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A Framework for cost-optimal zero-energy lightweight construction

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ABSTRACT

During the last decade, several roof extensions took place in the European cities with the purpose to increase the height of existing buildings using timber as a lightweight material. However, building regulations and green codes do not usually guarantee the achievement of multi-objective and highly performance roof extensions. Accordingly, this research aims to develop a state of the art framework to achieve cost-optimal zero-energy for timber construction, specifically when building on rooftops. Through a simulated and calibrated passive house model, the boundary conditions of the study have been identified and further parametric simulation and optimization have been carried out.

This research aims at linking scientific research with practice. The framework provides a fast track measurement that provides a solutions space for building engineers who are in charge of decision making on the design and construction process. Best practices of roof construction could be achieved in terms of cost and energy, giving a vast potential for a complete and deep renovation, and, therefore, reducing the overall ecological footprint on the city level.

Author Keywords

Multi-criteria optimization; parametric simulation; roof stacking; urban densification; methodology

ACM Classification Keywords

I.6.3 Applications; I.6.8 Types of Simulation;

1 INTRODUCTION

As stated by the European Commission, construction sector is responsible for more than 40% of the total energy consumption and 36% of the CO2 emissions in Europe. Thus, building's energy performance has been put forward as a key element to achieve the European Union's (EU) targets for 2020 to reduce each of the Green House Gas (GHG) and primary energy savings by 20%. A safe way towards fighting climate change could be achieved through providing cost-effective and highly energy efficient buildings [8]. Achieving zero-energy buildings requires using thick walls and insulations, which is accompanied in most cases with additional weight in construction [3]. For a conventional stick building, this does not represent a problem. However, when building on the rooftops of existing buildings, the weight of the construction is considered a main issue, especially when using prefabricated components (off-site construction) methods, which are needed to be transported and lifted over the rooftop. Moreover, cost-optimal measure has been a big concern in the last decade. On 2010, the European Commission has produced the Energy Performance of Building Directive EPBD-recast, which made it possible to make informed choices that aim to help saving energy while increasing cost-effectiveness. Since then, several tools and methods have been proposed scientifically and practically to achieve zero-energy levels while maintaining cost-optimal targets. For instance, Georges et al. [6] examined a single-family houses in Belgium by investigating a combination of heating systems and building designs. Marszal and Heiselberg [9] aimed to find optimum life cycle cost measure for net-zero energy residential house in Denmark by examining three energy demand and supply systems. Hamdy et al. [7] carried out a multi-stage, multi-objective optimization that aims to achieve cost-optimal and nearly zero energy building solutions through optimizing building envelop, active system and onsite renewable energy resources respectively, followed by a sensitivity analysis for the escalation rates of energy prices and their effect on the overall optimization results.

However, none of those methods or tools has been dedicated to include additional parameters concerned with using lightweight materials in construction. Accordingly, in this study, we propose a framework that aim to achieve cost-optimal lightweight construction for roof stacking. By bringing building performance simulation and parametric design tools, optimizing building's energy and cost performance could be achieved, while providing a space of solutions for lightweight building envelope sections, which is more likely to be preferred by the designers generally and architects specifically.

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2 METHODOLOGY

The methodology consists of four stages as shown in Figure 1. First, reference model has been selected. Second, boundary conditions are identified. Third, the reference model is simulated, calibrated and adjusted to represent a typical roof-stacking model in Brussels Capital Region in Belgium. In the last stage, a multi-criteria optimization is conducted and a space of nearly optimal solutions for building envelope measures are identified taking in consideration the identification of the specification and area of renewable energies to reach zero energy levels.

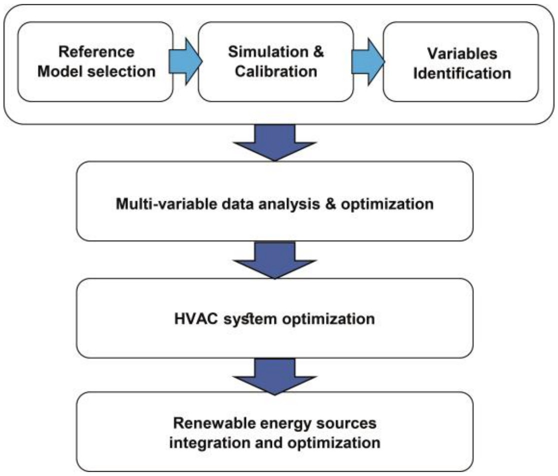

Figure 1. Framework for cost-optimal lightweight construction

2.1 Reference Model Selection

Given the shortage in the information available on roof stacking, a reference model for a full passive house has been used in this research. Several constrains have been set up for the selection of the reference model to ensure a maximum compatibility with the required roof stacking model. First, the selection of a passive house reference model has been set up as a prerequisite. The reason behind choosing a passive house reference model returns back to the requirement of the local regulations of Brussels Capital Region, which state that as of 2015, all new construction should comply the passive house standard requirements. Second, the usage of lightweight materials represents one of the main objectives of this study. Given that timber is considered a promising building material that satisfies the lightweight aspect, a reference model built in timber has been set for the selection criteria. Third, the reference model has to lie within the same climatic region of the case study, which is 5b climate zone according to ASHRAE classification.

A passive house reference model has been selected to meet the aforementioned constrains of selection. The specifications and measurements of the passive house reference model has been found in a cluster of 22 passive house built in Hannover-Kronsberg in Germany which is published by the Passivhaus institute [5]. The layout of the passive house reference model has been adjusted to match the layout and dimensions of the roof stacking case study in Brussels according to earlier studies [1,2,4].

2.2 Modeling, Simulation and Calibration

The modelling process has been carried out using Grasshopper parametric tool integrated in Rhinoceros 3D software. As for the simulation, Ladybug and Honeybee plugins have been used [10]. Ladybug tools have been used to load weather files and generate primary climate analysis, which is integrated with Honeybee tools that works as an interface for OpenStudio simulation software and EnergyPlus simulation engine. Honeybee is responsible of generating thermal zones and energy simulations. Lastly, Colibri plugin has been used to parametrically run the simulations and exporting results to Excel files.

The calibration process has been carried out in accordance with the monthly average monitored heating loads. Two indices are used to assess the *goodness-of-fit* of the building energy model: the Mean Bias Error (MBE) as shown in equation (1), and the Coefficient of Variation of the Root Mean Square Error (CV (RMSE)) as shown in equation (2).

$$\textbf{MBE} = \sum_{i=1}^{Np}(m_i - s_i) \,/\, \sum_{i=1}^{Np} m_i \qquad [\%] \qquad (1)$$

$$\textbf{CV (RMSE)} = \sqrt{\sum_{i=1}^{Np}(m_i - s_i)^2 \Big/ Np} \qquad [\%] \qquad (2)$$

where $\boldsymbol{m_i}$: (i = 1, 2, …, Np) represents measured data points, and $\boldsymbol{s_i}$: (i = 1, 2, …, Np) represents simulated data points. According to ASHRAE guidelines 14-2002 and 2014, a maximum value of 5% is required for MBE when monthly data points are calibrated and a maximum value of 10% when hourly data points are calibrated. Whereas for CV (RMSE), the maximum value of 15% is required when monthly data points are calibrated and maximum value of 30% when hourly data points are calibrated. In this study, the values of each of MBE and CV (RMSE) have met 2.1% and 7.3% respectively. The MBE is a non-dimensional measure of the overall bias error between the measured and simulated data in a known time resolution, and it is usually expressed as a percentage. Whereas RMSD represents the sample standard deviation of the differences between predicted values and observed ones. The RMSD serves to aggregate the magnitudes of the errors in predictions for various times into a single measure of predictive power.

Occupancy and operational schedules of windows have been hypothetically estimated based on the best practice, and then set as a variable to meet the calibration thresholds on one hand. On the other hand, indoor temperatures have been considered in the calibration process. According to the monitored indoor temperature of the passive house reference model, an average temperature of 20.9°C has been found even during the coldest days. Thus, during calibration, the same average indoor temperature has been maintained while ensuring the required ratio of goodness-of-fit values.

2.3 Boundary Conditions

Boundary conditions have been identified under four categories. The first category identifies fixed parameters represented by the weather file, layout, occupancy and operation schedules. The second, third and fourth categories identifies each of the variable measures of the building envelope, HVAC and renewable energy system respectively.

First, the weather file of Brussels city has been used. The layout of the case study has been identified according to the middle-class housing typology, which represents more than 75% of the housing typologies in Brussels. The layout is exposed to the North-South orientation, whereas the East-West facades are directly attached to neighboring houses (non-exposed surfaces). Occupancy and operational schedules are left the same to those have been used in the calibration process of the passive house reference model.

On the building envelope level, 6 items are given several variables. Starting with a construction type, two different timber construction types are examined: Timber framing and Cross Laminated Timber (CLT). A layer of insulation is added to the timber, in which four different types are examined: EPS, Cellulose, Mineral Wool and Wood Fiber. The thickness of the insulation ranges between 20cm and 40cm with 4cm uniform step. The variations of the insulation type and thickness had a maximum U-value of 0.15 W/m^2.K, to comply with passive house standards, and minimum U-value of 0.095 W/m^2.K. The U-value of the floor slab has been set to 0.125 W/m^2.K and not been considered in the parametric simulation. The air tightness of the building has been keep the same of the reference building in order to comply with Passive House standard level, which requires a value of 0.6 air changes per hour for 50 Pascal pressure. The window has a U-value of 0.6 W/m^2.K (which complies passive house standard requirement of a maximum U-value 0.8 W/m^2.K and g-value 50% for glazing surfaces). However, Window to Wall Ratio (WWR) varies between 10% up to 90%. Two different shading types are examined: interior venetian blinds and exterior shading rollers.

On the HVAC level, a heat pump has been used for heating and cooling purposes, in addition to a ventilation system with heat recovery. The variations have been given to the heat recovery effectiveness, which ranges from 70% to 90%, and the Coefficient of Performance (COP) of the heat pump, which ranges from 2 to 5. Finally, on the renewable energy level, each of a multi-crystalline silicon Photovoltaic (PV) panels and solar thermal system are examined. PV panels' area ranges from 0 – 50 m^2, while solar heater system's area ranges from 0 – 20 m^2, with an efficiency of 20% for the PV panel and 70% for the solar heater.

2.4 Multi-Objective Optimization

This study proposes a bi-objective optimization approach that addresses energy savings and cost-optimality. The bi-objective optimization comprises the results of different weight of construction. In order to achieve results, the optimization process took place on three stages. On the first stage, the 6 items of the building envelope are optimized, followed by the HVAC system, and finally renewable energy resources are added to ensure reaching zero energy targets while maintaining cost-optimality. Simulation and optimization have been conducted using Grasshopper with Honeybee plugin. Buildings materials' specifications have been obtained from the European timber materials database "Dataholz", whereas the equivalent prices for each building material, HVAC and renewable energy systems are provided by the Belgian database of construction works "*Bordereau des Prix Unitaires*".

3 RESULTS

In this paper, the primary results of the optimization process are presented. Parametric simulation has been conducted to generate over 600 attributions for the building envelope as shown in Figure 2.

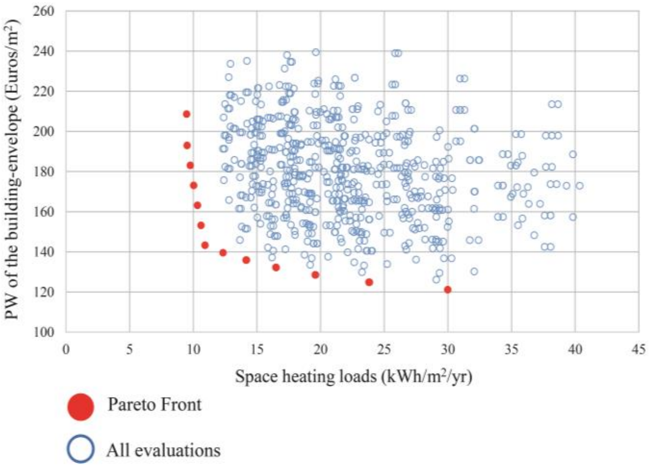

Figure 2. Multi-objective optimization for building envelope

In order to identify optimum results out of the generated attributions, MATLAB software has been used to generate Pareto Frontier (the attribution in red color). Pareto optimality frontier is the mathematical method that is used to identify optimum results giving two different objectives. Figure 3 shows a further step for bi-objective optimization. In this stage, the differences in Life Cycle Cost (LCC) have been considered instead of just initial cost. LCC takes in consideration initial, replacement, maintenance, and operational costs. Furthermore, the total energy consumption in terms of heating, cooling and fans (for heat pump and ventilation system) has been calculated. The results in Figure 3 are grouped into clusters according to their weight of construction. We found that the more weight added to the construction (that reaches up to 300 Kg/m^2), the better performance it achieves in terms of saving heating loads, and the less savings in terms of LCC. In contrary, the less weight of construction (less than 200 Kg/m^2) the more energy is consumed for heating and cooling. Hence, we found that by applying Pareto Front, we are able to choose optimum results, which represents a compromise between heavy and lightweight construction selections as shown in Figure 3.

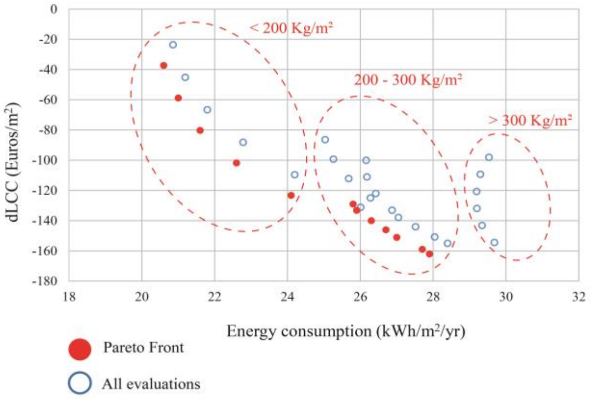

Figure 3. Cost-optimal measures for different sets of lightweight construction

CONCLUSION

This paper presents a framework that aims to achieve cost-optimal zero-energy lightweight construction. This paper is a part of research work that puts forward solutions to effectively increase the density of European cities through building on the rooftops of existing buildings.

We found that the more weight added to wall sections, the more energy efficient. However, within the space of solutions of the Pareto Front, energy efficient measures could be achieved with lightweight construction trading off with LCC values. While, construction that weights more than 300 kg/m^2 was not found to be selected in the optimization curve. The majority of the selected solutions were found in the intermediate zone, with construction that weights between 200 and 300 Kg/m^2, which is self-evident within the selection method of optimized results.

The results of this paper will be followed with optimizations for the heat pump and ventilation system. Moreover, electricity from photovoltaic panels and hot water from solar heaters will be integrated in the optimized solutions. The overall weight of the panels on the rooftop will be added and possible savings in the operational costs will be calculated within the whole Life Cycle Cost of the building.

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