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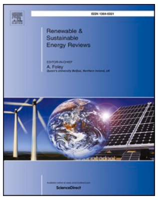

Modeling, simulation and control tools for nZEB: A state-of-the-art review

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ABSTRACT

Nowadays, most areas of human activity should be reviewed with the aim of reducing CO_2 emissions, since these activities are producing the majority of these emissions. Specifically, the building sector is one of the main responsible activities. In order to minimize the ecological footprint and ensure energy sufficiency, European Union created the nearly-Zero Energy Building (nZEB) concept. More than ten years have elapsed and it worth to review the current state around the concept, considering the new advances in computer development that are already applicable to this field. Accordingly, recent researches published in reputed indexed journals and international conferences have been reviewed. This paper explains the nZEB concept and reviews research articles focused on achieving it. A research gap is detected, so enabling concepts and technologies as Building Energy Performance Simulation (BEPS) tools and Model Predictive Control (MPC) are recalled, and relevant researches where used are included in a specific state-of-the-art for each concept, since the academia considers that these tools should be applied in building air conditioning to achieve nZEB. After this deep analysis, we conclude that the possibilities to optimize the energy consumption are huge combining properly in a holistic way BEPS tools for modeling and simulation and MPC for control strategies. It is possible to manage a Heating, Ventilation and Air Conditioning (HVAC) system using Renewable Energy Sources (RES) in an effective means, reducing CO_2 emissions problems worldwide and reaching considerable energy savings.

1. Introduction

The environmental degradation with its subsequent risk of natural disasters requires prompt action to be taken, because we, human beings, are the main culprits of this situation. The most important goal is to decrease CO_2 gases produced because our planet is facing a climate change without precedent and with unforeseen consequences due to the greenhouse effect. The building sector is one of the major liable human activity given the level of CO_2 emissions it generates. "*Buildings account for 40% of total energy consumption in the Union. The sector is expanding, which is bound to increase its energy consumption. Therefore, reduction of energy consumption and the use of energy from renewable sources in the buildings sector constitute important measures needed to reduce the Union's energy dependency and greenhouse gas emissions*", was stated in the Energy Performance of Buildings Directive (EPDB) 2010/31/EU [1]. This directive set a new term called "nearly-Zero Energy Building" (nZEB) when it was released by European Parliament.

More than ten years after the term nZEB was established in the EU, it worth assessing the advances that have been achieved in the scope through a state-of-the-art review, paying an especial attention to the tools that are the hand of scientists and practitioners. They are usually computer programs devoted to modeling, simulation, and control, and given the technological evolution and its progressive cheapening, it is expected to find out an interesting variety of modeling, simulation and control tools to achieve the goal of nZEB.

Hence the use of Building Energy Performance Simulation (BEPS) and Model Predictive Control (MPC) to help the achievement of nZEBs, the authors have reviewed different papers about these concepts published in the last years in reputed scientific journals and international conferences, and have analyzed the main factors to be taken into consideration. Obviously, the location of each building and also its surroundings, which includes topography conditions, vegetation, the distance between buildings, and the use of open spaces, are very important factors and should be taken into account by the architects in the design phase. It must also not be forgotten the climatic conditions to which this building will be subjected, that could change very quickly in function of the season of the year and the moment of the day. With the

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Nomenclature

ANN	Artificial Neural Networks
BAS	Building Automation System
BEPS	Building Energy Performance Simulation
EPBD	Energy Performance of Buildings Directive
FLC	Fuzzy Logic Controller
GHG	Greenhouse Gas emissions
HP	Heat Pump
HVAC	Heating, Ventilation and Air Conditioning
LCC	Life Cycle Cost
MPC	Model Predictive Control
MS	European Union Member States
nZEB	nearly-Zero Energy Building
PCM	Phase Change Material
PID	Proportional-Integral-Derivative
PV	Photovoltaic system
REHVA	Federation of European Heating, Ventilation and Air-conditioning Associations
RES	Renewable Energy Source
SMPC	Stochastic Model Predictive Control
STPV	Photovoltaic semi-transparent materials
WSN	Wireless Sensor Network
WWR	Window to Wall Ratio

implementation of suitable Passive Strategies during the design phase, the following steps, as the definition of the appropriate Heating, Ventilation and Air Conditioning (HVAC) system and its possible control alternatives, will be much more effective. To determine the active strategies is fundamental to consider an economic analysis: for instance, the selection of the type of HVAC system and the most adequate Renewable Energy Source (RES) to ensure the comfort levels required, as well as to reduce the impact of the climate inside the building. The behavior of the occupation is another crucial point. Such a varied set of factors advises the definition of strategies in a multidisciplinary way so that high levels of energy efficiency can be achieved, even reaching nZEB standards.

Due to the previous reasons, bearing in mind the different technological advances currently available, the efficiency of building management could also be improved by BEPS and MPC. These tools are barely being used in buildings now and, despite they have great potential. Their economic cost can be relatively low to achieve satisfactory results if we compare it to other passive approaches mentioned later. Based on the papers shown in Table 3 and discussed in Subsection 2.6, it can be stated that MPC is an interesting tool since its use allows optimizing the energy consumption of the buildings. For example, to manage cooling or heating with RES through occupancy and climate forecasts accessible from various existing modeling applications and meteorological services.

The major contribution of this work is to make a comprehensive review of the state of art on the scope of nZEBs, BEPS tools and MPC based systems for building climatization, providing a structured framework to understand and deepen into those concepts.

The structure of this paper is as follows. Within Section 2, the methodology applied for this review paper is explained in Subsection 2.1. The nZEB concept is outlined in Subsection 2.2, followed by a review of relevant literature conducted to achieve it in Subsection 2.3. In Subsection 2.4, a background is given to introduce the concept of the BEPS tools, and several successful investigations where these tools have been applied are reviewed. In Subsection 2.5 the MPC concept is explained, and Subsection 2.6 analyzes several relevant papers of MPC applied to buildings climatization. The main factors which influence an MPC implementation are discussed in Section 3. Finally, in Section 4 a critical review is made, the main conclusions are summarized and the future challenges are proposed.

2. Methodology, concepts and literature review

2.1. Methodology

This paper aims to clarify the nZEB concept, the reasons for its definition and importance, as well as the tools and the main factors that are required to achieve it. For this, it has been searched, using the keyword "*nZEB*" and "*nZEB buildings*", in articles published in prestigious scientific journals and international conferences during the last ten years. A summary of all these investigations is shown in Table 1. After a preliminary analysis, it has been considered that there is a research gap that is worth studying. All the researches reviewed had a specific focus, in most cases only considering passive actions on the building envelope. For these reasons, it was considered interesting to tackle the issue with a multidisciplinary approach and investigate studies where energy efficiency was improved by applying BEPS tools.

Following the same previous methodology, articles published in reputed scientific journals since 2010 have been reviewed, using the keywords "*BEPS Tools*", "*Building Modeling*" and "*Building Simulation*". These articles allowed us to check and compare the different BEPS tools that have been applied successfully, as shown in Table 2. This summary indicates these implementations together with the BEPS tool applied.

Finally, it was decided to provide further insight into this subject, specifically on the implementation of MPC systems. Nowadays, this seems the most logical choice in changing environment but where usage profiles can be established. Scientific articles on the development of "*MPC*" in buildings over the last ten years were researched, except for two previous articles (1989 and 2003) for being historical references. In these investigations, the main factors to be considered for its correct application have been found, as shown in Table 3. These factors have been analyzed and reviewed in the section Discussion, to finally state the pertinent Conclusions after all these analyses have been carried out.

2.2. nZEB concept

As indicated in the section Introduction, the EPBD 2010/31/EU [1] introduced the concept named nZEB and set down under its Art.9 that European Union Member States (MS) shall ensure that all new building constructions after December 31, 2020 must achieve all key principles of nZEBs. That means that these new buildings will have highly energy-efficient systems because the very low energy demand that requires an nZEB will have to be mainly covered by nearby or on-site energy production from RES, as stated in its Art.2 [1].

The EPBD 2010/31/EU [1] is an update of the EPBD 2002/91/EC [2]. MSs tried to tackle this global challenge by focusing their efforts on all components that affect building performance and laying down their minimum requirements to enhance the energy performance, setting nZEB as a policy objective. Indeed, to stave off a further growth in the Greenhouse Gas emissions (GHG) levels, MS decided to issue several directives with the target of encouraging the reduction of energy consumption and promoting the use of RES. A framework was initially defined for all the MS in order to:

- reduce GHG at least 20% below 1990 levels by 2020,
- increase the REás share in the overall energy mix to 20% within MS (and a share of biofuels of 10% in fuels for transport),
- achieve the 20% energy efficiency target by 2020, reducing the consumption of primary energy through the implementation of energy efficiency instruments and technologies.

This was denominated 20/20/20. The European policy statement issued with it a cross-cutting guideline of challenging objectives to realize high-energy efficiency in buildings. Later, the new guidelines have kept following with the same working policy and set out even more challenging goals as provided on energy performance [3] in 2012, that underlines key issues like "smart" grids. Another key factor was highlighted in January 2014 [4], where goals were established in terms of energy and climate looking forward to 2030. This new guideline seeks to decrease by 40% GHG compared to the levels reached in 1990, as well as to enhance energy performance by 30% to reach a binding target of at least 27% of RES along the MS.

These European regulatory frameworks about the EPBD mean a real change of the current way of designing (inside of the discipline of Architecture) and building (at Engineering level), through technical systems: from the HVAC to the lighting. In addition, a methodology about cost-optimal levels was defined for energy efficiency standards (both for existing and new buildings), which instructs MS on the way to lay down concerning minimum standards and keep them away from high costs of investment.

2.3. *Literature review of nZEBs*

The methodology followed in this work has been to review different papers published in the last years dealing with nZEB concept, in order to obtain a global vision and to detect if there is any knowledge gap. Several architectural researches [5–10] assess different passive strategies, which must be used from the design stage with the implementation of passive encourage natural techniques profiting from solar shading efficiency such as ground exchangers, night sky radiation or evaporative cooling. The building envelope performance can also be improved with new insulating materials, changing its inertia through Phase Change Material (PCM) or by modifying its Window to Wall Ratio (WWR). And in the same way, when it comes to a retrofitting building, where there are usually more restrictions and the original structure of the building often must be maintained, also attempts to apply new passive strategies that serve to improve its energy efficiency are considered. Among the most common there are the windows replacement and the improvement of the air-tightness.

Several researches analyze and suggest some improvements reported from different technical points of view at the engineering level, comparing the advantages of different HVAC systems using RES [11–13] or at the end-user level, following distinct strategies of comfort [14]. Nonetheless, other authors give more priority to economic issues [15–20] and examine the economic return of several alternatives, trying to seek the best cost-effective solution.

The analyzed papers are summarized in Table 1, where are listed including the following information:

- Focus of the article.
- Type of building analyzed (residential dwelling and/or public building).
- Contribution and strategy at the level of the building envelope (features, comparatives or new passive strategies).
- Whether occupancy behavior or analysis of comfort requirements were considered.
- Type of HVAC System, highlighting the use of renewable sources (Solar Thermal, Photovoltaic system (PV) or Heat Pump (HP)) and the kind of emitter (radiant floor, fan coil or radiator).
- How was defined its building energy management, if they have used some Wireless Sensor Network (WSN), it was applied MPC or any simulation programs.
- And finally, the country or region where they were implemented.

Loukaidou et al. [5] performed tests with different test-cell buildings for cost-optimal analysis of building envelope characteristics. Aste et al. [6] evaluated the energy efficiency of an integrated multifunctional system engineered to satisfy the HVAC requirements utilizing RES on residential buildings. Barthelmes et al. [7] analyzed an example building of a single-family house newly built using the cost-optimal methodology from the preliminary design phase of the project. Murano et al. [8] investigated under what conditions and extent a large imbalance of the energy needs occurs for heating versus cooling in different types of buildings located in several Italian climatic zones. Cornaro et al. [9] characterized a commercial PCM panel, and subsequently from their experimental data validated a PCM computerized tool performed in an energy and indoor environment computer application. In Ref. [10] authors presented an appraisal of potential energy savings of four distinct kinds of photovoltaic semi-transparent materials (STPV) compared to conventional double panel glass. Kurnitski et al. [11] determined cost-optimal and nZEB energy performance levels following the "*Federation of European Heating, Ventilation and Air-conditioning Associations*" (REHVA) definition. Kang et al. [12] developed a method for the optimization of the economic sustainability of the Life Cycle Cost (LCC) to implement energy-saving technologies in the early stages of building design. Karlessi et al. [13] proved the fundamentals of the integrated design process and linked the method to technologies of a smart building, and presented some methodologies for energy efficiency and others pioneering solutions implemented at the construction level. Péan et al. [14] carried out a simulation work to look into the impact of a strategy of control demand-side energy management in a refurbished nZEB dwelling. Guillén et al. [15] performed simulations to check the success of comfort criteria concerning power consumption for the climatization of nZEB dwellings following the Passivhaus ("Passive House") standard. Keltsch et al. [16] investigated the potential of nZEB standard by studying ten cases of non-residential buildings for various purposes uses in Bavaria. Cellura et al. [17] explained the experience of re-designing an already existing rural building located in Sicily, performed an energy audit on this building and its energy consumptions were fully inquired to validate a model aimed towards the achievement of the nZEB target. Monteiro et al. [18] evaluated the proper implementation of the nZEB process in the updating of a Portuguese typical house built in 1950. Becchio et al. [19] introduced a guideline for designing reference technical systems solutions and building envelopes for residential nZEB while, Adhikari et al. [20] showed that a zero-energy building can pose an affordable investment cost, especially if integrated with PV facilities. Paoletti et al. [21] made an overall description of the construction key characteristics in 17 countries from Europe, for both residential and public buildings, checking their efficiency performance and insulating materials together with the use of RES as solar thermal and PVs facilities. Attia et al. [22] made a general overview and identified the future challenges of nZEB design in Southern Europe. And lastly, Zangheri et al. [23] defined cost-optimal and nZEB retrofitting levels for different building typologies and several meaningful climates over Europe.

All these mentioned researches are highly interesting and worthy since they open up the opportunity to further develop in its field, but they do it from partial points of view of specific disciplines: new thermal insulation materials development, economic viability, engineering level solutions, architectural solutions, comparatives. However, it would be advisable to tackle the issue from a more holistic point of view, with a multidisciplinary approach taking into account that several areas can help to improve energy efficiency. More global management should help to reach the target attainment in a faster, more economic and

Table 1
List of the reviewed papers about nZEB.

			Type of building		Building Envelope		Occupancy		HVAC System		Building Energy Management			
Ref.	Authors	Focus of the article	Dwelling	Public	Contribution	Passive Strategies	Behavior	Requirements	Renewable Sources	Emitter	WSN	MPC	Simulation Program	Country /Region
[5]	Loukaidou et al. (2017)	"nZEBs: Cost-Optimal Analysis of Building"	Yes	Yes	Envelope features	Insulating &Windows	Yes	No	Boiler & HP	–	No	No	*Energyplus*	Cyprus
[6]	Aste et al. (2017)	"Multi-functional Integrated System for Energy retrofit"	Yes	No	Envelope features	Insulating &Windows	Yes	No	Air-Water HP & PVs	Radiant floor	No	No	*Energyplus* *TRNSYS*	Italy
[7]	Barthelmes et al. (2014)	"The Influence of Energy Targets and Economic …"	Yes	No	Comparative insulation	Insulating materials	–	–	Water HP &Ventilat.	Radiant panels	No	No	*Energyplus*	Italy
[8]	Murano et al. (2017)	"The significant imbalance of nZEB energy need"	Yes	Yes	Envelope features	Insulating & Shading	–	–	–	–	No	No	*Design Builder*	Italy
[9]	Cornaro et al. (2017)	"Outdoor Characterization of PCMs and Assessment"	No	Yes	Envelope features	PCM	Yes	Yes	No (boiler + chiller)	Fan coil	No	No	*IDA-ICE environment*	Italy
[10]	Cornaro et al. (2017)	"Energy Saving Assessment of Semi-Transparent PVs"	No	Yes	Envelope features	STPV	No	No	PVs	–	No	No	*IDA-ICE (EQUA Sim)*	Italy
[11]	Kurnitski et al. (2011)	"Cost optimal and nearly zero energy performance …"	Yes	No	Comparative HVAC systems	Insulating &Windows	–	–	Solar Th., HPvsBolier	Radiant floor	No	No	*IDA-ICE*	Estonia
[12]	Kang et al. (2017)	"Development of an nZEB Life Cycle Cost Assessment"	No	Yes	Comparative HVAC systems	Insulating &Windows	–	–	–	–	–	–	*Energyplus*	Korea
[13]	Karlessi et al. (2017)	"The concept of smart and NZEB buildings"	Yes	Yes	Comparative Smart Build.	Thermal mass	–	Yes	Solar Th., HP & PVs	Radiant floor	No	Yes	*MyLeaf, Idea Fresco*	Greece, Crete, Italy
[14]	Péan et al. (2017)	"Impact of Demand-Side Management on Thermal"	Yes	No	Efficiency Analysis	Thermal mass	Comfort Strategy	Comfort Criteria	HP & PVs	Radiator	No	Yes	*TRNSYS*	Spain
[15]	Guillén et al. (2017)	"Comfort settings and energy demand for residential nZEB"	Yes	No	Efficiency Analysis	–	–	Thermal Comfort	–	–	No	No	*TRNSYS*	France, Spain, Italy
[16]	Keltsch et al. (2017)	"nZEB Standard for Non-Residential buildings"	No	Yes	Efficiency Analysis	Thermal mass	No	No	Geo, Solar Th., HP&PV	–	No	No	No	Germany
[17]	Cellura et al. (2017)	"Redesign of a Rural Building in a Heritage Site"	No	Yes	Efficiency Analysis	Insulating materials	Yes	Yes	HP & PVs	Fan coil	No	No	*TRNSYS*	Italy
[18]	Monteiro et al. (2013)	"Application of the nZEB methodology in retrofitting"	Yes	No	Efficiency Analysis	Thermal Envelope	–	–	Solar Th., HP & PVs	–	No	No	No	Portugal
[19]	Becchio et al. (2015)	"Cost optimality assessment of a single-family house"	Yes	No	Efficiency Analysis	Insulating materials	–	–	Ventilation, HP&PVs	Radiant floor	No	No	*Energyplus*	Italy
[20]	Adhikari et al. (2012)	"Net Zero Energy Buildings: Expense or Investment?"	Yes	No	Efficiency Analysis	–	–	–	Ground HP & PVs	Radiant floor	No	No	*Energyplus*	Italy
[21]	Paoletti et al. (2017)	"nZEBs: An Overview of the Main Construction Features"	Yes	Yes	Efficiency Analysis	Insulating materials	–	–	Solar Th. & PVs	–	No	No	No	Europe
[22]	Attia et al. (2017)	"Overview and future challenges of nZEB design"	Yes	Yes	Challenges of design	Passive cooling	–	–	Solar Th., HP & PVs	Yes	–	–	–	Southern Europe
[23]	Zangheri et al. (2017)	"Identification of cost-optimal and nZEB refurbishment"	Yes	Yes	Benchmark	–	–	Comfort levels	PVs systems	–	–	–	–	Europe

straightforward way.

2.4. Literature review of buildings modeling and simulation tools

The energy consumed by air conditioning systems in buildings is very high, and therefore, it is the origin of much of the total GHG, as indicated in different studies and statistical reports as "*Why buildings*" [24] by United Nations Environment Programme, "*EU Energy in Figures*" [25] by the European Union and "*Monthly Energy Review*" [26] by the United States. These figures validate the worth of enhancing the effectiveness, at both economic and technical levels, of the management of heating and cooling in buildings. Furthermore, it is to be noted that several researches carried out in recent years, technological developments in building modeling applications and the existing databases enable us to be confident: Ruparathna et al. [27] went over distinct initiatives to enhance the building energy performance, and defined a road map in order to improve the energy performance in official and commercial buildings; Harish et al. [28] reviewed modeling and control of power systems in buildings; Roberts [29] analyzed passive and active actions implemented in existing constructions; Chandel et al. [30] showed norms, bylaws, codes, and energy performance metrics; Santos et al. [31] exposed the factors that influence the energy system of any building and Kneifel [32] calculated the LCC to make different cost-effective energy efficiency improvements in novel commercial buildings.

Every building is singular, not only because of its emplacement, orientation, or its surrounding conditions but also because of its dimensions, geometry, the construction materials utilized in its envelope, the distribution of each area, the use of each space, and its identification depending on its construction type. It is clear that the envelope of a building is one of the most significant factors since it takes into account the fenestration characteristics, air leakage or tightness of the envelope, building configuration, shape and height of the building, orientation, WWR, daylit areas, natural ventilation, characteristics of the wall and ceiling materials, as explained by Susorova et al. [33] and Lin et al. [34]. Many researchers have proposed actions to increase the thermal efficiency of the building. Among them, one possibility is to replace windows with better insulation as in Aste et al. [35] or to use PCM on the roof, as developed in Chung et al. [36]. Any improvement in a building opaque envelope in terms of its thermal insulation is very important because it can change its thermal inertia and significantly reduce its energy losses. For this purpose, the previous modeling of the building helps to make a correct analysis and development. At the same time, it allows evaluating different alternatives to obtain the desired result, reducing the time and investment required for it.

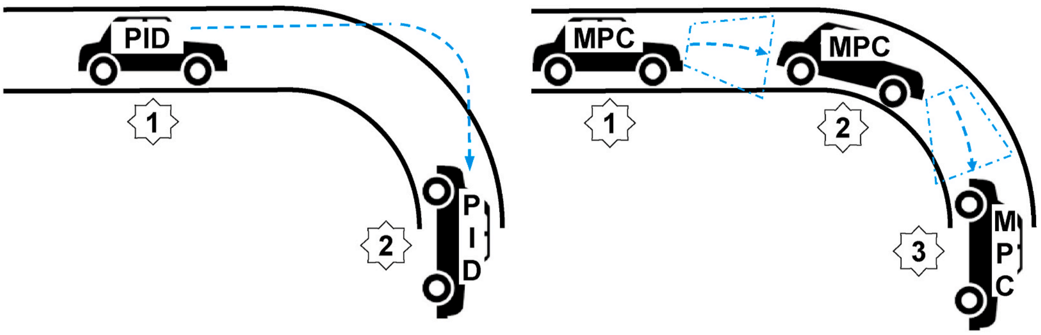
There are different Building Energy Performance Simulation (BEPS) tools that allow to model and perform energy simulations of buildings such as *IDA-ICE*, *EnergyPlus*, *CPLEX,* or *TRNSYS*, as shown in Table 2 along with a review of several researches with their focus and the BEPS tool used in each case. These investigations are mentioned throughout this paper and they have shown how the use of BEPS tools is applied successfully to optimize the climatization of buildings, and therefore they could also be applied in nZEBs.

BEPS tools can be used during their design phase, but they are also very useful during other phases of the buildings life-cycle because they enable to optimize energy consumption, especially in the retrofitting processes of buildings. Traditionally the BEPS concept consists of determining the building performance using mathematical models created on the basis of fundamental physical principles through a computer-based tool. Sha et al. [52] suggested a working process for a tool of integrated HVAC improvement design and explained the following concepts:

- "*White box*" or physical-based modeling: a method where a series of mathematical models are created relying on first principles of previous physical data of mass, momentum and energy conservation

Table 2
List of the reviewed papers about BEPS.

Ref.	Authors	Focus of the article	BEPS Tool
[37]	Magnier et al. (2010)	"Optimization of building design using TRNSYS simulations and algorithms"	*TRNSYS*
[11]	Kurnitski et al. (2011)	"Cost optimal and nZEB energy performance calculations for residential buildings"	*IDA-ICE*
[20]	Adhikari et al. (2012)	"nZEBs: Expense or Investment?"	*EnergyPlus*
[7]	Barthelmes et al. (2014)	"The influence of energy targets and economic concerns in design strategies for a residential nZEB"	*EnergyPlus*
[19]	Becchio et al. (2015)	"Cost optimality assessment of a single-family house for the nZEB target"	*EnergyPlus*
[28]	Harish et al. (2015)	"A review on modeling and simulation of building energy systems"	*TRNSYS*
[38]	De Boeck et al. (2015)	"A literature review about improving the energy performance of residential buildings"	*TRNSYS*
[39]	Valdiserri et al. (2015)	"Retrofit strategies applied to a tertiary building assisted by TRNSYS"	*TRNSYS*
[40]	Vocale et al. (2015)	"Space heating load estimation procedure for CHP systems sizing"	*TRNSYS*
[41]	Carrascal et al. (2016)	"Heating System use in aged buildings via MPC"	*TRNSYS*
[42]	Sarbu et al. (2016)	"Evaluation of radiator and radiant floor heating systems"	*TRNSYS*
[43]	Sarbu et al. (2016)	"Advances in geothermal energy, using ground-source heat pump systems"	*TRNSYS*
[44]	Harish et al. (2016)	"Reduced order modeling of a building energy system model through an optimization routine"	*TRNSYS*
[12]	Kang et al. (2017)	"Development of an nZEB life cycle cost assessment tool for fast decision making in the early design phase"	*EnergyPlus*
[6]	Aste et al. (2017)	"Multi-functional integrated system for energy retrofit of existing buildings: a solution towards nZEB standards"	*TRNSYS*
[45]	Ogando et al. (2017)	"Energy modeling and automated calibrations of ancient building simulations: a school"	*TRNSYS*
[46]	Baglivo et al. (2017)	"Envelope design optimization by thermal modeling of a building in a warm climate"	*TRNSYS*
[14]	Péan et al. (2017)	"Impact of management on thermal comfort vs energy costs in a residential nZEB"	*TRNSYS*
[15]	Guillén et al. (2017)	"Comfort settings and energy demand for residential nZEB in warm climates"	*TRNSYS*
[17]	Cellura et al. (2017)	"Redesign of a rural building in a Heritage site in Italy: towards the nZEB target"	*TRNSYS*
[8]	Murano et al. (2017)	"The significant imbalance of nZEB energy needs for heating and cooling in Italian climatic zones"	*EnergyPlus*
[9]	Cornaro et al. (2017)	"Energy saving assessment of STPV modules Integrated into nZEB"	*IDA-ICE*
[10]	Cornaro et al. (2017)	"Outdoor characterization of PCM and assessment of their energy saving potential to reach nZEB"	*IDA-ICE*
[5]	Loukaidou et al. (2017)	"nZEBs: Cost-optimal analysis of building envelope characteristics"	*EnergyPlus*
[47]	González et al. (2018)	"Optimization model for evaluating on-site renewable technologies with storage in nZEBs"	*CPLEX*
[48]	Bozkaya et al. (2018)	"A dynamic building and aquifer co-simulation method for thermal imbalance investigation"	*TRNSYS*
[49]	Palme et al. (2018)	"UWG-TRNSYS Simulation coupling for urban building energy modeling"	*TRNSYS*
[50]	Iturriaga et al. (2018)	"Optimal renovation of buildings towards the nZEB standard"	*TRNSYS*
[51]	Yoon et al. (2018)	"Strategies for virtual in-situ sensor calibration in building energy systems"	*TRNSYS*



(a) Proportional-Integral-Derivative (PID) Controller (b) Model Predictive Control (MPC)

Fig. 1. Example to explain graphically the concept of MPC.

equations, heat transfer, etc. These physical-based techniques are related to thermodynamic properties for in-depth modeling and analysis, which use physical concepts to solve calculations representing the physical phenomena of heat transfer. It is commonly used in the HVAC industry.

- "*Black box*" or data-based model: a method created from a large amount of empirical data obtained from the real-world. The reasoning of mathematical models and statistical techniques are applied to predict future values through an algorithmic method that is used on a large number of calculations. These methods do not require knowing the intrinsic nature of the phenomenon that is happening real-world phenomena because they are framed on a function derived only from physical-sample records that explain the behavior of a particular system. Among the black box models used in energy forecasting in buildings are Multiple Linear Regression (MLR) or statistical regression model, Support Vector Machine, and Artificial Neural Networks (ANN). One of the most used models of this kind is ANN, a machine learning approach taking the interrelation between output and input variables. Its principle is inspired by the human brain.
- "*Grey box*" or hybrid model: it uses both black box and white box methods. This approach relies on physical laws, although some process parameters are estimated by taking data-based models. Within this method, resistor-capacitor networks (a simile with an electric circuit representing the heat transfer through the building envelope) are highly used for estimating climatization loads.

After the model estimation process, the next step is the decision making and uncertainty analysis where existing methods indicated in Ref. [52] such as Genetic algorithms, Dynamic programming, Expert systems, and Monte Carlo simulation. And recently within these processes of decision making and uncertainty analysis, different implementations of ANN have been carried out successfully: Du et al. [53] in a rural house in China, where energy consumption and indoor environment parameters were recorded during one year and were compared with the obtained annual simulation results; Escandon et al. [54] developed a surrogate model to evaluate the thermal behavior of social housing stock in Spain; Ciulla et al. [55] implemented a parametric simulation to assess the energy performance of 195 scenarios and justified the use of MLR method; Besides to these successful implementations with ANNs of modeling approaches, they have been also used for control tasks. Hussain et al. [56] presented the energy modeling with a nonlinear-autoregressive ANN with exogenous input in a chiller plant; Mehboob [57] developed an optimization of parametric adjustment making ANN model optimal for five climatic regions and Nasruddin et al. [58] addressed the multi-target optimization of a two-cooler system, which shows the potential of this way to determine the proper operation of high-technology HVAC systems in a house.

It is also noted that the technological advances made in recent years have provided modeling and simulation tools with acceptable accuracy. After analyzing all previous researches, it is considered that conventional control systems based on Proportional-Integral-Derivative (PID) controllers or similar strategies are not an optimal solution for managing a building climate control, where there are changing situations and a high risk of uncertainty. Considering the variety of existing intelligent control strategies, which have been introduced in the last part of the 20th century, it has been thoughtful to analyze the most efficient advanced control techniques in the research of the last ten years in building climatization, as justified by Drgoňa et al. [59]. In this sense, the MPC systems have a wide transversal range of applications, and therefore, its development is being promoted in industrial areas for all types of applications. In building air conditioning, MPC is currently the most extended choice because there is a changing environment but the usage profiles can be established and/or predicted. Not many years ago, its computational requirements were a significant handicap for its use. However, the development achieved so far in hardware and software tools has overcome this drawback. Then, all the elements for its successful application are available. Also, it is possible to provide relatively good weather and occupation forecasts. Internal gains can be calculated via BEPS tools and the required comfort specifications are known. For all these reasons, it has been considered of interest to carry out an analysis of the current state-of-the-art on the MPC systems applied to building climatization.

2.5. *MPC concept*

To explain it graphically, it is typical to make the simile of when we drive a vehicle to move around. The variability in the consumption of fuels is under the influence of distinct variables such as the design of the vehicle, type of car, its weight, its aerodynamic, state of its tires, etc. The same applies in buildings with the effect of their design, orientation, size, insulating materials, shape and type of windows, etc. In the car example, this will also vary according to the route wherever we drive, the road type (motorway, mountain or urban roads), as well as the number of passengers, weight of the luggage, or traffic conditions, such as the state of the traffic lights, controls, traffic jams and long and interminable unpredictable situations that we are unable to control. For buildings, these factors are weather and occupation conditions which are predictable but not controllable. In spite of this apparent complex situation, we can have a great influence on consumption depending on the conditions of our vehicle, the state of the tires or the type of wheels. We can even improve their aerodynamics with spoilers, diffusers, side skirts and front wind splitters to minimize such consumption, as we do in buildings improving their envelope with new insulating materials or replacing their windows. Also we should have a "green driving" mode (less sporting and taking advantage of the inertia of our vehicle), thus decreasing fuel consumption. Moreover avoiding sudden braking at a red light or choosing the roads with the most advantageous conditions, there is a very positive impact on the final consumption of the car.

Continuing with the simile, many times a vehicle is used to make regular trips. That is, almost every day people go to their jobs through a route that based on their experience, is considered the best for being the most comfortable or faster. What would happen if we follow the same strategy in a building? That is to say, what would happen if we manage an adequate algorithm with which we could control the HVAC system to optimize the thermal inertia of the building, also considering a forecast of occupation and climate as the basis? Fig. 1 illustrates it with a classic example to show the differences between the two strategies that are normally used. Both controllers PID and MPC know the reference trajectory for the system (the map of the road to move out with the car). The PID controllers make the control action once the error has been done and measured, i.e., once that the car has passed the curve, without possibility of preventing it. It is like driving looking in the rear view mirror. However, MPC controllers have a model of the vehicle (how the dynamics of the system is) and make a calculus of several control actions applying only the first one of them, taking into account how they will affect the control of the car during several sampling times. In short, it is as driving looking forward the road.

That could help to lay down the most suitable "route" to decrease consumption as much as possible and within the cheapest time periods. Continuing with the car example, if anybody drives a car through the route that is theoretically the most appropriate and also the driver knows the state of the traffic and even when he sees a red light in a traffic light, he allows as much as possible for the vehicle to approach with its own inertia, without accelerating or barely using the brake, it is surprising the consumption ranges that it can reach. We consider parallelism can be established with energy consumption in buildings and therefore, considering the MPC as an interesting tool to achieve nZEBs.

2.6. Literature review of MPC applied to buildings climatization

Authors have reviewed several papers about MPC which have been published in the recent literature to show the current situation in this field and the alternative approaches in use. In this review, the development of MPC based techniques for building climatization in recent years can be observed. There are numerous researches from the late 1980s to the present day, studying the best way to work out an MPC based strategy to minimize energy consumption and various tests or deployments which have been conducted. The most significant ones are shown in Table 3, where they are analyzed with the following fields:

- Focus of the article.
- Type of building analyzed (residential dwelling or public building).
- Its contribution or improvement at the predictive control level and if the research has considered the behavior of the building thermal mass under study.
- Type of weather data managed (Real and/or Forecast).
- Whether occupancy behavior or analysis of comfort requirements were considered.
- Whether the research has considered the energy source and the kind of emitter used.
- How was defined its building energy management defined, and whether they have used some Wireless Sensor Network (WSN) or any simulation program.

García et al. [60] demonstrated that MPC is an accurate control alternative because it considers both occupancy and climate forecasting to achieve optimal energy management. Cho et al. [61] used and checked several approaches through which to enhance the power performance of discontinuous heating by means of radiant floor facilities, demonstrating that the MPC approach could achieve savings from 10% to 12% of the power requirement.

Oldewurtel et al. [62,63] developed climate management by applying a Stochastic MPC. Široký et al. [64] performed an experimental test of MPC for building air conditioning. Cigler et al. [65] applied an MPC strategy on building climatization. Fabietti et al. [66] operated HVAC systems through implicit and explicit MPC. Xiwang et al. [67] overviewed building power modeling techniques for its running and control. De Coninck et al. [68,69] created a toolbox to obtain accepted grey box models of buildings and carried out a real application of MPC.

There have been several applications of MPC algorithms in distinct kinds of building and emplacements: Carrascal et al. [41] in an apartments building in the north of Spain: Bilbao - Basque Country; Hu et al. [70] in a state building in the USA: California; Ascione et al. [71] in a dwelling building in Italy: Naples; Sturzenegger et al. [72] in an office block in Switzerland: Allschwil and Vaccarini et al. [73] in a subway station in Spain: Barcelona, where a WSN was implemented to find out actual records of temperature, occupation, humidity, etc. Another application of a WSN is provided by Reena et al. [74] in their research where the actual occupancy was captured by sensors and used to manage the indoor environment (air temperature, humidity,…) in a Building Automation System (BAS). A solution with WSN can be regarded as the most proper working approach to prevent perturbations related to any sudden change of occupancy and temperature data. As exposed by Oldewurtel et al. [75], the occupancy data are a very sensitive factor to achieve optimal management in the climatization of a building. Besides, these sensors can now be harvested, so they are easier to install and maintain. By arranging a WSN, the actual records could be provided to the operational control to apply even minor real-time adjustments to the HVAC system. In this way, the performance is enhanced because the management system can provide a more adequate response to the comfort requirements demanded and optimize the power consumption of the building.

These researches have been successfully developed. However they require expert personnel and have a high complexity because of the model which requires high accuracy. It should not be forgotten that buildings are in a changing environment, with high variability, and on which it is very complex to establish fixed rules. That leads to the need to develop an approach with a learning capacity that allows modeling complex systems. In this sense, architectures based on ANNs and Fuzzy Logic Controllers (FLC) could also be considered a very interesting option.

For these reasons, we have also examined several investigations where authors researched different approaches to process the data and control the HVAC systems, to obtain the required comfort conditions, but minimizing the energy requirements through the building climate control: Collotta et al. [76] put a forward ANN to check indoor climatic conditions which were utilized to provide data to an FLC, Marvuglia et al. [77] linked a neuro-fuzzy model for indoor climatic conditions automatic and dynamic adjustment, Dragomir et al. [78] made an identification of the most commonly used criteria involved in every step of the modeling process, in order to determine an optimal forecasting tool with an ANN and Ghadi et al. [79] designed an update a FLC in a BAS.

Table 3
List of the reviewed papers about MPC.

			Type of building		Applied strategy		Weather data		Occupancy		HVAC System		Energy Management	
‘	Authors	Focus of the article	Dwelling	Public	Contribution/ Improvement	Thermal mass	Real	Forecast	Behavior	Requirements	Source	Emisor	WSN	Simulation
[60]	García et al. (1989)	“Model predictive control: Theory and practice—A survey”	–	–	Predictive Control	Yes	No	Yes	No	No	No	No	No	Yes
[61]	Cho et al. (2003)	“Predictive control operated by radiant floor heating systems”	–	–	MPC implementation	Yes	No	Yes	No	Yes	No	Yes	No	Yes
[62]	Oldewurtel et al. (2010)	“Climate control using stochastic model predictive control”	–	–	Stochastic strategy	Yes	No	Yes	No	No	No	No	No	Yes
[63]	Oldewurtel et al. (2011)	“Use of model predictive control and weather forecasts”	–	–	MPC implementation	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes
[64]	Široký et al. (2011)	“Experimental analysis of model predictive control”	Yes	No	MPC implementation	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes
[65]	Cigler et al. (2013)	“Implementing Model Predictive Control in building”	No	Yes	MPC implementation	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes
[66]	Fabietti et al. (2014)	“Control of HVAC Systems via Explicit and Implicit MPC”	No	Yes	MPC implementation	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes
[67]	Xiwang et al. (2014)	“Review of building energy modeling for control”	–	–	Modeling and prediction	Yes	No	Yes	No	No	No	No	No	Yes
[68]	De Coninck et al. (2015)	“Toolbox for development and validation of grey-box building”	–	–	Predictive Control	Yes	No	Yes	No	No	No	No	No	Yes
[69]	De Coninck et al. (2016)	“Practical implementation of model predictive control”	No	Yes	MPC implementation	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
[41]	Carrascal et al. (2016)	“Heating System use in aged buildings via MPC”	Yes	No	MPC implementation	Yes	No	Yes	No	Yes	No	No	No	Yes
[70]	Hu et al. (2016)	“Building Model Identification during Regular Operation”	No	Yes	MPC implementation	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes
[71]	Ascione et al. (2016)	“Simulation-based model predictive control”	Yes	No	MPC implementation	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes
[72]	Sturzenegger et al. (2016)	“Model Predictive Climate Control of a Swiss Office”	No	Yes	MPC implementation	Yes	No	Yes	No	Yes	Yes	Yes	Yes	Yes
[73]	Vaccarini et al. (2016)	“Model predictive energy control of ventilation for underground”	No	Yes	MPC & WSN	No	Yes	Yes	Yes	Yes	No	No	Yes	Yes
[76]	Collotta et al. (2014)	“A Dynamic Fuzzy Controller to Meet Thermal Comfort”	–	–	Dynamic Fuzzy controller	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes
[77]	Marvuglia et al. (2014)	“Coupling a neural network predictor and a fuzzy logic”	No	Yes	Fuzzy logic controller	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes
[78]	Dragomir et al. (2015)	“Adaptive Neuro-Fuzzy Inference Systems as a Strategy”	–	–	Neuro-Fuzzy Systems	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes
[79]	Ghadi et al. (2015)	“Development of advanced fuzzy logic controllers”	No	Yes	Fuzzy logic controllers	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes

3. Discussion: main factors MPC to buildings climatization

Considering as previously mentioned that MPC is currently the most used advanced method to control for building climatization, it is convenient to review the main factors to take into account when applying MPC-based strategies. The geospatial information of the location of a building and the historical data of the climatological conditions together with the occupancy forecast data and the comfort conditions required by the current legislation are the basis for defining its appropriate HVAC system. Besides, a building model through an energy performance simulation software to take advantage of its thermal inertia is highly needed to optimize energy consumption.

3.1. *Meteorological data*

In developed countries, it is easy to access databases available from governmental organizations and National Meteorological Institutes as indicated by Oldewurtel et al. [63] and Široký et al. [64], or even from meteorological stations located at airports or cities, as exposed by Hu et al. [70] and Collotta et al. [76]. It is also possible to use applications that allow calculating the incident solar radiation on flat surfaces arbitrarily oriented in any geographic emplacement. For example, *EnergyPlus* was used by Cigler et al. [65] and Ascione et al. [71] or other web sites as in Fabietti et al. [66]. This information can be complemented with other climatic parameters like air temperature, humidity, luminance, infrared radiation, atmospheric pressure, cloudiness, wind direction and speed, etc., related to the emplacement of the building.

A large proportion of these data are available through Geographic Information Systems (GIS). That allows having a database to gather historical data with different ranges of temperatures and humidities to define patterns from which create varied “recipes” to work on an HVAC system for a specific building.

3.2. *Occupancy and usage information of a building*

The number of people or the density of occupation, the kind of the activities performed in a building, the length of the stay, the type and the power of the lighting equipments and other electrical devices as informatic hardware, or the air infiltrations control, as well as air renewals requirements, are vital in order to make a proper building energy simulation, as indicated in Roberts [29]. Furthermore, it is significant to determine its mode of operation: intermittent or continuous, and also to have a schedule for the use during distinct times of the year.

It is difficult to be completely sure of this information. Nevertheless, some standards can be known based on the comfort level required and the expected occupancy rate, as Oldewurtel et al. [75] point out. It is even more useful if the management also includes the option to set based on current registers collected by field sensors in a BAS, as indicated by Reena et al. [74]. These detectors allow to meet the real-world operating conditions and operate the HVAC system based on real conditions and minimizing its energy consumption.

3.3. *HVAC system layout information*

The running and type of HVAC systems are essential, as well as their capability and their efficiency to reach the requested comfort standard minimizing the power required for it. In addition, if the goal is to reduce the economic impact, the fuel needed or electricity tariffs in the HVAC system should also be regarded as a substantial constraint. Also, considering all the possible HVAC systems, a properly insulated radiant floor, for instance, would be a highly effective system, as explained by Sarbu et al. [42] and Hawila et al. [80]. That allows the climatization of distinct zones of a building to a pre-established set point temperature depending on the occupancy and weather forecast. Besides, it is possible to get the most of the benefits of the thermal mass of the building envelope to reduce energy costs in function of the applicable energy tariff depending on its forecast. For instance, a building could climatize itself at night by taking advantage of a cheaper energy tariff, because its thermal mass could keep a comfort conditions while minimizing energy consumption at higher energy prices in other time slots.

It might also be possible to implement a WSN that allows the real occupation and temperature data to be known online to balance the on-site requirements at distinct periods. For this purpose, the use of high-performance HPs is considered in order to adjust the claimed comfort requirements in a faster way and thus, avoid any perturbation in the indoor environment of the building. These high-efficiency HPs have the ability to correct deviations caused by sudden changes in occupancy and/or comfort demands. Currently, these HPs achieve high efficiency and a great performance, as it is indicated by Tsai et al. [81] and Ruelens et al. [82]. Both high-efficiency HPs and radiant floor using solar water collectors are empowered to cool or heat the ubication where they are placed. Therefore, with them is possible to climatize a building at any time of the year.

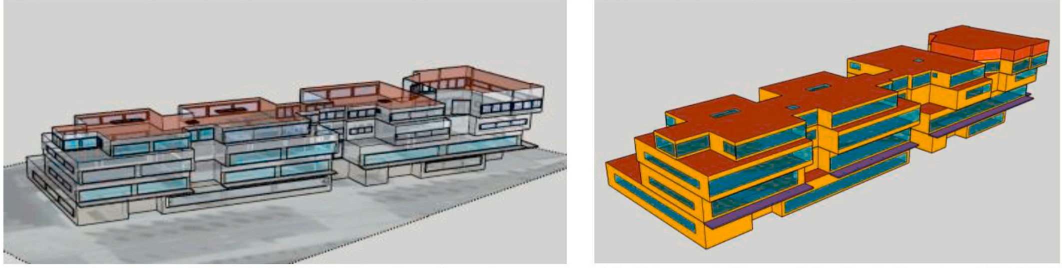
4. Conclusions and future challenges

In this paper, the first concept that we have recalled has been nZEB. Through an analysis of several relevant papers of the literature, different factors that are important to reach this concept have been examined. However, the researches have been carried out normally considering some of these factors independently, e.g., making improvements on envelope features with a new insulating material or windows replacement to improve the air-tightness. Various researches have considered the occupancy behavior and the comfort requirements, while others have conducted an analysis of the HVAC facilities, and sometimes building energy management has been also reviewed. In our opinion, all of them are very worthwhile as they provide an opportunity to further develop energy efficiency in buildings, but it is required to tackle the issue with a broader perspective. In this sense, holistic treatment is desirable, i.e., a multidisciplinary approach that takes into account different areas of action (architectural solutions, development of insulation materials, improvements in the level of engineering, economic viability, etc.) since it facilitates the achievement of the objective of improving the energy efficiency of buildings.

Next, the BEPS tools have been considered very interesting to apply in buildings with the aim of improving their energy efficiency. Consequently, these tools have also been reviewed since using them, the possibility of minimizing energy consumption is huge. For these reasons, many recent papers about BEPS tools have been analyzed and three methods have been explained enabling the modeling of the energy efficiency of a building. Firstly, the “white box” method (or relying on physical models) has been introduced. This method is more appropriate in contexts where building design information is at hand and particularly in the new building design phase, but sometimes it is not possible. A second option is the “black box” method (or model based on machine learning), which uses statistical processing of temperature data and power consumption in the building, so we have highlighted some research about ANN. The “black box” method is useful when one has all the actual building operating conditions and real power consumption, but limited information about its design. However, it can be computationally expensive. Both methods are highly dependent on the quantity and quality of available data. Compared with physical based methods, a “black box” modeling demands less building design data and may seem simpler to perform, but it is not useful if an understanding of physical phenomena is required. The last method, we have considered is the “grey box” model (or hybrid approach), which is founds on both physical methods and automatic learning tools to modeling the building thermal behavior. Therefore, the “grey box” method seems to be a very promising focus at present because it can be considered as a nice balance between both types of models. This approach is very useful when a physical model of the construction is obtainable, but it is unfinished, or it cannot offer enough guarantee, and hence it must be supplemented. It

(a) External photograph of the building under study

(b) 3D drawing by computer of the building



(c) 3D modeling of the building by *Sketchup*

(d) 3D modeling of the building by *TRNSYS*

Fig. 2. Rectorate building of the University of the Basque Country.

is especially suitable in buildings already finished, where it is generally complicated to modeling a "perfect" physical pattern due to the lack of data because part of the information of the materials used is not available or they have just suffered a degradation of their characteristics. After the modeling process through the BEPS tools, a control management must be applied out to minimize energy consumption in the building HVAC systems. It has been considered of interest to first make a reflection on the current state based on the number of existing relevant papers, where the MPC is the most extended option. However, new advances in computer development makes it very likely that in the short or medium term, new trends could arise that would apply to the field of building climatization. Artificial Intelligence will probably have a considerable weight in this development, as shown by the existence of some research that is already applying it successfully.

Focusing on the most extended option up to the moment (MPC), the main factors affecting it when applying in building climatization have been shown. The MPC is considered an excellent control option for optimizing energy consumption, based on occupancy and climate forecasts. This conclusion is supported by several relevant papers, where implementations of MPC have been carried out in distinct kinds and emplacements of buildings. Therefore, using the BEPS tools and applying MPC in the air conditioning of buildings would lead to a change in the current work philosophy. The first step would be to carry out an analysis and modeling of the building by specialized technicians, and then to propose an energy management system that optimizes energy consumption in the HVAC, instead of carrying out laborious works, and in most cases costly, for modifying the envelope of the building under study. The levels of savings can be similar to the proper optimization of the energy consumption of HVAC systems through the management of occupancy forecasts, degree of use, and external environmental conditions. Indeed, that approach is supplementary to the conventional one, which improves with passive measures on the building envelope. It is possible to combine both techniques to achieve higher energy savings and consequently reduce CO_2 emissions.

From our point of view, it is crucial to promote the enhancement of power performance in stock buildings because their current rate of renovation or replacement is very low. In retrofitting buildings, it is advisable to use the new MPC and BEPS tools together with conventional solutions: insulation materials and architectural and engineering improvements, because as it has been shown, this combined use is a smart way to reach energy consumption reduction goals. And for these reasons, our recommendation is to start with public office buildings because they have high power consumption in their climatization and their data prediction (forecasts and operational requirements) are simpler to know.

It is proposed as work to be developed in a next future to apply these concepts to a public office building: the Rectorate building of the University of the Basque Country (North of Spain) after its refurbishment from 2016 to 2019, in order to check on a real case the process of modeling, simulation, processing, and data analysis. In Fig. 2, (a) an external image of the building under study is shown, (b) its corresponding 3D drawing also of its exterior, (c) 3D modeling of the building by *Sketchup* software, and (d) 3D modeling of the building after plugin *Sketchup-TRNSYS17*.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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