Results from cost optimal analyses across Europe: methodological aspects

Maria Ferrara¹, Valentina Monetti², Enrico Fabrizio³

¹Department of Energy (DENERG) Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Turin, Italy
²maria.ferrara@polito.it
³valentina.monetti@polito.it

Abstract
Since the introduction of the EPBD, several applications of the cost optimal analysis were carried out either by academic research groups and by national bodies. Different approaches pursuing the definition of cost optimal levels can be found, distinguishing from a dynamic simulation-based approach to simplified models and from deterministic models to optimization-based models. This review paper presents a comprehensive research on the state-of-the-art of cost optimal analysis applications in Europe since the EPBD recast was enforced, pointing out the differences in the analyzed studies and comparing their outcomes. The results from the papers were gathered based on the methods employed, with special attention to the methods and tools used for assessment of the building energy performance and for the selection of the energy efficiency measures. A critical discussion about gaps and criticalities of cost optimal studies for providing the research community with a comprehensive and up-to-date understanding to improve the methodology and recommend future advancements is also presented.

A critical discussion about problems and advances of the cost optimal analysis is presented based on the review results. The results in terms of cost optimal levels and the related energy performance of the studied buildings show some differences, mainly due to the great amount of variables that makes the nZEB design strictly related to the local scale. At the same time, a shared vision on the most promising methodologies for the evaluation of the cost optimal level of buildings is emerging and is presented in the paper.

Keywords - EPBD recast; Nearly zero energy buildings (nZEB); Cost optimal Analysis; Dynamic simulation; Energy efficiency measures; optimization methods

1. Introduction
In Europe (EU) the building sector is responsible for about 40% of the final energy demand [1] and 36% of CO2 gas emissions [2]. To this regard, the recast of the European Directive on the Energy Performance of Building (EPBD) imposed 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. Moreover, EPBD recast has set out that Member States (MSs) ensure that minimum energy performance requirements are set with a view to achieve the cost optimal level, that is defined as the energy performance level that leads to the lowest cost during the estimated economic
lifecycle. Therefore, through the so-called Cost Optimal Analysis (COA), based on Global Cost method, each MS define their optimal energy performance level base on global cost minimization, and therefore the most cost-effective strategies to improve building performance.

To this regard, the principles of cost-optimal energy performance are decisive to move national requirements to more effective levels, towards the achievement of the ZEB target. Results of the MSs from the application of COA demonstrated that, even though the ZEB target is technically feasible for low-rise buildings (many examples of existing ZEBs or nZEB can be listed), ZEB of nZEBs are still not cost efficient in terms of cost. This is because the direct consequence of the application of the COA is the estimation of the existing gap between the resulted cost optimal energy performance levels and the (nearly) Zero Energy performance. Given this context, the COA can be considered as a methodology for studying not only the building energy performance in relation to costs, but also for studying how to reach the ZEB or nZEB target.

These are the reasons why, since its introduction by the EPBD recast in 2010, several applications of the cost optimal analysis (most of them also aimed at achieving nZEB levels) can be found in many papers reporting the work of different academic research groups from different countries working in the field of building energy design.

Based on these facts, the Authors believe that the introduction of COA, beyond its regulatory purpose, has given a strong impulse to the scientific studies on the energy performance of (nearly) Zero Energy Buildings. After some years of development of this field of studies, it is worth analyzing and compare their outcome, in terms of objective of the studies, methods and tools used, and results. Such a review work may result in identifying a shared vision on the most promising technologies and methodologies for bridging the gap between the zero energy goal and the economic affordability.

The present work analyzes most of the applications of COA since the EPBD recast entered into force, in order to point out the different approaches and compare the results. In particular, this paper focuses on the methods used for solving the optimization problem related to the cost optimal search and shows how the method may influences the results. The different approaches for the selection of the packages of energy efficiency measures to be applied to the reference buildings and the methods for their energy performance assessment are investigated.

2. The cost optimal analysis

This section presents the cost-optimal methodology as defined by the European Directive 2010/31/EU (EPBD recast), which came into force in June 2010 [1]. This methodology represents the EU normative reference with regard to the building energy performance assessment. Specifically the EPBD recast stipulates that “MS must ensure that minimum energy performance requirements are set with a view of achieving at least cost-optimal levels for buildings, building units and building elements”. MS must hence calculate the cost-optimal levels of minimum energy performance requirements in order to compare them with the minimum energy performance requirements, which they have adopted.
The European Commission has to be notified with regular reports on the results of these comparisons, in order to assess the national MS progress towards cost-optimal levels achievements.

The main steps of the methodology for calculating the cost-optimal levels of energy performance are the following [7]:

- **Definition of reference buildings (RBs)**
  To apply this methodology MSs are expected to define a series of Reference Buildings (RBs) as baseline and representative models of the national building stock.

- **Selection of energy efficiency measures (EEMs) to be applied to the RBs**
  EEMs should be assessed, as a single measure or as a package of measures, for the selected RBs, for individual buildings as a whole and/or for individual or combination of building elements. The measures defined should cover high-efficiency alternative system solutions (decentralized supply, cogeneration, district heating and cooling and heat pumps, as well as systems based on RES) that are technically, functionally and economically feasible. The number of measures/variants calculated and applied to each RB has to be equal or superior to 10 packages/variants, plus the case of the RB. The measures should be calculated both for new buildings and for completed renovated buildings. Firstly, in order to define the current ambition level, the packages need to comply with minimum performance requirements in force. Secondly, the measures also need to go beyond current minimum requirements, focusing on higher ambition levels like low energy building and nearly zero-energy building levels. The measures should also consider all measures with a possible impact on the primary or final energy use of a building. Innovative solutions, based also on other MS experiences, are encouraged to enlarge the combination of measured considered within the calculations.

  It is important to remember that the more packages are evaluated, the more accurate the calculated economic optimum is, however it is essential to ensure calculations to be manageable and proportionate, with special regard to the number of packages.

- **Energy performance assessment**
  After the EEMs definition, step three of the methodology concerns the assessment of the building energy performance. The energy assessment involves firstly the calculation of the building final energy needs for all uses, secondly the energy delivered and thirdly the primary energy use. The EPBD does not identify the calculation method to be used but specifies that calculations have to be performed according to national methodologies harmonized with the European Standards, especially those developed for supporting the regulation implementation. For this reason, the CEN technical report TR 15615 [4] provides an ad hoc overview of the 31 CEN standards developed to be applied in the framework of the EPBD. With respect to the energy needs for heating and cooling, the energy balance of the building and its systems should be assessed according to standard EN ISO 13790 [5]. Moreover, the guidelines suggest performing calculations based on a dynamic method rather than a quasi-steady approach.

- **Global cost calculation**
  As prescribed in compliance with the Regulation [3], the economic assessment is based on the net present values calculation, by using the global cost calculation method. Under the recommendations of [4], the EN 15459 [6] is specified as standard to be used for
carrying out the financial calculations. The global cost is assessed as a sum, during the calculation period, of the initial investment, of annual costs for every year and of the final value as well as of disposal costs if appropriate, all with reference to the starting year. It important to note that the global cost, as intended for cost-optimal calculations, takes into account only energy-related costs. Therefore the concept of global cost as intended in the EBPD recast is not in compliance with a full life cycle assessment, where the environmental impacts are also considered.

The global cost formula can be written as:

\[ C_G(\tau) = C_I + \sum_j \left[ \sum_{i=1}^{\tau} \left( C_{a,i}(j) \times R_d(i) \right) - V_{f,\tau}(j) \right] \]

where \( C_G(\tau) \) represents the global cost referred to starting year \( \tau_0 \), \( C_I \) is the initial investment cost, \( C_{a,i}(j) \) is the annual cost for component \( j \) at the year \( i \) (including running costs and periodic or replacement costs), \( R_d(i) \) is the discount rate for year \( i \), \( V_{f,\tau}(j) \) is the final value of component \( j \) at the end of the calculation period (referred to the starting year \( \tau_0 \)). The discount rate \( R_d \) is used to refer the replacement costs and the final value to the starting year; it depends from the real interest rate.

The calculation period is defined for the whole building. However, considering that the lifetime of single building components could be shorter or longer than it, residual values should be included in the calculations, for those components with longer lifetime than the calculation period. On the other hand, components with shorter lifetime are replaced during the selected calculation period.

- **Determination of cost optimal levels**

In order to determine the cost optimal level, the global cost value is reported as a function of the energy performance expressed into the global net primary energy need in a graph. The energy performance value that has the lower global cost is defined as the cost optimal level.

### 3. Methodology

The present work is based on scientific papers only, published on peer-reviewed journals, declaring the application of the cost optimal methodology as defined by the EPBD and the related regulation and guidelines. They were retrieved from “Scopus” and “ScienceDirect” databases by means of an advanced search based on the keywords “cost optimal” “building” to be present in Title, Abstract or Keywords of the paper and “EPBD” to be recalled in the paper text.

The refinement of the search lead to select 50 papers that follow the cost optimal methodology for scientific purposes. The selected papers were classified according to the country of application, the type of building, the financial framework and the methods and tools that have been used for the selection of the energy efficiency measures and for assessing the energy performance of the building to which the different packages of energy efficiency measures were applied.

Concerning methodological aspects, there are two of the five COA phases in which the analyzed works present differences. These are the selection of energy efficiency measures (and their combinations into packages) and the energy performance assessment
of the so-created building design alternatives. The choice of the method to be used in these phases may differ in relation to the final objective of the work and to the desired accuracy of the cost optimal calculation. In fact, the application of the cost optimal methodology can be seen as a complex optimization problem, where the objective function is the Global cost and the optimization variables are the energy efficiency measures.

The different methods that can be used for the selection of EEMs leading to the cost optimal point can be divided into two main groups.

One is the manual approach, that means selecting a defined number of packages of EEMs and calculating and comparing the global cost values; another approach is the automated search, based on different optimization algorithms driven by computer engines, that allows exploring a wider search space and identifying the point minimizing the global cost objective function.

The Fig. 1 reports the number of published papers as a function of the year of publication and of the approach that was used for selecting the EEMs or packages of EEMs to be applied to the reference building. As shown, since 2010 there is an exponential increasing trend of published papers for both approaches. As shown in the right part of Fig.1, there are many tools used for the automated approach. The most used are those implementing non-derivative, population-based optimization algorithms, such as GenOpt and Matlab [8]. Also other techniques has been set up and tested by the authors of the papers, such as an automated parametric analysis [9] or sequential search optimization technique, that was developed specifically for the cost optimal calculations [10]. The aspects to be considered when comparing the EEMs selection method are the number of evaluated EEMs packages and the related accuracy of the cost optimal search, the computational time and the data availability after the optimization process.

The other methodological issue is related to the energy performance assessment (Fig.2). One approach is the use of simplified methods, such as the quasi-steady state method defined by UNI EN 13790 and the various national implementations. When using the simplified approach, the authors use commercial tools that are compliant with the
regulations [11] or they develop their own calculation tool for energy performance assessment [12]. The other approach is dynamic simulation that allows a more detailed and precise hourly calculations of outdoor and indoor temperatures and energy consumptions. The most used dynamic simulation tools are EnergyPlus [14], IDA ICE® [15] and TRNSYS® [16].

The left part of Fig. 2 reports the number of published papers in function of the year of publication and of the used approach for the energy performance assessment of the building when different packages of EEMs are applied. As shown, the dynamic simulation is getting more and more used and, in 2015, the number of papers where dynamic simulation is used exceeds that of papers when simplified approach is used. However, the simplified approach has not been abandoned, because of its easiness of application in compliance with national regulations.

![Fig. 2 Methods for energy performance calculation: Simplified (S) vs Dynamic (D). Number of papers using the two approaches for year of publication (left) and the tools used (right).](image)

Combining the different methods for addressing the two phases of the COA, four main approaches for carrying out the cost optimal analysis were identified, as shown in Table 1.

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<th>EEMs selection</th>
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<td>Manual (M)</td>
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<td>Simplified method (S)</td>
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<td>Dynamic calculation</td>
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The number of papers for each approach in function of the year of publication is reported in Fig. 3. As shown, the emerging approach is the Dynamic energy simulation with Manual selection of EEMs (D-M), however there is an increasing trend for all approaches that give rise to expect that the other approaches will be implemented and developed in the future.
4. Results

In this section, the four approaches identified from the analysis of the previous section are presented by means of highlights from some representative papers. The papers were selected among those reporting a study on the same building typology (single-family building), in order to make it possible a mutual comparison.

- **S-M: Simplified energy performance assessment with Manual selection of EEMs**
  
  This approach typically leads to evaluate a limited number of design alternatives. In one of the exemplifying paper [12], Tronchin et al. define six construction scenarios for the single-family house taken as reference building, beyond the existing situation. One scenario reflects the minimum law requirements, while the others consider improvements in the construction of different part of the building opaque envelope, more performing technologies for windows, the use of PV and solar thermal. The definition of these scenarios requires preliminary design efforts (such as system sizing, construction layer thickness, etc.), but it ensures the easiness of the cost calculation when only a few data are available and the feasibility of the resulting cost-optimal design, because of the assured technical feasibility of all the evaluated design alternatives. The quasi-steady method for the energy performance assessment ensures the calculation not to be time-consuming and the results to be understandable within the national regulatory framework for the building energy performance classification.

  However, this approach may lead not to consider all the existing design alternatives and therefore excluding energy efficient alternatives with lower global cost. This is why it is recommended that validated criteria are used for defining the design alternatives or in presence of additional constraints that limit the number of possible design options, such as those occurring in existing building retrofit [13].

- **D-M: Dynamic energy simulation with Manual selection of the EEMs**
  
  This approach typically leads to evaluate a limited number of design alternatives in a very detailed way. In the selected paper [17], Kurnitski et al. define four construction concepts for the single-family house taken as reference building. The criteria for determining the four design concepts as packages of EEMs related to many design variables (envelope construction, leakage, window type, efficiency and size of the HVAC
system) is the building envelope specific heat loss coefficient (DH), which includes transmission and infiltration losses through the building envelope and is calculated per heated net floor area. As for the previous described approach (S-M), the definition of design concepts requires a preliminary design effort but ensures the feasibility of all the evaluated design alternatives.

The energy simulation of a few construction concepts allows an accurate and validated assessment of the energy performance, leading this approach to be useful not only in the preliminary design phase, but also in the advanced design phase. When using a dynamic simulation tool with manual EEMs selection approach, the limited number of design alternatives is essential in order to ensure the cost-optimal search to be manageable and not too time-consuming [14].

- **S-A: Simplified energy performance assessment with Automated selection of the EEMs**

  The papers classified in this category exploit the potential of an automated optimization technique in order to evaluate a great number of packages of EEMs. This is done by means of an optimization algorithm that drives an iterative process toward the minimization of the objective function (the global cost function).

  As an example, Kapsalaki et al. [18] report a study where more than 7 millions of packages of EEMs are evaluated by means of a model implemented and optimized in Matlab®.

  Because of the automatism of the EEMs selection, this approach requires to define the constraints for the optimization problem, that means defining the design variables to be varied (e.g. insulation thickness, glazing type, HVAC system) as EEMs and the limits of their variations (e.g. insulation thickness from 10 to 30 cm). Therefore, the automated approach for the selection of EEMs allows defining a wider n-dimensional search space with respect to the previous approaches with Manual selection of EEMs, which is composed by all the points representing a combination of design variables (the so called packages of EEMs).

  To do so, it is necessary to create a system of equations for calculating the total primary energy demand and the related global cost of each package of EEM. In this S-A approach, the calculation the energy performance of each package follows the quasi-steady state method, so that the system of equations remains manageable and the computational time for energy performance assessment is reduced. However, depending on the number of design variables, their range of variation and the resulting dimension of the search space, the optimization process may take a long time before converging to a solution.

  With respect to the D-M and S-M approaches, this approach allows a more accurate search of the cost optimal point and reduces the risk of overlooking some effective solutions. However, the technical feasibility of the resulted optimal solutions must be checked at the end of the optimization process, as there is less control on the selected combinations of EEMs even if constraints are set carefully.

- **D-M: Dynamic energy simulation with automated selection of the EEMs**

  This approach is typically used when a great number of design alternatives has to be systematically evaluated, in order to provide an accurate search of the cost optimal
point with a detailed energy performance assessment. This can be done by coupling a dynamic simulation software with other tools able to run optimization algorithms and minimize the global cost objective function, leading to what is also known as simulation-based optimization method [21].

The definition of the search space and the potential number of evaluated design alternatives is the same of the previous approach (S-A), however the computational time may increase because of the accuracy of energy performance assessment driven by the engine of the dynamic simulation software able to solve complex systems of partial and differential equations at each calculation time step. This is why, when using this approach, is essential to control the number of objective function evaluations before reaching the minimum point. To do so, it is possible to set up optimization algorithms that perform efficiently in this kind of optimization problems [19], or to perform the optimization with a multi-stage methodology [20]. In the last paper, Hamdy et al. found the cost optimal energy performance of a single family house in Finland through a three-stage simulation-based optimization. The first stage leads to the optimal combination of building envelope and heat recovery design options, the second stage combines the heating/cooling systems with optimal building design, while the last stage integrates RES-system design. This approach allows to explore an enormous number of possible EEMs packages (more than $3 \times 10^9$) with a suitable number of iterations (less than 3400).

Furthermore, this kind of approach can be used in ZEB oriented studies, where a multi-objective optimization can be performed in order to minimize both the global cost and the energy performance level.

5. Conclusions

The introduction of COA has been embraced from the scientific community, at least in most EU countries (Austria, Estonia, Finland, France, Greece, Ireland, Italy, Latvia, Norway, Poland, Portugal, Romania, Spain, Sweden, Turkey, UK) not only as a legislative requirement but rather as a new and powerful tool to progress the research in building design towards the affordability of the Zero Energy objective.

This is because, on the one hand, the COA introduced to researchers the possibility to evaluate different single energy efficiency measures (measures related to the envelope, measures related to HVAC system, measures dealing with renewable sources, etc.) and/or packages of measures within a common calculation framework, which is harmonized across all Europe.

On the other hand, this methodology for the search of the economic optimum lead to investigate and develop different methods and algorithm for the building design optimization problems, and to discuss how the calculation method for the energy performance assessment can influence the selection of the optimal solutions.

Further studies will be done concerning other aspects related the application of the COA across Europe for scientific purpose, such as those related to the definition and selection of the reference building, to the global cost calculation and, last but not least, concerning the different resulted cost optimal solutions across Europe.
References

[6] CEN, EN 15459