A review on optimization and cost-optimal methodologies in low-energy buildings design and environmental considerations

Abstract

The topic of low-energy buildings received a widespread and growing interest in last years, thanks to energy saving policies of developed countries. The design of a low-energy building is addressed with energy saving measures and renewable energy generation, but the correct assessment of phenomena occurring in a building usually requires to perform dynamic simulations and to analyze multiple scenarios to attain the optimal solution. The optimality of a technical solution may be subject to contrasting constraints and objectives. For this reason, designers may employ mathematical optimization techniques, a non-familiar topic to most of building designers. In this paper, a review on optimization of low-energy buildings design is provided, in order to collect the results of previous works and to guide new designers. The topic received an increasing interest in last years, with multi-objective optimization and genetic algorithms being the most popular. The most common objective functions are the costs and the operating energy consumption, while the environmental aspects are often neglected. As low-energy buildings should reduce the global energy demand, their design may benefit enormously from the assessment of energy consumption and environmental impacts in the whole life cycle, even in a simplified way.

Keywords — BPS; Cost-Optimal; Low-Energy buildings; Multi-objective; NSGA II; NZEB; Optimization; Review.

Acronyms

AEE	Annualized Embodied Energy
AEU	Annual Energy Use
ALCE	Annualized Life Cycle Energy
BPIE	Buildings Performance Institute Europe
BPO	Building Performance Optimization
BPS	Building Performance Simulation
CAGR	Compound Annual Growth Rate
CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power
DGI	Discomfort Glare Index
DHW	Domestic Hot Water
DM	Decision Maker
DOE	Department of Energy (of USA)
ENSES	Elitist Non-dominated Sorting Evolution Strategy
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate

EU	European Union
GA	Genetic Algorithm
GII	Grid Interaction Index
GUI	Graphical User Interface
GWP	Global Warming Potential
HVAC	Heating, Ventilation and Air Conditioning
IBPSA	International Building Performance Simulation Association
LC-ZEB	Life Cycle Zero Energy Building
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
MILP	Mixed Integer Linear Programming
MOBO	Multi Objective Building Optimization tool
MODA	Multi-Objective Dragonfly Algorithm
MODE	Multi-Objective Differential Evolution algorithm
MOGA	Multi-Objective Genetic Algorithm
MOOP	Multi-Objective Optimization Problem
MOPSO	Multi-Objective Particle Swarm Optimization
MS	Member State
NER	Net Energy Ratio
NPV	Net Present Value
NSGA	Non-dominated Sorting Genetic Algorithm
NZEB	Net Zero-Energy Building
nZEB	nearly Zero-Energy Building
OF	Objective Function
PCM	Phase-Change Material
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PSO	Particle Swarm Optimization
PV	Photovoltaic
RES	Renewable Energy Source
SHGC	Solar Heat Gain Coefficient
SOOP	Single-Objective Optimization Problem
STD	Standard Deviation
TH	Time Horizon
UDI	Useful Daylight Illuminance
WDT	Weighted Discomfort Time

1. Introduction

The building sector is considered as one of the most impacting on energy consumption in developed countries. In detail, European Union (EU) stated that buildings are responsible for 40% of its energy consumption and 36% of its CO_2 emissions [1]. Considering only the residential sector, it accounts for 25,4% of EU final energy consumption [2]. One of the tools identified by the EU countries to reduce this fraction of its energy requirement is the nearly

Zero-Energy Building (or nZEB) paradigm, defined in the Energy Performance of Buildings Directive (EPBD) Recast in 2010 as "*a building that has a 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*" [3]. This definition is very generic and provides only with principles on which to start the design of a nZEB, as the EU Commission preferred not to quantify fixed requirements, letting the single Member States (MS) to set the preferred quantitative limits for energy consumption and renewable energy integration in national nZEBs. The EPBD Recast imposes that new buildings will have to be nZEBs from 31 December 2020 [3], but the topic might interest also refurbishment, as about 35% of buildings in EU are over 50 years old [1].

Pushed by this regulation, academics and designers started developing design criteria and pilot projects for energy-efficient buildings, but even definitions, categories and limits, e.g. low-energy buildings (LEBs), plus-energy buildings or Net Zero Energy Buildings (NZEBs). In detail, referring to the most commonly adopted definition, a NZEB is a building exchanging energy with the surrounding grids with an annual zero balance between exported and delivered energy [4], while a plus-energy building overperforms NZEBs, generating more energy than the requirement. Another categorization exists according to the boundary considered for the energy balance of the building, as it may account for primary or final energy, and the Renewable Energy Sources (RES) plants may be installed on the building or nearby. Further, if a building is equipped with an adequate storage system, it may also be independent from surrounding energy networks as electricity and natural gas grids or district heating/cooling [5], [6].

Notwithstanding this widespread number of definitions, the approach to the design of an energy-efficient building should always be based on the following rules:

- minimization of building's thermal loads, i.e. reduction of the envelope transmittance;
- employment of passive strategies, i.e. attribution of the burden of a part of the thermal loads' removal to natural phenomena;
- implementation of efficient HVAC systems, as low temperature surface embedded heating and cooling systems;
- adoption of renewable energy generation technologies to cover a variable (but generally high) percentage of remaining thermal and electrical loads.

This set of actions has to be followed with the aim to compare energy generation and loads. Thus, designers often have to assess different solutions and perform many dynamic thermophysical simulations in order to find the configuration of the building showing the lowest energy consumption and to correctly design the renewable energy systems that will cover these consumptions. This is due to three main reasons:

- multiple energy efficiency solutions available: designers have to consider and combine the huge series of energy efficiency solutions on the market, both *passive* and *active* measures (i.e. envelope insulation, RES, Home and Building Automation technologies);
- conflicting measures: solutions that might have both positive and negative impacts on the building. An example is the use of large windows, whose installation may lower electrical

consumption for lighting but rise solar heat gains (positive in winter but negative in summer) and thermal transmittance of the building;

- multiple objectives to attain: the goal that designers or Decision Makers (DM) want to reach can be evaluated from different points of view, e.g. minimal cost, maximum energy saving or maximum internal comfort, that can be conflicting objectives. If two or more goals have to be attained ate the same time, the search of an optimal technical solution for a low-energy building becomes a Multi-Criteria or a Multi-Objective Optimization Problem (MOOP), characterized by constraints such as structural problems, legal obligations or cost-effectivity.

For the above reasons, in order to find the optimal combination of technical solutions for the building, researchers and designers often combine Building Performance Simulation (BPS) and mathematical optimization tools, thus embracing areas of knowledge that are distant from each other, which are hardly part of the cultural baggage of a single professional figure. Indeed, the design process is usually carried out by design teams, composed by figures as architects, responsible for aspects as the shape, space, and functions of a building, and engineers, who care about the energy efficiency through a sensitivity analysis or optimization techniques performed with appropriate tools. The main aim of this paper is to illustrate the state-of-the-art about the use of optimization techniques in low-energy buildings sector, with a particular focus on nZEBs and NZEBs, comparing main features as objectives, constraints, methodologies and optimization algorithms, in order to sum up the almost ten years-experience of technicians in this field and to provide beginners and non-insiders with a guide on this topic.

During this review, Authors realized that scientific literature already presented a large number of review papers in the same topic or in similar ones [7], [8], [17], [18], [9]–[16]. In these papers, following aspects are described:

- the analytical form of the optimization problem applied to the energy performance of buildings [7], [10], [12];
- general description of most popular optimization algorithms [7]–[10], [12], [16], [18] and commercial BPS and BPO software [8], [12]–[15], [18];
- analysis and categorization of objective functions [12], [16], [17] and optimization variables [9], [12];
- uncertainty and/or sensitivity analysis on input parameters [11], [17];
- future perspectives and challenges [7], [12], [16].

For this reason, although some of these features are analyzed in this paper as well, the aim of this review is to differentiate from previous works and provide scientific community with new outcomes. The original contribution of this review is based on the analysis of the approaches adopted by researchers, highlighting general research trends and most commonly adopted algorithms, but also on other innovative aspects, such as social and environmental considerations related to the low-energy building performance optimization. In fact, notwithstanding the increasing number of scientific studies and the relatively high number of reviews on the topic, an important issue as the environmental impact of the building was often neglected in the past. As the main aim of LEBs is to reduce the energy consumption occurring in use phase by a massive employment of insulation or RES, an amount of the avoided use phase energy consumption is shifted to the construction and demolition phases of the life cycle of the building [19]. Authors feel to state that this aspect should be always kept into account in the optimization of buildings energy performance, thus, in order to further provide readers with useful suggestions, environmental considerations on insulating materials considered in the analyzed studies are also given in this review.

2. Background

2.1. Mathematical optimization

As previously stated, the design of a building with very high-energy performance can be considered as a Single or a Multi-Objective Optimization Problem. In general terms, mathematical optimization (or mathematical programming) is the branch of applied mathematics aimed at studying methods to find maximum and minimum points of an Objective Function (OF) by changing values assumed by the *variables*. In most engineering optimization problems, variables are subject to physical bounds (lower and upper bounds), as external dimensions limits for buildings, and the problem is limited by equality and inequality constraints, that confine the values assumed by the variables to the *feasibility space*.

Multiple categorization criteria may be applied to optimization problems and algorithms. Depending on the variables and on the OF's analytical representation, optimization problems can be classified as convex or non-convex, linear or non-linear, integer or real, and different algorithms are available for each kind of problem. Instead, regarding the desired solution, optimization problems can be categorized as single or multi-objective, depending on the considered number of OFs. In detail, in Single-Objective Optimization Problems (SOOP) the OF typically has only one global minimum and only one best solution exists (or none, eventually). On the opposite, MOOPs aims at finding a vector of decision variables that satisfies constraints and optimizes a vector function whose elements represent the OFs. These functions form a mathematical description of performance criteria, which usually conflict with each other, so that minimizing each OF separately gives a different solution. As a result, the solution to a MOOP is a set of trade-off solutions that are considered equally optimal, i.e. it may happen that solution A is better than B (A outperforms B) according to one criterion or OF, but B outperforms A according to another one. In this way, since these two solutions are equally optimal, the output of a MOOP is a set of optimal solutions, called *Pareto front* [20]. The Pareto front is composed by a set of solutions that outperform or are equal, in terms of quality, to all other solutions for all criteria and strictly outperform the other solutions for at least one criterion. When this happens, a solution *dominates* the others. Fig. 1 shows an example of a two-dimensional Pareto front.

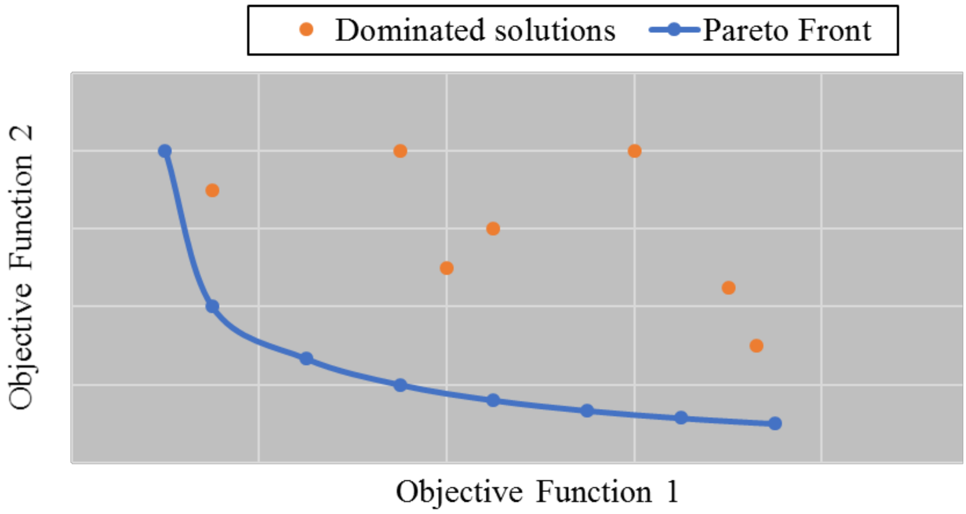

Fig. 1. Two-dimensional Pareto front example

Finding a unique solution for a MOOP generally involves two stages: optimization and decision-making. According to the order of these operations, MOOP algorithms can be classified as *a priori* or *a posteriori methods* [21]. A priori methods require a deep knowledge of the problem before the optimization is performed, as the order of priority of the OFs has to be specified before the optimization is run. An example of a priori method is the *scalarization technique*, that involves the minimization of a weighted sum of the objective functions, thus reducing the analysis to a single-objective optimization and to the search of one optimal solution. A posteriori methods, instead, are oriented to identify the whole Pareto front, in order to obtain diversified solutions that may facilitate the decision-making process.

Another classification of optimization techniques consists in the method of exploration of the feasibility space. According to this criterion, algorithms may be classified as *exact* (or *deterministic*) methods or *heuristic* methods. The exact methods are based on mathematical operations that involve derivatives, so that they require the OF to be expressed in a continuous and differentiable analytical form. On the opposite, heuristic methods are based on criteria derived from the experience of the analyst, and they generally do not require continuity and differentiability of the OF. For these algorithms, the evaluation of a *fitness function* (deriving from the OF) is generally used as convergence criterion. Lastly, depending on the quantity of alternatives considered, algorithms may be considered as *single-point* (or *local search*) or *population-based*. In detail, single point methods consider the perturbation of variables one by one, while population-based algorithms manage multiple sets of values of decision variables in each iteration.

A widely-used category of a posteriori, heuristic, population-based methods is known as *evolutionary algorithms*. These algorithms search the optimal solutions combining sets of values of decision variables by miming biological evolution mechanisms such as reproduction, mutation, recombination, and selection, and obtaining new *generations* of individuals, i.e. the sets of variables values. A widespread category is composed by the *genetic algorithms*. The feature of being population-based techniques is intrinsically a feature that can be fruitfully exploited to find out sets of solutions such as the MOOP solution requires. Indeed, these techniques are often employed in the design of a high performing building, as they can efficiently handle non-linear problems with discontinuities and many local minima, and moreover they do not require to calculate explicitly the objective function's gradients but are based on improvement along iterations using the evaluation of the *fitness function* to assess the quality of solutions. This feature allows the interaction between the thermophysical software and the optimization tool, as the optimization algorithm "sees" the building only through the output of the thermophysical simulator, making evolutionary algorithms particularly suitable for building energy optimization [22].

2.2. Optimization of buildings' design or refurbishment

The optimization of a building during the design/refurbishment phase can be defined as the search of the set of features (design) or interventions (refurbishment) on the building envelope, on the HVAC systems and possibly on the energy production plants, whose combination gives the minimum of the objective function. This approach is quite different with respect to the "classical" approach to the design of a low-energy building depicted in *Introduction* section, as the order of intervention has to be condensed in a set of variables to be combined and analyzed, in order to identify the combination providing the optimal value of the objective functions.

In many cases, in a building optimization study, the objective function is related to the energy consumption. Although this implies multiple terms to be considered, this target has been translated for NZEBs with simple analytical equations. This can be made according to two criteria, considering the building as a black box and analyzing the balance between local loads and generation or between the energy import and export [4], as in Eq. (1).

Load-Generation balance for NZEBs *Import-Export balance for NZEBs*

$$\sum_{t=t_1}^{t_2}\left[\sum_{k=k_1}^{k_2}\left(L_k\cdot w_{l,k}\right)-\sum_{j=j_1}^{j_2}\left(G_j\cdot w_{g,j}\right)\right]\leq 0 \qquad \sum_{t=t_1}^{t_2}\left[\sum_{k=k_1}^{k_2}\left(I_k\cdot w_{i,k}\right)-\sum_{j=j_1}^{j_2}\left(E_j\cdot w_{e,j}\right)\right]\leq 0 \qquad (1)$$

where G_j are the building generation flows, L_k the building loads, E_j the building exports, I_k the building imports and w indicates weighing factors, adopted to make homogeneous the energy quantities. This formulation can be also adapted to low-energy buildings in terms of optimization problem, as in Eq. (2):

Load-Generation balance for LEBs *Import-Export balance for LEBs*

$$\min\sum_{t=t_1}^{t_2}\left[\sum_{k=k_1}^{k_2}\left(L_k\cdot w_{l,k}\right)-\sum_{j=j_1}^{j_2}\left(G_j\cdot w_{g,j}\right)\right] \qquad \min\sum_{t=t_1}^{t_2}\left[\sum_{k=k_1}^{k_2}\left(I_k\cdot w_{i,k}\right)-\sum_{j=j_1}^{j_2}\left(E_j\cdot w_{e,j}\right)\right] \qquad (2)$$

These equations only consider the energy consumptions occurring during the use phase of the building, thus neglecting the amounts of energy necessary to the construction and the disposal of the building, often referred to as *embodied energy* of the building. The assumption of neglecting these two terms is effective for conventional buildings, but the reduced energy consumption occurring in the use phase of a LEB suggests to reconsider the energy optimization of a building in a life cycle perspective. Indeed, some attempts to integrate construction and disposal terms into Eqs. (1) - (2) have already been made [23], [24], but further work is still necessary. In detail, the work in [23] introduces the concept of *Annualized Life Cycle Energy* (ALCE) of a building as the sum of Annualized Embodied Energy (AEE) and Annual Energy Use (AEU), all expressed in kWh of primary energy, and defining a *Life Cycle Zero Energy Building* (LC-ZEB) as a building with $ALCE = 0$. Furthermore, a new indicator, the Net Energy Ratio (NER), is proposed in this work, in order to compare the AEU reduction with the AEE increase related to a retrofit intervention.

$$ALCE = AEE + AEU \tag{3}$$

$$NER = \frac{AEU_{before} - AEU_{after}}{AEE_{after} - AEE_{before}} \tag{4}$$

The other approach proposed in literature [24], related to NZEBs or plus-energy buildings, proposes a relation that can be considered as a more detailed and exploitable form of Eq. (3), including three additional terms in Import-Export balance of Eq. (1), as in Eq. (5):

$$\sum_{t=t_1}^{t_2}\left[\sum_{j=j_1}^{j_2}\left(E_j \cdot w_{e,j}\right) - \sum_{k=k_1}^{k_2}\left(I_k \cdot w_{i,k}\right)\right] - \left(EE_{i,a} + EE_{r,a} + DE_a\right) \geq 0 \tag{5}$$

where $EE_{i,a}$ is the annualized initial embodied energy, $EE_{r,a}$ is the annualized recurring embodied energy and DE_a is the annualized demolition energy.

Although the terms in Eqs. (1) - (5) appear as simple and linear functions, it is necessary to evaluate dynamic thermophysical simulations in order to calculate accurately each hourly energy flow in a building. Thus, BPS tools are often employed, simulating the building dynamic behavior and providing only results as output. This feature hides the analytical form of the objective function to an optimization tool that may be coupled to the BPS software, inhibiting from calculating derivatives of the function to find the minimum value. For this reason, although many differences exist between the aims and the developed techniques of the studies analyzed in this review, it is possible to identify a general scheme in the optimization of a building that has been generally followed by researchers [25]–[27], that is based on the following steps (Fig. 2):

- definition of the base case (e.g. existing building, preliminary design);
- assessment of the objective function and variables of the optimization;
- execution of the algorithm / coupling of multiple algorithms, generally heuristic-based, to perform iterations by using a convergence criterion and a fitness function;
- data post-processing and analysis.

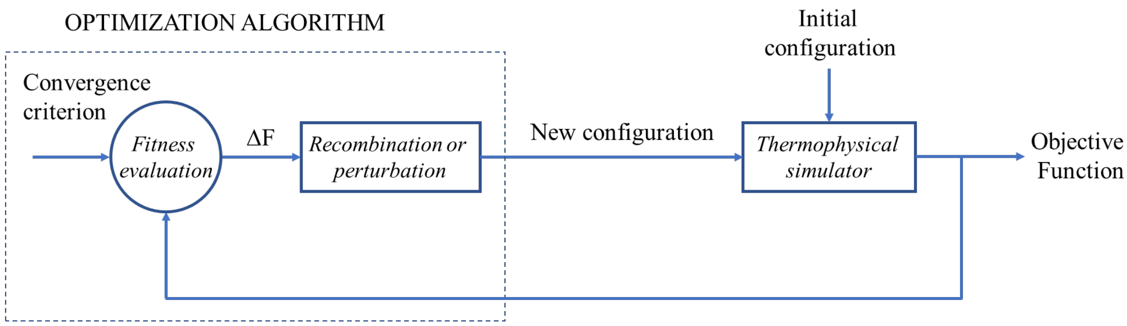

Fig. 2. Example of one simulation cycle of heuristic algorithm for thermophysical optimization

Another commonly used objective is the cost minimization, that is considered with multiple approaches, as the investment cost only, both the investment and operating costs (e.g. electric energy purchase) or the Life Cycle Cost (LCC), that considers all the costs quantities occurring during the life of the buildings. In the EU's legislative framework, the concept of building cost optimization has been included in the *cost-optimal methodology*, defined in [28]. This methodology requires to calculate the global costs of a building (Eq. (6)), defined as the sum of initial investment cost, C_I, annual cost for component j at the year i, $C_{a,i}(j)$ (composed by energy, running and periodic or replacement costs), and the final value of component $V_{f,\tau}(j)$, if the expected lifetime is longer than the period considered in the analysis, and to compare the Net Present Value (NPV) of different solutions to find the best option, by actualizing annual terms with discount rate $R_d(i)$. This methodology is based on standard EN 15459 [29], and is quite similar to the cost categorization systems usually adopted for Life Cycle Cost (LCC) assessment.

$$C_G(\tau) = C_I + \sum_j \left\{ \sum_{i=1}^{\tau} \left[C_{a,i}(j) \cdot R_d(i) \right] - V_{f,\tau}(j) \right\} \quad (6)$$

Other Objective Functions usually employed are indicators used to assess:

- $CO_{2\text{-eq}}$ emissions [30]–[37] (e.g. Global Warming Potential (GWP), shown in Eq. (7) [38]);
- the interactions between the building and the electrical grid [33]–[35], [39], [40] (e.g. Grid Interaction Index (GII), shown in Eq. (8) [41]);
- thermal internal comfort [36], [39], [42]–[49], often assessed by Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) static indicators (Eqs. (9) - (10)) [50], [51] that correlate the metabolic rate of occupants and psychrometric quantities to estimate people satisfaction. Although more accurate models can be found in literature, as adaptive comfort model, only one study [47] employed a dynamic indicator (Weighted Discomfort Time (WDT)). This aspect highlights that, as optimization models often require simplified equations, in order to reduce computational time, researchers prefer to employ a static model as PMV + PPD in lieu of dynamic thermal comfort models;
- visual internal comfort [46], [52], evaluated by Discomfort Glare Index (DGI) or Useful Daylight Illuminance (UDI), reported in Eqs. (11) - (12) [46],

$$GWP = \frac{\int_0^{TH} a_x \cdot \left[x(t)\right] \cdot dt}{\int_0^{TH} a_r \cdot \left[r(t)\right] \cdot dt} \quad (7)$$

$$GII = STD\left[\frac{E(i)}{\max\left|E(i)\right|}\right] \quad (8)$$

$$PMV = \left[0.303 \cdot \exp(-0.036 \cdot M) + 0.028\right] \cdot L \quad (9)$$

$$PPD = 100 - 95 \cdot \exp\left(-0.03353 \cdot PMV^4 + 0.2179 \cdot PMV^2\right) \quad (10)$$

$$DGI = 10 \cdot \log_{10}\left[0.478 \cdot \sum_{i=1}^{n}\left(\frac{L_{s,i}^{1.6} \cdot \omega_{s,i}^{0.8}}{L_b + 0.07 \cdot \omega_{s,i}^{0.5} \cdot L_{win} \cdot P_i^{1.6}}\right)\right] \quad (11)$$

$$UDI = \frac{\sum_i \left(wf_i \cdot t_i\right)}{\sum_i t_i} \quad (12)$$

where a_x and a_r are the radiative efficiencies due to a unit increase in atmospheric abundance, respectively, of the considered substance, x, and of the reference gas, r (CO_2), $x(t)$ and $r(t)$ are their time-dependent decay in abundance of the instantaneous release, TH is the time horizon of the calculation, STD is the standard deviation, $E(i)$ is the net energy export to the grid in *i-th* hour, M is the metabolic activity of the occupant, L is the thermal load on the occupant's body, $L_{s,i}$ is the luminance in the direction connecting the observer with each source, L_b is the background luminance that, for windows, is the average luminance of the wall excluding the window, L_{win} is the luminance from the windows, $\omega_{s,i}$ is the solid angle subtending the source from the point of view of the observer, P expresses the dependence of perceived discomfort glare on the position of the source i with respect to the observer, t_i is the hour of the year and wf_i is a weighting factor, equal to 0 or 1 depending on external illuminance.

A complete description of the topics behind these indicators is out of the scopes of this review paper, readers can refer to bibliography for further information.

2.3. Main Building Simulation tools

Thermal simulation of buildings received a great importance in last years, becoming a standard in both research and design fields, thanks to the growing performance of computers in terms of computational capacity and to the introduction of energy saving policies in buildings construction. The growing number of available solutions pushed the US Department of Energy (DOE) to create a web resource, the Building Energy Software Tools (BEST) Directory, collecting main features of commercial BPS. The resource is now managed by IBPSA-USA and describes more than 150 tools.

Instead, the application of optimization techniques in building design and performance simulation, also called Building Performance Optimization or BPO, is still rarely employed, and although building-specific optimization tools already exist, researchers mainly employ generic optimizers, i.e. optimization software suitable for each kind of application [46], [49], [53]–[55]. A list with the most important tools used for energy design of buildings is reported in Table 1, while a description of software that were employed in the analyzed studies is provided in Table 2, highlighting the interoperability between geometrical modelling, thermophysical and optimization tools. A more comprehensive description of main BPO tools may be found in [13].

Table 1. List of the most important tools used for energy design of buildings

Building Performance Simulation	Building Performance Optimization
TRNSYS [56]	GenOpt [57]
EnergyPlus [58]	MATLAB Optimization Toolbox [59]
IDA-ICE [60]	modeFRONTIER [61]
ESP-r [62]	BEopt [63]
DOE-2 [64]	Opt-E-Plus [65]

Table 2. Main features of main software employed in the analyzed studies

Software	Category	Operative System [59], [66]	Interactions with Geometrical Tools	Interactions with Thermophysical Tools	Interactions with Generic Optimization Tools	Interactions with Specific Optimization Tools
EnergyPlus	Thermophysical simulation	Windows Mac Linux	SketchUp [67] OpenStudio [68] DesignBuilder [48], [66] Rhinoceros + plug-ins [52], [66]	-	GenOpt [13], [15] modeFRONTIER [13] MATLAB Opt. Toolbox [44] MOBO [69] DesignBuilder [48], [66] Rhinoceros + plug-ins [52]	Opt-E-Plus [13], [15] jEPlus [66] jEPlus+EA [15]
TRNSYS	Thermophysical simulation	Windows	SketchUp (through TRNSYS3D) [66]	-	GenOpt (through TRNOPT) [13], [15] MATLAB Opt. Toolbox [66] MOBO [15]	TRNOPT (connection with GenOpt) [15] BEopt [13], [15] Multiopt2 [15]
IDA-ICE	Thermophysical simulation	Windows	SketchUp [66] ArchiCAD [66] Revit [66]	-	GenOpt [13], [15] MATLAB Opt. Toolbox [70] MOBO [15]	IDA-ESBO

			MagiCAD [66]			
MATLAB	Programming environment Optimization tool	Windows Mac Linux	-	TRNSYS [66] EnergyPlus [44] IDA-ICE [70]	modeFRONTIER [13]	Topgui [13]
DesignBuilder	Geometrical modelling Optimization tool	Windows Linux	-	EnergyPlus [48], [66] Radiance [66]	MATLAB Opt. Toolbox [49]	-

3. Methodology

In this review, algorithms and methodologies employed to optimize the energy performance of a building have been examined, focusing on design or refurbishment phases, thus neglecting optimization algorithms aimed at optimize the scheduling or the control of building systems. In order to analyze the optimization techniques applied to low-energy buildings, with a special focus on NZEBs, a bibliometric analysis has been conducted in mid-2018, selecting all papers prior to 2017 and using *NZEB* and *optimization* as keyword in scientific databases *Scopus, ScienceDirect, MDPI* and *IEEE Xplore*, and referring also to the bibliography of the selected papers, in order to collect also works not strictly related to Zero Energy Buildings. Furthermore, many papers reporting the word "NZEB" were focused only on low-energy buildings. The number of paper collected was drastically reduced as multiple papers had to be excluded, mainly because of the improper use of the keywords (e.g. NZEBs only cited in the introduction to describe the EU energy context, optimization used as synonymous of improvement) [71], [72], [81]–[90], [73], [91]–[93], [74]–[80].

The final set of this bibliometric research is composed by 64 works on energy saving in buildings, which may be categorized according to three criteria:

- works on optimization to achieve NZEB or nZEB target, both on new and existing buildings: 37 papers;
- works on optimization applied to low-energy buildings, without pursuing the zero-energy target, both on new and existing buildings: 13 papers;
- works on cost-optimal nZEBs design, according to [28], both on new and existing buildings: 23 papers.

Although this paper is mainly oriented on optimization algorithms, a description of cost-optimal evaluations is considered very useful for designers, who are more interested on a regulation-oriented approach. This review is conducted starting from general considerations on examined papers and then focusing on three classes above depicted, providing an in-depth description of various algorithms, variables, objective functions and software employed by researchers in this topic. At the bottom of each sub-section, a description of the most notable approaches and original ideas is also given. As a summary of this analysis, a discussion section is provided at the end of the paper, highlighting lacks in literature and suggesting new ideas and research lines.

4. Review

4.1. General considerations

The Directive 2010/31/EU imposes to EU Member States that new buildings will have to be nZEBs starting from 31/12/2020. As this date is approaching, the topic of nZEB and low-energy buildings is gaining an increasing interest. As already stated, realizing a low-energy building requires a detailed investigation of multiple technical alternatives, and optimization techniques can improve the design process in terms of time for the investigation and quality of the final solution. This is corroborated by the fact that the analyzed papers show a Compound Annual Growth Rate (CAGR) higher than 29% between 2008 and 2017, with the greatest increment between 2012 and 2013, as shown in Fig. 3. The peak of publications was reached in 2015, with a decrease in last two years.

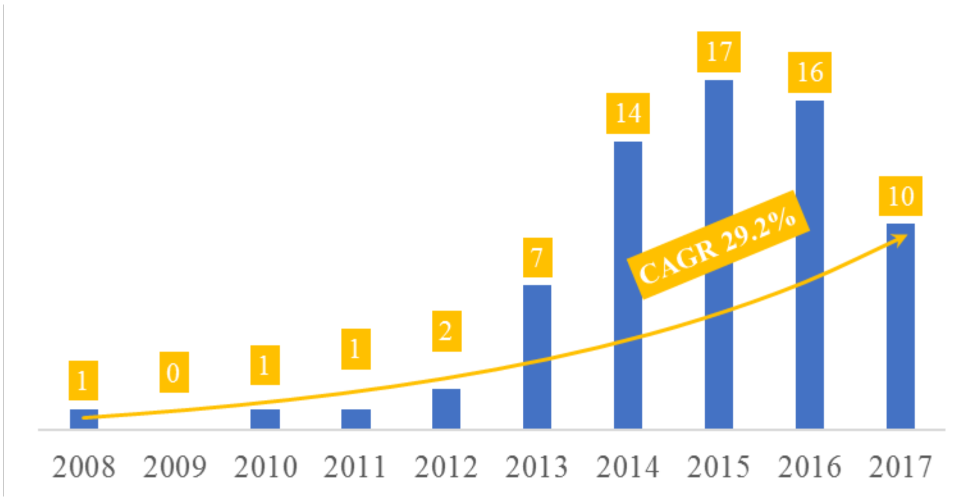

Fig. 3. Publication of analyzed studies between last ten years (2008-2017)

This decrease has not to be confused with a diminishing interest in the topic of low-energy buildings, as can be proved by the histogram reported in Fig. 4, obtained by searching "low", "energy" and "buildings" as keywords on *ScienceDirect* database:

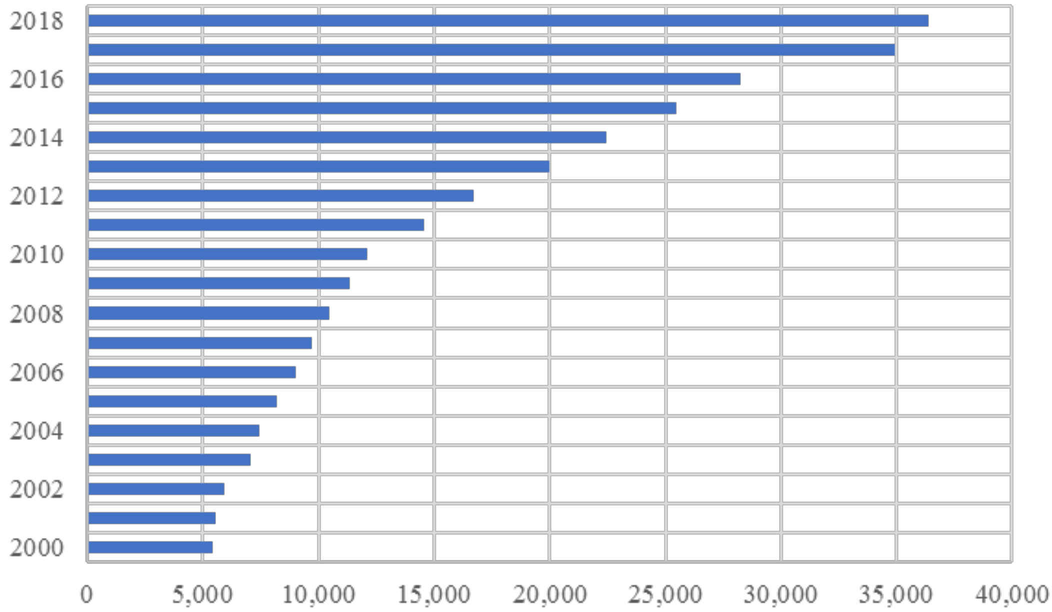

Fig. 4. Number of studies on low energy buildings on ScienceDirect database after 2000

In Fig. 5, a geographical distribution of the research groups involved in the reviewed studies is reported. As some studies were conducted by researchers coming from different countries, the sum of values in Fig. 5 is higher than 64. Thanks to EU energy saving policies, as one may expect, European countries are the most interested in the topic of the NZEBs, and specifically on the optimization of its performance, while in other countries this subject appears to still be in developing phase.

Further focusing on Europe (Fig. 6), the main outcome is that Italian researchers result as the most prolific in the topic of the optimization of energy-efficient buildings with 23 studies [44], [46], [96]–[105], [47], [106]–[108], [48], [49], [53], [54], [67], [94], [95], followed by Finnish [26], [70], [109]–[112], Portuguese [32], [42], [100], [113]–[115] and Spanish [31], [100], [116]–[119] researchers (all with 6 studies). It is worth to be highlighted that 6 of the 12 works in Asia have been conducted in Hong Kong [33]–[35], [39], [40], [45], focusing on the application of the uncertainties of parameters in the renewable systems design.

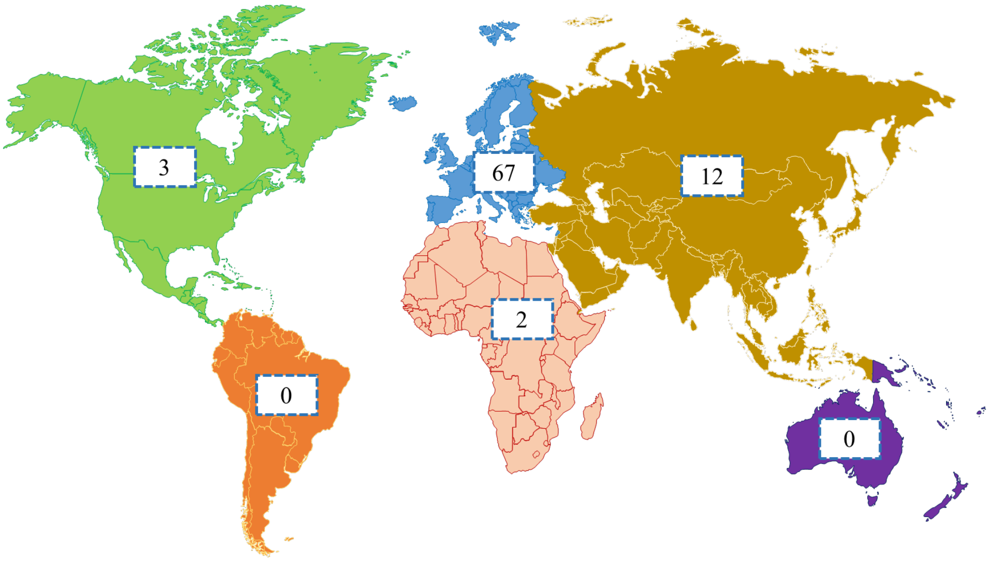

Fig. 5. Geographical distribution of analyzed studies in the world

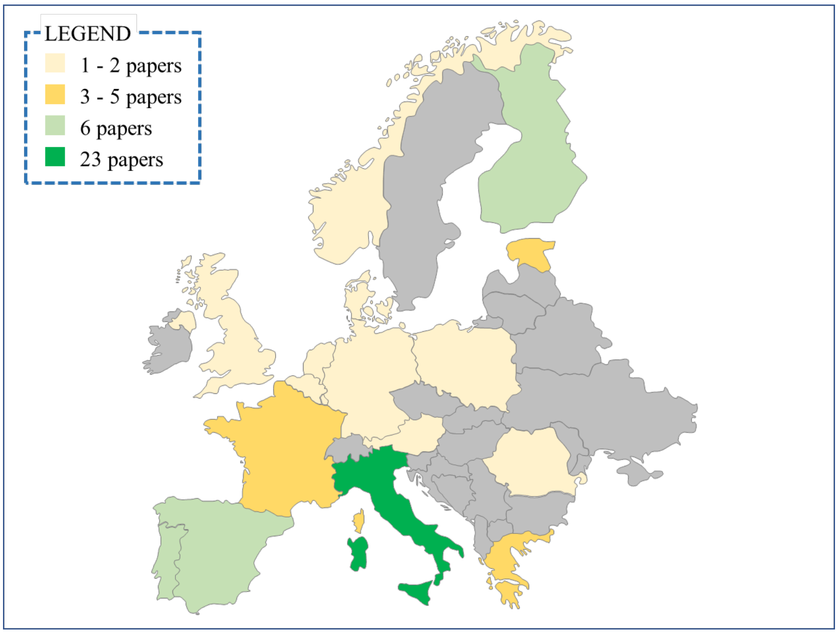

Fig. 6. Geographical distribution of analyzed studies in Europe

Considering the main topic of the analyzed works, it is possible to state that the greatest effort has been done in the refurbishment of existing buildings [25], [26], [67], [70], [94], [95], [98]–[100], [106], [109], [110], [31], [112]–[115], [120]–[125], [32], [126], [39], [42], [47], [49], [53], [55] (31 studies) and in the design of new buildings [30], [36], [68], [101]–[103], [107], [111], [116]–[118], [127], [37], [128], [129], [40], [43]–[46], [48], [52] (22 studies), as shown in Fig. 7. These studies are mainly focused in residential buildings, but also some studies on industrial or office buildings are slowly emerging [49], [52], [99], [122], [125]. As stated by a 2011 study from BPIE [130], the current annual growth rate in the residential sector in EU is equal to 1%, so the refurbishment is considered as the most effective way to introduce nZEBs along the European continent. For this reason, the fact that research is currently focusing on the refurbishment rather than on the design of new buildings is a positive outcome. 9 papers [96], [97][33], [54][34], [104], [105][35], [108] focused on the design of single components of the building, as an optimized wall stratigraphy or optimal RES size, while 2 works [119], [131] focused on the use phase energy consumption minimization.

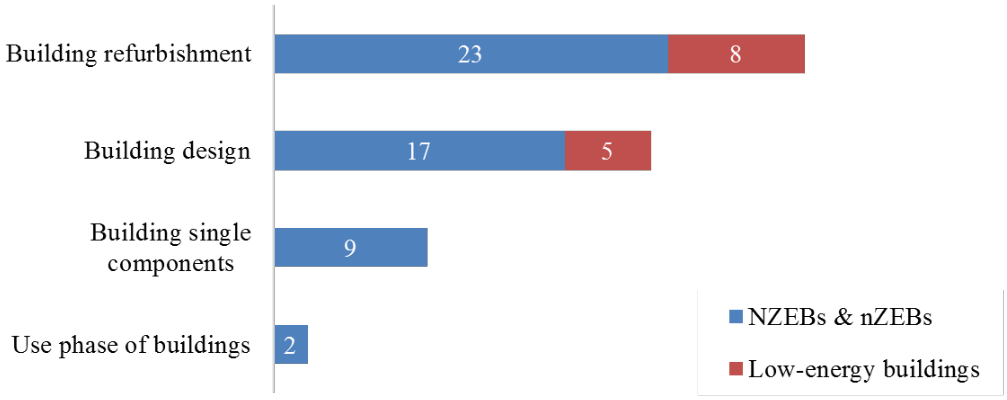

Fig. 7. Main topic of analyzed studies

Another useful analysis concerns variables considered for the optimization of the building, that have been arranged as follows:

- Building envelope (thermophysical properties of walls, roofs, and floors, shape and orientation of the building, shadowing systems, or PCMs employment);
- Fixtures (thermophysical properties of windows and doors, emissivity and SHGC of glass);
- HVAC and equipment (air conditioning systems, CHP plants, energy storage);
- RES plants (solar collectors, PV, wind turbines, bio-diesel generators, wood or pellet boilers).

Although HVAC and electrical equipment (e.g. electrical pumps) have been considered slightly less than other groups of variables, as shown in Fig. 8, it is possible to state that all categories appear to be equally useful to the researchers in their contribution to minimize the energy consumptions of a building.

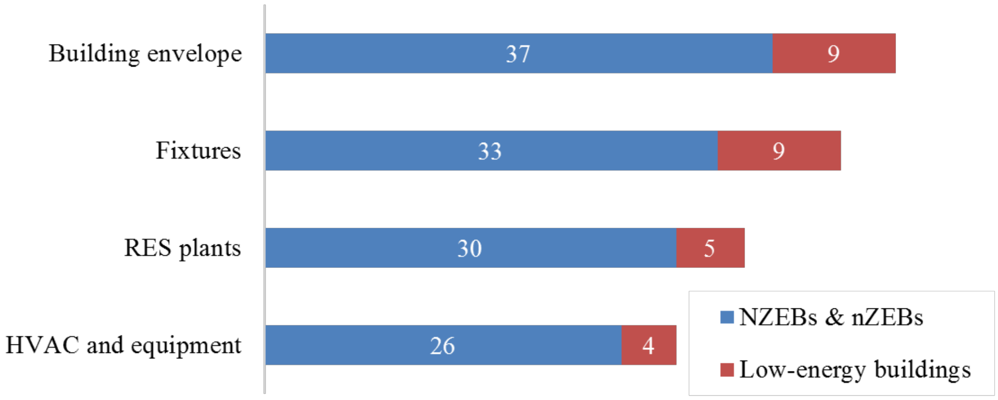

Fig. 8. Main categories of variables considered for the energy optimization of buildings

By changing the point of view and considering the different categories of energy consumptions in a building (Fig. 9), it is possible to reach different conclusions. Indeed, as it could be easily expected, the space conditioning is by far the most frequent considered energy sink (i.e. category of energy consumption) in the analyzed literature. Most of studies consider both space heating and cooling, but in selected locations it is replaced by only space heating or cooling. The second most considered energy sink is the internal lighting, both artificial and natural, as rising the natural lighting also increases the cooling loads. Ventilation and Domestic Hot Water (DHW) are also considered, with both mechanical and natural ventilation being aggregated because of scarcity of studies regarding natural ventilation, depending on the typology of the building. The embodied energy, i.e. the energy needed for production, installation and possibly disposal of building components and equipment, has been considered only in three studies [36], [111], [128]. A fourth study also considered the embodied impacts of a building, but as it was focused on the carbon footprint of a building, the embodied carbon was calculated, rather than embodied energy [25].

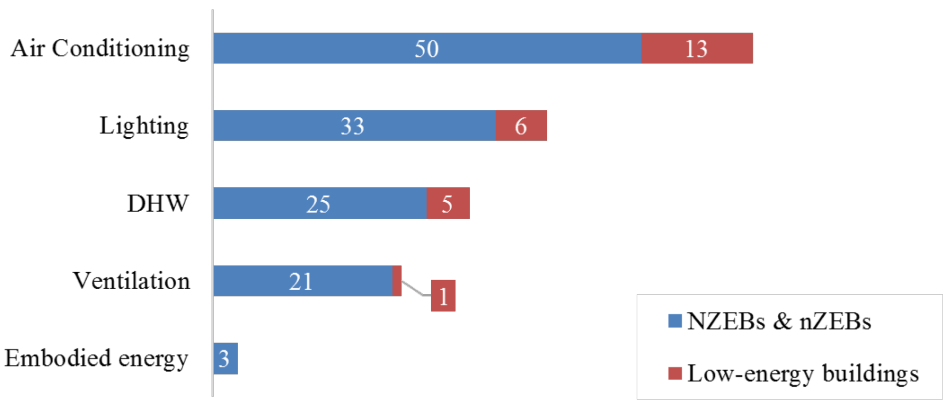

Fig. 9. Objective functions-related energy sinks considered for the optimization of buildings

Information contained in Figs. (7)-(9) are summarized in Table 3:

Table 3. Summary of main topics, categories of variables and objective functions

	NZEBs & nZEBs	Low-energy buildings
Main topic of analyzed studies		
Building refurbishment	23	8
Building design	17	5
Building single component	9	0
Use phase of buildings	2	0
Main categories of variables for the energy optimization of buildings		
Building envelope	37	9
Fixtures	33	9
RES plants	30	5
HVAC and equipment	26	4
Objective functions-related energy sinks for the optimization of buildings		
Air conditioning	50	13
Lighting	33	6
DHW	25	5
Ventilation	21	1
Embodied energy	3	0

Another interesting feature to be recapped is the uncertainty analysis of parameters and the robustness of models. It is well known that energy simulations of buildings are based on a weather file, representing a standardized set of outdoor conditions (air temperature, solar radiation, wind speed, etc.) for a given climate location. These conditions should represent the typical average year for a geographic site, smoothing variations that might occasionally occur. But nZEBs and NZEBs are based on the measurement of energy consumption and production occurring in reality, thus these values are subject to variability and uncertainty. A similar argument may be discussed on financial parameters (e.g. interest rates), that are estimated based on the current and past financial trends. The statistical analysis on input parameters have been rarely considered in the analyzed papers. Neglecting sensitivity analyses performed over optimization outputs, thus non optimization-integrated approaches [109], [110], [112], [120], [123], [127], the uncertainty analysis was assessed by the integration of Monte-Carlo simulations in the process, adopting probability distributions for input parameters as climate data or thermophysical features of building [34], [35], [39], [40], [45]. This kind of analysis was mainly adopted for avoiding the oversizing of equipment ad RES plants, and it proved to be an effective and reliable way to design the components in a NZEB.

Regarding the analysis of computational burden related to adopted methodologies, very few data are available. In detail, 14 studies provided various and different information about the technical features of computers employed for running simulations, and it is not possible to extrapolate useful information. Available data are reported in Table 4.

Table 4. Details on computational burden of simulations conduced in analyzed studies

Paper	CPU	RAM	Problem Features - Simulations	Problem Features - Variables and constraints	Calculation Time
[68]	Intel Xeon E5540 processors in a 10 cores mini cluster	-	139,968 combinations explored through 1,350 simulations (population size 10 and 135 generations)	11 integer variables	- 5 generations: 18 min - 60 generations: 3 hours and 36 min - 135 generations: 8 hours
[117]	Intel C2D E7400 @ 2.8 GHz	4 GB	-	4 variables	- 40 s for a 2-storey building for each run - 2 min and 40 s for a 4-storey building for each run
[131]	Quad core Intel processor server	-	-	11 categories of variables	More than 50 hours
[118]	Quad core i5 computer	-	4,096 simulations	-	Approximately 2 min per simulation (6 days for the whole optimization)
[31]	Computer AMD Athlon(tm) II X2 B24 with a processor @ 2.99 GHz	3.49 GB	-	1,110 continuous variables, 2,800 binary variables, and 3,513 constraints	The CPU time is in the order of seconds depending on the instance being solved
[32]	Server with 16 CPUs	72 GB	-	11 categories of variables	Stop criteria for the optimization process is an optimality gap of less than 3% or an optimization run time of one hour. The average computation time increases from 341 s without the consideration of passive measures to about 728 s by considering them
[43]	Dual core laptop	-	9,600 simulations (population size 300 and 32 generations)	-	3 days globally, about 30 s per simulation
[46]	Intel Core i7 with 4 cores (8 threads) @ 2.2 GHz	8 GB	17,006,112 combinations explored through 600 simulations (population size 24 and 25 generations)	-	13 hours to complete the optimization run
[25]	Intel i7	6 GB	55,296 combinations	9 integer variables	10 hours
[108]	Intel Core i7 @ 2.00 GHz	-	76,800 combinations	9 integer variables	A thermophysical simulation takes around 360 s by using the 'conduction transfer function' algorithm with 6 time-steps per hour. For this reason, the paper adopts only few thermophysical simulations and many optimization runs, that require around 1 second
[119]	Intel Core i5-2430M CPU @ 2.40 GHz	8 GB	-	37,440 continuous variables, 6,963 integer variables, and 51,282 constraints	Elapsed time is case dependent. Stop criteria: simulations run until a gap of 1% or, alternatively, 2 h of operation
[111]	Intel Core i5-3470 CPU @ 3.20 GHz (4 CPUs)	-	4,992 combinations explored through 800 simulation runs (the same search space is explored through 1,600 simulation runsbut optimal solutions were very similar)	4 integer variables	A thermophysical simulation requires about 300 s
[49]	Intel Core i7 @ 2.00 GHz	-	134,217,728 combinations	10 integer variables	Each simulation requires about 600 s. The computational time required by an exhaustive sampling would be prohibitive, around 'hundreds of years'. The GA is employed to save time
[112]	Quad-core i5-3570 CPU @ **3.70 Hz**	-	4,608 combinations	7 integer variables	-

From the analysis of the whole bulk of papers in literature, it is hard to compare different works in order to identify a general trend or to suggest an approach instead of another, as many combinations of tools, algorithms and applications have been found. The main evidence that is possible to derive is that genetic algorithms are preferred for the interaction between a thermophysical software and an optimization tool, thanks to the fact that they do not require the analytical expression of objective function or constraints. Multi-objective approach appears to be most reliable for the selection of an optimal solution, as it allows to consider multiple aspects of a project or system.

4.2. Net and nearly-Zero Energy Buildings optimization

In this review, 37 works that employ optimization algorithms to attain the NZEB or nZEB targets have been collected. It is possible to divide these studies into three macro-categories, according to the nature of the developed technique (one paper compares both single and multi-objective algorithms, thus this work is double-counted):

- Single-objective optimization (10 papers) [33], [53], [94], [95], [106], [112], [117]–[119], [131];
- Multi-objective optimization (28 papers) [26], [32], [45]–[49], [52], [54], [68], [70], [96], [33], [97], [102], [107], [108], [111], [121], [122], [128], [34]–[37], [39], [40], [44].

The most numerous group of works is certainly the one employing multi-objective optimization, that is often preferred to single-objective algorithms. This orientation highlights the complexity of the energy optimization of a building, and also confirms data reported in some of examined review papers [13], [14], where it is stated that 70% of the interviewed designers perform multi-objective optimization.

In single-objective optimization papers, there is a great predominance of heuristic algorithms. Indeed, excluding 2 works [95], [131] where the employed technique was not explicated, only 1 work used a deterministic Mixed Integer Linear Programming (MILP) algorithm [119], another study experimented a statistical optimization through Yates algorithm [118] and 6 papers out of 8 used heuristic algorithms, and specifically:

- 3 used Particle Swarm Optimization (PSO) algorithm [53], [94], [106];
- 2 used unspecified genetic algorithms [33], [112];
- 1 used Tabu Search algorithm [117].

About multi-objective optimizations works, 3 out of 27 papers didn’t specify the algorithm [52], [102], [107]. Most of the remaining studies reported the use of heuristic algorithms, with a great predominance of Non-dominated Sorting Genetic Algorithm (NSGA) II algorithm [132], that was used 12 times [26], [33], [108], [111], [36], [44], [46]–[49], [68], [70], both in the original or modified versions. This frequency of employment is corroborated by [27], where NSGA II’s performance has been compared to other six multi-objective algorithms, resulting one of the best, although Two-Phase Optimization Genetic algorithm (PR_GA) [133] is reported to be the best one. In general, in this category of papers have been found:

- 12 works using NSGA II (Non-dominated Sorting Genetic Algorithm) [26], [33], [108], [111], [36], [44], [46]–[49], [68], [70];
- 4 works using MOGA or MOGA II (Multi-Objective Genetic Algorithm) [54], [96], [97], [121];
- 3 works using unspecified genetic algorithm [37], [122], [128];
- 6 works using Scalarization technique (deterministic algorithm) [32], [34], [35], [39], [40], [45].

The objective functions explicitly considered in all these studies are summarized in Fig. 10. The main outcome is that economic aspects are the most preferred metrics to reach the optimal solution in a building. Indeed, although most works are not pursuing the cost-optimal building solution, they usually evaluate investment cost [34], [39], [40], [45], [54], [108], [118], [121], [122] or both investment and operating costs [32], [33], [35], [117], [131]. Energy consumptions are also considered as a quantity to be minimized in a complementary way to cost functions [34], [39], [96], [97], [102], [107], [108], [118], [121], [122], [40], [44], [45], [48], [52], [54], [68], [95]. Thus, it can be stated that consumption is always considered, as the operating costs also account for the economic expenses for energy supply. Carbon dioxide emissions have been mainly evaluated through the operating energy consumption of the building, but a study involving LCA analysis was also present [36]. Internal comfort refers to thermal or visual comfort and it is generally assessed through synthetic indicators. Thermal comfort has been maximized through Fanger's indicators Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) [44], discomfort hours [36], [39], [49], Weighted Discomfort Time (WDT) [47], Long-term Percentage of Dissatisfied [46]. Visual comfort has been calculated with Useful Daylight Illuminance (UDI) [46], [52] and Discomfort Glare Index (DGI) [46]. Even building interactions with the electrical grid has been minimized through indicators as Grid Interaction Index, that has been considered by two different research groups in Hong Kong, indicating that the NZEB is considered as a way to reduce the electrical demand in their country, as well as a means to reduce the energy and carbon footprint of human activities.

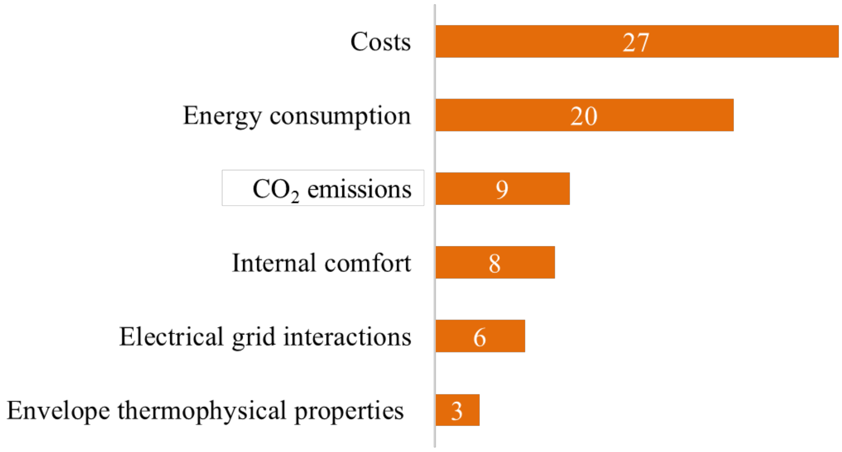

Fig. 10. Objective functions considered in NZEB and nZEB analyzed works

An interesting feature is that few studies specify the constraints used in their model. In this category, only 4 studies explicitly explained what variable was subject to constraints, although is highly probable that at least geometrical constraints were considered, in order to obtain feasible building solutions. Indeed, only [45] clearly specifies that the Net Zero annual balance has been considered as a constraint. Other constrained variables were:

- the internal comfort [45], [46], [48], outlined as a minimum air changes value or minimum thermal comfort hours;
- a minimum number of hours of independency from the electrical grid [45];
- constraints linked to legal requirements (maximum energy consumption from non-renewable sources) or to national incentives (minimum Primary Energy Saving for CHP plant) [119].

Considering the BPS tools used in these studies, it is possible to state that TRNSYS and EnergyPlus are the most employed thermophysical tools. Although both of them provide optimization software interfaces, i.e. TRNOPT, jEplus+EA and Opt-E-Plus, these tools are still rarely used, while MATLAB is the most preferred optimization software (Figs. 11 and 12). MATLAB shows a great versatility in this research field, as it has been used both for energy calculations [35], [54], [96], [97], [102], [107], [119], often using simplified models, and for optimization, recurring to MATLAB Optimization Toolbox [27], [33], [108], [34], [36], [37], [44], [45], [47], [49], [70]. There is also a number of researchers who preferred to develop on their own an optimization tool rather than using an existing one.

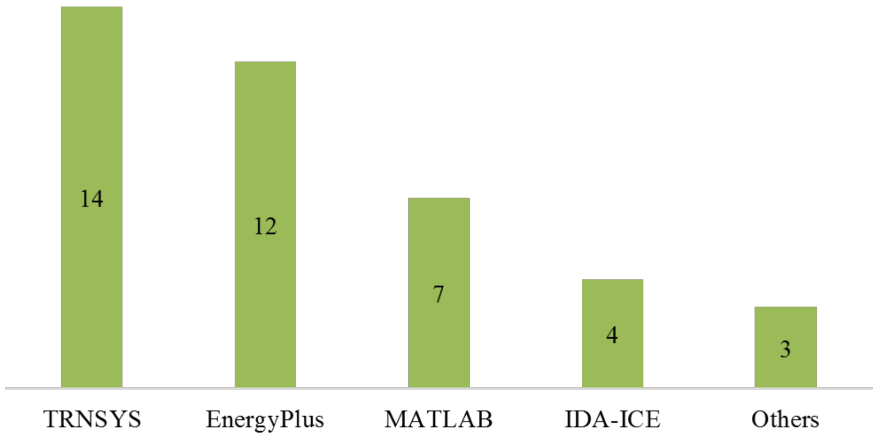

Fig. 11. Thermophysical BPS used in literature review on NZEB and nZEB

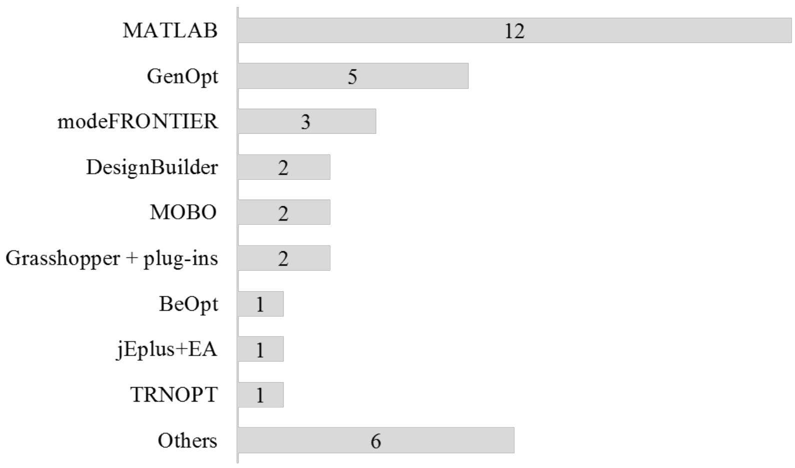

Fig. 12. Optimization BPS used in literature review on NZEB and nZEB

Regarding innovative approaches introduced in this category of studies, two particular sets of studies are recapped here.

The first set of studies has been conducted in University of Salento (Lecce, Italy), and is focused on finding the optimal stratigraphy for the external walls of a building located in Mediterranean area through multi-objective optimization [54], [96], [97]. Differently from other studies, this research neglects time-consuming energy simulation of a building, focusing only on dynamic performance of the opaque components. Indeed, the objective functions of these works are quantities as thermal admittance, periodic thermal transmittance, decrement factor, and time shift. Furthermore, a special attention is given to eco-friendly materials through the maximization of the ITACA score, i.e. a percentage of compliancy with ITACA Protocol standards [134]. Calculation procedure has been developed in MATLAB, coupled with modeFRONTIER optimization tool using MOGA II algorithm.

Another group of interesting studies involves two different research teams in Hong Kong, belonging to The Hong Kong Polytechnic University [33]–[35] and to City University of Hong Kong [39], [40], [45]. These research groups, apparently independently, introduced an interesting topic in the design of a NZEB, stating that the conventional engineering approaches, based on the definition of a worst case for the design of an equipment, may result to be fallacious, because it leads to oversizing that may affect the achievement of the NZEB target. The design approach applied in these works is based on Monte-Carlo statistical analysis on physical parameters (e.g. building transmittance), design parameters (e.g. internal loads, ventilation rate), and scenario parameters (wind speed, air temperature, sun radiation), and has been applied both on the HVAC systems (mainly for cooling, since in Hong Kong this is the most impacting thermal load) and on the RES plants (PV, wind turbines and bio-diesel generators).

An interesting outcome has been provided by [68], where a performance comparison between scenario-by-scenario, parametric and evolutionary optimization approaches for a nZEB design is done. This work shows that the optimization appears much appealing, as it allows to evaluate multiple combinations and contemporarily saving up to 2,5 times the needed hours, even with lower computational performance, equally allowing to identify the Pareto front with a good diversity of solutions.

4.3. Low-Energy Buildings optimization

In order to further deepen the topic of optimization applied to low-energy buildings, other 13 papers were selected [25], [30], [123], [124], [129], [31], [42], [43], [55], [103], [113], [116], [120], with 3 employing single-objective and 10 adopting multi-objective approaches. The algorithms employed in this category are various, in detail:

- 4 studies, conducted by 2 different research groups, developed a mathematical model in order to describe the thermal behavior of the building, that were solved by deterministic combinatorial Tchebycheff programming technique [30], [42], [55], [113]. Their importance is also due to the fact that these models represent first attempts to evaluate the building optimization with multi-objective approach [55];
- 2 studies employed scalarization technique to turn the problem in a single-objective optimization, that was solved with evolutionary algorithms. In detail the first study used a genetic algorithm [120] and the last a differential evolution algorithm [123], considered to outperform the genetic ones;
- 2 studies employed genetic NSGA II multi-objective genetic algorithm [25], [103];
- 1 study used SPEA2 multi-objective evolutionary algorithm (Strength Pareto Evolutionary Algorithm) [43];
- 1 study considered a deterministic MILP single-objective algorithm coupled with the ε-constraint algorithm to manage multi-objectives and overcome non-convex solutions [31];

- 2 between the single-objective studies employed genetic algorithms to obtain the minimum LCC of the retrofit actions [124][129];
- The other study employing single-objective optimization adopted heuristic Tabu Search algorithm [116].

As for the *Net and nearly-Zero Energy Buildings optimization* group, analyzing the explicitly considered objective functions in these studies (Fig. 13), cost functions are the most employed, with 12 studies out of 13 considering investment or operating costs (1 study considered 2 cost functions) [25], [30], [124], [129], [31], [42], [43], [55], [113], [116], [120], [123]. Energy consumptions have been assessed in 10 studies [30], [42], [43], [55], [103], [113], [116], [120], [123], [124], being replaced in other 2 works by environmental aspects calculated with LCA methodology [25], [31], while another paper minimized both energy consumption and CO_2 emissions [30]. Only 2 studies also considered the thermal comfort [42], [43], the first calculating the PMV while the last only by comparing cooling loads and air-conditioning peak power.

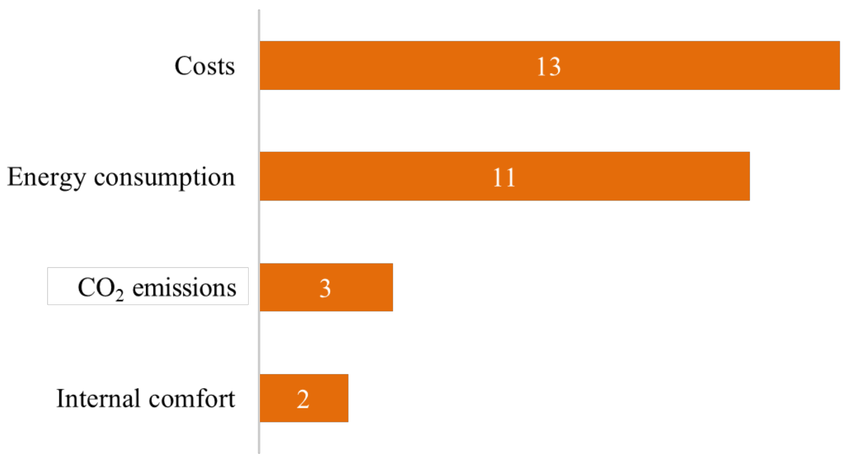

Fig. 13. Objective functions considered in Low-Energy Buildings analyzed works

Again, as already stated for *Net and nearly-Zero Energy Buildings optimization* group of works, only 2 studies in this group specify the constraints used in their model. These constraints are design-oriented, as they concern a maximum value of investment cost, a maximum payback time and a minimum attained energy saving [120], [123].

Regarding thermophysical BPS and BPO tools, various combinations have been adopted. Excluding studies which do not specify the employed software, EnergyPlus [25], [103], [124], [129] TRNSYS [42], MATLAB [113], and Be10 [43] were used for thermophysical simulations, while GenOpt [42], MATLAB [42], Octopus [43] and jEPlus+EA [25] were employed for optimization. In detail, MATLAB was used for both building simulation and optimization in [113], while LINGO was used in the same way in [55]. Two approaches of integrated design with specific tools can be found in [25], [43]. The first is based on Rhynoceros, a 3D CAD commercial software, whose performance can be improved with Grasshopper and its plug-ins to evaluate parametric analyses. In detail, Be10 plug-in allows to perform energy calculation, while multi-objective analysis can be done through Octopus plug-in. The second has been done in EnergyPlus, using SketchUp for the geometrical modelling, jEPlus for parametric analysis and jEPlus+EA for multi-objective optimization.

4.4. Cost-Optimal nearly-Zero Energy Buildings

More than one third of the reviewed papers is concerned on cost-optimality of nZEBs (23 papers). All these works have been conducted in Europe, as the cost-optimal technique has been set by EU in [28] as the methodology to follow for calculating minimum energy performance of buildings. These works are quite inhomogeneous, so it is not possible to further categorize them in smaller groups.

The unique common feature of these works, as the name of this category suggests, is that the objective function is always a cost function. The most used is the Global Cost, a methodology introduced by the standard EN 15459 [29] that accounts for the initial investment, the sum of annual costs among the considered time period and the final value. This function is quite similar to the Life Cycle Cost (LCC), that is used as an alternative in these studies. Both Global Cost or LCC functions are often actualized through Net Present Value calculation. In some studies, multi-objective optimization is performed, also considering energy consumptions or thermal comfort (Fig. 14).

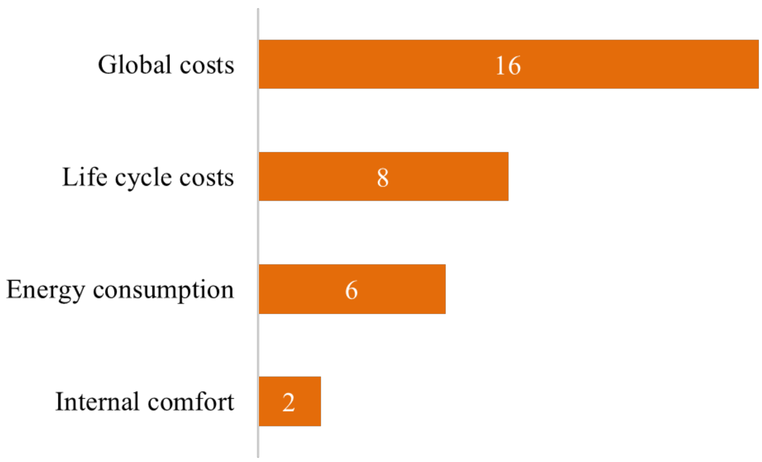

Fig. 14. Objective functions considered in Cost-Optimal nearly-Zero Energy Buildings analyzed works

As EU guidelines suggest to assess a minimum of ten alternative package in order to select the cost-optimal alternative, there are few studies on cost-optimal nZEBs that employ optimization algorithms, as previously stated. These studies have been mainly conducted by two research teams, and are structured as follows:

- First group, composed by Italian and French researchers [53], [94], [106], employs the single-objective Particle Swarm Optimization algorithm to calculate the global cost. In their studies, the optimal solution is assessed by comparing multiple envelope, windows, HVAC and RES variables, by the coupling of TRNSYS with GenOpt;

- The second group is composed mainly by Finnish researchers [70], [111], [112], and in their works LCC is used as objective function, evaluated through genetic algorithms. The thermophysical simulations have been conducted with IDA-ICE in these studies, while MATLAB, MOBO and an original tool were used for the optimization.

A special attention is to be granted to MOBO, a BPO software developed by Finnish researchers and presented in [15]. According to his developers, MOBO (Multi Objective Building Optimization tool) was created in order to provide a freeware able to overcome the limitations of other existing BPOs, integrating multiple kinds of optimization algorithms (single or multi-objective optimization, constrained or unconstrained problem, continuous or integer variables) and providing a Graphical User Interface (GUI) to define the problem.

In this group of works, an interesting approach has been proposed in [49], where a multi-step calculation has been followed. The first step involves the time-consuming energy simulation of design alternatives, where energy consumption and internal comfort are optimized through a multi-objective genetic algorithm, determining the Pareto front. The second step concerns the calculation of the global cost for each alternative and the determination of the cost-optimal one. This two-step approach allows to save time because the thermophysical simulations are performed only during the first step, thus calculating the cost related only for a subset of solutions (Pareto front solutions) and executing a second optimization that is based on simpler and shorter calculations.

With respect to the BPS employed in these works, many studies were performed using commercial software or tools originally developed following standard ISO 13790, highlighting that these researchers are more regulation-oriented, while others used IDA-ICE (often preferred in North European countries), TRNSYS and EnergyPlus, as stated in Fig. 15.

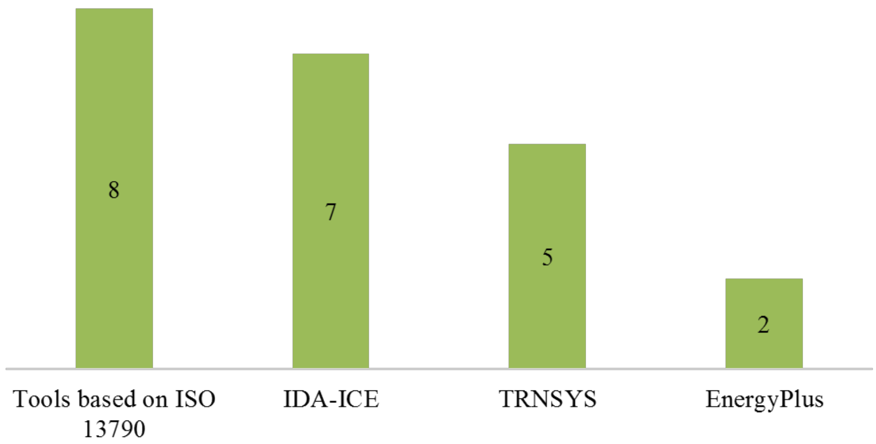

Fig. 15. Thermophysical BPS used in literature review on cost-optimal nZEBs

5. Discussion and Conclusions

In this paper, academic works on building energy optimization have been reviewed, with a special focus on Net and nearly Zero Energy Buildings. Although other similar papers already exist, this study is one of the first attempts to summarize literature on this topic, focusing on algorithmic features in order to provide beginners with a useful view on already explored methodologies. Although some technical figures as architects may be less familiar with this topic [12], they should also benefit from this review, earning a basic knowledge about the optimization techniques and the available commercial tools, allowing to move their first steps with more awareness.

European countries are at the forefront of this sector, mainly because of the EU energy saving policy, with Italian researchers being the most involved, while other countries in the world are increasingly interesting in the topic.

After almost ten years of experience in this research field, many methodologies have been explored, considering different kinds of optimization algorithms, variables, objectives and software, that were deeply analyzed and compared in this study. As so many approaches have been investigated by the scientific community, it is not possible to identify a general trend or a common frame of investigation. Nevertheless, genetic multi-objective algorithms are often preferred, first of all the NSGA II algorithm, as their structure appear to be the most convenient for the connection with BPS tools and the management of their outputs.

To date, only few integrated thermophysical and optimization tools exist, conversely researchers often combine specific thermophysical BPS with optimization software through programming languages as MATLAB. TRNSYS and EnergyPlus have shown to be the most popular BPS tools, thanks to their accuracy and relative user-friendliness, while IDA-ICE is growing interest, mainly in northern Europe countries. The MATLAB computing environment has shown a great versatility, as it has been employed both to evaluate and to optimize energy performance of buildings, although the thermophysical performance have been estimated through simplified models. MOBO, a BPO freeware developed in scientific environment [15], appears to be a very interesting tool, as already stated in [7], since this software allows to employ a great variety of optimization algorithms, but has still been rarely used.

As the aim of the optimization should be the identification of the optimal building configuration to be implemented, the legal requirements and constraints should be also taken into account in the optimization process. In EU Countries, the energy performance of buildings is rated in a synthetical way through the Energy Performance Certificates (EPC), introduced by the first EPBD in 2002. EPCs attribute a letter to each building, from G (the worst class) to A (the best class), that are determined by the yearly energy requirements of the building. In a similar way, the optimal building performance may also be assessed by comparing them with EPC classes. A categorization of optimal solutions within a certification scheme was analyzed in only 4 between the reviewed studies [26], [98], [114], [117], considering European EPCs or the Italian CasaClima certification. Moreover, as EPCs are usually collected to develop databases at national and international level, a further evolution of EPCs may include a specific section, to be filled in whether the building was designed with optimization techniques, in order to indicate parameters (input data), variables, their bounds and objective functions adopted in the design process. This database should be public, as it may help future designers in the setting of new optimization processes.

One of the main outcomes of this analysis is that most commonly optimized variables are cost functions as Global cost, Life Cycle Cost or investment cost, while energy consumption in use phase of the building are considered secondly, showing a general market-oriented trend of the studies. More surprising is that other aspects, as the environmental implications of the building or the internal comfort of dwellers, have been often ignored. Focusing on the first one, although the main aim of the LEBs is the energy saving, this was often accounted in literature as the operating saving only, neglecting the implications on the embodied energy of the building deriving from the retrofit interventions, that are particularly important in this kind of buildings [19]. This may be caused both by the difficulty in analyzing these kinds of impacts for non-insiders and by the scarcity of tools that integrate thermophysical and environmental analyzes available. In order to account for the global energy footprint of the building, a reliable methodology as the Life Cycle Assessment (LCA) [135], [136] should be employed, but few examples exist in literature, as already highlighted in [36] with respect to the coupling between TRNSYS and EQUER. In detail, the only commercial software reported in the BEST Directory performing both dynamic thermophysical simulations and Life Cycle Assessment of buildings is PLEIADES, a French software composed by a module for each aspect of the design of a building. The STD COMFIE (formerly COMFIE) is the part dedicated to the energy simulation, while PLEIADES ACV (formerly EQUER or novaEQUER) is the module performing the LCA [137]. Regarding research studies, two attempts to integrate the Life Cycle Assessment in dynamic energy simulation were found in literature [138], [139]. In the first study [138], a new type for TRNSYS was developed, allowing to perform calculations according to the standard EN 15978 [140], the European standard dedicated to the LCA of buildings. The second study [139] shows the development of a framework for linking EnergyPlus with a multi-objective optimization tool (Honeybee), also recurring to an LCA database available in MS Excel format.

In order to show the advantages that the employment of LCA may bring to the design of a low-energy building, a further analysis was conducted on papers considering the insulation of the envelope (i.e. external wall, roof or floor) as an improvement action. Insulation materials adopted in the reviewed studies were categorized in High impact (embodied energy > 200 MJ/FU, red filling in Fig. 16), Mid impact (100 MJ/FU < embodied energy < 200 MJ/FU, yellow filling in Fig. 16) and Low impact (embodied energy < 100 MJ/FU, green filling in Fig. 16), according to the LCA impact reported in [141], where materials' embodied energy per given thermal performance is provided. In Fig. 17 it is possible to see that 19% of papers considered High impact materials and 35% used Mid impact materials, while 23% of papers didn't take into account the material but only the insulating performance.

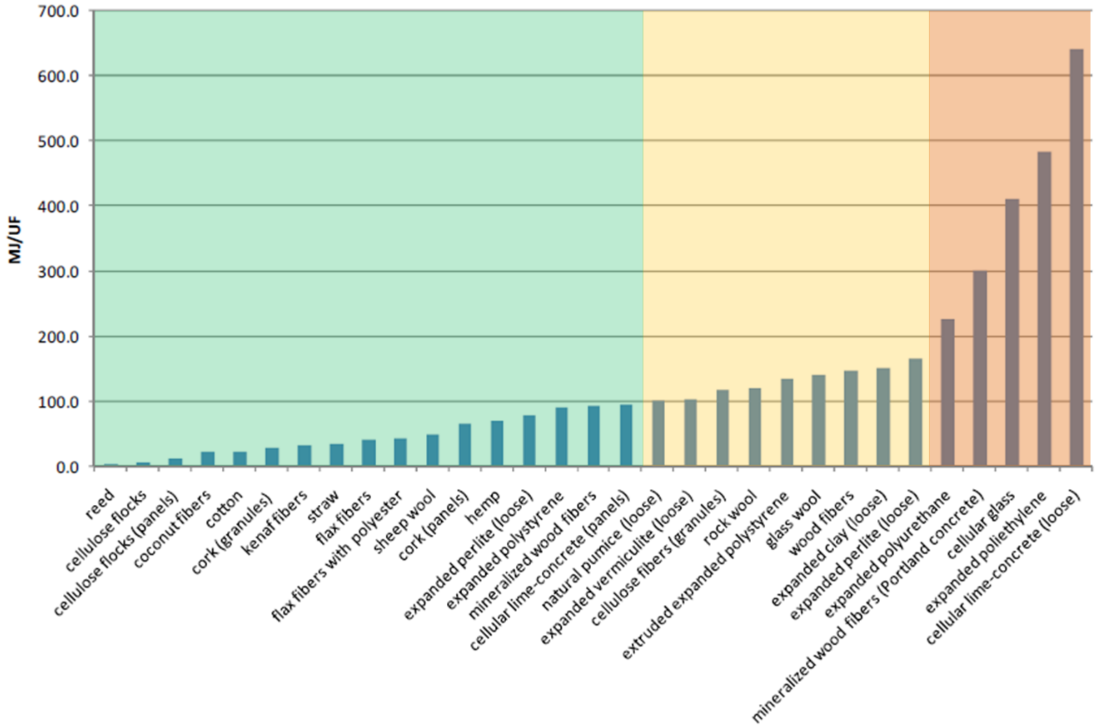

Fig. 16. Insulation materials' embodied energy per given thermal performance [141]

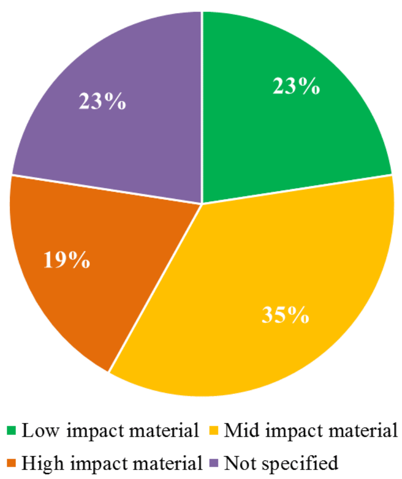

Fig. 17. Insulation materials' embodied energy in the analyzed papers

One of the few quantitative proofs of the disadvantages given from the employment of insulation materials available in literature can be found in [138], where a comparison of main LCA indicators trend for a given building for different thicknesses of insulation material (expanded polystyrene) is provided. In this specific case, although the use phase electricity consumption lowered exponentially with higher insulation thicknesses, the Global Energy Requirement underwent a quasi-linear increase.

A more comprehensive way to rate buildings performance, also accounting for environmental impacts, are the Sustainable Building Certifications. The sustainability certifications assess and rate buildings performance and environmental impacts, promoting more eco-friendly measures to be adopted in the building sector. There are currently hundreds of certification systems, comparing different aspects, and are mainly based on Life Cycle Assessment methodology. Main examples are the British Building Research Establishment Environmental Assessment Method (BREEAM), the American Leadership in Energy and Environmental Design (LEED), the Japanese Comprehensive Assessment System for Built Environment Efficiency (CASBEE) and the Italian ITACA (Institute for the Innovation and Transparency of Contracts and Environmental Sustainability, *Istituto per l'Innovazione e Trasparenza degli Appalti e la Compatibilità Ambientale* in Italian) Protocol [97], [134], [142]. Some of the papers analyzed in this study took into account the ITACA protocol indicators between their objective functions, as already reported in 4.2 section [54], [97], [99], and this example represents a useful guide for non-insiders to include in a simplified way an LCA in the optimization framework of a low-energy building design/refurbishment. Indeed, some similarities between Sustainable Building Certifications and multi-objective optimization approach to the design of a building can be recognized, but while the rating's main aim is to categorize the performance, and only secondarily to give advices for the reduction of impacts, an optimization process is primarily oriented to the creation of a sustainable building through the best available combination of alternatives.

Thus, although embodied energy and embodied carbon are often neglected in traditional buildings, as NZEBs are shifting building energy consumption from the use phase to the construction phase, authors strongly recommend to assess also for environmental implications of buildings, in order to identify the technical solution for the building that *really* allows to save energy, ultimately introducing a way to design buildings supporting the sustainable development. According to this recommendation, as future development of this study, available thermophysical, optimization and LCA tools will be further analyzed in order to integrate the most promising ones into a unique framework for the integrated energy and environmental design of buildings.

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