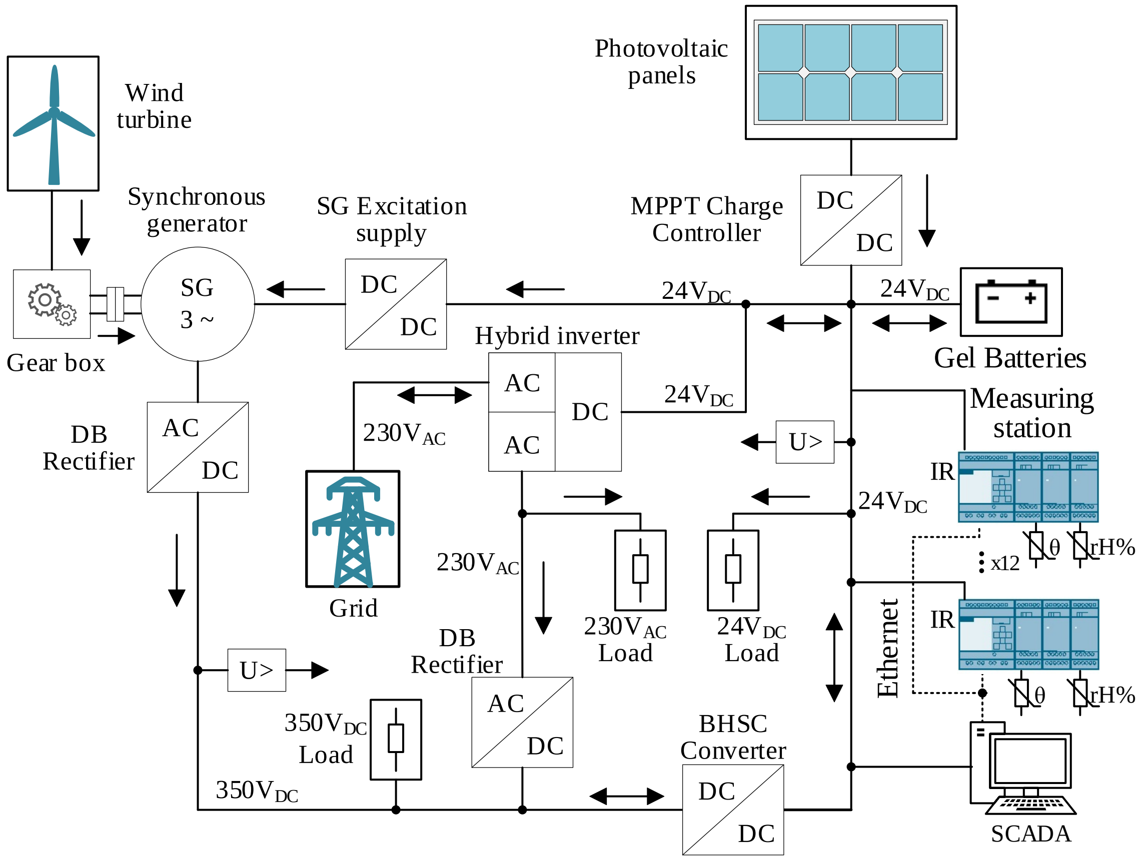

Figure 3. Architecture of the implemented smart nanogrid.

In the off-grid mode, in case of low power production by the renewable sources, the loads are priority and are supplied from the batteries. On the other hand, when too much power is available, if the batteries are already charged, then the energy production from the renewable sources is lowered. Each renewable source will reduce its power depending on the loads in order to have the lowest amount of power through the BHSC converter.

3.3.3. Measuring station

For studying the characteristics of the façades in various whether conditions, Experimentarium is equipped with 53 temperature sensors, 14 humidity sensors and three CO_2 sensors, as presented in figures 4 and 5. For acquiring the data from the sensors, a measuring station, composed from 12 so-called “intelligent relays” (IR) is used [22]. One IR can integrate 8 sensors and provide digital inputs and outputs which can be used for small residential automation. Also, the IR has the capabilities to store the data internally on a micro SD card and the possibility to create a web server on it. Using the ethernet network, the web server on the IR can be access and the data from the micro SD card can be uploaded. The solution of using 12 dedicated devices for the acquisition was chosen based on their redundancy, the conditions given by the mechanical construction and the distributed positioning of the sensors.

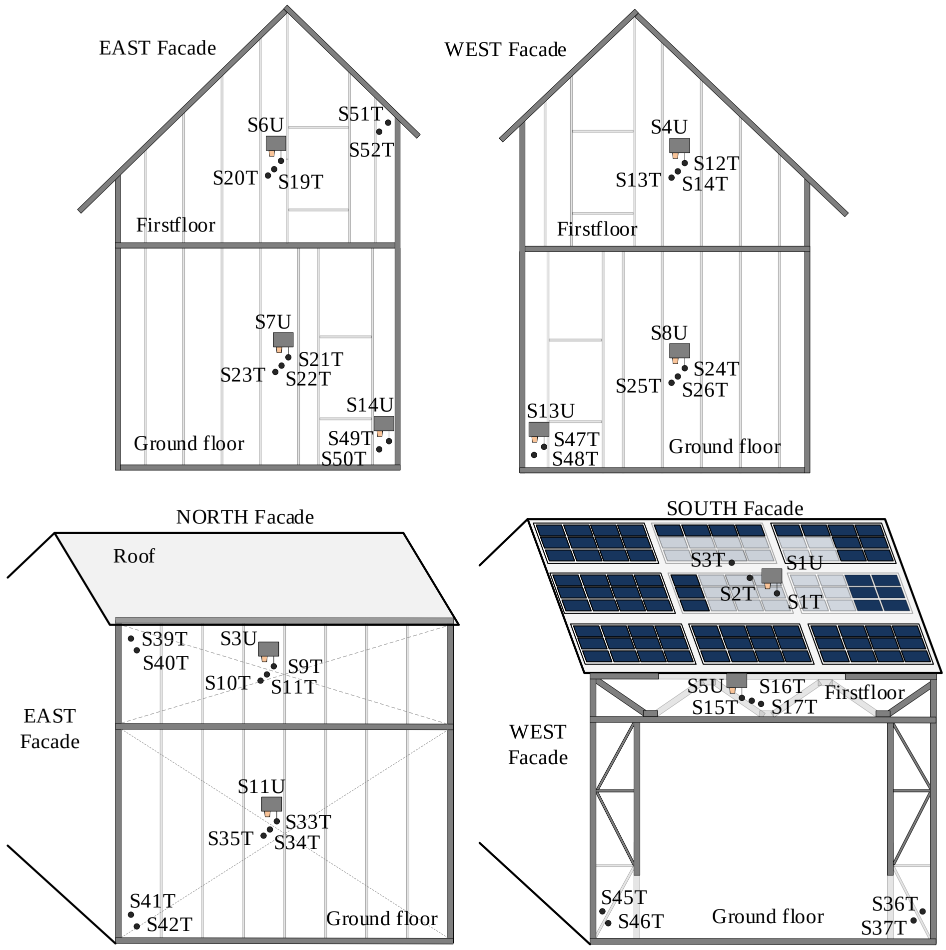

Figure 4. Sensors' distribution on Experimentarium façade.

The SCADA interface was designed with the Logo Web Editor V1.0 software development platform [22]. Compared with other SCADA systems which run over a dedicated station like a desktop or a server unit, the IR supports the SCADA and can be access using a web page.

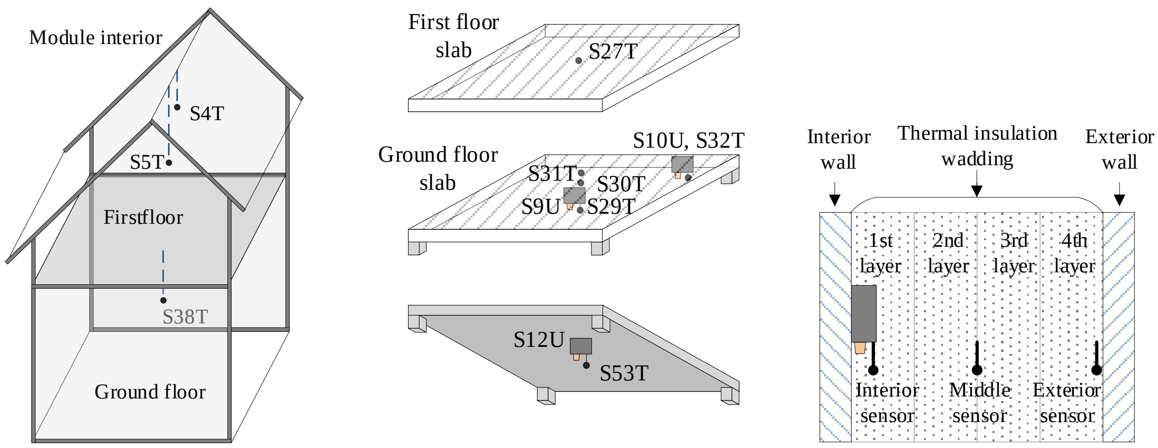

Figure 5. Sensors' distribution in slabs (left and middle) and between thermal insulation layers (right).

3.4. Preliminary empirical data on Experimentarium building

A database was created on a PC station in which all information provided by the sensors and by the SN is stored, using Modbus TCP/IP Protocol over ethernet network as communication and an OPC Server as interface.

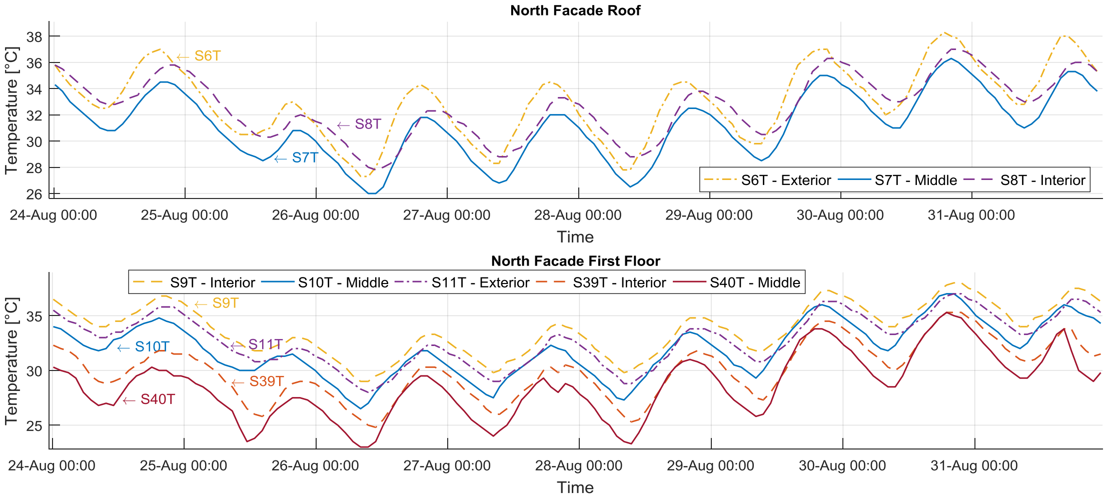

Figure 6. Example of Temperature information provided by the sensors for North Façade Roof (above) and First Floor (below).

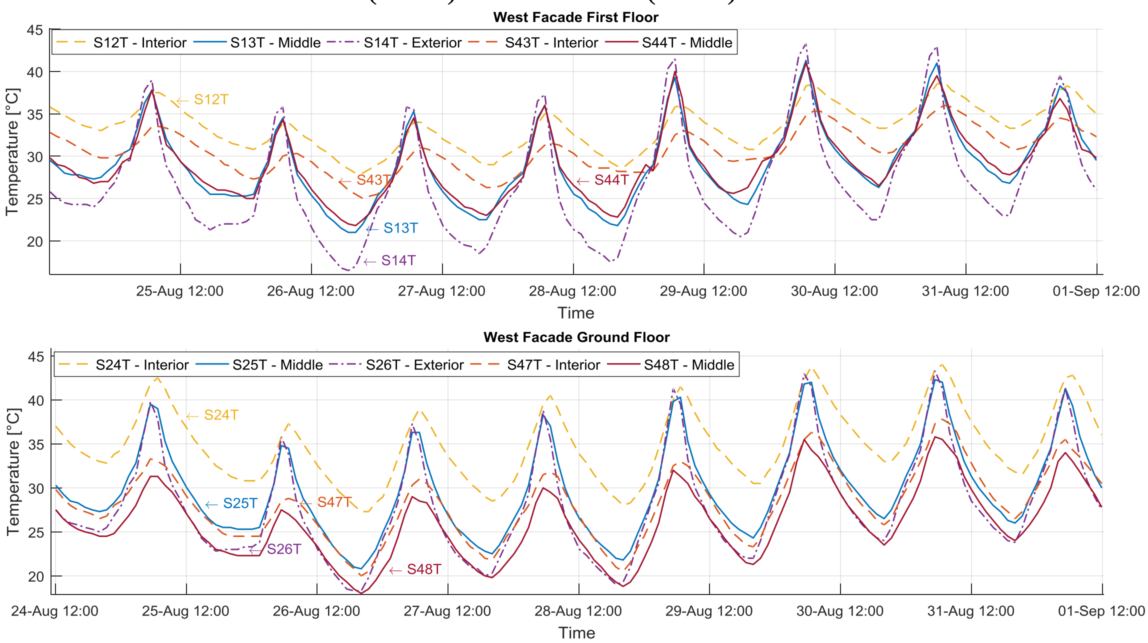

Figure 7. Example of Temperature information provided by the sensors for West Façade First Floor (above) and Ground Floor (below).

The information provided by the sensors and by the SN, illustrated above, was registered during August 24, 2020 – September 01, 2020 interval. Although the monitoring is still in an incipient phase, the recordings show promising results in regard to behaviour of recycled-PET thermal wadding and indoor comfort conditions. It should be noted that at the time of monitoring the external photo-voltaic shading lamellae were not installed yet, nor any other HVAC system, therefore no cooling system contributed to indoor temperature.

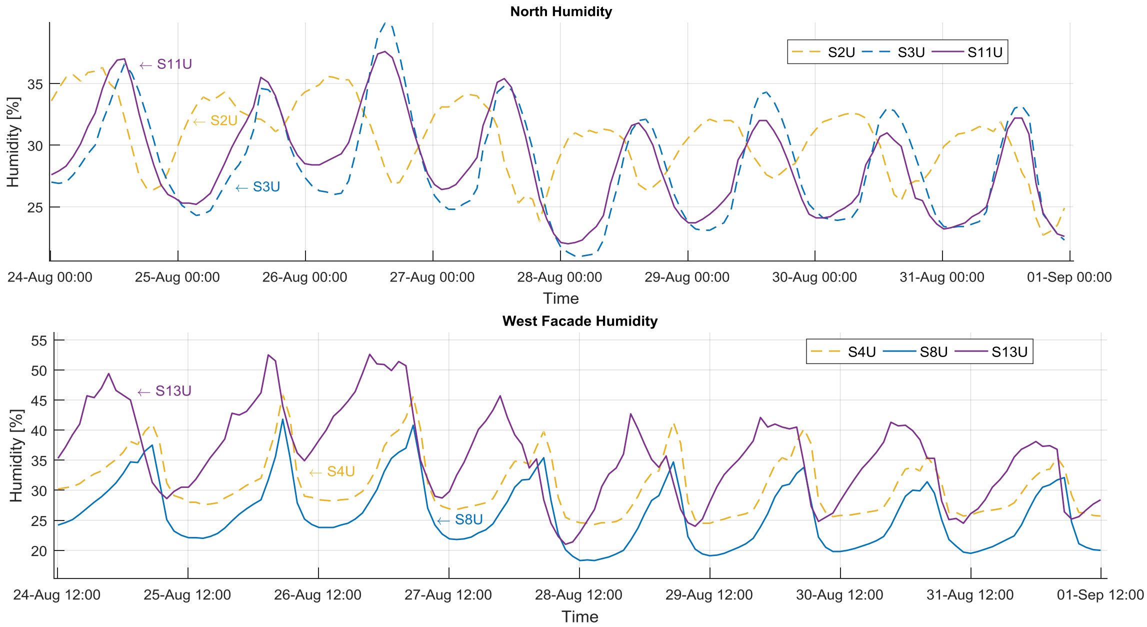

Figure 8. Example of Humidity [%] information provided by the sensors for West (above) and South Façade (below).

4. Conclusions and discussion

The building sector continues to face challenges in reducing its impact over environment and, in consequence, it needs to improve building performance in the interest of decreasing greenhouse gas emissions. With careful planning, buildings with reduced long-term operating cost, diminished impact on environment and moderate construction costs, can be achieved. Conducive to realize such results, multi-object optimization and cross-disciplinary analysis, embodying a holistic approach is needed in a construction project's life cycle. Following the main principles of the holistic sustainable design approach, the paper presents an ecological experimental modular laboratory: Experimentarium building.

The holistic design approach of Experimentarium involves various strategy and criteria in regard with sustainable building, like resource efficiency, cost efficiency, material efficiency, site efficiency, health and well-being, ecology preservation, waste generation assessment, environmentally conscious design, life cycle design, modular and standardized design, reusable/recyclable element, environment-friendly demolition method, waste recycling and reuse, security consideration, safety design, consideration of life cycle cost, materials cost and waste disposal cost.

Besides the installation of renewable energy sources and conservation of energy, a holistic construction of energy efficient buildings requires also an integrated design that considers technology, operation and maintenance. In the interest of having an accurate overview of the building's performance during operational phase, the design of Experimentarium included a monitored energy management system. Although the monitoring is still in an incipient phase, the recordings showed promising results regarding the behaviour of recycled-PET thermal wadding and indoor comfort conditions. Yet, conclusive evaluations and corollary are to be carried-out only after at least one year of continuous monitoring, as the results will show the direct performance of recycled-PET thermal wadding.

Acknowledgments

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