Optimal design of Net Zero Energy Buildings

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Abstract: The new recast of the Energy Performance of Buildings Directive (EPBD) calls for all new buildings to be nearly zero energy buildings by the end of 2020. Besides, there are many evolving new definitions of Net Zero Energy Building (NZEB) that need to be fulfilled. To achieve the above mentioned targets is quite challenging. In this paper the author presents his approach for the optimum deign method for NZEBs, which is by using combined simulation-optimisation. The method takes the problem as one-integrated design problem, where all possible components of the on-site renewable production, energy conversion, HVAC systems, building envelope and grid-connection are considered together as options in the design. It is a multi-objective problem, because it is to simultaneously minimise energy, CO2 emission, cost and indoor discomfort. Since these are conflicting objectives, thus it is an optimisation problem. An optimisation example is presented, which is solved by two methods: as a single objective problem and a two-objective problem.

Keywords: *NZEB, cost-optimal design, simulation, optimisation*

1. Introduction

The new recast of the Energy Performance of Buildings Directive (EPBD) calls for all new buildings to be nearly zero energy buildings by 31.12.2020 and two years prior to that for new public buildings. The rest of the energy is to be covered by renewable sources. Achieving the above mentioned targets is quite challenging. In order to fulfil the requirements for a Net Zero Energy Building (NZEB), it is to find the answers to the following question: What are the "best" components to be used in the building (materials of constructions, windows, air-tightness, insulation thickness, daylighting .vs. artificial lighting, shading type, etc), in the Heating, Ventilating and Air Conditioning (HVAC) systems (type of systems and equipments) and in the energy supply (including options for on-site renewable energy sources)? Those "best" components used to fulfil the energy target should not impose very high investment costs; otherwise the concept will not be economically viable. Besides, thermal comfort should also be kept on a high level. In addition, those best solutions will be different according to different definitions of the NZEB Concepts (e.g. NZ Site- Energy Buildings, NZ Primary Energy Buildings, NZ CO2 Emission Buildings, NZ Cost Buildings, etc). This leads us to think about: how to find the "best" components since there many targets to be achieved related to energy, cost, indoor-air comfort etc?

Then about the way to design a NZEB: the conventional way is to go first for minimising the energy demand on the building side and then to introduce on-site renewable energy. So is this the "optimum" approach?

In this paper an overview of the general method proposed by the EPBD, and as described by the Buildings Performance Institute Europe (BPIE), for finding cost-optimal solutions for nearly energy buildings is presented. Besides, the conventional method for designing buildings for the fulfilment of the NZEB definition according to the IEA-SHC Task 40 / ECBCS Annex 52 is also presented. Then, the author presents his own approach for the optimum deign as a part of his position as a research-fellow of the Academy of Finland (2010-2015). The project aims for developing a combined simulation-optimisation tool for the optimal design of the NZEB's.

2. The EPBD recast 2010 and the IEA-SHC Task 40 Annex 52

2.1. The EPBD recast 2010 [1]

According to the recast of Energy Performance of Buildings Directive (2010/31/EU), all new buildings shall be "nearly zero energy buildings" as of end of 2020, and two years prior to that for the public sector. Such buildings should have very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby. Minimum energy performance requirements should be set for all existing buildings that undergo any energy relevant renovation. Besides it is to specify the level of minimum energy performance requirements for new buildings and renovations by developing benchmark method to achieve cost-optimal levels.

Overview of the cost-optimal method
The method in brief is:

- To define and select representative reference buildings (residential and non-residential, both for new and existing).
- To define combinations of compatible energy efficiency and energy supply measures to be applied to the reference buildings (packages of measures)
- To assess the delivered energy and primary energy of the selected building
- To find the corresponding global costs
- To develop cost curve(s) and derive an optimum.

The EPBD recast prescribes that the cost-efficiency of different packages of measures (combinations of compatible energy efficiency and energy supply measures) can be assessed by calculating and comparing the energy-related lifecycle costs. From the variety of specific results for the assessed packages, a cost curve (global costs .vs. primary energy) can be derived (Figure 1). Global costs are defined as the net present value of all costs during a defined calculation period (investment costs, maintenance and operating costs, earnings from energy produced and disposal costs). It is first to start with packages of measures that comply with the minimum performance requirements in force, and then to find ambition solutions beyond current minimum requirements up to and including nearly zero-energy buildings. The lowest part of the curve in Figure 1 represents the economic optimum for a combination of packages.

To establish a comprehensive overview, all combinations of commonly used and advanced measures should be assessed in the cost curve. The packages of measures should range from compliance with current regulations and best practices to combinations that realise nearly zero-energy buildings. The packages should also include various options for local renewable energy generation. The variety of solutions will form a "cloud" of data points from which a cost curve can be derived. The minimum energy performance requirements are represented by the portion of the curve that has the lowest cost in Figure 1. The part of the curve to the right of the economic optimum represents solutions that underperform in both aspects (environmental and financial). To prepare for higher energy or environmental targets related to 2020, certain Member States might choose even stricter requirements than the economic optimum (left part of the curve). The distance to the target for new buildings "nearly zero-energy buildings as from 2021" is shown in Figure 1.

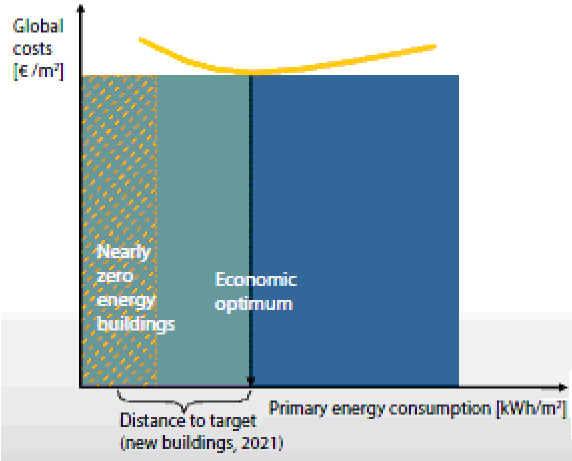

Fig. 1. Cost optimum and distance to target [1].

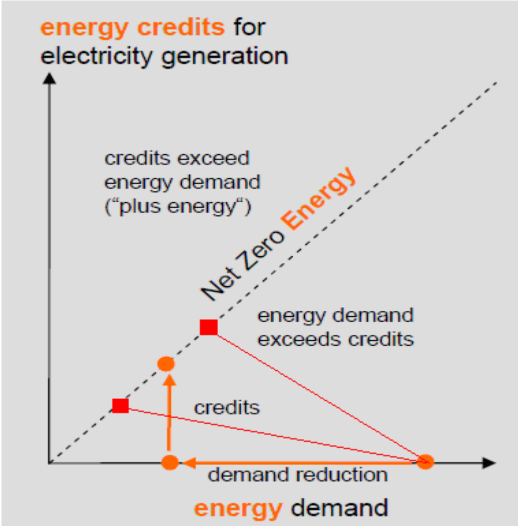

Fig. 2. Conventional way to achieve NZEB [2].

2.2. IEA-SHC Task 40 Annex 52 definition for NZEB [2]

For a NZEB, the balance between energy export (feed-in energy to the grid) and import (delivered energy from the grid) over a period of time must be zero or positive. The following inequality defines a NZEB:

$$Export - Import \geq 0.$$

The balance is normally calculated by means of some credits rather than directly on physical units of energy. The terms of the above inequality are expressed as follows:

$$Import = \sum_i delivered\ energy(i) \times credits(i)$$
$$Export = \sum_i feed\text{-}in\ energy(i) \times credits(i)\ , \quad \text{where } i \text{ is the energy carrier.}$$

The credits are therefore the metric used to calculate the balance. Figure 2 gives a graphical representation of the general pathway for the design of NZEBs in two steps (indicated by the orange circles): it is firstly to reduce the energy demand on the building side and secondly to generate renewable energy to get enough credits to achieve the balance.

2.3. Comments on the above mentioned methods

A crucial issue in the EPBD method is how to define the packages of measures (i.e. how can we say that for this package let us take x_1, x_2, x_3 and x_4 as the insulation thickness in the external wall, roof, floor, and the U-value of the window, respectively?). This is also pointed out by the IBPE publication [1]. On the other hand, and even for one package, searching for the optimum values and types of the design variables by making a comprehensive overview of all possible combinations of commonly used and advanced measures is not a simple task. This is because if we make an exhaustive search, the total number of combinations is a result of multiplication of the options for each variable. This will produce a huge number of combinations to be investigated. And then for both EPBD and IEA-Annex 52 methods, the approach should not be split into two steps, firstly reducing the energy demand to nearly zero energy and secondly introducing on-site renewable energy production. This is because if we apply this approach, we will first end-up with an extremely low-energy house or a passive-house before giving a very small chance for on-site renewable energy production to participate in the solution, which is not the best method for all cases (e.g. a case using micro-CHP).

3. Optimum Method for Designing NZEBs

The optimum method is to take the problem as a one-integrated problem, where all possible components of energy production (e.g. on-site renewables), energy conversion (e.g. via heat pumps), HVAC systems, building envelope and grid-connection are considered together as options. It is a multi-objective problem, because it is to simultaneously minimise the targets of energy (heating/cooling energy, primary energy), CO2 emission, cost (investment cost, operating cost, net present value costs), indoor discomfort, etc. Since these are mostly conflicting objectives, thus it is an optimisation problem, where optimal trade-off designs are searched. This holistic approach will produce a huge optimisation problem. However, it could be converted into a manageable size using e.g. problem specifying heuristics and considering most promising components in the building and the HVAC system. An optimisation problem is formulated by specifying the variables and objectives of the problem. The parameters are classified as fixed and variable parameters. These latter we call “design variables”, are the ones we seek to find their optimum values that will make the best impact in achieving the objective functions (i.e. targets).

The implemented approach is “combined simulation-optimisation”, which is made by coupling the dynamic building simulation program with optimisation algorithms, to find optimal values of the design variables. Figure 3 shows a typical combination of an optimisation program with a simulation program. To perform the optimisation, the optimisation program automatically writes the input files for the simulation program. Then it starts the simulation program, reads the value of the function to be minimised from the simulation result file and then determines the new set of input parameters for the next run. The whole process is repeated iteratively until a p re-defined criterion is fulfilled or a maximum number of iterations is reached. Two optimisation programs are implemented in our studies. In our implementations, we have modified those programs [3, 4], so that we are able to handle single and multi-objective function problems, with or without constraints, having continuous and discrete variables. Discrete design variables are very common in building designs (e.g. different types of windows, walls, shadings, HVAC equipments etc).

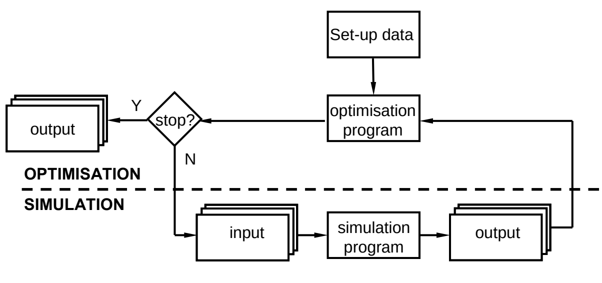

Fig. 3 Combined simulation-optimisation.

Table 1. Design variables and bounds.

	$dX_{extwall}$ (m)	dX_{roof} (m)	dX_{floor} (m)	U_{window} (W/m^2K)	*Eff.*
Min. (m)	0	0	0	1.0	07
Max. (m)	1.0	1.0	1.0	Or	or
Step (m)	0.05	0.05	0.05	1.4	0.8
Initial (m)	0	0	0	1.4	0.7

Min. is the lower bound value
Max. is the upper bound value
dX is the additional insulation thickness to be added to the standard
U_{window} is the window’s thermal transmittance
Eff. is the efficiency of the heat recovery unit

3.1. Example

To demonstrate the method, a building design example is presented here. In this example, a detached house (floor area 147 m^2) designed according to the Finnish Building Standard-2003 is studied (Standard House). The task is to modify the house by finding optimal values for five design variables that will need minimum investment while making best impact on lowering the operating energy cost. These variables are: three continuous variables as additional insulation thicknesses to be added to the Standard House (in the external wall, roof and floor) and two discrete variables (types of windows and ventilation heat recovery exchanger). The given bounds for the values of those variables are indicated in Table 1. The problem is solved in two ways, as a single objective problem and a two-objective problem. In this paper, data from [4 and 5] are reproduced to explain the implementation.

3.1.1. Solution as a Single Objective Problem

The objective is formulated as a single objective optimisation problem for minimising of one objective (ΔLCC) (€), the difference in the life cycle cost of the house discounted to net present value compared with its standard design. ΔLCC is defined as

$$\Delta LCC = \Delta IC + \Delta RC + \Delta OC$$

ΔIC difference in the investment cost (€) for the specified design variables

ΔRC difference in the replacement cost (€) due to replaced items (in the building envelope or system) in specified years due to shorter life of those items with respect to the building life.

ΔOC difference in the operating cost (€) due to difference in energy consumption

All above cost differences are with respect to those for the Standard House. This is an optimisation problem because it in cludes conflicting targets (i.e. increasing the investment cost will decrease the operating energy cost and vice-versa). An exhaustive search method to find the optimal values of the design variables will need a huge number of simulations even for this simple case. For example, if we assume that there is 1 cm step in the additional insulation thickness in Table 1, t hen the total number of possible combinations to be investigated is $100 \times 100 \times 100 \times 2 \times 2 = 4\times10^6$. The combined simulation-optimisation does it in much less number of simulations.

For this example, eight cases were studied [5] with different assumptions for the life-cycle span *n*, escalation in the energy price *e* and the source of the design variable prices. Figure 4 shows the optimisation-simulation iterations for one case (n = 20 years, e = 0.01 and real interest rate = 4.90 %). Only 241 simulations were needed to find the cost-optimal solution using a hybrid algorithm (PSO and Hooke-Jeeves). Each point in the figure is a full-year hourly dynamic simulation. From this figure, it can be seen that the solution has a minimum value of ΔLCC (−2102 €) as a r esult of the reduction made in the energy cost for space heating ΔOC (−4229 €) when investment is made in the insulations, windows and heat recovery including associated replacement costs ΔIC+ΔRC (+2127 €). Since ΔLCC for the Standard House is 0, therefore the negative value of ΔLCC means lower LCC cost is reached compared with the Standard House. The optimisation results give the optimised values of the five design variables to achieve this target. The simulation-iteration runs, when searching for the optimal solution, are indicated in Figure 5 as ΔLCC .vs. annual space heating energy. From this figure, we can conclude that there is no need to make an exhaustive search and draw the whole energy-cost curve to find the cost-optimal solution because the optimisation algorithm finds shortest ways to that. In addition to minimising the LCC, Figure 5 shows that the annual space heating energy demand at the cost-optimal solution is about 71 kWh/m^{2}a, which is 28% lower than that for the Standard House. This means that the obtained cost-optimal solution achieves both the financial and energy targets. By this method, the optimisation method took the problem as one investigation for minimisation of the LCC, which inherently accomplished the environmental target.

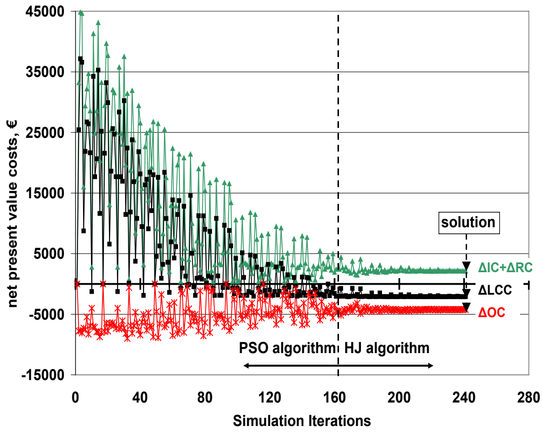

Fig. 4. Simulation-optimisation iterations.

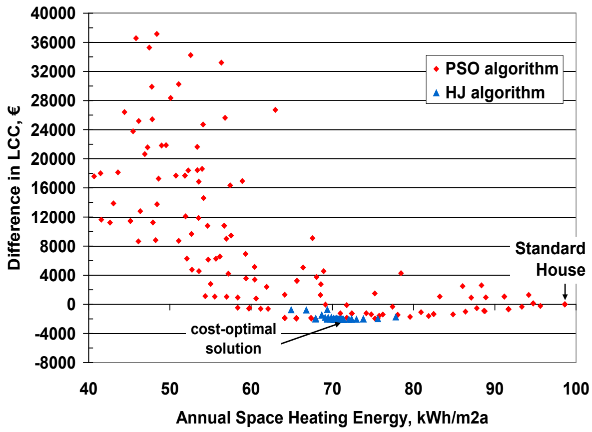

Fig. 5. Finding the cost-optimal solution.

3.1.2. Solution as a Multi-Objective Problem

By taking the problem as a multi-objective optimisation problem, we can draw the cost-curve, find the cost-optimal solution and specify other potential solutions towards nearly zero energy buildings, without making an exhaustive search. To explain this method, the previous example is converted into a two-objective optimisation problem where it is to simultaneously minimise both the difference in the investment cost (ΔIC) and the annual space heating energy demand. Figure 6 shows the optimisation solutions for this two-objective problem using combined simulation and a Genetic-algorithm optimisation [4]. In this figure, the results of an exhaustive search (Brute-force) made on preferable solutions are also shown. The Brute-force search is made by keeping the floor thickness according to the Standard House. This makes the number of variables four. Besides, a maximum value of 0.39 m is considered for ($dX_{extwall}$) and (dX_{roof}). Assuming a 1 cm step in the insulation thickness, the total number of Brute-force candidate solutions is 40×40×2×2 =6400 and as shown in Figure 6. These hints were concluded from the single-objective case results; otherwise a complete exhaustive search will be needed with 4×10^6 candidate solutions. It can be seen that the optimisation solution captures the optimal Pareto-front of the Brute-force, which is an indication of the high accuracy of the optimisation results. Figure 7 presents the difference in the life cycle cost (ΔLCC) based on the data from the optimisation solutions and the Brute-force results from Figure 6. It can be seen from Fig. 7 that the cost-curve is constructed and the cost-optimal solution can be found. In comparison with the single-objective solution, this two-objective solution facilitates assessing potentials for nearly-zero buildings (range of optimal solutions to the left of the cost-optimal in Fig. 7), which is a big advantage over the single objective approach. It is to note that a constraint of 6000 € was applied on (ΔIC) in the optimisation problem to obtain similar range of results as those got from the brute-force search in Fig. 6. We could have got a more complete cost-curve without such a constraint.

Similarly for the NZEB case, the optimisation method can find optimum solutions (indicated by the red squares in Figure 2) without going through the conventional two-step solution method.

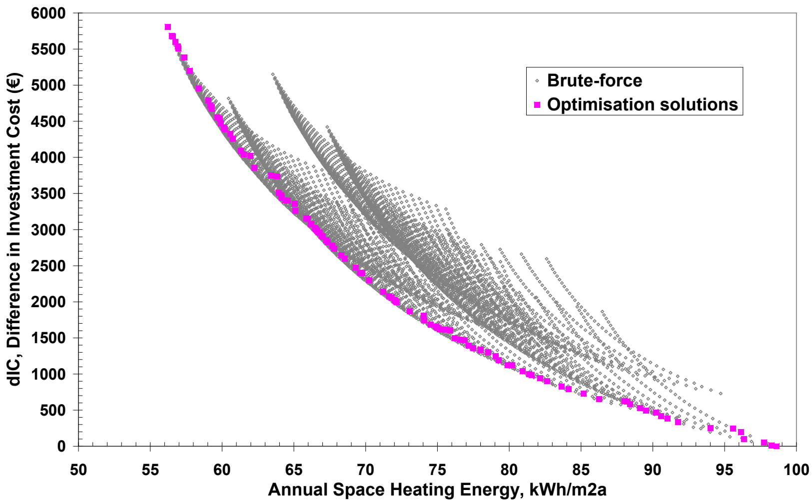

Fig. 6. Two-objective optimisation results and Brute-force candidate solutions [4].

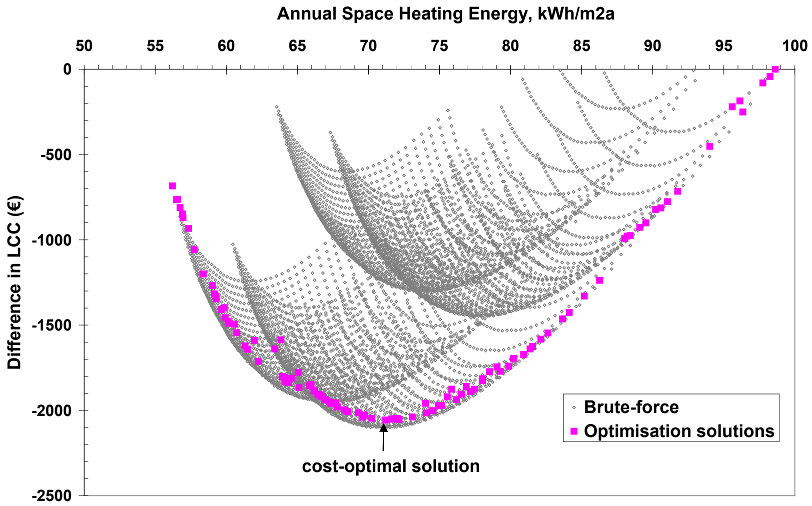

Fig. 7. Cost-curve and cost-optimal solution found from the two-objective optimisation results.

4. Conclusion

It is concluded that optimisation tools have to be combined with simulation tools for finding optimal designs of NZEBs. This is valid for the two methods discussed in this paper: the EPBD recast method and the IEA-Annex 52 NZEB definition. Otherwise it is very difficult for a designer to make a "good" guess at best candidate combinations of measures that will be compared for their cost-energy performance especially when there are many variables in the problem and also due to the nonlinear interaction between the variables. Another way is to make exhaustive searches for each case to define candidate packages, which will then need a huge number of simulation iterations.

The approach should not be split into two steps, firstly reducing the energy demand to nearly zero energy and secondly introducing on-site renewables. If we apply such approach, we will end-up with an extremely low-energy house before giving a very small chance for on-site renewables to participate in the solution, which is not the best method for all cases. For example a house with on-site energy generation from a micro-CHP dose not need to have high quality windows or very thick insulations because of the ample heat accompanied with the generation of electricity. Besides, the selection of the optimal measures should not be only dependent on achieving cost and energy targets, but indoor air comfort should be considered as target in the problem as well, otherwise overheating could be faced when using more insulations and air-tight envelopes or overcooling could be faced when low-energy value sources are used for heating.

The optimum design method for NZEBs is by taking the problem as one-integrated problem (envelope + HVAC systems + en ergy supply including renewables) using combined simulation-optimisation. The optimisation tool will find the best combinations of measures that will fulfil the objectives of the problem. This approach was applied in the presented example. The problem was solved by two methods. In the first method, the problem was formulated as a single objective LCC minimisation problem, where search was done for finding the cost-optimal solution. In the second method, the problem was formulated as a two-objective problem, where search was done for minimising both energy and investment cost, from which the whole cost-curve was constructed and the cost-optimal and other alternative solutions were found.

Acknowledgment

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