Energy and Buildings 84 (2014) 442–457

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

A simulation-based optimization method for cost-optimal analysis of nearly Zero Energy Buildings

Maria Ferrara [a], Enrico Fabrizio [b],*, Joseph Virgone [c], Marco Filippi [a]

[a] DENERG, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
[b] DISAFA, University of Turin, Largo Paolo Braccini 2, 10095 Grugliasco, TO, Italy
[c] CETHIL, UMR5008, Université Lyon 1-INSA-Lyon, 9 Rue de la Physique, 69621 Villeurbanne Cedex, France

ARTICLE INFO

Article history:
Received 22 June 2014
Received in revised form 15 August 2014
Accepted 20 August 2014
Available online 28 August 2014

Keywords:
EPBD recast
Cost optimal analysis
nZEB
Dynamic building simulation
Particle swarm optimization algorithm
France
Building elements cost function
Single family house
Design parameters

ABSTRACT

This study was developed in the context of new challenges imposed by the recast of the Energy Performance of Buildings Directive 2010/31/EU (EPBD) and its supplementing regulation. The aim is to find the cost-optimal level for the French single-family building typology, while providing an effective method to deal with a huge number of simulations corresponding to a large number of building configurations. The method combines the use of TRNSYS, dynamic energy simulation software, with GenOpt, Generic Optimization program.

The building that was taken as a reference is a real low-consumption house located in Amberieu-en-Bugey, Rhône-Alpes, France. The model was created and calibrated in TRNSYS and the energy efficiency measures, concerning different technologies for envelope systems and technical systems, were set up as parameters in GenOpt. After a research on the French market, a cost function was created for each parameter and the global cost function (EN15459 Standard) was taken as objective function for the optimization. The particle swarm optimization algorithm was used to minimize the objective function and find the cost-optimal building configuration within the current regulatory framework.

1. Introduction

In the context of the European Union efforts to reduce the growing energy expenditure, it is widely recognized that the building sector has an important role, accounting 40% of the total energy consumption in the European Union and 36% of the EU's CO_2 emissions [1]. The recast of the Directive on the Energy Performance of Building (EPBD) [2] imposes the adoption of measures to improve energy efficiency in buildings in order to reach the objective of all new buildings to be nearly zero energy building (nZEB) by 2020. This practice represents the first effective way for the implementation of the greenhouse emission reduction policy requirements [3], however the challenge of refurbishment of the existing building stock should also be addressed in order to reach the objective of reducing the greenhouse gas emission in the building sector by 90% by 2050 compared to 1990 [4]. Moreover, as usual, measures related to environmental sustainability could not be pursued without taking into account the financial feasibility, as nowadays the design of a nZEB is not yet profitable in terms of costs; however it is recognized that improving energy performance of building is a cost-effective way of addressing the problem of climate change and improving energy security, given the great European energy saving potential [5–7].

Furthermore, even if the results in term of energy efficiency are evaluated at a global (or at least European) scale, it is remarkable that an efficient nZEB design is strictly related to the local scale: the optimal design solutions, from both energy and cost point of view, depend on many variables, such as climatic data, available technologies and materials, population lifestyle, the age of the building and its use (commercial buildings, residential, etc.) [8]. Consequently, EPBD recast has set out that Member States (MSs) ensure that minimum energy performance requirements are set with a view of achieving cost optimal levels for buildings, building units, and building elements using a comparative methodology framework established by the European Commission.

This methodology, which is defined in the Guidelines [9] accompanying the Regulation [10] supplementing the EPBD and in the EU Standard 15459 [11], consists of different steps. First, a reference building must be identified as a representative model of the national building stock. Secondly, a set of energy efficiency measures (EEMs) must be defined, in order to improve energy performance of the building. EEMs can be combined in packages of

---

* Corresponding author. Tel.: +39 011 6705525; fax: +39 011 670 5516.
E-mail address: enrico.fabrizio@unito.it (E. Fabrizio).

http://dx.doi.org/10.1016/j.enbuild.2014.08.031
0378-7788/

Nomenclature

Latin letters

A	area (m^2)
C_a	annual cost (€)
C_G	global cost (€)
CF	fixed unit cost (€/m^2)
CI	investment cost (€)
CR	replacement cost
CS	specific cost for insulation parameters (€ kJ/m^4 Kh)
CU	unit cost for insulation parameters (€/m^2)
f_{pv}	present value factor
k	multiplying parameter of exponential cost functions
m	slope parameter of linear cost functions
p	parameter
q	intercept parameter of linear cost functions
Q	energy consumption (kWh)
R_d	discount rate
R_r	real interest rate
Var	variable value
V_f	final value

Greek symbols

α	exponential parameter of exponential cost functions
τ	calculation period (years)

Subscripts

o	outwall
r	roof
s	slab
w	window

measures. Then the energy consumptions related to the various packages of EEMs are calculated through energy simulations, and the costs of the different packages are estimated, in order to establish which of them has the lowest global cost and, consequently, represents the cost optimal level. Finally, the distance between the cost optimal performance (the energy performance – in terms of primary energy – leading to the minimum Global Cost over the calculation period) and the ZEB target can be assessed and evaluated, orienting policies for reducing the distance.

The main challenge of this calculation methodology is to ensure that on the one hand all measures with a possible impact on the primary or final energy use of a building are considered, whilst on the other hand the calculation exercise remains manageable and proportionate, as applying several variants to a reference buildings can quickly result in thousand of calculations. Test runs performed for the European Commission [12] revealed that the number of packages/variants arbitrarily selected among the all possible design solutions and applied to each reference building should certainly not be lower than 10.

Therefore, it is clear that this approach cannot guarantee to result in the absolute cost-optimal solution because it explores only some of the available combinations of design options. It is clear that the more packages (and variation of the measures included in the analyzed package), the more accurate the calculated economic optimum will be.

Furthermore, the methodology requires the calculation of investment and replacement costs related to all the building envelope and HVAC system variables, but also the operation cost, such as maintenance and energy costs: because of the high number of independent variables involved in the calculation, the cost-optimal level research can be seen as a complex optimization problem, whose objective function is the Global Cost Function. In order to achieve the optimal solution with less time and labour while exploring many design options, a simulation-based optimization method may be used [13]. It consists in the use of a computer-automated model where a building simulation programme is coupled to an optimization engine. In this way the optimization problem is solved using iterative methods driven by optimization algorithms [14] that construct sequences of progressively better approximations to a solution, which is a point satisfying an optimality condition within the search-space. In this work the coupling of the TRNSYS® [15] building dynamic simulation programme with the Generic Optimization program GenOpt® [16] is performed, creating a system of tools and approaches able to support the application of the cost-optimal methodology with high accuracy (Fig. 1).

1.1. Relevant studies

There is a great interest on computer-based optimization techniques among building research communities. The first efforts of combining building energy simulation with an algorithmic optimization engine date back to the 80s: Bouchlaghem and Letherman [17] optimized the passive thermal performance of a building with a computer based model, while Wilson and Templeman [18] studied the optimal thermal design of a building office. However, most studies related to the application of simulation based optimization methods were performed in the late 2000s, with a sharp increase since the year 2005, covering a wide range of applications in different aspects of building designs [13]. Most of the studies are focused on optimization of various building design variables related to the building energy performance, with the purpose of minimizing the energy demand [19–23].

Many studies using simulation-based optimization methods focus also on maximizing the efficiency of an high-performing building HVAC heat exchanger [24], a ventilation system [25] and a hybrid-photovoltaic collector system [26]. Other studies are focused on the optimization of one design parameter of the building, such as the window [27,28] or the façade design [29]; some works focus on design parameters for building renovation [30], another study is related to the optimization of the internal comfort related to the indoor humidity [31]. Simulation-based methods are used also for optimization problems related to the outdoor environment of a building, as in [32].

Though these methods may seem to frame design problems as only mathematical calculation driven, it is demonstrated that the final role of the designer is fundamental, as reported by Coley and Schukat [33]. They optimize the design of a community hall from the energy performance perspective, highlighting the fact that the computer-based optimization could lead to alternative optimal design solutions among which the human choice has to intervene.

Within this wide range of application of simulation-based optimization methods, there are also some works where these methods are used for optimization of high-performing buildings from the cost point of view. In the North-Europe context, Hasan et al. present the optimization of Finnish houses [34,35] from the CO_2 emissions and the life-cycle cost points of view, using multi-objective optimization approaches; Bambrook et al. [36] follow the same method for optimizing an Australian low energy house. Znouda et al. [37] optimized energy and cost of a building in Mediterranean climate (Tunisia) using genetic algorithms, but the calculation of energy consumptions were performed with a simplified method without dynamic energy simulation.

Since the introduction of the cost-optimal methodology in 2012, some studies were performed in different EU Member States, trying to identify the cost-optimal range of different building typologies [38–41]. However, these studies were conducted exploring a limited number of evaluated design options, therefore the