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Energy systems in cost-optimized design of nearly zero-energy buildings

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ABSTRACT

Cost optimization is one of the key elements of the EU regulatory framework concerning the energy performance of buildings. From this economic point of view, the optimum occurs when the global cost over the lifecycle of a building is minimized, and the cost-optimal energy performance level is that related to the minimum global cost. To determine this cost-optimal level by evaluating a great number of design alternatives, it is necessary to exploit automated optimization search procedures. The work presented here concerns the application of cost-optimal methodology, as defined by European regulation, to a low-consumption single-family house in France. The calculation is performed through an iterative input-output process in a computing environment that combines TRNSYS®, transient system simulation tool, with GenOpt®, generic optimization program. The methodology that was adopted allowed around ten thousand building configurations to be simulated in a reasonable computational time. The paper focuses on how the energy system affects the technical and economic optimal design solutions of the building in two different French climate conditions.

1. Introduction

In the context of the European Union's efforts to reduce growing energy consumption, it is widely recognized that the building sector plays an important role, accounting for 40% of the total energy consumption in the European Union [1]. The recast of the Energy Performance of Buildings Directive (EPBD) [2] imposes the adoption of measures to improve energy efficiency in order that all new buildings will be nearly zero-energy buildings (nZEBs) by 2020 [3]. As the results in terms of energy efficiency are evaluated at a global (or at least European) scale, it is a remarkable fact that a good nZEB design is strictly related to the local scale, depending on parameters such as climatic conditions, available technologies and materials and population lifestyle.

The architectural design process (new construction, renovation or retrofit) includes important choices that may greatly affect the energy performance of the building, mostly related to the envelope design and the energy system.

Traditionally, the nZEB design [4] consists in two steps: firstly, minimizing the energy demand of the building, which, for given boundary conditions (weather, orientation, building typology), depends on the building envelope geometry and construction; secondly, minimizing the primary energy demand of the building through the use of high efficiency energy systems and renewable energy sources. In order to reach these objectives, it is necessary not only to investigate the impact of the different design variables on the energy performance of the building, but also to study how they influence each other when looking for the optimized building configuration in a specific boundary context. In [5] the authors developed a methodology for performing this kind of research concerning the design variables related to the building envelope and geometry, but variables related to the energy system have not previously been studied.

Moreover, as the measures for reaching a high energy performance in a building are not always profitable in terms of costs [6], it is necessary to perform some economic studies in order to evaluate the global cost of different design options from a lifetime perspective, that is designing the building from the so called cost-optimal point of view [7].

One of the main challenges of cost-optimal calculation methodology is to ensure that while all the possible measures impacting the primary energy demand of a building are evaluated, the calculation exercise remains manageable and proportionate, as the great number of variables involved in the building design can easily result in thousands of design alternatives.

Many studies [8,9] concerning this cost-optimal methodology have been conducted by manually selecting a limited number of packages

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of energy efficiency measures. However, this manual procedure may not lead to a high level of accuracy when looking for the minimum global cost of the building and an automated process could improve the accuracy of the search [10].

In [11] ZEB design was studied from the aforementioned cost perspective by combining the energy efficiency measures related to the envelope design with others related to the energy system and evaluating their global cost. It was found, when looking for the cost-optimal building configurations, that the optimal envelope design varies depending on the energy system considered. Therefore, as a further step in the context of the cost-optimal analysis, this paper aims to apply an automated optimization method in order to study:

- how the selection of a specific energy system affects the cost-optimal level of the energy performance of a building and the related cost-optimal design of the envelope;
- the influence of the choice of the energy system on the global cost of the building, evaluating both the investment and the operational costs;
- the comparison between the influence of systems in the cost-optimized design of nZEBs in different climatic conditions.

The automated search was conducted by combining dynamic simulation and optimization algorithms in order to evaluate a great number of design options and perform deep and accurate optimization research.

2. The case-study building

The case-study building is a two-floor residential building situated in Ambérieu-en-Bugey, in the French region of Rhône-Alpes. Because of its typical and recent construction (it was built in 2011), the house can be considered as representative of a high-performing new construction of a single-family house in this French region and it was taken as the Reference Building configuration (RB) for the purposes of the present study.

2.1. The building envelope

The conditioned volume of the case study has a compact shape that minimizes the exchange surface between the outside and inside, leading to a Surface-to-Volume ratio equal to 0.68 m^{-1}. The conditioned floor area is equal to 155 m^2 (Fig. 1).

The envelope is well insulated (Fig. 2): the external walls (overall thermal resistance $R = 7.53$ m^2 K/W) are composed of 20 cm of concrete blocks (thermal resistance $R = 1$ m^2 K/W) and 20 cm of internal insulation ($R = 6.3$ m^2 K/W), the wooden roof (overall thermal resistance $R = 12.81$ m^2 K/W) includes 40 cm of insulation ($R = 12.5$ m^2 K/W) and the floating slab (overall thermal resistance $R = 10.92$ m^2 K/W) incorporates 30 cm of insulation material ($R = 9.3$ m^2 K/W). Based on this data, the thermal transmittance of the vertical walls is $U_o = 0.13$ W/m^2 K, the thermal transmittance of the roof is $U_r = 0.08$ W/m^2 K and the thermal transmittance of the slab is $U_s = 0.09$ W/m^2 K.

The use of thermal bridge breakers limits the thermal bridge at the intermediate floor. All windows have triple glazing for a thickness of 44 mm (4/16/4/16/4), the solar factor is equal to 0.5 and the thermal transmittance U_w of the entire opening (glasses and frame) is equal to 0.7 W/m^2 K.

These values are fully compliant with the Passivhaus standard, which requires that all parts of the opaque envelope have a U-value lower than 0.15 W/m^2 K and the windows have a U-value lower than 0.8 W/m^2 K.

Coherently with the principles of passive or low consumption houses, in order to reduce heat loss due to windows and benefit from solar gains, the majority of large openings are south-oriented (49% of the total glass surface on the south external wall, 19% on the south roof slope), while the percentage of openings in the east and west orientations is less relevant (10% and 15% of the total glass surface, respectively) and there are only very small north oriented openings (7% of the total glass surface). The window area is approximately 1/5 of the floor area; so the minimum imposed by national regulations [12], which is equal to 1/6 of the floor area, is largely exceeded. A roof overhang protects the south-oriented windows.

A double-height internal wall made of stone and concrete increases the internal thermal mass. A blower door test has been performed, attesting that the air tightness of the house is equal to 0.6 m^3/hm^2.

2.2. The energy system

The case-study building is equipped with an all-in-one energy system, which is composed of a dual-flow mechanical ventilation system combined with a cross-flow heat exchanger and an air-to-air reversible heat pump. Before entering the cross-flow heat exchanger, the air is pre-treated by a geothermal heat exchanger. Once the desired internal set point temperature is met, the system is able to modify its operation mode and manage the comfort through the perfect control of flows induced by ventilation while providing air to guarantee internal comfort regardless of the season.

In winter, the temperature control system is generally set to the heating mode, and the heat pump is on. The cross flow heat exchanger is able to recover about 60% of heat from the extracted air. The heating/cooling capacity of the heat pump varies depending on the outdoor temperature, the desired indoor temperature and the flow rate. The different capacity levels are regulated by the variation of the compressor speed of the heat pump. The global coefficient of performance (COP - Table 1), which takes into account both the heat pump efficiency and the heat recovery from heat exchangers and air recycling, also varies in relation to the combination of all these parameters, going up to 7.6 in particular conditions. It is interesting to note that, contrarily to the case of a simple heat pump, the global COP of this packaged system is higher when the outdoor air temperature is lower (for the same conditions of others parameters), because of the heat recovery performed by heat exchangers.

In summer, the described system works in cooling mode so that the heat pump reverses its cycle and cools the air entering the house. Its cooling power and EER also varies depending on the outdoor and indoor temperatures, the flow rate and the compressor speed and the medium seasonal EER is equal to 3.2. In addition, a system of over-ventilation is implemented when the outside air is cooler than the indoor air (particularly at night). Finally, the heat exchanger can also be switched on if the internal temperature is colder than the outside temperature, in order to help cooling the fresh air.

The ventilation-only mode allows mediating between the heating mode and the cooling mode, when heating or cooling requirements are very low, typically in spring and autumn. In this case, the heat pump never turns on and the only energy consumptions are due to the fans allowing the requested airflow rate to pass through the heat exchanger.

The detailed operation and the performances of this system are described in [13].

2.3. The calibrated model for dynamic simulation

The case-study building was modeled using the TRNSYS dynamic building simulation program. Each room was modeled as a thermal zone, in order to better evaluate the evolution of temperatures and the thermal exchanges from one zone to the other, as the HVAC system is considered active only in the main rooms of the house. In fact, the set-point temperatures for heating (19 °C) and cooling (26 °C) were set only in the living-room, in the bedrooms and in the mezzanine, while other zones like restrooms, dressing and passages are not directly conditioned but they are supposed to benefit from the heat exchanges with the