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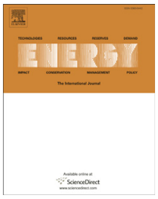

Artificial neural networks to predict energy performance and retrofit scenarios for any member of a building category: A novel approach

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ABSTRACT

How to predict building energy performance with low computational times and good reliability? The study answers this question by employing artificial neural networks (ANNs) to assess energy consumption and occupants' thermal comfort for any member of a building category. Two families of ANNs are generated: the first one addresses the existing building stock (as is), the second one addresses the renovated stock in presence of energy retrofit measures (ERMs). The ANNs are generated in MATLAB® by using the outcomes of EnergyPlus simulations as targets for networks' training and testing. A preliminary 'Simulation-based Large-scale sensitivity/uncertainty Analysis of Building Energy performance' (SLABE) is conducted to optimize the ANNs' generation. It allows to identify the networks' inputs and to properly select the ERMs. The developed ANNs can replace standard building performance simulation tools, thereby producing a substantial reduction of computational efforts and times. This can allow a wide diffusion of rigorous approaches for retrofit design, which are currently hampered by the excessive computational burden. As case study, office buildings built in South Italy during 1920–1970 are investigated. Comparing the ANNs' predictions with EnergyPlus targets, the regression coefficient is between 0.960 and 0.995 and the average relative error is between 2.0% and 11%.

1. Introduction and state of the art

The sustainable development and the effort towards a low-carbon economy are some of the most crucial challenges of our generation. The admirable purpose is a better world, in which healthy environment, economic prosperity and social justice are pursued simultaneously to ensure the well-being of present and future generations. Within this context, the 'Roadmap for moving to a competitive low-carbon economy in 2050' (EU COM112/2011 [1]) establishes the target of reducing greenhouse emissions by 80–95% by 2050 in comparison to the levels of 1990. This goal cannot be reached without a substantial effort for the improvement of building energy performance, because the building sector is highly energy-intensive by accounting for about 40% of primary energy consumption in the European Union (EU) [2] and 32% in the World [3]. This scenario has generated a great focus in designing nearly zero-energy buildings (nZEBs). However, along the next decades, the impact of new nZEBs will be quite limited, given the low turn-over rate of the building stock, particularly in the developed countries. Therefore, building energy efficiency retrofit (BEER) is fundamental to achieve a significant reduction of energy uses in the building stock [4], but the path is very challenging. As perfectly outlined by Ma et al. [5]:"there is still a long way for building scientists and professionals to go in order to make existing building stock be more energy efficient and environmentally sustainable". Indeed, the design of building energy retrofit is an arduous task that involves two distinct perspectives associated to two main actors: the collectivity (public perspective), pursuing energy and environmental benefits, and the private (single building perspective), pursuing economic benefits. Often, these perspectives are divergent, and thus a crucial question arises: How to design energy retrofit strategies that produce the best trade-off? The Energy Performance of Buildings Directive (EPBD) Recast (2010/31/EU) [6] answers this question by prescribing the cost-optimal analysis to identify effective packages of energy retrofit measures (ERMs). In detail, a new comparative methodology framework has been

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Nomenclature

Symbols

a	absorption coefficient to solar radiation (−)
DH	annual percentage of discomfort hours (%)
EER	nominal energy efficiency ratio of electric chillers (−)
E_{PV}	electricity produced by photovoltaic panels and consumed per unit of net floor area (Wh/m^2 a)
E_{RES}	energy produced by renewable energy systems and consumed per unit of net floor area (Wh/m^2 a)
PEC_c	primary energy consumption for space cooling per unit of conditioned area (Wh/m^2 a)
PEC_h	primary energy consumption for space heating per unit of conditioned area (Wh/m^2 a)
PEC_{tot}	total primary energy consumption for space conditioning per unit of conditioned area (Wh/m^2 a)
p_i	i-th parameter related to the existing building stock (−)
R	coefficient of regression (−)
r_i	i-th parameter related to the energy retrofit measures (−)
S_1	building sample related to the existing stock (as is) (−)
S_2	building sample related to the renovated stock, in presence of ERMs (−)
SRRC	standardized rank regression coefficient (−)
U_w	thermal transmittance of the windows (glass + fame) (W/m^2 K)
η	nominal efficiency of natural gas boilers related to the low calorific value (−)
μ	mean value (−)
σ	standard deviation (−)

Acronyms

ANN	artificial neural network
BPO	building performance optimization
BPS	building performance simulation
ERM	energy retrofit measure
HVAC	heating, ventilating and air conditioning
LHS	Latin hypercube sampling
MLP	feed-forward multi-layer perceptron
PV	photovoltaic
RefB	reference building
RES	renewable energy source
RMSE	root mean square error
SLABE	simulation-based large-scale uncertainty/sensitivity analysis of building energy performance

introduced to assess and improve building energy performance “with a view to achieving cost-optimal levels”. The cost-optimal package of ERMs is the one that minimizes the global cost related to energy uses over building lifecycle, calculated according to the Delegated Regulation (EU) No. 244/2012 [7]. The global cost takes into account investment and replacement costs of ERMs, operating costs, as well as state financial incentives. The cost-optimality is a powerful concept that ensures high reductions of energy consumption and greenhouse emissions by minimizing, at the same time, building lifecycle costs [8]. Thus, it addresses the interests of both main actors involved in retrofit design, i.e., the collectivity and the private. However, also other rigorous building performance optimization (BPO) approaches and algorithms [9] can be used to plan proper retrofit strategies in order to consider other objective functions that express the interests of the referred-to stakeholders. Since there are multiple – and usually competitive – goals and variables [10], multi-objective optimization is very suitable [11], allowing to minimize simultaneously different functions, such as different components of energy demands [12–19], operating costs [20,21], investments [13,14,16,22], thermal discomfort [12,14,15,18,20,21] and polluting emissions [13,22,23]. Moreover, cost-optimal analysis and multi-objective BPO can be combined [24–26] to achieve a more robust assessment of cost-optimality by considering also further goals in addition to the minimization of global (i.e., lifecycle) costs, such as the reduction of energy consumption [24,25] and lifecycle carbon footprint [26] as well as the improvement of thermal comfort [24,25].

In any case, a rigorous approach for the design of energy retrofit requires reliable predictions of building energy performance, in terms of both energy consumption and occupants' thermal comfort. This prediction should be carried out for the base building configuration, as well as in presence of numerous packages of energy retrofit measures (ERMs) in order to find the actual best retrofit scenario. Definitely, there is the need of several energy simulations, which must yield dependable outcomes for the success of retrofit strategies. Therefore, simplified steady-state methods are inadequate, whereas the recommended choice is the adoption of proper BPS (building performance simulation) tools that perform reliable dynamic energy simulations [27]. In this regard, Poel et al. [28] proposed an overview of the most popular methods and programs for the energy analysis of existing buildings. Several software and tools are available and thus the best choice, for a specific project, is not immediate nor unique but depends on different factors, such as client needs, required level of accuracy, available time and budget and so on. In the same vein, Richalet et al. [29] delineated three approaches to predict building energy performance: the computational-based approach, based on the use of BPS tools; the performance-based approach, based on the information coming from building utility bills; the measurement-based approach, based on monitoring and in-situ experimental measures. Definitely, in the retrofit design, the computational-based approach represents the only option because bills and experimental measures are not available for the retrofit scenarios. Finally, the implementation of proper BPS tools is necessary. There are several whole building energy simulation programs, such as EnergyPlus [30], TRNSYS [31], ESP-r [32], IDA ICE [33], which ensure a reliable and rigorous assessment of the impact of ERMs on building performance. These programs are widely used within the scientific community because of their high capability and reliability. However, their implementation determines a critical issue concerning the high computational complexity and burden required by building modeling and, especially, by energy simulations. Clearly, this issue intensifies when a rigorous energy retrofit design is carried out, for instance by performing cost-optimal analysis or BPO, because a huge number of simulations is required. This implies a large amount of computational time that can assume an order of magnitude from days for simple buildings, to weeks for complex ones. Definitely, rigorous approaches for the design of energy retrofit, which investigate numerous retrofit scenarios by running BPS tools, cannot be applied to each single building because the computational burden gets prohibitive if all existing constructions are considered. That is why the aforementioned EPBD Recast demands the EU member states to define a set of reference buildings (RefBs) [34,35] to represent the national

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