I-ZEB: Design and Development of a ZEB Test-Laboratory for an Integrated Evaluation of Building Technologies

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Abstract. Energy efficiency of buildings is a critical issue for international and national policy. The European Directives provide strict requirements for buildings, imposing the near Zero Energy Building (nZEB) standard for new or refurbished public and private buildings starting from 2018 and 2020, respectively. Furthermore, Zero Energy Building (ZEB) is recognized as a standard in order to improve the energy efficiency of the building sector. The collaboration of the professional and industrial sectors along with the scientific research allows to face these challenges. Within a research project, called I-ZEB, a ZEB test-laboratory where the stakeholders can test their solutions is designed and developed. The facility is designed in compliance with ZEB standard and is suitable for performing researches on new building technologies and their interaction with the built environment. The paper describes the design, the testing and the validation phases of the facility. High performing envelope, efficient HVAC, renewable energy source systems and advance control logics are the technical pillars of I-ZEB. Several characterization tests, including thermal, acoustic and environmental performance, have been carried out in order to detect the most suitable technical solutions. Moreover, the results will be tested and validated through a continuous monitoring of energy and environmental variables within the laboratory.

1. Introduction

The scientific community, along with the governments, has been debating about the thermal and energy performances of buildings in an attempt to define new strategies for reducing the impact of the most consuming sector worldwide [1]. The most recent analyses and projections highlight future scenarios in which both total primary energy consumption and CO2 emissions coming from energy consumption are set to grow. In this field, the consumption related to buildings will play a key role. Many governments and international institutions have defined different sets of specific rules conceived to reduce the energy consumption of buildings and their environmental impact, mainly based on the improvement of energy performances of building systems and the promotion of solutions involving renewable energies. The Zero Energy Building (ZEB) concept has become the standard reference to face this issue.

The concept of ZEB was introduced in the early 2000’s and it has rapidly spread worldwide [2], both in terms of concept and real applications [3]. The basic idea behind a ZEB is the design of a building with zero balance between the energy required for its operation and the energy that can be produced, on- or off-site, by the building itself, under a series of imposed restrictions such as, for
example, the nature of the energy produced, which must come from Renewable Energy Sources (RES). The two fundamental requirements to achieve this target are, on the one hand, the application of energy efficiency measures, related to both building envelope and services and, on the other hand, power self-sufficiency based on RES.

In the design of a ZEB a holistic approach has to be followed in order to achieve high energy and environmental performance proving an economic sustainability [4]. Often co-benefits are not adequately perceived by end users or by the investors, not even they are supported by the specialist technical adviser of the investment decisions [5]. These benefits are often difficult and nearly impossible to quantify and measure accurately, which makes it much more difficult to add their contribution into a traditional cost-benefit analysis [6]. The satisfaction of end users is a key issue both in design and operational phase. The analysis and the control of all variables of Indoor Environmental Quality (IEQ) allows to face this problem. Thermal [7] and visual [8] comfort, indoor air [9] and acoustic [10] quality affect the choice of the more efficient integrated solutions related to the envelope and to the HVAC equipment.

A multi-objective optimization analysis permits to take into account several aspects of the building behavior at the same time identifying the most suitable solutions according to the expected constrains: energy, economic and environmental issues are often analyzed for this purpose.

Following this approach, the paper describes the design and the development of a ZEB test-laboratory called I-ZEB placed at the Construction Technologies Institute of the National Research Council of Italy (ITC-CNR), financed within the framework between the CNR and Lombardy Region and also realized in collaboration with involved companies. The authors present the energy and the environmental analyses that have allowed the choice of the best technical solutions and the achieved overall performance. Moreover the potential of the facility in future research programmes is analysed.

2. Methodological approach
The research project provides a deep renovation of an existing building aimed at the realization of an experimental laboratory following two main phases: pre-design and optimization (Figure 1).

In the pre-design all external constrains are analysed, starting from the current national [11] and regional (Lombardy Region) standards and laws on energy efficiency of building up to the constructive constraints due to the building itself and the surrounding. The result is the definition of a first set of technical solutions whose performances and characteristics meet the design requirements. In this phase, the energy behavior of the building is investigated through a steady state monthly balance approach. The acoustic performances are tested as well in order to verify the ante operam internal (airborne sound insulation) and external insulation (façade sound insulation).

![Figure 1. Methodological approach flowchart](image-url)
The optimization phase consists in identifying the best design scenarios by combining some aspects of the building behavior thus allowing to verify the energy consumption, the economic feasibility and the indoor comfort conditions. During this phase also the regulation and control system of some components and their performances are optimized.

The experimental laboratory will be used for on-site monitoring of energy consumption, thermo-hygrometric comfort, lighting and the measurement of the acoustic requirements in order to verify the real performance during the operational phase of the building and of the component installed.

3. Pre-design

3.1. Case study

The test-laboratory, located in an industrial area of San Giuliano Milanese on the southwest outskirt of Milan (45°23’N, 9°15’E), consists of an existing single-storey structure with a concrete-based flat roof and brick walls that simulates an office building. The intervention provides a deep renovation of the building following the ZEB requirements. The external dimensions are about 7 x 8 x 4 m (length x width x height), with 2 windows on the South-East facade and 1 window on the North-West facade. The laboratory is internally divided into three spaces: two are intended for office use (A1 and A2) and the small one (A3) is dedicated for the installation of plants.

3.2. Ante operam characteristics of the building

At the ante operam state, the existing building presents obsolete technical solutions and, as a consequence, bad energy performances. In particular, the opaque envelope is a hollow brick wall without thermal insulation and a thickness variable from 14 to 23 cm. The floor, with a thickness of 37 cm, consists of a layer of concrete casted on a gravel layer, and exterior stoneware paving, the roof has a layer of ceiling bricks and cast concrete covered with a waterproofing layer (30 cm thickness). Both the previous elements have no thermal insulation layers. The envelope is characterized by thermal bridges (Figure 4): in addition to the shape ones, there are also those caused by reinforced concrete pillars and by load-bearing structures on the roof.
The windows are single glazing without solar radiation coating and aluminium frame without thermal break. Similarly, doors are completely opaque with aluminium frame and panel.

The building is provided with heating, cooling and lighting systems without mechanical ventilation; air changes are guaranteed by windows opening and infiltration. The heating system consists of a generator of 13.8 kW with fan coils. The system is regulated by a thermostat placed in room A1. The cooling system consists of direct expansion mono-split electric air conditioners (two indoor units, one for A1, one for A2). The total cooling power is about 6.0 kW.

Finally, the lighting systems present T8 linear fluorescent lamps placed on the room ceiling with manual on/off control. The lighting power density installed is about 10 W/m².

The choice of the technological solutions is influenced by technical feasibility themselves, like: the impossibility to install the exterior thermal coating on the South-West facade due to presence of another property; the observance of the minimum net room height; the impossibility to remove the existing floor.

3.3. Steady state analysis

With the steady state analysis, the main critical issues of the existing building are analysed and then the solutions of envelope and plants are identified meeting the law requirements. The energy needs for heating, cooling and domestic hot water are calculated according to the methodology provided by the Italian standards UNI TS 11300 [12]. The lighting consumption is calculated according to EN 15193 Standard [13]. The acoustic requirements are verified by calculation according to ISO 12354 [14] Standard and tested according to ISO 16283 Standard [15]. Each hypothetical intervention is analysed from a technical and an energy point of view, with the aim of achieving the ZEB target.

4. Optimization

Simulation-based optimization has become an efficient measure to satisfy several requirements for high performance buildings (e.g. low-energy buildings, passive houses, green buildings, net zero-energy buildings, zero-carbon buildings, etc.) [16]. The approach is based on a computer model running a building simulation tool coupled with an optimization engine. An iterative method driven by optimization algorithms progressively solves the analyzed problem. The solution is gradually approached until it is reached and it is established as the level that satisfies an optimal condition selected by the user [17].

Among different analysis methods [18] the dynamic simulations are carried out with Design Builder, the user friendly GUI for EnergyPlus. This software supports the optimization analysis with a specific module using a NSGA2 algorithm. Fixed two design objectives, the process continues until the Pareto Front shows the best design solutions as function of the selected design variables. In the present study, several optimization analyses are carried out during multiple simulations with main objectives like minimum energy consumption and CO₂ emissions, minimum construction and operational costs, maximum comfort level (EN 15251 [19]). Meanwhile, an optimization of the lighting system with Ecotect and Daysim software is done considering the interaction and contribution of natural and artificial light in visual comfort. While Ecotect allows laboratory and lamps modeling, Daysim provides a sub-hour simulation for each ambient using customized utilization profiles and
calculates daylighting indicators on a virtual sensor grid and an overall energy consumption. In this case, using an ambient dense grid (10 x 10 cm) the previous approach allows to define the ideal position, typology and control strategy of the lamps minimizing energy consumption.

From the acoustic point of view, the optimization of the internal partition between A3 and A2 (Figure 2) involves not only the estimation of acoustic performances but also the on-site measurements to take into account the critical flanking transmissions. The structural transmissions caused by flanking elements are minimized with the use of acoustical linings on these elements, added step by step and tested each time to maximize the acoustic insulation.

As this is an experimental laboratory, this phase is carried out in close collaboration with the companies involved in the project to choice the best envelope, plants and RES configurations:

- mineral wool for the realization of external thermal insulation composite systems (ETICS) with different thicknesses and density as a function of the existing thermal bridges and the required thermal and acoustic performance;
- an internal partition with high acoustic performances, to avoid noise equipment transmission between A3 and A2 (see Figure 2);
- a range of thermal, acoustic and visible performance of the glazing systems and doors, according to law requirements;
- a system plant constituted by a 4.4 kW air to water heat pump integrated with tank and solar panels, split air to air with heat recovery system;
- floating radiant floor with built-in hot/cold radiant system;
- mechanical ventilation system [20];
- dimmable led lighting;
- Oled lighting system;
- 3 kW of PV panels;
- South-Est ventilated façade;
- Indoor green wall;
- Cool roof.

5. Results

The realization of this laboratory is an example of integrated design (Figure 5 and Figure 6) that, from the analysis of the criticalities and objectives to be achieved, has led to the definition of the solutions of envelope and plant useful to reach a ZEB, optimizing the conditions of internal comfort and minimizing the economic and environmental impacts.
With the characteristics shown before the energy simulation carries out the results listed in Table 1.

| Indicator | Ex-ante | Ex-post |
|-----------|---------|---------|
| $H'_T$    | 1.47    | 0.15    |
| $A_{SOL}'$ | 0.0986 | 0.005  |
| $EP_{h,nd}$ | 348.69 | 31.68  |
| $EP_{c,nd}$ | 31.80  | 14.34  |
| $EP_{gl,ren}$ | 482.05 | 0.00   |
| $EP_{gl,ren}$ | 15.39  | 38.13  |
| $\eta_{G,h}$ | 0.84   | 0.97   |
| $\eta_{G,c}$ | 1.34   | 2.62   |
| $P$       | 0       | 3.00    |

Note: $H'_T$ is the global heat transfer coefficient for transmission, $A_{SOL}'$ is the summer solar equivalent area, $EP_{h,nd}$ and $EP_{c,nd}$ are the net energy needs for heating and cooling respectively, $EP_{gl,ren}$ and $EP_{gl,ren}$ are the non-renewable and renewable primary energy consumption respectively, $\eta_{G,h}$ and $\eta_{G,c}$ are the global efficiencies of heating and cooling systems respectively and $P$ is the electric renewable power installed.

The performance of all technological solutions installed will be tested with a specific monitoring activity, like:

- Energy consumption;
- RES production;
- Efficiency of heating and cooling systems;
- Efficiency of mechanical ventilation and heat recovery;
- Thermo-electric generators;
- Recovery of energy from light sources;
- Predicted Mean Vote (PMV), Predicted Percentage of Dissatisfied (PPD);
- Illuminance level, Daylight Glare index (DGI), Unified Glare Rating (UGR), daylight factor;
- Standardized level difference of façade $D_{ls,2m,nT}$, apparent sound reduction index $R'$ and reverberation time $T$;
- Hygro-thermal balancing, reduction/absorption of CO₂ and Volatil Organic Compounds (VOC);
- On-site thermal transmittance, surface temperature and interstitial condensation verification;
- Reduction of thermal bridges;
- Optimisation of consumption;
- Performances of ventilated façade.

The acoustics influence of ETICS [21] is evaluated by ante and post operam measurements. The weighted standardized level difference of façade $D_{ls,2m,nT,w}$ shows an increment of 5 dB from 44 dB ante operam to 49 dB post operam.

The optimization of the lighting system allows both an increase and a better distribution of illuminance (E) values within the indoor environment A1 and A2. For example in A1 the average overall E value increase from 267 to 307 lux with a more homogeneous distribution of the light levels, as reported in Figure 7 and 8 (0 lux – blue, 500 lux – yellow), due to a better performance of the artificial light system artificial with an increase of the average artificial E value from 145 to 200 lux, as reported in Figure 9 and 10 (0 lux – blue, 500 lux – yellow).
6. Conclusion
The ZEB laboratory is realized according to flexibility, adaptability and integrability criteria. Each technical element and indoor environment is constantly monitored in order to characterize its energy performance and to analyse the variations in terms of thermo-hygrometric, visual and acoustic well-being. The test schedule will vary according to the external climatic conditions, the control logic to be tested and the objectives to be achieved.

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