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COST-OPTIMAL ANALYSIS OF CONCRETE SOLUTIONS FOR SINGLE-FAMILY NZEBS APPLYING AN OPEN BIM WORKFLOW

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Abstract

In this study, Building Energy Simulations (BES) have been performed to check the impact of concrete-based building materials as part of the building envelope on the primary energy consumption of a single-family nearly Zero Energy Building (nZEB) to be built in Spain. The aim of this study is to evaluate different concrete solutions and determine which configurations combine the lowest primary energy consumption and the lowest cost by analyzing the building's energy performance throughout its life cycle. An Open BIM workflow, proposed by CYPE Software, was used for the achievement of these objectives. An architectural model was developed using the freeware application IFC Builder and synchronized though the online platform, BIMserver.center, where its project data was available for the energy simulations performed later in CYPETHERM HE Plus. Although the results refer to a Spanish-Mediterranean residential reference, the methodology applied in this study is applicable in other cases and can be useful to support nZEBs design and decision making.

1. Introduction

Cement-based products must play a key role in the transition towards a more sustainable construction, replacing traditional forms of construction with more advantageous, economic and durable ones. In Spain, in 2016, 11.08 million tons of cement were used, with 46% destined to the buildings construction sector [1]. Concrete buildings can provide substantial energy savings during their lifetime. The high level of thermal mass in concrete constructions means that indoor temperatures remain stable, regardless of external fluctuations [1]. In the following years, across the European Union, every new building must fulfill the requirements of the nearly Zero Energy Buildings (nZEB) concept, as it is stated by the Directive 31/2010 - Energy Performance of Buildings Directive (EPBD) [2]. The deadline, 2020 targets the reduction of the primary energy consumption, but there are no general requirements for the application of the nZEB concept in all countries. In Spain, the basic document outlining Energy Savings, part of the national construction normative "Technical Building Code (CTE-DB-HE)", published in 2013, will be updated during 2018 as the Directive 31/2010 establishes in its Article 4 that "minimum energy performance requirements shall be reviewed at regular intervals which shall not be longer than five years". Cost optimal levels can be seen as a first step towards the achievement of the nZEB target. They refer to the energy performance in terms of primary energy leading to the minimum life cycle cost, and according to the EPBD Guidelines, must include the initial investment and running, replacement and disposal costs.

Building Information Modeling (BIM) can be a useful tool to evaluate the economical and technical viability of a project. In the past decade, BIM has become widely used in the Architecture, Engineering and Construction (AEC) sector [3]. The use of BIM and its visual programming interface has become an integral tool for building design, not only for the conceptual design stage, but also for optimizing the design for thermal performance [4]. It is a remarkable improvement in terms of cooperation and management of the documentation, since it establishes a common platform between the different subjects involved in a project [5]. The term "Open BIM" appears when we take advantage of this protocol to implement an open collaboration system that does not depend on a specific application. The main property of Open BIM technology is that it is based on the use of IFC standard interchange formats. By using this format, which is also public and not linked to a specific developer, the durability of the work that has been carried out is guaranteed [5].

This study focused on the evaluation of different concrete solutions and configurations which combine the lowest total energy consumption of primary energy of non-renewable origin (Ct,nr) and the lowest cost. This was done by analyzing the building's energy performance throughout its life cycle, including the Costs of Construction (CC), Maintenance/Replacement (CM) and Operation (CO), in the Open BIM Workflow proposed by CYPE Software.

2. Methodology

2.1 The Reference Building

The selected reference building consisted of a two-story, single-family house with a net floor area of 164.97 m^2, a net floor height of 2.70 m and a net volume of 573.15 m^3. The aspect ratio was 1.29:1 and the window-to-wall ratio was 16%. Technical drawings and an isometric view of the building are provided in Fig.1. Since the building is located in Colmenar Viejo (Madrid, Spain), it was designed in compliance with the maximum values of energy consumption required by national regulation (CTE DB-HE). Air permeability of the envelope, considering a reference pressure of 100 Pa, was 16 $m^3/(h.m^2)$ for façades and roofs, 60 $m^3/(h.m^2)$ for doors and 10 $m^3/(h.m^2)$ for the other openings.

The demand for sanitary hot water was 112.0 l/day and the set point temperatures established in CTE DB-HE (17 °C to 28 °C) were conditions of operation and internal comfort, considering a residential profile of use. The efficiency of the heat recovery system of the mechanical ventilation system was 87.1%. The values of infiltrations were obtained the calculation method of Enhanced Model (ASHARAE), with a calculated flow coefficient, without admission openings and considering that the operational conditions were constant. The total ventilation of the habitable enclosures was 0.63 ren/h. The solution adopted for the air-conditioning-heating system consisted of a set of low temperature under floor radiant system complemented by fan coils of low silhouette ducts, associated with an aerothermal system with air/water heat pump and reversible cycle (total cooling power of 10000 W, energy efficiency ratio of 2.78, total heating power of 11200 W and a coefficient of performance of 4.55).

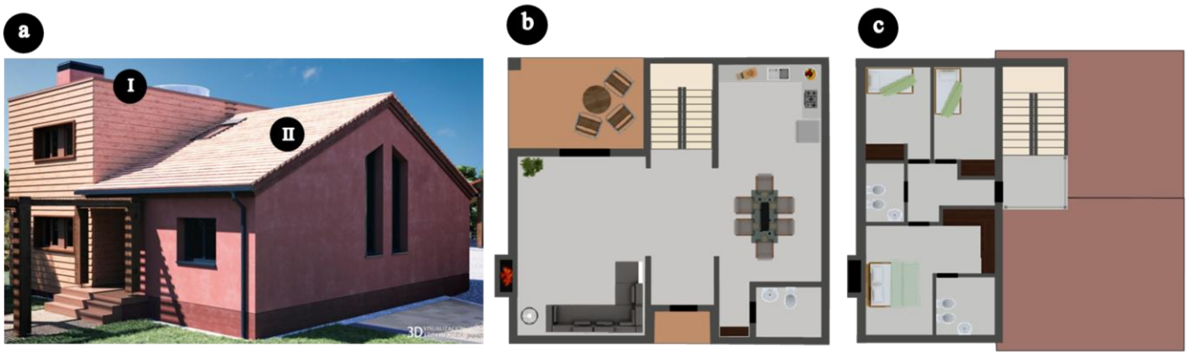

Figure 1: Technical Drawings and Isometric View of the Case Study.

Reinforced concrete slabs (thickness of 15 cm) were used for the horizontal structural system. Its resultant thermal transmittance (U), associated with its insulation layers, were 0.19 W/(m²·K) for the ground floor slab, 0.22 W/(m²·K) for the flat roof slab (I in Fig. 1a) and 0.31 W/(m²·K) for the sloped roof slab (II in Fig. 2a). Windows were composed wood frames (thermal conductivity (λ) of 1.10 W/(m²·K) and solar factor of 0.61) and double low emissivity glass with argon cavity and aluminum spacers (λ = 1.43 W/(m²·K)), resulting in a frame-glass ratio of 22%. Eight additional photovoltaic panels, with a total area of 12.78 m^2, provide 16.92 kWh/m^2 yearly.

2.2 Concrete Solutions Studied

The vertical surfaces (Fig.2) were the main elements evaluated in this work. In all cases, the walls have structural and enclosing function. An External Thermal Insulation Cladding System (ETICS) was considered for the external surface of the façades in order to reduce the losses caused by thermal bridges. ETICS was formed by one layer of a 60 mm rigid expanded polystyrene panel (λ = 0.04W/(m.K)) and four layers, of 4 mm each, of mortar as part of the system, but with no relevant thermal properties. Internal surfaces of the façades were covered by 10 mm plasterboards (λ=0.25W/(m.K)) spaced 10 mm from the structural core.

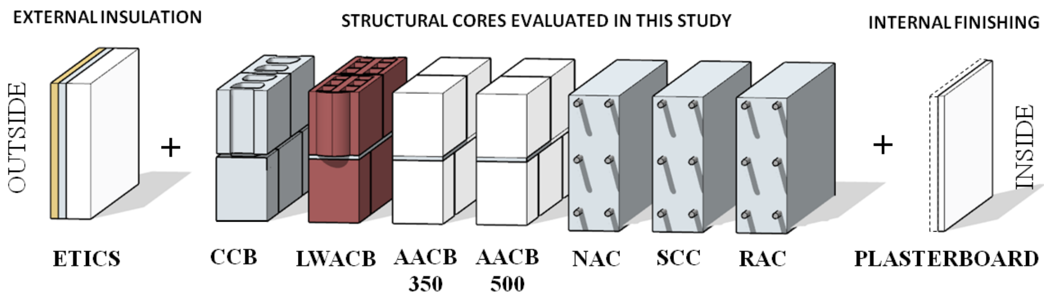

Figure 2: External walls evaluated in this study.

Six different solutions were evaluated as wall-core materials. Three types of cast-in-place concretes were included in the simulations as reinforced concrete walls with materials commonly used in Spain: Natural Aggregate Concrete (NAC), Recycled Aggregate Concrete (RAC) and Self-Compacting Concrete (SCC). In the same way, the structural masonry walls are formed by Conventional Concrete Blocks (CCB), Lightweight Aggregate Concrete Blocks (LWACB) and two different types of Autoclaved Aerated Concrete Blocks (AACB). The thicknesses considered in this study are dimensions commonly used and commercialized by manufactures in Spain (Table 1).

Table 1: Thermal Properties of the Concrete Wall-Cores Evaluated in this Study

		Thickness (cm)											
Material		**10.0**	**12.0**	**15.0**	**20.0**	**22.5**	**25.0**	**30.0**	**34.0**	**35.0**	**36.5**	**40.0**	**42.0**
CCB	λ	0.605	0.670	0.759	0.891	-	1.009	1.117	-	-	-	-	-
	ρ	1337	1247	1201	1112	-	1048	998	-	-	-	-	-
LWACB	λ	-	0.202	0.224	0.256	-	0.285	0.310	-	-	-	-	-
	ρ	-	1066	1001	924	-	868	824	-	-	-	-	-
AACB 350	λ	-	-	-	-	0.090	0.090	0.090	0.090	-	0.090	-	0.090
	ρ	-	-	-	-	350	350	350	350	-	350	-	350
AACB 500	λ	-	-	-	0.125	-	0.125	0.125	-	-	-	-	-
	ρ	-	-	-	500	-	500	500	-	-	-	-	-
NAC	λ	2.300	2.300	2.300	2.300	-	2.300	2.300	-	2.300	-	2.300	2.300
	ρ	2400	2400	2400	2400	-	2400	2400	-	2400	-	2400	2400
SCC	λ	2.300	2.300	2.300	2.300	-	2.300	2.300	-	2.300	-	2.300	2.300
	ρ	2400	2400	2400	2400	-	2400	2400	-	2400	-	2400	2400
RAC	λ	2.300	2.300	2.300	2.300	-	2.300	2.300	-	2.300	-	2.300	2.300
	ρ	2400	2400	2400	2400	-	2400	2400	-	2400	-	2400	2400

λ – Thermal conductivity (W/(m.K)). ρ – density (kg/m^3)

2.3 Open BIM Workflow

The Open BIM Workflow proposed by CYPE Software was employed for the achievement of the objectives (Fig 3).

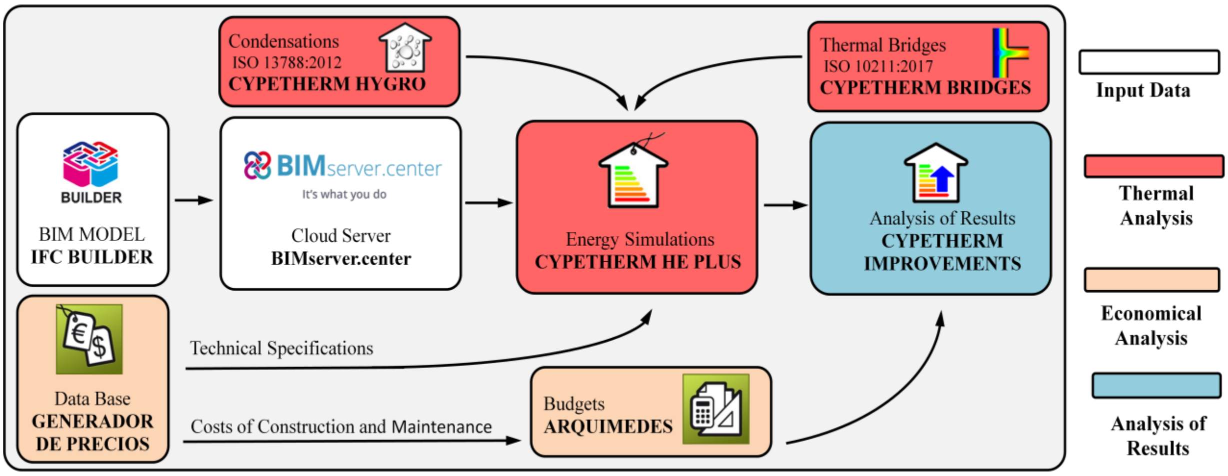

Figure 3: Flowchart of the Methodology Adopted in this Study

First, an architectural model was developed using the freeware application IFC Builder (IFC4 format), where the spaces, orientation and other aspects of the building's geometry were described. Subsequently, the model was synchronized though the online platform BIMserver.center, where its project data became available for the following steps of the workflow. Forty-four energy simulations were performed in CYPETHERM HE Plus employing technical data from CYPE´s data base (Generador de Precios) to characterize the building´s envelope, thickness detail, materials and thermal characteristics of each element. In the same way, the thermal transmittances in linear thermal bridges were evaluated, solving and processing a heat transfer finite element model based on the EN ISO 10211 using CYPETHERM Bridges. The results of each energy simulation were exported to CYPETHERM Improvements, where the budget information related to each hypothesis was also included. Construction and maintenance costs considered were also obtained from CYPE´s data base. The global costs method described by Signes-Orovay et al [6] was adopted considering a 50 year building life-cycle.

3. Results and Discussion

$C_{t,nr}$ was assessed in terms of delivered primary energy, including energy use for heating, cooling and domestic hot water. Primary energy values were calculated using the Spanish primary energy factor (2.368 for electricity). The results for the energy consumption (kWh/m^2.y) versus global cost (€/m^2) were reported for all scenarios in Fig. 4a.

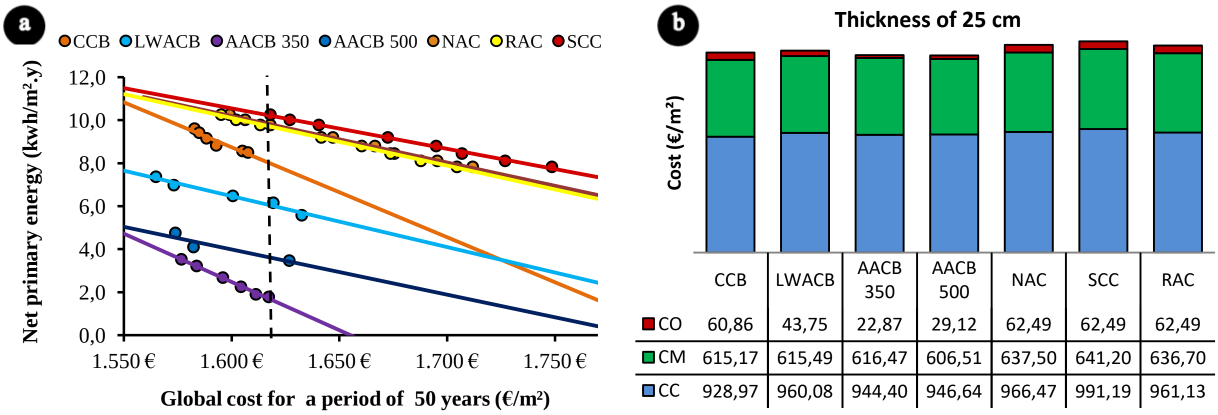

Figure 4: a) Global Costs versus Net Primary Energy b) Costs Breakdown Analysis for Examples with Thickness of 25 cm

The minimum $C_{t,nr}$ was achieved by the scenario considering AACB350/42cm (1.78 kWh/m^2.y). For comparative purposes (indicated by the vertical dashed line in Fig. 4a) and considering linear interpolated data, the same global cost necessary to implement this solution (1617.19 €/m^2) would increment the $C_{t,nr}$ from 106% to 450% if AACB500 or NAC solutions were respectively employed in substitution of AACB350. Global cost (50 years) ranges from 1564.82 €/m^2 (LWACB/12cm) to 1748.59 €/m^2 (SCC/40cm). Construction Costs (CC) are the most relevant cost, ranging from 57% to 61% of the global cost. Although the initial investments for CCB solutions are lower compared with other solutions, the best results for the whole life cycle of the building were found in AACB solutions, which had their operational costs reduced due the optimization of the thermal performance of the envelope. The Cost of Operation (CO), related to energy consumptions, could be reduced from 5% (cast in place solutions) to 1% (AACB solutions) of the total overall cost if AACB solutions were employed. Costs of Maintenance/Replacements (CM) are important during construction. The same HVAC and photovoltaic systems were employed for all combinations, and since the calculation period was set to 50 years, replacements occurred twice during the building life cycle. All combinations presented similar results for the Costs of Maintenance/Replacement (CM), ranging from 37 to 39% of the total cost. Fig 4b shows the costs breakdown analysis for examples with thickness of 25 cm.

4. Conclusion

In this study, energy simulations have been performed to check the impact of concrete-based building materials as part of the building envelope on the primary energy consumption of a single-family nZEB. From the results presented, the following conclusions are drawn:

- Since just one architectural model was developed and all scenarios were simulated in specialized applications linked to the workflow, applying the Open BIM method proposed by CYPE led to a compact, but complete, final consolidation of the project.
- Since both masonry and cast-in-place concrete walls can be employed as the building structure, results presented in this work suggest that concrete masonry walls are possible solutions to be used in projects of single-family nZEBs once it presents better energy and economical performances.
- The results also indicate higher energy-economical performances of Autoclaved Aerated Concrete Blocks (AACB), when compared to other structural masonry wall solutions.

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