

The role of the energy performance modelling with a view to low energy buildings

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Doctoral Dissertation
Doctoral Program in Energy Engineering (30th Cycle)

The role of the energy performance modelling with a view to low energy buildings

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2018

Declaration

I hereby declare that, the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

Domenico Dirutigliano

2018

* This dissertation is presented in partial fulfillment of the requirements for **Ph.D. degree** in the Graduate School of Politecnico di Torino (ScuDo).

*I would like to dedicated this thesis to my beloved family
for their love, encouragement, endless support, and sacrifices.*

Acknowledgment

"I know that a PhD path is something needing a high degree of motivation and enthusiasm..." I wrote in my motivational letter for my admission to PhD course at 2014 . Now, I can say that it is enormously true. I met in these years difficulties, stress and pains. However, I also received pleasures, satisfactions, knowledges and unique experiences. The PhD path has been an opportunity for personal and professional change. It has been hard but exciting.

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Abstract

Climate change requires courageous choices, the European Union has accepted this challenge. One of the 2050 European low-carbon targets is energy savings in the building sector which is responsible for around 40% of energy consumption and 36% of CO₂ emissions in the EU.

The role of Building Performance Simulation (BPS) is central in that it allows to improve the design, optimization, construction, operation and maintenance of new and existing buildings. In order to achieve the correct estimate of energy consumption of buildings, different models have been developed in the last decades. They can be grouped into three categories: black box models, gray box models and white box models. They are differentiated by the degree of detail with which they describe the physical phenomena that govern the calculation of energy performance instead of using statistical algorithms for the estimation of the same or some characteristics of the building. However, the most detailed models are still only a representation of reality and therefore with margins of error due to assumptions and approximations of calculation. These aspects could be critical in the estimation of energy performance of nearly Zero Energy Buildings (nZEBs) where low performance values could become comparable with errors in estimating energy performances themselves. nZEBs are currently not diffuse in the EU building stock, however are those on which Europe is pointing as a key to building renewal.

This thesis aims to investigate the role of energy performance modelling of buildings with low energy consumption. For this reason, research fields of BPS are identified in which the energy performance modelling has been used. They are: climatic data versus energy performance, energy performance rating and ranking of buildings, definition of minimum building requirements and exploring of technologies and valuation methods of energy efficiency measures. For having a wider vision on which model can be used, with what simplifications and what expectations, a research was carried out for each application field. Numerical models are applied both to single buildings and to building stocks, but first ones

are the main focus of the investigation. Concerning the first application field, in order to estimate the energy performance (EP) of buildings which have a very low amount of energy covered to a very significant extent by energy from renewable sources accurate and reliable climatic data are necessary.

The analysis of EP estimated with different calculation methods shows that the sources of climate data currently available lead to results which can be very different from each other. An improved Typical Meteorological Year construction procedure is proposed to higher the reliability and representativeness of climatic data.

Two data mining methods for selecting energy efficiency measures on an urban scale are tested and validated by saved energy of dynamic models.

With reference to application field of definition of minimum building requirements the thesis analyses the process to define them. Moreover, it studies how the energy performance modelling influence the definition of minimum building requirements (about the fabric or the HVAC system) and as a fixed requirement could have an imbalance effect between different services. An improved procedure is shown to define the notional reference building and an analysis is led on a heating generator to show how the modelling of technology can affect minimum requirements.

Finally concerning EP in valuation methods, case studies with Cost-Optimal Analysis (COA) and Multi-Criteria Analysis (MCA) are performed. The first one gives the possibility to compare results obtained with two calculation methods, the second one permits to investigate the role of energy performance in MCA.

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Nomenclature

Acronyms

AB	Apartment Block
BES	Building Energy Simulation
BIM	Building Information Modelling
BIO	Biomass
BPS	Building Performance Simulation
BS	Biomass boiler plus split system
CART	Classification and Regression Tree
CFD	Computational Fluid Dynamics
DE	Description
DHW	Domestic Hot Water
DMs	Decision-Makers
EU	European Union
e , EXT	outdoor (facing)
EC	Energy Consumption

ED	Energy Demand
EEMs	Energy Efficiency Measures
EP	Energy Performance
EPBD	Energy Performance of Buildings Directive
GIS	Geographic Information System
HDD	Heating Degree Days
HP	Heat Pump
HVAC	Heating, Ventilation, Air Conditioning
i, INT	Internal
LOM	Low Order Model
MCA	Multi-Criteria Analysis
MD	Ministerial Decree
MI	Milan
MV	Mechanical Ventilation
NV	Natural Ventilation
n	total number
nZEB	nearly Zero-Energy Building
OB	office building
p	preference threshold
PA	Palermo
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation

PV	Photovoltaic
q	indifference threshold
SA	Sensitivity Analysis
SFH	Single-Family House
TEASER	Tool for Energy Analysis and Simulation for Efficient Retrofit
TMY	Typical Meteorological Year
TRY	Test Reference Year
TST	Total Solar Transmittance
TT	Thermal Transmittance
UNC	Unconditioned space (facing)
UTC	Coordinated Universal Time
w	weight
WWR	Window-to-Wall Ratio

Symbols

A	area [m^2]
Alt	altitude [m]
b	adjustment factor for heat transfer coefficient [-]
C	cost [€]
COP	coefficient of performance [-]
EER	energy efficiency ratio [-]
EP_{yearly}	Energy Performance [kWh m^{-2}]

EP^M	monthly Energy Performance [kWh m^{-2}]
F, f	factor [-]
g	total solar energy transmittance [-]
H	heat transfer coefficient [W K^{-1}]
H_T	overall heat transfer coefficient [W K^{-1}]
H'	mean overall heat transfer coefficient [$\text{W m}^{-2}\text{K}^{-1}$]
HDD	heating degree-days [$^{\circ}\text{Cd}$]
I	global solar irradiance on a horizontal surface [W m^{-2}]
M_s, m_s	areal mass [$\text{kg}\cdot\text{m}^{-2}$]
P	peak load per unit floor area [$\text{W}\cdot\text{m}^{-2}$]
Q	thermal energy [Wh]
RH	air relative humidity [-]
T	(dry-bulb) air temperature [$^{\circ}\text{C}$]
U	Thermal transmittance [$\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$]
U_{avg}	average U -value [$\text{W}\cdot\text{m}^{-2}\text{K}^{-1}$]
V	volume [m^3]
W	power [W]
W_p	peak power [kW]
Y_{ie}	periodic thermal transmittance [$\text{W m}^{-2}\text{K}^{-1}$]
WVP	water vapour pressure [Pa]
WS	wind speed [m s^{-1}]

Greek symbols

η	efficiency [-]
θ	temperature [°C]
κ	areal heat capacity [kJ m ⁻² K ⁻¹]
ρ	reflection coefficient [-]
τ	transmission coefficient [-]
Φ	heat flow [W]
ϕ	Phi net flow [-]

Subscripts

a	air, annual
A	adjacent
adj	adjusted
bio	biomass
C	space cooling
c	control (subsystem)
coll	collectors
D	direct (external)
d	distribution (subsystem)
del	delivered (energy)
<i>DHU</i>	dehumidification
E	energy
e	emission (subsystem)
el	electricity

env	building envelope
F	frame
F	cumulative distribution function for a specific year
f , fl	floor
F_S	Finkelstein-Schafer statistic
g	ground, gross
gl	glazing, global
gn	generation (subsystem)
gr	ground
H	space heating
HU	humidification
ht	heat transfer
I	investment
i	internal
ι	index
J, K, L	rank order
ls	heat losses
lw	lower
m	month
N_m	number of months when the considered energy service is provided
N	number of days in a calendar month for long-term data
n	net , normal

n	number of days in an individual month
nd	need (energy)
net , n	net
nren	non-renewable
ob	obstacles
op	opaque (component)
P	primary (energy)
Pn	nominal power
p	projected
p	parameter
R	ranking
r	roof
rc	heat recovery
ren	renewable
S	energy service
s	solar
sh	shading
sol	solar
sum	summer
sup	supply (air)
σ	standard deviation
sh	shading

T, tr	thermal transmission
tot	total
U , un	unconditioned (space)
u	utilisation (subsystem)
up	upper
V , ve	ventilation
W	domestic hot water
w	window
wl	wall (external)
y	year
Φ	cumulative distribution function regarding long-term data

Chapter 1

Introduction

1.1 The climate challenge

The climate change is certain, as evidenced by its impact on natural systems. Hydrological systems are altered by the changing precipitation and melting snow and ice, affecting water resources in terms of quantity and quality. There are a rise of the global air and ocean temperatures, acidification of the oceans, and average growing sea level too [1].

For achieving the task of limiting global temperature rise to 2°C, European Commission proposed a target to mitigate the climate change and to review its energy consumption. It is one of European Union (EU) challenges which will steer the process of social and economic improvement. The other challenges are for the employment, for research and innovation, for education and for combating poverty. In particular European Commission fixes to reduce greenhouse gas emissions by at least 20% compared to 1990 levels, if the conditions are right, increase the share of renewable energy sources in our final energy consumption to 20% and a 20% increase in energy efficiency [2].

European Commission considers buildings responsible for, approximately, 40% of energy consumption and 36% of CO₂ emissions in EU, given that about 35% of EU's buildings are over 50 years old. The EU could reduce own total energy consumption by 5-6% and lower CO₂ emissions by improving the energy efficiency of buildings [3]. EU promulgates the Directive 2010/31/EU on energy performance of buildings (EPBD recast) [4] to promote the improvement of the energy performance of existing buildings and new buildings.

1.2 Building Performance Simulation

As shown in the section before, the improvement of the building energy performance is pursued and supported by the EU. It passes through the Building Performance Simulation (BPS). The latter is developed in the last decades in order to improve the design, optimization, construction, operation and maintenance of new and existing buildings, as shown in [5] and [6]. Many topics have been addressed by BPS, main these are the Computational Fluid Dynamics (CFD), Building Energy Simulation (BES) and Building Information Modelling (BIM). The CFD has applied to check and to improve the thermal comfort inside the buildings, as showed Farouk [7] in a hotel. BES evaluates the building energy performance and can be coupled with CFD as showed from Tian et al.[8]. BES can be applied on building and urban scale. In recent years, CFD is also developed to study the urban microclimate which can affect building energy performance, human morbidity and thermal comfort [9]. Over recent years the BIM has been developing to designers and stakeholders of constructions sector to face the interdisciplinary that a project needs nowadays. In this perspective, it is understandable efforts of the research to standardise information exchange between BIM and BES, as showed in [10].

Concerning the BES, the building has been considering in whole, including fabric and technical building systems. According to the EN ISO 52016-1 standard on energy performance of buildings [11], technical building systems taken into consideration are these which change the condition of indoor environment (by heating and cooling), provide domestic hot water, illumination and other services related to the use of building (elevators).

The whole building is also studied in relation of the environment where is located because climate and urban conditions can change the building energy behaviour. Citherlet et al. [12] showed as the integrated building performance analysis is important at the design stage in order to prevent the delivery of buildings with unsatisfactory characteristics and to compare the impact of different solutions on the whole building. BPS offer the possibility to explore such complexity and costs associated to this design phase are low and for this reason its wide used.

In some countries the legislation mandates BPS approach to improve the building energy performance, as for instance in United States with ASHRAE Standard 209-2018 [13] and in Europe with the EPBD recast [4].

1.3 Performance calculation models

In science, computing, and engineering applications, numerous modelling approaches are applied to describe systems. They can be regrouped in three categories of models:

- white box model,
- black box model,
- grey box model.

These models are also suitable to describe the whole building with the aim to estimate the overall energy consumption of the building for different energy services. In the followings sections, previous three categories of models applied to building environment are described.

White box model is a physical model. Characteristics of building components and the thermal behaviour of the building are described through physical knowledge of systems and thermal balance equations. The white box model permits to predict operational energy use with both known indoor and outdoor environmental conditions. Most of common energy simulation software as TRNSYS, EnergyPlus, IDA ICE, etc. use this model [14].

Detailed white models are time consuming, because a large number of parameters are required, as inputs, for this reason the calibration process of detailed simulation models is a great challenge as showed Roberti et al. [15]. Moreover, as Hensen [16] shown, there is a wide-spread misconception that increasing the model complexity will decrease the uncertainty of the results. In reality, the author highlighted that the deviation from the optimum to either higher complexity increases the potential error in the simulation results.

Black box model is also called data driven model. It requires a large amount of training data as input and output. They can be generated by co-simulation. It is a integration of software by runtime coupling, for instance EnergyPlus and Matlab [17]. This process is due because data driven model needs to acquire data over a long period of time. Thank to this process, models are trained for accurate predictions under numerous conditions. As Killian et al. [18] explain, these measurements should include typical behaviour of building heating dynamics, and also contain stronger excitation of heat supply than during normal process. For a good and realistic black box model these measurements have to describe the main nonlinear ties, that is the building dynamics.

The grey box model is a mix of previous categories. Short term operation data monitoring are used by grey models to predict long-term energy performance.

Grey models can represent physical properties of building system and predict energy consumption. Available building information can be utilized to enhance simplified models, this is to reduce the number of parameters to be identified with operation data [19]. The equivalent RC network is often used in grey model. For instance Wang et Xu [20] presents a method to simplify building models and identify their parameters using easily available building physical properties and short-term operation data monitored.

1.4 Calculation algorithms

This dissertation has as object the built environment, included both the fabric and technical building systems. Building thermal behaviour is studied considering heat and humidity exchanges, interactions between the building and occupants, and coupling with renewable systems. In literature, two methods of calculating the energy performance of buildings have been developed to solve the white box models: through transfer functions or finite volume method.

Models based on transfer functions relate the stresses which act on a system with the response of latter.

Transfer functions are used for the calculation of the thermal flow: by conduction within envelope walls, by convention supplied to the ambient air and supplied by the air conditioning system.

The main limitations of this method are: the constant properties, the fixed values of some parameters and no information is provided on thermal situation inside surfaces.

Nowadays, main dynamic simulation software (ex. TRNSYS and EnergyPlus) combine the transfer functions for calculation of thermal flow transmitted by conduction with air heat balance to evaluate thermal flow which must be supplied to environment to maintain the set-point temperature [21].

In recent years the energy analysis field moves to simulate advanced components with new materials, such as phase change materials. For this reason software as EnergyPlus improves it with conduction finite difference solution algorithm to improve this algorithm [22].

In the finite volume method the analysed environment is divided into control volumes. For each one are applied balance equations. The control volume is limited by border area of system. The tools for modelling thermo-physical

behaviour of confined environments are essentially referable to following balances:

- mass balance of air,
- mass balance of water vapour,
- energy balance.

This method is used by some energy simulation software to study the thermal stratification inside the walls (ex ESP-r) [21].

Crawley et al. [14] provided up-to-date comparison of twenty major building energy simulation programs. The comparison was based on information provided by the program developers in the following categories: general modelling features; zone loads; building envelope and daylighting and solar; infiltration, ventilation and multi-zone airflow; renewable energy systems; electrical systems and equipment; HVAC systems; HVAC equipment; environmental emissions; economic evaluation; climate data availability, results reporting; validation; and user interface, links to other programs, and availability.

1.5 Dynamic thermal simulation modelling

Simulations can differ on base on calculation method, hourly or monthly. In the first case the incremental time step is hourly, in second case is monthly. However in dynamic thermal simulations, solutions of balances can be sub-hourly. Difference of results with different simulation time step is shown by Mazzarella and Pasini [23]. In literature, the common time step is fifteen minutes for dynamic energy simulation program [14], [24]. However, time steps more short can be useful to appreciate the effect of control systems.

The main following assumptions and simplifications are reported by the literature [21][25][26][27] to realize detailed simulation with physical model.

The monthly calculation of energy need for heating and cooling is based on same assumptions and boundary conditions as the hourly calculation of energy need for heating and cooling as show EN ISO 52016-1 [11]. The standard also suggest to use the same inputs as far as possible.

Physical models perform in this thesis, consider surfaces of building elements, as inside, outside frame and divider surfaces, are isothermal. Each surface emits or reflects diffusely and is gray and opaque. The energy flux leaving a surface is evenly distributed across the surface. These assumptionsai are considered to calculate building loads according to Chapman [28] and Lienhard [29]. Convective and radiant heat exchanges with a high wavelength on internal

surfaces are considered separately, according to EN ISO 52017-1:2017 [25] for thermal modelling. Moreover the rate of air exchange for infiltration and ventilation takes into account the variation in time of chimney effect and the effect of wind.

For calculating thermal flux by conduction, considered assumptions [21][25] are the following. Thermos-physical properties of materials that make up closing elements are time-independent and isotropic. This means that, for instance, it is not considered a decreased of the thermos-physical performance of the envelope due by the time factor. The heat conduction through the building elements, with exception of the ground, is assumed to be one-dimensional and the heat conduction to the ground through building elements is treated by an equivalent one-dimensional heat flow rate according to EN ISO 13370. The heat storage contribution of thermal bridges can be neglected, whereas thermal bridge effects on energy performance can be significant, as showed [30]. Heat flows due to thermal bridges are represented through linear thermal flows, UNI EN ISO 14683, or through equivalent mono-dimensional building elements, whose thermal and mass characteristics are derived from calculations in stationary conditions, UNI EN ISO 10211. Linear or point thermal bridges are directly thermally coupled to the internal and outdoor air temperatures. Air cavities inside the casing elements are considered air layers limited by two isothermal surfaces, UNI EN ISO 6946. Air spaces are treated as air layers bounded by two isothermal and parallel surfaces. Finally heat storage effects in various planes of a glazed element are neglected.

For calculating thermal flux by convection, assumptions [21][25] are needed. The air temperature is considered uniform throughout the building zone. Convective heat exchange coefficients on internal surface are fixed, whereas coefficients of convective heat exchange on external surface depend on speed and direction of the wind, those on internal surface depend on the direction of the thermal flux.

Heat exchanges due to high wavelength irradiation are calculated with the radiant temperature of external environment, excluding the celestial vault, equal to the temperature of external air. The radiation heat flux is related to the surface absorptivity and temperatures. It is also calculated from sky and ground temperatures and view factors. Moreover, the radiative heat exchange coefficients on the external surface are independent of time [21][25]. For calculating heat exchanges due to low wavelength irradiation other the assumption are considered. The spatial distribution of solar radiation within the environment is fixed and independent of time and the angular dependence of solar transmission properties

of glazing is taken into account on the basis of data of manufacturers [21][25]. External mobile screens are taken into consideration and they can be activate when there is an threshold value of irradiation. The density of heat flow rate due to the short-wave radiation absorbed by each plane of a glazed element is treated as a source term.

Concerning internal gains, sensitive internal thermal inputs include a portion of energy exchanged by convection with air and a portion of energy emitted in the form of electromagnetic radiation this aspect. The spatial distribution of radiant heat flux due to the internal sources is uniform on the internal surfaces of building elements [21][25].

Regarding thermal comfort assumptions [21][25], the average internal radiant temperature is calculated as weighted average on the areas of internal surface temperatures of each component. Moreover, the internal operating temperature is the arithmetic mean of indoor air temperature and the average radiant temperature.

Chapter 2

Research fields, main questions and outline

What is the role of the energy performance modelling with a view to low energy buildings?

This is the main question of this thesis. It is well known that the energy performance derive from a simulated model. Clarke and Hensen [6] said that ultimate aim of BPS is to support innovation by providing a high integrity representation of the dynamic, connected and non-linear physical processes that govern the disparate performance aspects that dictate the overall acceptability of buildings and their related energy supply systems. For these characteristics, as said Reinhart [31], BPS is suitable to be used in many technology roadmaps for sustainable buildings and cities. Therefore, application scales can be two, the building and urban levels. This thesis studies both scales to have a full overview.

Considering the literature, the main BES research fields are:

- climatic data versus energy performance,
- energy performance rating and ranking of buildings,
- definition of minimum building requirements and related technologies,
- energy performance in valuation methods.

This thesis investigates the role of the energy performance modelling with a view to low energy buildings through these topics. Descriptions of these research fields are provided in following paragraphs.

2.1 Climatic data versus energy performance

Energy performance of buildings are influenced in various ways by climate data. The dry bulb air temperature and solar radiation have effects on the heating and cooling loads. This is due to different aspects. Temperatures gradient on the opaque envelope induces heat transmissions and, where there is not the envelope, ventilation enthalpy flow of the sensible part. The energy balance of building is influenced by solar heat gains, which are derived both from transparent and opaque envelopes, and air infiltration. The latter is induced by pressure difference caused by stack (chimney) or induced temperature gradient. Wind and difference of temperatures influence convective surface heat transfer coefficients. Moreover, sky temperature and atmospheric radiation influence radiative surface heat transfer coefficients. Moisture gradient generates ventilation enthalpy flow (latent part) due to heat exchange between outdoor and indoor zones.

Cartalis et al. [32] showed as the energy demand of buildings can be modified as a result of climate changes. They highlighted as the heating demand will decrease for the simulation year 2030 for the climate changes.

Moreover, the climatic condition can influence the energy performance of technical building systems. For instance, Fong and Lee [33] underlined how a tri-generation plant based on the design point is not sufficient to have high energy performance.

Concerning on urban scale, climatic data continue to influence the energy performance of buildings and in recent years, it is observed a following phenomenon. Climatic data recorded inside and outside the city (for instance in airport) are highly different. This phenomena is called Urban Heat Island (UHI) and, as showed Zinzi et al. [34], can lead a reduction of heating consumption up to 21% and an increase of cooling consumption up to 74% for a residential building.

2.2 Energy performance ranking and rating

Building sector is steered towards energy efficiency standards and increased use of renewable energy sources, according to EPBD recast [4]. The Energy Performance Certificate (EPC) plays a key role in this process, as it informs potential tenant and buyers about the energy performance of a building or

of an entire building, and allows for comparison of buildings and building units in terms of energy efficiency. As explained in the Implementing the EPBD [35], underlying idea is that the EPC should influence the demand for buildings with excellent energy efficiency performance and a high proportion of energy from renewable sources, increase their market value, and thus influence building owners to renovate their buildings.

Moreover, energy audit is became the first step to identify opportunities to reduce energy consumption of buildings and to achieve the nZEB target, as Corrado et al. [36] shown. In Europe, energy audit standard are defined through EN 16247-1:5 [37].

2.3 Minimum building performance requirements and related technologies

According to EPBD [4], Member States (MSs) had to set energy performance requirements for new and existing buildings in different ways. Some national codes set requirements only for those individual building components that are being renovated or replaced, while other MSs set requirements for the whole building. Setting requirements for new buildings also differs among MSs, not only in terms of energy performance levels, but also in terms of other properties in building envelope. As explained in Implementing the EPBD [35], MSs set different requirements not only in terms of energy performance levels, but also in terms of other properties in the building envelope. There are also differences among properties of building envelope. For example, the infiltration is handled by compulsory tests or quality certification programmes. A frequently requirement of MSs is to set limits on U-values. There are also very different ways of checking compliance. For example, Sweden set requirements that are verified through comparison with the measured energy consumption two years after taking the building into use.

BPS is used to simulate the energy behaviour of new building materials or components. This allows to improve the energy performance of technology changes its characteristics (dimensions, materials, control strategy, etcetera).

For estimating the correct energy consumption it is necessary to model the new material or component. This phase is a simplifications of reality. Robinson [38] explained that the issue in conceptual modelling is to abstract an appropriate simplification of reality. The overarching requirement is the need to avoid the development of an overly complex model [16]. So, in general the target should be: to realize the model as simple as possible to achieve the objectives of simulation

study. The issue is to know what is the margin of error of model and if it is acceptable.

2.4 Energy performance in evaluation methods

For achieving the target of limiting global temperature rise, the priority should be given to refurbishing existing buildings, particularly in the United States, Russia and the European Union where about 60% of current building stocks will still be in use in 2050 [39], [40], [41].

Therefore, the definition of proper retrofitting strategies toward nZEB is a requirement, especially in Italy with its building stock contest. Delponte et al. [42] remarked the importance of building retrofit. However, the selection of retrofit solution may result difficult among numerous energy efficiency measures for a decision maker. In that case, Multi-Criteria Analysis (MCA) is a proper method that can help to generate better decisions when there is more than one criterion [43]. MCA methods are able to translate complicate problems in simpler ones in order to provide a complete image to the Decision-Makers (DMs)[44]. EPBD recast introduced the cost-optimal calculations for setting minimum requirements and the path towards nZEBs by 2020. The EPBD [4] define cost optimal level is the energy performance level which leads to the lowest cost during the estimated economic lifecycle” from two different perspectives: financial and macro-economic. In this last case, analysed criteria are only two.

2.5 Thesis outline

For addressing the main research question, the PhD candidate identified research fields of the EP and for each one carried out a research. Studies were conducted with a point of view both on building and urban scales. Several calculation methods were used. In the Figure 1 is shown a graphical representation of matches among questions, research fields and used calculation methods.

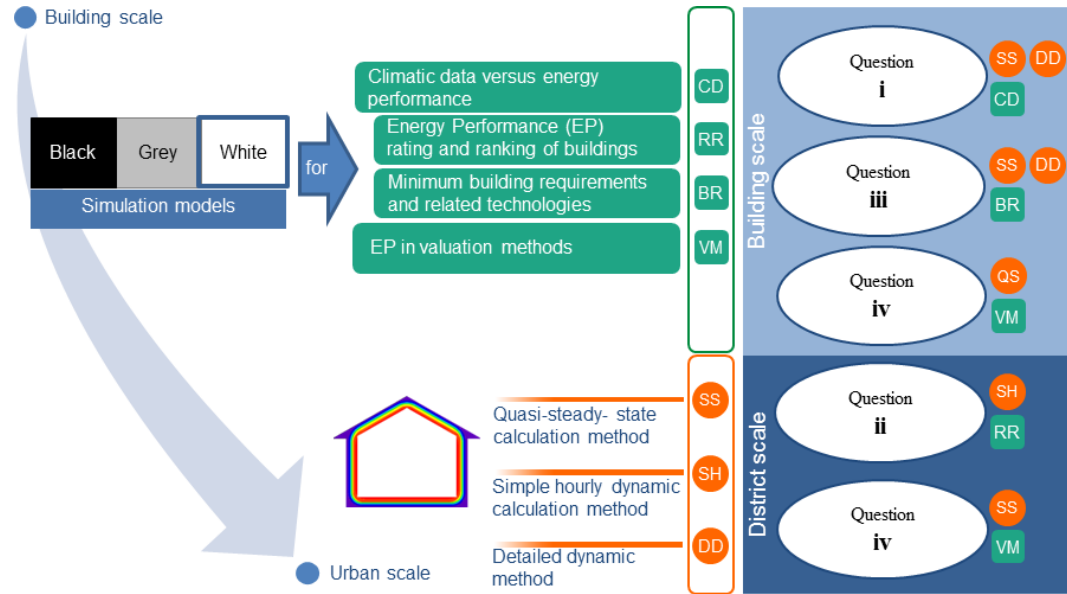


Figure 1: Schematic summary of PhD thesis

PhD candidate's researches gravitate around main question. Most of the PhD researches were published during the PhD course. They showed the same research path. For this reason is provided a summary of related publications with the PhD dissertation and their coupling with research questions.

Table 1: List of research papers relevant to the thesis

Research question	Paper	Authors and title
i	Paper I	G. Murano, V. Corrado, D. Dirutigliano, <i>The new Italian climatic data and their effect in the calculation of the energy performance of buildings</i> , 71 st Conference of the Italian Thermal Machines Engineering Association, ATI 2016, 14-16 September 2016, Turin, Italy, Energy Procedia, vol. 101 n. 71 st C, pp. 153-160, doi:10.1016/j.egypro.2016.11.020 [45].
	Paper II	G. Murano, D. Dirutigliano, Vincenzo Corrado, <i>Improved procedure for the construction of a typical meteorological year for assessing the energy need of a residential building</i> , Journal of Building Performance Simulation, Special Issue,

		doi: 10.1080/19401493.2018.1479774 [46].
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ii	Paper	D. Dirutigliano, M.A. Brüntjen, C. Fliegner, J. Frisch, V. Corrado, C. van Treeck, <i>Case study for energy efficiency measures of buildings on an urban scale</i> , 3 rd BSA (Building Simulation Applications) Conference, 8 th -10 th February 2017, Bolzano, Italy, Conference Proceedings, ISBN 978-88-6046-136-0, pp. 403-410 [47].
	III	
<hr/>		
	Paper	V. Corrado, I. Ballarini, D. Dirutigliano, G. Murano, <i>Verification of the new Ministerial Decree about minimum requirements for the energy performance of buildings</i> , 71 st Conference of the Italian Thermal Machines Engineering Association, ATI 2016, 14 th -16 th September 2016, Turin, Italy, Energy Procedia, vol. 101 n. 71 st C, pp. 200-207, doi: 10.1016/j.egypro.2016.11.026 [48].
	IV	
<hr/>		
iii	Paper	D. Dirutigliano, I. Ballarini, G. Murano, V. Corrado, <i>Reference building approach combined with dynamic simulation in designing nZEBs</i> , 15 th International Conference of IBPSA (International Building Performance Simulation Association), BS (Building Simulation) 2017, 7 th -9 th August 2017, San Francisco, California, USA, ISBN 978-1-7750520-0-5, ISSN 2522-2708 [49].
	V	
<hr/>		
	Paper	G. Murano, I. Ballarini, D. Dirutigliano, E. Primo, V. Corrado, <i>The significant imbalance of nZEB energy need for heating and cooling in Italian climatic zones</i> , 72 st Conference of the Italian Thermal Machines Engineering Association, ATI 2017, 6 th -8 th September 2016, Lecce, Italy, Energy Procedia, vol. 126, 2017, pp. 258-265, doi: 10.1016/j.egypro.2017.08.150 [50].
	VI	
<hr/>		
iv	Paper	V. Corrado, I. Ballarini, D. Dirutigliano, S. Paduos, <i>Cost-optimal analysis of Italian office buildings through the application of a quasi-steady-state model validated by detailed dynamic simulation</i> , 14 th International Conference of IBPSA - Building Simulation 2015, 7 th -9 th December 2015, Hyderabad, India, Conference Proceedings, ISBN 978-93-5230-118-8, pp. 2043-2050 [51].
	VII	
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Paper VIII	I. Ballarini, A. Costantino, D. Dirutigliano, E. Fabrizio, S. Paduos, V. Corrado, <i>On the cost-optimal design: comparison of quasi-steady-state and dynamic simplified methods of calculation of H/C energy needs</i> , 8 th -10 th February 2017, Bolzano, Italy, Conference Proceedings, ISBN 978-88-6046-136-0, pp. 129-136 [52].
Paper IX	D. Dirutigliano, C. Delmastro, S. Torabi Moghadam, <i>Energy efficient urban districts: A multi-criteria application for selecting retrofit actions</i> , 11 th AGE 2017 Conference, 12 th -13 th June 2017, Genoa, post - reviewed and published in the International Journal of Heat And Technology, vol. 35 n. Special Issue, pp. 49-57, ISSN 0392-8764 [53].
Paper X	D. Dirutigliano, C. Delmastro, S. Torabi Moghadam, <i>A multi-criteria application to select energy retrofit measures at the building and district scale</i> , 2018, Thermal Science and Engineering Progress, Volume 6, Pages 457-464, ISSN: 2451-9049, doi: 10.1016/j.tsep.2018.04.007 [54].

In Chapter 3 the first research field of BES was addressed. The research question was:

- i. What is influence of climatic data on energy performance? Are they reliable?

The research was lead on building scale, but obviously climatic data influence the energy performance on urban scale too. Concerning the UHI (see section 2.1), the research did not explore this phenomenon because the climatic data were representative of the climatic condition of the city.

The degree of description of the building can change in function of the observation scale. Therefore, different calculation methods can be used which need different input data. For this reason, the study of climatic data influence on energy performance was lead with two calculation methods, monthly and hourly. The research started from the climatic data available in Italy for the quasi-steady-state method and it was extended to analyse climatic data available for a dynamic calculation method. In a second phase, an implementation of the methodology of Typical Meteorological Year (TMY) generation was proposed. This

implementation improved the reliability of climate data. The research considered as case studies three types of buildings with different thermal mass, two energy systems (cooling and heating) and both in terms of net energy and of primary one dividing renewable and non-renewable share.

Successively the study of the climatic data, the PhD candidate focused the research on modelling approaches to describe the building. Input data for BES and calculation models for the determination of Energy Efficiency Measures (EEMs) were studied. The analysis showed, as said before, that the degree of description of building can change in function of analysis scale and the purpose. Detailed dynamic model can describe the EP of single building with high accuracy. However, for this model an high availability of data are needed. Therefore, a question arose when numerous buildings were considered.

- ii. Which can models and data be used for EEMs of buildings on urban scale?

In Chapter 4 this question was addressed. The PhD candidate collaborated on a project with RWTH Aachen University where he had the possibility to address problems of description and modelling of an high number of buildings. The candidate conducted a search to identify EEMs and buildings object of renovation. The modelling of a building with detailed dynamic model was time consuming, as well as the detect phase of thermal features of building. For this reason, a with simple hourly dynamic model was preferred to the detailed dynamic model on urban scale. Building data were gathered through statistics approach and data mining techniques were suggested to select buildings and EEMs. In this chapter, results by two data mining techniques were compared and results were commented.

The research field of definition of minimum building requirements and related technologies was addressed in Chapter 5. The research question was the following.

- iii. How can the chosen EP model affect the specification of minimum building requirements?

The building energy performance requirements can be define in different ways in regulations. The research starts with an analyses of the Italian regulation which has been introduced the notional reference building approach on 2015. Requirements can be affect the envelope or technical building systems on building scale. The analysis on urban scale is not related to district of city, but to sets of buildings. These sets are selected buildings from the building stock by geographic

location, for example climatic zones, or building features, as the building topology explained in the project EPISCOPE [55]. The research was lead on residential building, located in two climatic zones and with two heating and cooling systems.

The second part of the research aimed at enhancing the application of the notional reference building approach. Moreover, it provided guidelines so as minimum energy performance requirements of high energy efficiency buildings were effectively verified. Finally, a research was focused to investigate in which conditions a significant imbalance of energy needs for heating and cooling occur when a requirement on the envelope was fixed.

In Chapter 6 the last research filed was addressed. The question was as follows.

- iv. How can the chosen EP model affect to valuation methods?

The research was lead on two valuation methods, cost-optimal design and multi criteria analysis. The first method was applied at case studies with quasi-steady-state and dynamic calculation methods at the building scale (in Paper VII and Paper VIII). Moreover, a Multi-Criteria Analysis was performed to observe the role of energy performance when was used as criterion in this kind of analysis. The study was performed on both urban and building scale in Paper IX and X.

Research fields, secondary questions and respective chapters are summary in

Table 2.

Table 2: Correlation among application fields, research questions and chapters.

Application field	Research question	Chapter
Climatic data versus energy performance	i	Chapter 3
Energy performance rating and ranking of buildings	ii	Chapter 4
Definition of minimum building requirements and related technologies	iii	Chapter 5

Energy performance in valuation methods

iv

Chapter 6

Chapter 3

Climatic data versus EP

3.1 Research question

What is influence of climatic data on energy performance? Are they reliable?

These questions arose while the PhD candidate investigated how the energy performance is used to rank and to rank of buildings.

The question has been addressed as shows the fellow Figure 2.

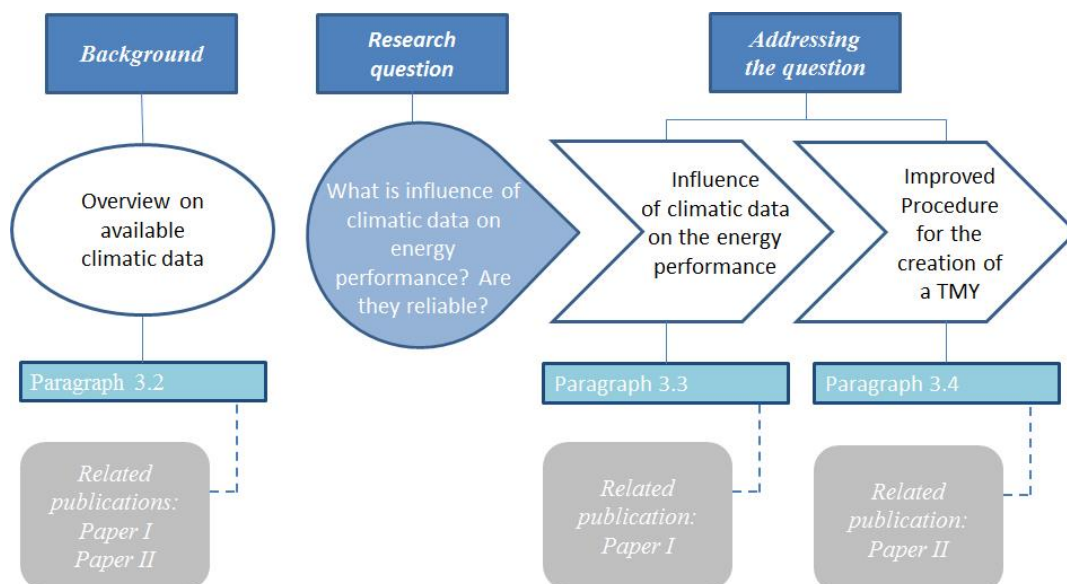


Figure 2: Scheme chapter 3

In the first part the climatic data are studied as an input in energy building simulation. They affect both the heat transfer, through the building envelope, that size and efficiency of HVAC systems and renewable solar systems. In the second part the research is focused on the climatic data reliability which is often unknown.

The following sections are a re-arranged of related papers. An extension of this work is provided in the Section 3.4.8.

3.2 Overview on available climatic data

3.2.1 Origin of climatic data

Given the spatial variability of the climate, the energy performance requirements of nZEBs provided by the national legislation [56] are different for climatic zones. The energy performance for new buildings, or buildings to be renovated, is based on the reference U-values and other parameters as prescribed by the law. In Italy, since 1994, the buildings have been designed using the national standard UNI 10349 [57] that reports monthly means of single meteorological elements (temperature of air, water vapour pressure, reference wind speed, global solar irradiation, direct solar irradiation, diffuse solar irradiation).

The Standard provides conventional climatic data needed for design and verification of both buildings and heating and cooling thermal systems. The data utilized to compile it date back to the period 1951–1970, they are determined by stations for the acquisition of climate data equipped with low accuracy sensors or even lacking at all as far as solar radiation is concerned [58]; consequently, it was necessary to update this database by means of models. Furthermore, the data acquired during this period do not respect the rules and the advice on good practices for meteorological measurements and observations elaborated by the Meteorological Instruments and Methods of Observation WMO [59] as required by the new standards developed by ISO and CEN [60].

In 2016, a new version of the standard UNI 10349 divided into three parts has been published. The standard UNI 10349-1:2016 [61] contains monthly average data calculated from test reference years developed by CTI for 110 Italian locations. Therefore, at national level, there are two different official archives that are mutually consistent for determination of building energy performance in the context of the EPBD. The first is the standard UNI 10349-1:2016 [61] that reports climate monthly average data as used in the steady state

method given in EN ISO 13790 [62], the second is the archive of the test reference years with hourly values used in dynamic simulation procedures.

3.2.2 Typical Meteorological Year and Test Reference Year

Building energy simulation programs use climatic data in the form of data sets of hourly values, which are determined from selected weather data generated from a data bank much longer than a year in duration and consistent with the typical long-term distribution data. In scientific literature, the most commonly used archives are the TMY (Typical Meteorological Year) and the TRY (Test Reference Year). These two archives are similar but the TMY represents an evolution of the TRY methodology. In the first versions of TRY datasets, for example, there was no information on solar radiation estimated starting from cloud cover. The methodologies available in literature differ according to the weather variables used in the analysis, the type of statistics employed and the use of weighting coefficients of variables diversified for climatic parameters. In both cases, the main requirements are true frequencies, true sequences and true correlations between different climatic variables.

The TMY can be used to estimate the operating costs for heating and cooling for the design of new buildings or for the renovations of existing buildings and, as indicated by Directive 2010/31/EU, for the determination of cost-optimal balance between the investments involved and the energy costs saved throughout the lifecycle of the building. Reliable and realistic climate data are needed to make the estimates of energy performance of buildings in the medium and long-term as reliable as possible.

The TMY can also be used for different applications, including energy and environmental analyses and to estimate the productivity of installations powered by renewable sources (for instance solar thermal, photovoltaic panels, heat pumps, etc.).

Argiriou et al. [63] summarized the different methodologies used for the generation of TMYs available in the literature. Various methods for deriving TMY provide results that can be significantly different. In the study, the authors developed the Sandia National Laboratories method [64], the Danish method, and the Festa and Ratto method. Zang et al. [65] proposed a modified method to generate TRY based on the Sandia National Laboratories method and on a simplified method introduced by Pissimanis et al. [66] based on the root mean square difference (RMSD). The Sandia National Laboratories methodology [67] involves the application of Finkelstein-Schafer statistic (F_S) [68] of ten climate

parameters (max, min, mean dry-bulb air temperature; max, min, mean dew point temperature; max e min wind velocity; global and direct irradiance). For each climatic parameter considered, the Finkelstein-Schafer statistic is a measure of the closeness of two cumulative distribution functions concerning the considered month, the first one (F) relating to a specific year and the second one (Φ) regarding long-term data.

$$F_S(p, y, m) = \sum_{i=1}^n |F(p, y, m, i) - \Phi(p, m, i)| \quad (1)$$

The procedure uses weighting coefficients that multiply the Finkelstein-Schafer statistic of parameters so as to select the candidate months that have the lowest weighted sum. The TRY made for United States by the National Solar Radiation Data Base for 1020 locations was created using procedures similar to those developed by Sandia National Laboratories [67]. Modifications were made to optimize the weighting of the indices, to provide preferential selection for months with measured solar irradiance data, and to account for missing data.

Taylor et al. [69] examined how the external climate can influence the overheating risk inside dwellings by looking at a large range of building types and potential retrofit measures under different UK climate scenarios.

Arima, Ooka, and Kikumoto [70] propose a new type of climate data TDWY (Typical and Design Weather Year) based on the Finkelstein-Schafer statistic that can be used both as a typical weather year and as design weather data. Sughrwan et al. [71], applying EN ISO 15927-4 [60], generated TMYs of the major 18 meteorological locations in South Korea. The analysis has some limitations; for example, the internal heat and moisture loads in the modelling of the case studies were neglected. Pernigotto et al. [72] investigated two possible modifications of the EN ISO 15927-4 procedure aimed at improving the representativeness of TMY, by introducing weighting coefficients for the different climate parameters. According to Pernigotto et al., using separate TRYs for the heating and cooling needs assessment provides good performance in terms of the representativeness of the energy results with respect to long-term averages. For this reason, weighting the different climatic parameters ensured more reliable results. However, there were no correlations between the lengths of the multi-year series and the optimum weighting coefficients. Rahman and Dewsbury [73] on the contrary suggested avoiding the use of weighting coefficients. Hensen [74] and Kershaw, Eames, and Coley [75] proposed variables weighting coefficients according to the characteristics of the building.

In 2004, to allow the introduction of obligatory energy performance certification for buildings, Poland prepared TMYs in accordance to EN ISO

15927-4, using data from 61 weather stations from 1971 to 2000. Grudzińska and Jakusika [76] noted that the results of simulations, with TMYs, showed that the cooling demand in summer was significantly underestimated respect to that calculated with long-term climatic data. They recommended updating the calculation methodology. Sorrentino et al. [58], for the city of Palermo, Italy, compared different TRY construction methods. In the calculation of the energy performance of building the analysis carried out with a dynamic model showed that the TRY prepared in accordance with the approach of Hall et al. [64] is more reliable than the Dogniaux and Sneyers approach [77] and the EN ISO 15927-4 method. Chan [78] developed a set of TRYs based on climate change and analysed their impact on an office building and a residential apartment with EnergyPlus. The research indicated that there is a substantial impact of climate data on the performance of air-conditioning systems. Bhandari, Shrestha, and New [79] compared TRY with data collected from a weather station inaccessible to the service providers and estimated the impact of discrepancy in various climate parameters as well as heating/cooling loads.

In 2016 the Italian Thermotechnical Committee (CTI) processed the new versions of national Typical Meteorological Year for 110 locations in Italy, to be used for a detailed energy performance simulation of the buildings [80]. The selection of representative months was carried out according to EN ISO 15927-4, only considering the outdoor temperature and the global solar irradiance on the horizontal plane without any weighting coefficient.

Huld et al. [81] have presented a method to generate TMY data sets based on satellite derived solar radiation data and other meteorological parameters obtained from reanalysis products. In the validation process, TMYs generated with the ground station data have been compared with reanalysis data. To validate the method for the generation of TMYs, the authors have made calculations of building energy performance using EnergyPlus. The study has shown that the generated data sets using a long time series perform better than the TMY data generated from station with relative standard deviations remaining below 6% for heating calculations. Although the EN ISO 15927-4 standardized methodology is recognized as reference for the creation of TMY, ongoing research [72] [74][75] [76] show that its application without adjustments can lead to reference years that underestimate or overestimate the energy-related needs.

3.3 Influence of climatic data on the energy performance

The outdoor climatic data are an important factor in the assessments of the energy performance of buildings: they affect both the heat transfer through the building envelope, and the size and the efficiency of HVAC systems and of thermal and photovoltaic solar systems.

In order to evaluate the buildings that have a very low amount of energy covered to a very significant extent by energy from renewable sources (nZEB), detailed models under dynamic conditions and reliable and accurate climatic data are necessary. The analysis has showed that the sources of climate data currently available lead to results in terms of energy performance of a nearly zero-energy building that, in some cases, can be very different from each other. Nevertheless, in Italy as intended by the national legislation, the design of nZEBs will take place with the use of the national standard UNI 10349-1:2016.

Comparative analysis of official databases has been carried out with the aim to highlight the main differences and to reply at the question i. The full study is showed in [45].

The published work focuses on the effect of three official climate datasets (of UNI 10349-1:2016, UNI 10349-1:1994 and TMY of DOE) on the results of energy performance assessment. Firstly, a climate analysis was conducted on all Italian localities using different climatic sources as regards temperature, wind velocity, humidity, and solar radiation monthly-averaged data. Secondly, a test on a sample residential nZEB located in all Italian localities was performed to evaluate the effect of the divergence of climate database on the results of energy performance calculated in accordance with the quasi-steady-state method [82]. Finally, a test on the same building located in seven Italian localities, Catania, Palermo, Bari, Ancona, Roma Milano and Torino was performed to evaluate the effect of Test Reference Year divergence on the results of dynamic energy simulations using Design Builder with EnergyPlus code.

3.3.1 Main difference of datasets

The national standard UNI 10349-1 [61] reports the monthly means of the following climate data: external air temperature; incident solar irradiation on a horizontal surface; wind speed; water vapour pressure of external air. The EnergyPlus weather data for the Italian cities, available today, refer to two sources: the International Weather for Energy Calculation (IWECC), typical

weather files © 2001 ASHRAE, and the Italian Climatic data collection “Gianni De Giorgio” (IGDG), based on recorded data from 1951-70 period.

In 2016 CTI has drawn national Typical Meteorological Year (NTMY) for all locations [83], they can be used for the detailed simulation and include the following data: hourly external air temperature, direct normal solar irradiance and diffuse solar irradiance on a horizontal surface; wind speed; relative humidity of external air.

UNI 10349-1 [61] and NTMY are mutually consistent. In fact, the average climate data of UNI 10349-1 are calculated from the national Typical Meteorological Year.

Therefore, while the previous standard UNI 10349:1994 [57] shows average data calculated over the long term, the new standard UNI 10349-1:2016 [61] contains data that are been calculated from test reference year processed according EN ISO15927-4 [12]. Figure 3 and Figure 4 show for all Italian locations, a comparison of the total global solar radiation on a horizontal surface for the full year and average annual temperature for the full year, respectively. Each point represents an Italian locality while, the dashed line represents the perfect correspondence between the data sources analysed. The Figures take into account the following sources a) UNI 10349:1994 [57], b) database ENEA [82] and c) files EPW (IWE, IGDG) [84].

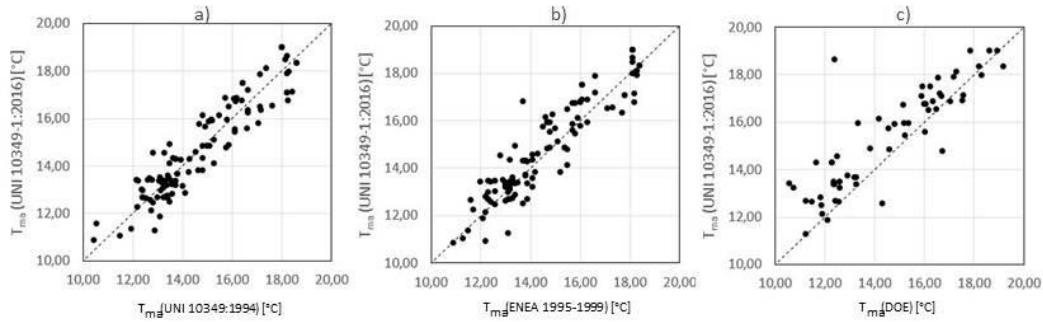


Figure 3: Total annual global solar radiation. (a) UNI 10349:1994 vs. UNI 10349-1:2016 (b) Archive ENEA 1995 – 1999 vs. UNI 10349-1:2016 (c) EPW files vs. UNI 10349-1:2016 [45]

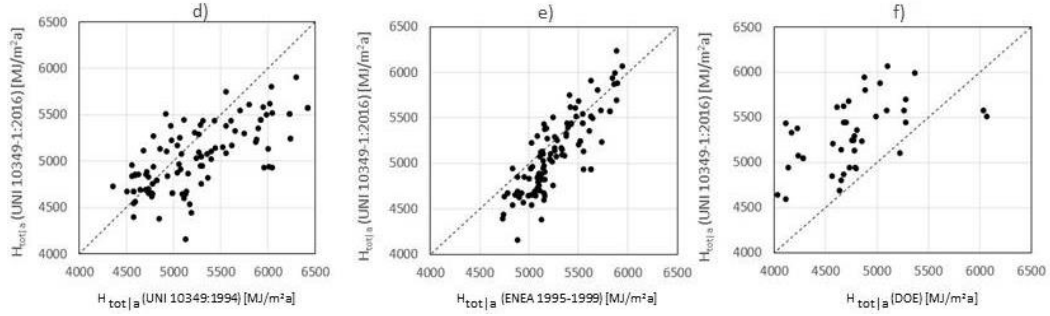


Figure 4: Average annual temperature (a) UNI 10349-1:2016 vs. UNI 10349:1994 (b) UNI 10349-1:2016 vs. Archive ENEA 1995 - 1999 (c) UNI 10349-1:2016 vs. EPW files [45]

In the paper [45] are shown in detail the deviation of the between the data UNI 10349:1994 and UNI 10349:2016.

3.3.2 Case study

The case study is a two-floor residential building. As it regards the geometrical, technological and construction characteristics, it can be considered as representative of a new nZEB, specifically a single-family house in Italy. The conditioned space has a compactness ratio (envelope surface-to-heated volume) equal to $0,72 \text{ m}^{-1}$. The conditioned floor area is equal to 158 m^2 . As regards the envelope system, it was selected an externally insulated massive envelope technology that changes for each climate zone as to satisfy the minimum requirements defined by D.M. 26/06/2015 [56]. All windows have double or triple glazing with a thickness variable as a function of climatic zone, the solar factor is equal to 0,6 and the thermal transmittance U_w of the entire opening (glasses and frame) is variable. It is provided the use of curtain (outside white venetian blinds) for all orientations except for the North side.

*The majority of large openings are south-oriented. More details are given in the **Table 3** that shows data determined with the standards EN ISO 6946, EN ISO 13786 and EN ISO 13790.*

Table 3: Thermo-physical properties of the case study envelope [45]

Component		Zone A/B	Zone C	Zone D	Zone E	Zone F
		HDD≤ 900	900<HDD ≤ 1400	1400<HDD≤ 2100	2100<HDD≤ 3000	HDD>3000
Walls	U	0,43	0,34	0,29	0,26	0,24
	[W/m ² K]					
	κ_i	50,10	49,78	49,58	49,48	49,43
	[kJ/(m ² K)]					
Roof	U [W/m ² K]	0,35	0,33	0,26	0,22	0,20
	κ_i	69,51	69,49	69,42	69,36	69,34
	[kJ/(m ² K)]					
Groundfloor	U [W/m ² K]	0,44	0,38	0,29	0,26	0,24
	κ_i	65,39	65,44	65,50	65,51	65,52
	[kJ/(m ² K)]					
Windows	U_w	3,00	2,20	1,80	1,40	1,10
	[W/m ² K]					
	$g_{gl,n}$	0,67	0,67	0,67	0,67	0,67
	[-]					

3.3.3 Calculation models

To quantify the effect of the new Italian climatic data in the calculation of the energy performance of buildings, two calculation approaches are used in this study: quasi-steady-state calculation method and dynamic simulation.

The quasi-steady-state calculation method evaluates the steady state balance of heat losses (transmission and ventilation) and heat gains (solar and internal) in average monthly conditions. It determines the net energy need for space heating and cooling. The method is specified in UNI/TS 11300-1:2014 [85]

and based on the standard EN ISO 13790 [62], substitute by EN ISO 52016-1:2017 [11].

The dynamic effects on the net heating and cooling energy needs are considered by introducing dynamic parameters, such as the utilization factors, that accounts for the mismatch between transmission plus ventilation heat losses and solar plus internal heat gains; and an adjustment of the set-point temperature for intermittent heating/cooling or set-back.

The dynamic simulation is conducted by means of EnergyPlus (version 8.3). It is a modular building energy analysis and thermal load simulation program, developed by the DOE research labs (DOE, US Army Construction Engineering Research Lab, Illinois Univ., LBNL, Oklahoma Univ., Gard Analytics). The building thermal zone calculation method of EnergyPlus is an air heat balance solution method, based on the assumptions that, by default, the temperature of the air in the thermal zone and of each surface are uniform, the long and short-wave irradiation is uniform, the surface irradiation is diffusive and the heat conduction through the surface is one-dimensional. The geometrical model of the building is developed in DesignBuilder (version 4.7.0.027) which presents a graphical interface of EnergyPlus.

The simulations with quasi-steady-state calculation method are run for all the Italian locations using data from UNI 10349:1994 [57] and UNI 10349-1:2016 [61]. Other simulations, realized with EnergyPlus, were run for seven Italian locations, characterized by different weather conditions: Catania, Palermo, Bari, Ancona, Roma Milano and Torino. The hourly weather data of the locations are used in the dynamic simulation and got from U.S. DOE [84] and CTI NTMY [83] (Italian Thermo-technical Committee).

3.3.4 Comparison between different climatic data of the UNI 10349

The results of quasi-steady-state calculation method show important deviations between the results of UNI/TS 11300-1:2014 using the climatic data of the UNI 10349:1994 and UNI 10349-1:2016 respectively. The analysis takes into account changes both in terms of energy consumption for heating and cooling.

Figure 5 shows, for all Italian locations of the standard, a comparison of energy performance in the heating (a) and cooling (b) season, respectively. Each point represents an Italian locality.

In Table 4 are reported, for each climate zone, the percentage rate of variation (minimum and maximum, determined on all set of localities available in

the standards) between the energy performance calculated using the climatic data of the technical national standards UNI 10349:1994 and UNI 10349-1:2016, respectively. The comparison shows that the difference for the variables $EP_{C,nd}$ and $EP_{H,nd}$ can be as high as 50%.

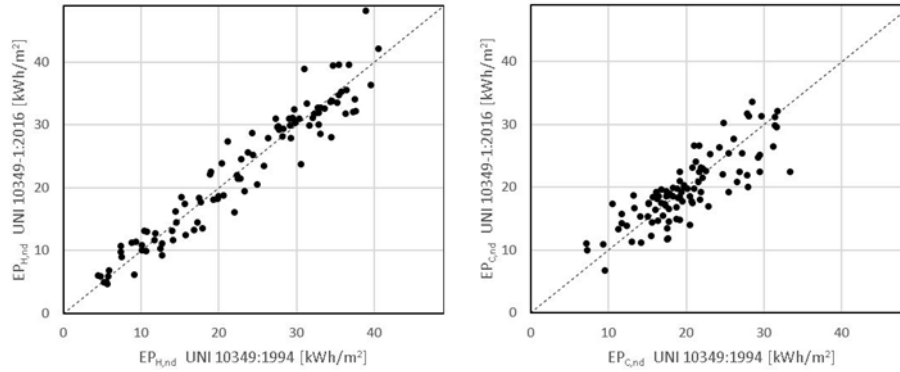


Figure 5: Energy performance in the heating (a) and cooling (b) season. Comparison between UNI 10349-1:2016 and UNI 10349:1994 (b) [45]

Table 4: Deviations between the results of the state steady calculations (UNI/TS 11300-1:2014) using the climatic data of UNI 10349:1994 and of UNI 10349-1:2016 [45]

Climatic Zones	HDD	Number of locations	Percentage rate	$EP_{H,nd}$	Locality	$EP_{C,nd}$	Locality
A/B	$HDD \leq 900$	8	Minimum	-25,95%	SR	-15,21%	PA
			Maximum	49,51%	KR	49,20%	AG
C	$900 < HDD \leq 1400$	16	Minimum	-31,53%	CA	-20,69%	LT
			Maximum	36,52%	IM	38,94%	CS
D	$1400 < HDD \leq 2100$	29	Minimum	-22,76%	AP	-18,65%	FI
			Maximum	36,89%	FI	45,79%	NU
E	$2100 < HDD \leq 3000$	45	Minimum	-20,26%	TN	-39,47%	PN
			Maximum	28,88%	VI	49,91%	TN
F	$HDD > 3000$	2	Minimum	-19,32%	BL	-14,36%	CN
			Maximum	-7,21%	CN	41,21%	BL

Table 5: Geographic coordinates of considered cities [45]

Climatic Zones	Locations	Geographic coordinates DOE			Geographic coordinates NTMY		
		Lon.	Lat.	Elev.	Lon.	La	Elev.
B	Catania	15,05	37,47	17	15,07	37,50	7
	Palermo	13,10	38,18	21	13,34	38,11	14
C	Bari	16,75	41,13	49	16,85	41,12	5
	Bari	16,93	40,77	350	16,85	41,12	5
D	Ancona	13,37	43,62	10	13,51	43,60	16
	Roma	12,50	41,95	24	12,48	41,91	20
E	Milano	9,27	45,45	104	9,18	45,48	122
	Torino	7,65	45,22	287	7,68	45,08	239

Table 6: Results of the simulation conducted by means of EnergyPlus using the Typical Meteorological Year CTI (NTMY) and the TMY of DOE [45]

Climatic Zones	Locations	EP _{C,nd} [kWh/m ² a]		Δ EP _{C,nd} [%]	EP _{H,nd} [kWh/m ² a]		Δ EP _{H,nd} [%]
		DOE	NTMY		DOE	NTMY	
B	Catania	13,45	19,76	46,96%	10,69	5,41	-49,37%
	Palermo	16,29	24,64	51,23%	5,13	4,51	-12,03%
C	Bari	11,34	18,93	67,02%	16,74	14,77	-11,77%
	Bari	6,23	18,93	203,90%	25,25	14,77	-41,49%
D	Ancona	11,93	24,03	101,40%	26,08	26,34	0,98%
	Roma	16,61	24,05	44,76%	15,64	11,66	-25,46%
E	Milano	17,51	22,47	28,36%	33,31	22,93	-31,15%
	Torino	13,88	20,60	48,44%	34,93	29,54	-15,44%

Table 5 and Table 6 summarize the results of the simulation analysis conducted by means of EnergyPlus using the Typical Meteorological Year CTI (NTMY) and the TMY of DOE and provides the annual energy need in terms of heating and cooling. EP_{C,nd} calculated with the CTI TMY is always higher than

that calculated with DOE TMY. The differences are between 28% and more than 200%. The latest value refers to Bari where the altitudes of the weather stations have the maximum difference. Countertrend the $EP_{H,nd}$ are higher with DOE except in Ancona where the values get close.

3.4 Improved Procedure for the creation of a TMY

This part of research investigates the reliability of the TMY determined according to EN ISO 15927-4 in the energy need assessment for heating, cooling, humidification, and de-humidification. This study proposes the implementation of the procedure of EN 15927-4 for TMY elaboration, consisting in the introduction of weighting coefficients for different climatic variables. The study aims at detecting the best representative data set for different types of buildings, focussing on the fabric, while recognising that the performance of technical building systems (passive and active systems) are also affected by climatic variables. The introduction of the weighting coefficient in the procedure of EN ISO 15927-4 can be used either to compensate a dataset of unsatisfactory climate data quality (i.e. high presence of gaps, length of the historical series less than 10 years), or to increase the representativeness of the TMY by taking into account the influence of the individual climate variables on specific energy services correctly. In this work, this second case is explored.

An example of TMY optimisation is reported for the city of Turin from a fifteen year archive of meteorological records.

In order to generalise the results of the work as much as possible, a limited number of TMYs, which can be representative of long-term energy performance for several buildings, are suggested.

3.4.1 Construction and improvement of representativeness of TMY

In the standardized methodology, EN ISO 15927-4:2005, dry-bulb air temperature, global solar irradiance and relative humidity (or alternatively air absolute humidity, water vapour pressure or dew point temperature) are taken as the primary parameters (p) for selecting the “best” months to form the reference year, with wind speed as a secondary parameter. As highlighted by Nielsen et al. [86] the use of Finkelstein-Schafer statistic was a robust selection methodology because the function did not rely on probability of distributions of climate values. The procedure of EN ISO 15927-4 includes the following steps.

- a) From at least 10 years of hourly values of p , calculate the daily means, \bar{p} .
- b) For each calendar month (m), calculate the cumulative distribution function of the daily means overall years in the data set, $\Phi(p,m,i)$, by sorting all the values in increasing order and then using the following equation, where $K(i)$ is the rank order of the value of the daily means within that calendar month in the whole data set.

$$\Phi(p,m,i) = \frac{K(\bar{p}_i)}{N+1} \quad (2)$$

- c) For each year (y) of the data set, calculate the cumulative distribution function of the daily means within each calendar month, $F(p,y,m,i)$, by sorting all the values for that month and that year in increasing order and then using Eq. (3), where $J(i)$ is the rank order of the value of the daily means within that month and that year

$$F(p,y,m,i) = \frac{J(\bar{p}_i)}{n+1} \quad (3)$$

- d) For each calendar month, calculate the Finkelstein-Schafer statistic, $FS(p,y,m)$, for each year of the data set using Eq. (1)
- e) For each parameter and for each calendar month, rank the individual months from the multiyear record in order of increasing size of $FS(p,y,m)$ using Eq. (4), where $L(FS)$ is the rank order of the yearly value of the $FS(p,y,m)$

$$R(p,y,m) = \frac{L(F_s)}{n_y+1} \quad (4)$$

- f) For each calendar month and for each year, add the separate ranks (R) for the three climate parameters.

$$R_{\text{tot}}(y,m) = R(T,y,m) + R(I,y,m) + R(RH,y,m) \quad (5)$$

- g) For each calendar month, for the three months with the lowest total ranking $R_{\text{tot}}(y,m)$, calculate the deviation of the monthly mean wind speed from the corresponding multi-year calendar-month mean. The month with the lowest deviation in wind speed is selected as the “best” month to be included in the reference year.

h) *For each selected calendar months, adjust the hourly values in the selected month to provide a smooth transition when the different months were linked to form the TMY.*

In this work the methodology of EN ISO 15927-4 is applied with some variations in the selection procedure; in particular, the implemented method operates changes on point f), while point g) is neglected.

There are two reasons for neglecting the wind speed: the first one is that its effect on the energy performance of buildings is little; the other one is that the focus of this work is to investigate the effect of air temperature, global solar irradiance and air relative humidity on the selection of the “best” month.

Three different weighting coefficients (α , β , γ) are applied to the ranks of the climate variables, air temperature, global solar irradiance and air relative humidity respectively.

$$R_{\text{tot}}(y,m) = \alpha \cdot R(T, y, m) + \beta \cdot R(I, y, m) + \gamma \cdot R(RH, y, m) \quad (6)$$

In the proposed procedure, the month with the lowest R_{tot} is considered as the “best” month regardless the monthly mean wind speed and it is included in the reference year.

This study aims at verifying if these weighting coefficients should be diversified in function of building characteristics (window-to-wall ratio, thermal inertia, solar shading device) or of energy services analysed. The introduction of weighting coefficients aims to make TMYs more representative of long term time data and, therefore, more reliable for energy performance estimates.

Weighting coefficients express the relevance of different climatic parameters to the energy performance of building. The use of the weights associated with Finkelstein- Schafer statistic expresses this concept.

Nineteen combinations of weighting coefficients were chosen to generate different TMYs as represented in Figure 6. The ternary plot is used to represent the weighting coefficients of the three climatic variables.

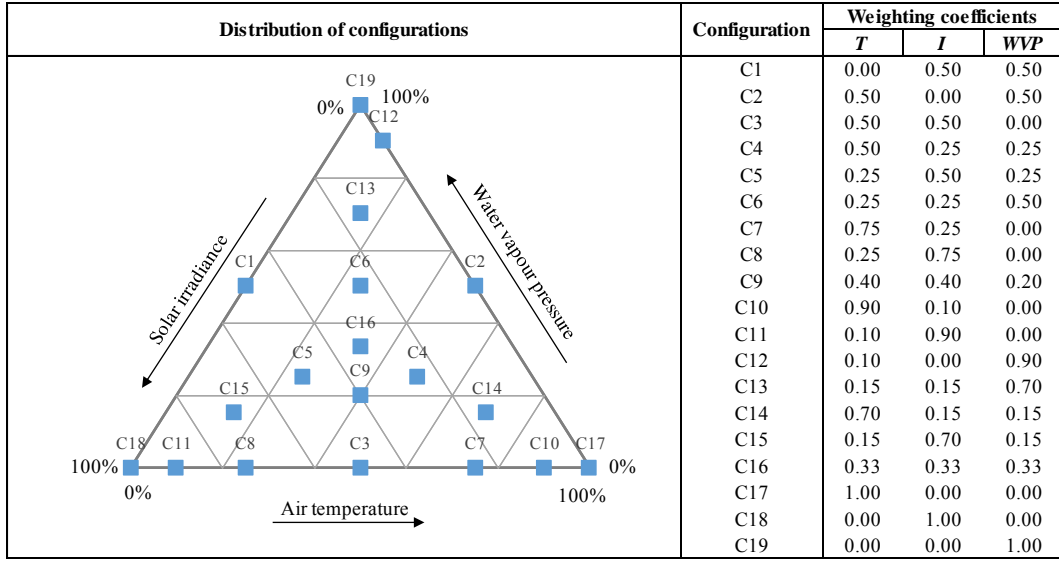


Figure 6: Weighting coefficients configurations on ternary plot [46]

3.4.2 Climatic data set

The climatic hourly data set was provided by the Regional Agency for the Protection of the Environment (ARPA) of Piedmont for academic studies [45] [46]. The period considered in the research comprises the years from 2002 to 2016. Source data used in simulations included hourly values of the following measured parameters: UTC, dry-bulb air temperature, air relative humidity, wind velocity and total solar irradiance on a horizontal plane. The diffuse solar irradiance on a horizontal surface is calculated according to Boland and Ridley [87], and UNI 10349-1 [61]. Generally, the collected data are of good quality, as there are not too many gaps or invalid records.

In the present study the Finkelstein-Schafer statistic has been applied to the following climate parameters: dry-bulb air temperature (T), global solar irradiance on a horizontal surface (I) and water vapour pressure (WVP). Although all the climate parameters are related to each other, any Finkelstein-Schafer statistic of each parameters could have different distribution for the same calendar real months. Air vapour pressure is the climatic parameter with the highest F_S , especially in the winter months. This means that the TMY will be less accurate for that parameter. For each climatic parameter and month of considered period, the Finkelstein-Schafer statistic permits to assign a rank (with reference to c) step in par. 3.4.1).

3.4.3 Case study

The case study is a single-family house located in Turin (Italy), a location where space heating is the dominant energy service. Turin is located in the humid subtropical climate zone according to Köppen's classification. The building model and the main geometric features are shown in **Table 7**. In order to guarantee the representativeness of the result, the proposed method was applied to a typical residential building taken by the TABULA European project [40]. The work considers different kinds of envelope, including a low insulation solution, as shown in TABULA for a building constructed in 1946-1976, and a highly insulated solution, as indicated in the Italian Ministerial Decree 26/06/2015. In this last case, as shown in **Table 8** two different envelope configurations were tested, taking into account a different position of the thermal insulation and a different thermal mass.

As regards the transparent envelope two variants of window-to-wall ratio (WWR) were analysed. All configurations are characterized by a movable solar shading device. The plant is considered ideal load, that is with unlimited capacity, for the determination of the energy need. Heating system is active from 15th of October to 15th of April, in the complementary annual period the cooling system is activated.

Table 7: Geometric data of case studies [46]

Geometric data	Case study	
	B1 – B3– B5	B2 – B4– B6
$A_f [m^2]$		158
$V_g [m^3]$		576
$A_e/V_g [m^{-1}]$		0.74
$A_w [m^2]$	62.0	24.8
$A_w/A_f [-]$	0.392	0.157
WWR [-]	0.264	0.105

Table 8: Thermo-physical characteristics of the case studies [46]

Case study	B1	B2	B3	B4	B5	B6
Level of thermal insulation	H	H	H	H	L	L
Level of thermal inertia	L	L	H	H	H	H
WWR	H	L	H	L	H	L

Wall	U	[W m ⁻² K ⁻¹]	0.26	0.26	0.26	0.26	1.48	1.48
	κ_i	[kJ m ⁻² K ⁻¹]	13.5	13.5	87.5	87.5	94.2	94.2
Roof	U	[W m ⁻² K ⁻¹]	0.80	0.80	0.80	0.80	2.20	2.20
	κ_i	[kJ m ⁻² K ⁻¹]	87.6	87.6	121.8	121.8	149.0	149.0
Last Floor	U	[W m ⁻² K ⁻¹]	0.31	0.31	0.31	0.31	1.68	1.68
	κ_i	[kJ m ⁻² K ⁻¹]	27.4	27.4	105.3	105.3	149.0	149.0
Ground Floor	U	[W m ⁻² K ⁻¹]	0.26	0.26	0.26	0.26	2.00	2.00
	κ_i	[kJ m ⁻² K ⁻¹]	103.6	103.6	103.6	103.6	174.8	174.8
Windows	U	[W m ⁻² K ⁻¹]	1.40	1.40	1.40	1.40	4.90	4.90
	g_{gl+sh}	[-]	0.35	0.35	0.35	0.35	0.40	0.40

3.4.4 Validation of the methodology

The proposed methodology was validated through calculation of the Energy Performance (EP) and a comparison of the results obtained by a TMY with those deriving from by a long-term (multi-year) simulation.

In this work, the EP is defined as the ratio of the thermal energy need to the conditioned useful floor area. EP is split by different energy services: heating (H), cooling (C), humidification (HU), and dehumidification (DHU).

The EP of the case study was calculated by means of Energy Plus 8.5 with one hour time step. The geometrical model of the building was developed in Design Builder 5.0.1.024.

The main modelling hypotheses are the followings: (a) exterior convection coefficient derived from DOE-2 with the total convection coefficient related and changed in function of the local wind speed; (b) sky temperature derived from the horizontal infrared radiation intensity and used for the calculation of the net long wavelength thermal radiation flux exchange with the air and surroundings; (c)

anisotropic radiance distribution of the sky; (d) ground temperature profile according to the model of Kusuda and Achenbach [88], which allows the air temperature to be derived at ground level from the weather file; (e) conduction heat fluxes, calculated with the Conduction Transfer Functions [89] [90] [91] expressed as a function of the environmental temperatures (interior and exterior).

The following boundary conditions are considered: (a) the internal heat gains (sensible and latent) and ventilation flow rate are derived from UNI/TS 11300-1, and are represented by daily profiles; (b) the solar shadings are activated when solar irradiance exceeds 300 W m^{-2} . There is not any solar shading reduction from external obstacles. The global sensible internal heat gain, obtained as the mean value of the weekly profile, has a value of 2.85 W m^{-2} while the global moisture flow has a value of 250 g h^{-1} . The average ventilation flow rate is $0.50 \text{ m}^3 \text{ s}^{-1}$. The case studies have been modelled considering internal heat and moisture loads and natural ventilation. The following assumptions were considered: heating and cooling temperature set-points are 20°C and 26°C respectively, air relative humidity set-point for humidification and de-humidification is equal to 50%, in accordance with the prescriptions of national specification UNI/TS 11300-1 [85] for residential buildings. Continuous operating schedules during the conditioning period are assumed, as indicated by the Italian regulations.

Figure 7 shows the long-term average EP split by energy service for the different case studies. The thermal energy need for space heating (EP_H) appears as the most relevant for all case studies, while EP_C is significantly dependent on WWR, EP_{DHU} has similar values regardless insulation level, and EP_{HU} is generally negligible.

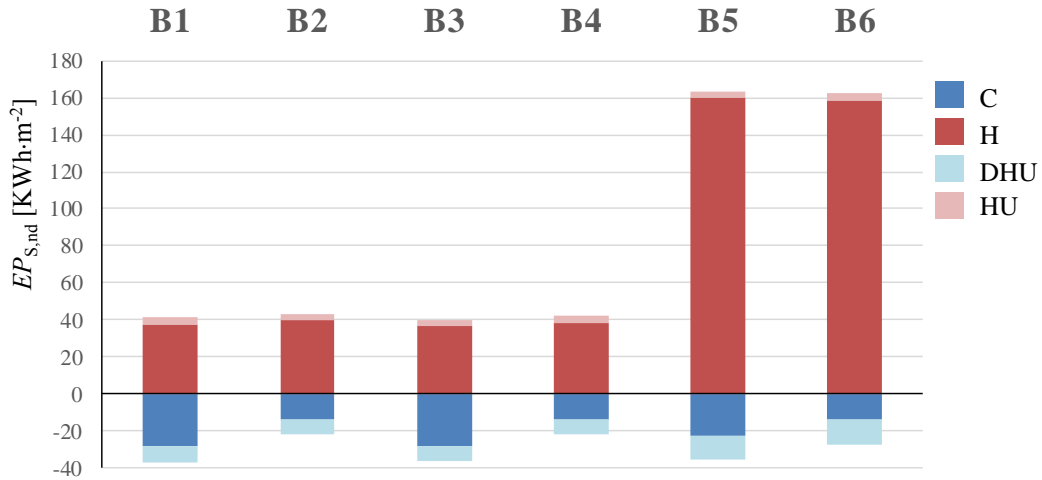


Figure 7: Long-term average EP split by energy service [46]

3.4.5 Yearly EP relative deviation ($\iota_{\Delta EP_S}$)

Each TMY is identified by an array of three numbers, e.g. (0.50; 0.50; 0), of which the first one is the weighting coefficient for air temperature, the second for solar irradiance and the last for water vapour pressure.

For each energy service (S), the “best” TMY is defined as the TMY that best approximates the energy need calculated on long-term data.

The representativeness of a TMY is assessed through two different indexes.

The first one, $\iota_{\Delta EP_S}$, as reported in Eq. (7), is the relative absolute deviation of EP_S for a specific energy service (S) and for the given TMY.

$$\iota_{\Delta EP_S} = \frac{|\Delta EP_S|}{\overline{EP_S}} = \frac{|EP_S - \overline{EP_S}|}{\overline{EP_S}} \quad (7)$$

The $\iota_{\Delta EP_S}$ indicator does not provide sufficient indications on the representativeness of the TMY for single months, as there may be compensations of energy needs among the monthly deviations. The results are also analysed using the standard deviation divided by the long-term mean to take into account EP monthly differences.

The second index, $\iota_{\sigma EP_S}$, as reported in Eq. (8), is the relative standard deviation of monthly energy performance referred to a specific energy service (EP_S^M).

$$\iota_{\sigma EP_S} = \frac{\sigma_{EP_S^M}}{EP_S^M} = \frac{\sqrt{\sum_{m=1}^{N_m} (EP_{S,m}^M - \overline{EP_{S,m}^M})^2 / (N_m - 1)}}{\overline{EP_S^M}} \quad (8)$$

where N_m is the number of months for which the considered energy service is provided.

Figure 8 shows the effects of the combinations of the weighting coefficients on indexes $\iota_{\Delta EP_S}$ and $\iota_{\sigma EP_S}$ with the lowest values in red colour. In the same table the first row (ISO) refers to a strict application of EN ISO 15927-4 in its complete form, including the choice of the month according to the monthly mean deviation of wind speed (see step g) of subsection par.3.4.1).

As regards the cooling energy need indicator ($\iota_{\Delta EP_C}$), the best TMY weighting coefficients are: C19 (0;0;1) for the case study with low insulation (B5 and B6), C1 (0; 0.50; 0.50) for highly insulated buildings with high WWR (B1 and B3), C3 (0.50; 0.50; 0) for highly insulated buildings with low WWR (B2), and C10 (0.90; 0.10; 0) for case B4 but with C3 having very similar $\iota_{\Delta EP}$ value.

Regarding space heating, the best TMY is C7 (0.75; 0.25; 0) for all kinds of buildings.

The energy dehumidification calculated with long-term data is close to the value calculated with C19 (0; 0; 1) for all highly insulated buildings, with the exception of B2 that has the minimum with C13 (0.15; 0.15; 0.70); the buildings with high thermal capacity (B5 and B6) have the lower $\iota_{\Delta EP}$ value for dehumidification for C15 (0.15; 0.70; 0.15).

Concerning humidification the best TMY is C7 (0.75; 0.25; 0) for all the buildings with the exception of B3, which has the minimum value for C3 (0.5; 0.5; 0).

In case of poorly insulated buildings, using ISO leads to $\iota_{EP,C}$ between 10% for case study B5 (high WWR) and 15% for case study B6 (low WWR). On the contrary, in case of highly insulated buildings $\iota_{EP,H}$ and $\iota_{EP,C}$ show values below 4% and 3% respectively. It does not happen the same for the other energy services and in particular for dehumidification where, for all the case studies, $\iota_{EP,DHUM}$ is always over 5%.

3.4.6 Monthly EP relative standard deviation ($\iota_{\sigma EP_S}$)

The bottom part of Table 4 reports the relative standard deviation, $\iota_{\sigma EP_S}$, calculated according to Eq. (7). The $\iota_{\sigma EP_S}$ values are also shown in Figure 4, as the dimensions of circles in a ternary plot.

As regards the energy need for cooling, the minimum value of the relative standard deviation ($\iota_{\sigma EP_C}$) corresponds to C10 (0.90; 0.10; 0) for highly insulated buildings with high WWR (B1 and B3), and to C17 (1; 0; 0) for highly insulated buildings with low WWR (B2 and B4) and for buildings with high thermal capacity (B5 and B6). The $\iota_{\sigma EP_S}$ index is lower for buildings with small heat transfer and high solar heat gains (B1-B2), as shown in Figure 4.

As regards the energy need for heating, the best TMY is the one elaborated according to EN ISO 15927-4 for highly insulated building (B1, B2, B3, B4). Instead, three configurations, C10 (0.90; 0.10; 0), C14 (0.70; 0.15; 0.15), and C17 (1; 0; 0), show equal performance for poorly insulated buildings (B5, B6). An exception is the highly insulated building with high WWR (B1), for which all the above TMYs give the same performance. It must be noted that both C10, and C14, and C17 are composed by the same months in the winter season. In Figure 4, for all case studies, $\iota_{\sigma EP_S}$ is lower for heating than for the other energy services.

In the search of optimal configuration, the influence of air temperature is generally dominant for heating and cooling services. The only exception concerns the space cooling of buildings with large transparent surfaces and highly insulated envelopes; in this case, in the best TMY, the weighting coefficient of air temperature slightly decreases, while the weighting coefficient of solar irradiance slightly increases.

As regards the energy need for dehumidification, the minimum value of the relative standard deviation ($\iota_{\sigma EP, DHU}$) corresponds to C13 (0.15; 0.15; 0.70) and C6 (0.25; 0.25; 0.50) for highly insulated buildings with high level of WWR (B1 and B3); to C1 (0; 0.50; 0.50) and C6 (0.25; 0.25; 0.50) for highly insulated buildings with low level of WWR (B2 and B4 respectively); to C1 and C2 (0.50; 0; 0.50) for the buildings with low insulation and high thermal capacity (B5 and B6 respectively). In the selected configurations, the weighting coefficient related to water vapour pressure is greater than 0.50; that highlights the weight of this variable for the considered energy service.

As regards the energy need for humidification, for all cases studies, the lowest relative standard deviation ($\iota_{\sigma EP, HU}$) corresponds to C1 (0; 0.50; 0.50).

TMY	ISO	EP Average [kWh·m ⁻²]	B1			B2			B3			B4			B5			B6			$t_{SEP,s} = \frac{\Delta EP_s}{\Delta EP_s}$						
			C	H	U	C	H	U	C	H	U	C	H	U	C	H	U	C	H	U							
0.33	0.33	0.33	1.53%	3.94%	6.36%	4.30%	2.99%	3.44%	7.06%	4.06%	1.41%	3.41%	7.61%	4.31%	2.73%	2.98%	9.17%	3.86%	9.72%	3.23%	9.78%	4.44%	15.32%	3.17%	9.38%	4.21%	
C1	0.50	0.50	0.57%	7.46%	4.26%	8.80%	5.13%	4.90%	5.13%	2.72%	4.46%	3.78%	3.36%	3.78%	5.43%	2.83%	4.59%	15.47%	4.93%	15.47%	4.93%	1.49%	4.93%	22.84%	3.29%	3.90%	4.24%
C2	0.50	0.50	6.91%	3.80%	2.98%	8.80%	7.23%	4.34%	6.93%	3.70%	7.08%	4.03%	2.19%	8.23%	7.33%	4.48%	5.95%	3.29%	10.92%	5.55%	10.92%	5.55%	12.87%	3.64%	3.41%	1.76%	
C3	0.50	0.50	1.90%	3.93%	11.70%	0.18%	0.09%	3.27%	12.19%	0.96%	2.33%	3.89%	12.71%	0.35%	5.07%	3.36%	0.58%	0.86%	13.86%	1.14%	13.86%	1.14%	15.51%	2.46%	12.82%	0.98%	
C4	0.50	0.25	5.08%	5.25%	4.67%	3.91%	8.24%	4.01%	5.26%	3.62%	5.07%	5.55%	4.85%	3.74%	8.20%	4.26%	4.40%	3.60%	13.91%	2.84%	5.89%	3.46%	17.75%	2.69%	7.53%	3.28%	
C5	0.25	0.50	3.41%	3.63%	1.78%	6.62%	5.20%	2.62%	0.82%	4.17%	3.4%	3.75%	2.45%	5.95%	5.28%	2.85%	0.62%	3.95%	9.91%	1.86%	0.41%	3.51%	12.39%	1.75%	1.65%	3.08%	
C6	0.25	0.25	7.69%	6.75%	2.24%	0.29%	13.13%	4.69%	1.87%	1.46%	7.49%	7.08%	2.59%	0.19%	12.48%	4.93%	0.92%	1.57%	27.55%	3.32%	3.02%	1.98%	37.73%	2.97%	4.47%	2.23%	
C7	0.75	0.25	4.22%	1.27%	15.55%	0.15%	1.97%	1.80%	19.23%	0.40%	4.56%	1.35%	14.46%	0.53%	4.50%	1.11%	2.48%	0.66%	20.50%	0.21%	20.50%	0.18%	10.41%	1.24%	18.29%	0.26%	
C8	0.25	0.75	4.66%	7.07%	11.22%	8.55%	1.67%	6.78%	14.88%	9.25%	4.98%	7.23%	10.09%	8.85%	7.11%	5.18%	13.37%	9.29%	7.11%	5.18%	20.71%	9.28%	15.69%	4.99%	19.61%	9.40%	
C9	0.40	0.40	8.80%	3.33%	2.84%	5.34%	11.32%	3.06%	4.79%	4.35%	8.95%	3.27%	2.70%	4.90%	11.31%	3.16%	6.26%	4.38%	15.89%	2.23%	4.96%	4.10%	16.04%	2.51%	3.76%	4.01%	
C10	0.90	0.10	1.23%	3.53%	18.89%	5.85%	1.37%	3.63%	22.48%	4.28%	1.58%	3.86%	17.89%	6.31%	9.87%	3.87%	9.87%	4.35%	20.37%	2.49%	22.17%	3.88%	16.04%	2.51%	20.37%	3.52%	
C11	0.10	0.90	8.00%	6.32%	4.98%	11.35%	10.29%	6.94%	4.15%	11.11%	8.20%	6.37%	5.66%	11.97%	14.85%	5.86%	9.87%	11.14%	14.85%	5.86%	0.82%	10.79%	18.24%	5.81%	2.58%	10.53%	
C12	0.10	0.90	14.22%	7.75%	1.02%	5.24%	22.94%	6.42%	2.66%	2.71%	14.18%	7.90%	1.43%	4.48%	32.69%	5.18%	2.29%	2.71%	32.69%	5.18%	2.29%	2.71%	42.80%	4.92%	6.22%	1.98%	
C13	0.15	0.15	11.56%	7.75%	1.94%	5.27%	18.03%	6.45%	20.50%	4.30%	11.38%	7.91%	2.09%	4.52%	37.62%	5.19%	5.23%	2.41%	37.62%	5.19%	5.23%	2.41%	52.21%	4.94%	4.50%	2.47%	
C14	0.70	0.15	16.58%	5.85%	1.72%	3.63%	2.98%	10.29%	7.14%	7.49%	4.54%	3.86%	15.51%	3.87%	5.23%	2.49%	19.16%	4.37%	14.90%	6.61%	0.20%	9.80%	11.76%	2.51%	19.35%	3.48%	
C15	0.15	0.70	7.05%	7.44%	2.45%	10.64%	9.43%	7.84%	2.98%	10.29%	7.14%	7.49%	2.70%	11.24%	8.88%	7.91%	2.34%	10.34%	14.90%	6.61%	0.20%	9.80%	18.82%	6.49%	0.65%	9.59%	
C16	0.33	0.33	5.08%	7.22%	4.67%	1.68%	8.24%	5.32%	5.27%	1.26%	5.07%	7.33%	4.85%	2.29%	8.20%	5.50%	4.41%	1.34%	13.91%	4.06%	5.89%	1.44%	17.75%	3.65%	7.53%	1.66%	
C17	1.00	0.00	2.97%	3.53%	21.48%	5.85%	0.80%	3.63%	24.57%	1.28%	3.38%	3.86%	20.60%	6.31%	1.76%	3.87%	23.41%	4.35%	6.25%	2.49%	23.78%	3.89%	12.60%	2.51%	21.72%	3.52%	
C18	0.00	1.00	5.25%	6.32%	8.72%	11.35%	5.07%	6.94%	8.48%	11.11%	5.49%	6.37%	8.00%	11.97%	4.85%	7.00%	8.42%	11.14%	7.57%	5.86%	8.99%	10.80%	8.61%	5.81%	6.80%	10.54%	
Weighting coefficients	Weighting coefficients	Weighting coefficients	0.25%	5.24%	6.81%	6.42%	1.38%	2.73%	4.50%	7.90%	0.33%	4.48%	6.82%	6.50%	0.37%	2.33%	3.02%	5.18%	3.02%	5.18%	3.03%	2.90%	2.16%	4.93%	6.29%	2.14%	
TMY	TMY	TMY	ISO	ISO	ISO	ISO	ISO	ISO	ISO	ISO	ISO	ISO	ISO	ISO	ISO	ISO	ISO	ISO	ISO	ISO	ISO	ISO	ISO	ISO	ISO	ISO	
0.33	0.33	0.33	0.107	0.074	0.233	0.146	0.143	0.056	0.278	0.148	0.104	0.070	0.216	0.154	0.131	0.051	0.257	0.149	0.235	0.052	0.269	0.146	0.369	0.049	0.277	0.151	
C1	0.50	0.50	0.180	0.111	0.344	0.283	0.082	0.081	0.360	0.252	0.088	0.111	0.335	0.286	0.083	0.084	0.347	0.250	0.083	0.084	0.347	0.250	0.083	0.084	0.347	0.250	
C2	0.50	0.50	0.078	0.096	0.344	0.303	0.065	0.074	0.354	0.268	0.083	0.100	0.339	0.313	0.068	0.078	0.346	0.268	0.068	0.078	0.346	0.268	0.241	0.053	0.312	0.259	
C3	0.50	0.50	0.123	0.086	0.367	0.307	0.140	0.084	0.362	0.331	0.123	0.088	0.363	0.316	0.126	0.085	0.354	0.331	0.126	0.085	0.354	0.331	0.359	0.063	0.310	0.32	
C4	0.50	0.50	0.181	0.107	0.230	0.286	0.260	0.080	0.278	0.258	0.177	0.113	0.223	0.290	0.241	0.085	0.262	0.257	0.241	0.085	0.262	0.257	0.781	0.056	0.308	0.248	
C5	0.50	0.50	0.014	0.074	0.356	0.331	0.053	0.062	0.369	0.205	0.045	0.075	0.351	0.247	0.044	0.064	0.361	0.210	0.200	0.050	0.240	0.198	0.272	0.046	0.323	0.206	
C6	0.50	0.50	0.162	0.091	0.231	0.339	0.234	0.095	0.247	0.373	0.157	0.089	0.231	0.349	0.221	0.093	0.236	0.373	0.235	0.373	0.235	0.373	0.648	0.080	0.333	0.276	
C7	0.50	0.50	0.245	0.108	0.076	0.167	0.366	0.083	0.169	0.128	0.243	0.113	0.073	0.153	0.355	0.087	0.144	0.125	0.385	0.066	0.171	0.132	0.777	0.062	0.320	0.118	
C8	0.50	0.50	0.211	0.108	0.072	0.167	0.336	0.084	0.130	0.128	0.205	0.113	0.070	0.152	0.318	0.087	0.108	0.124	0.673	0.066	0.181	0.132	0.975	0.062	0.312	0.118	
C9	0.50	0.50	0.162	0.093	0.207	0.269	0.063	0.062	0.349	0.205	0.083	0.075	0.335	0.247	0.066	0.064	0.340	0.210	0.177	0.050	0.334	0.198	0.240	0.046	0.312	0.200	
C10	0.50	0.50	0.172	0.105	0.106	0.110	0.254	0.084	0.146	0.109	0.158	0.092	0.203	0.277	0.227	0.093	0.218	0.291	0.448	0.079	0.222	0.296	0.648	0.047	0.307	0.291	
C11	0.50	0.50	0.043	0.074	0.412	0.231	0.043	0.062	0.408	0.205	0.047	0.075	0.410	0.247	0.044	0.064	0.404	0.210	0.526	0.071	0.170	0.115	0.770	0.066	0.196	0.111	
C12	0.50	0.50	0.182	0.091	0.372	0.340	0.279	0.095	0.373	0.349	0.175	0.089	0.373	0.349	0.258	0.093	0.351	0.373	0.511	0.079	0.326	0.373	0.742	0.080	0.318	0.377	
C13	0.50	0.50	0.207	0.108	0.080	0.167	0.305	0.083	0.163	0.128	0.201	0.113	0.078	0.153	0.283	0.087	0.137	0.125	0.573	0.066	0.173	0.132	0.733	0.062	0.311	0.118	

Figure 8: TMY quality indicators for different energy services and case studies [46]

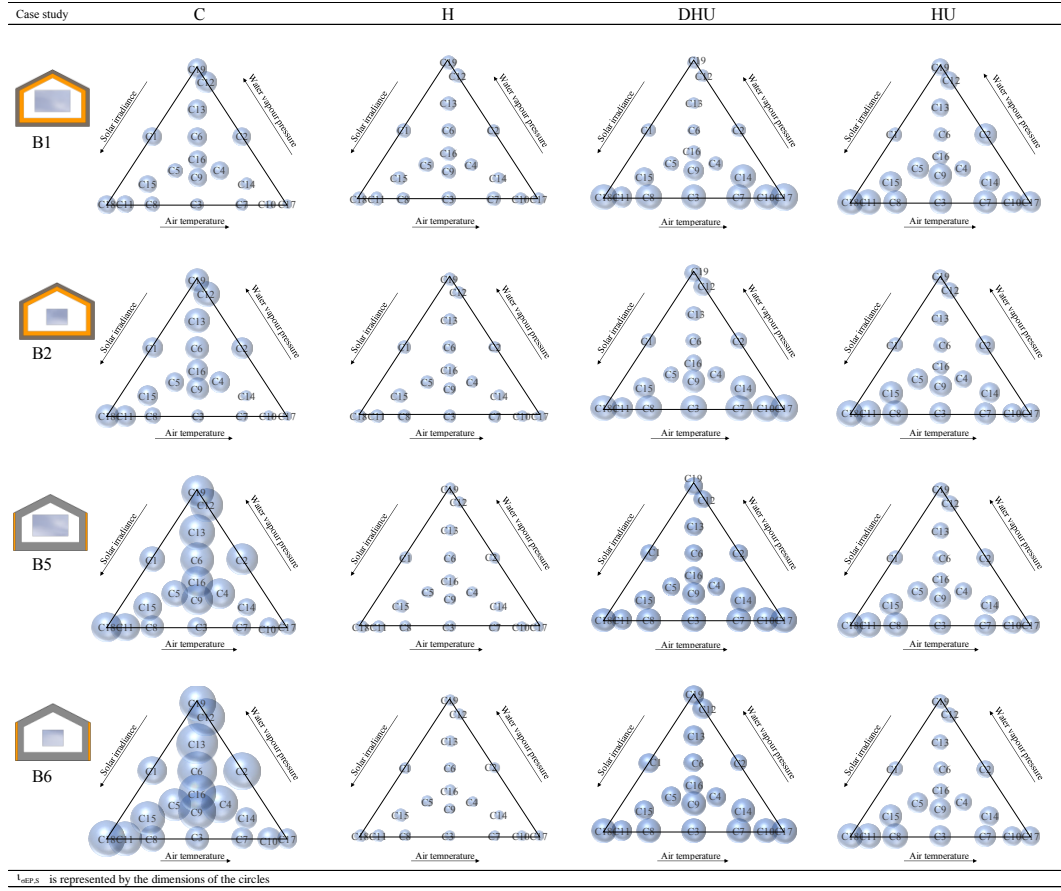


Figure 9: Ternary plots of the $\iota_{EP,S}$ indicator for the different weighting coefficients configurations [46]

The minimum values of $\iota_{EP,HU}$ correspond to weighting coefficients for water vapour pressure higher than 33% for all the buildings. The TMY that best approximates long term EP_{HU} does not consider air temperature as a selection parameter; but only solar irradiance and water vapour pressure in equal measure. This configuration is common for all case studies.

3.4.7 Evaluation of aggregated energy service

The final part of the study concerned the use of TMYs for the evaluation of aggregated energy needs. The analysis was carried out by evaluating the sum of the energy needs according to equation (8) where the aggregated energy services ($S1+S2$) can be either heating plus humidification, or cooling plus dehumidification.

$$\sigma_{EP^M_{S1+S2}} = \sqrt{\sum_{m=1}^{N_m} \left(EP^M_{S1+S2,m} - \overline{EP^M_{S1+S2,m}} \right)^2 / (N_m - 1)} \quad (9)$$

The optimum weighting coefficients for climate variables for different energy services and building types are shown in Figure 10 and in Table 9, also for aggregated services.

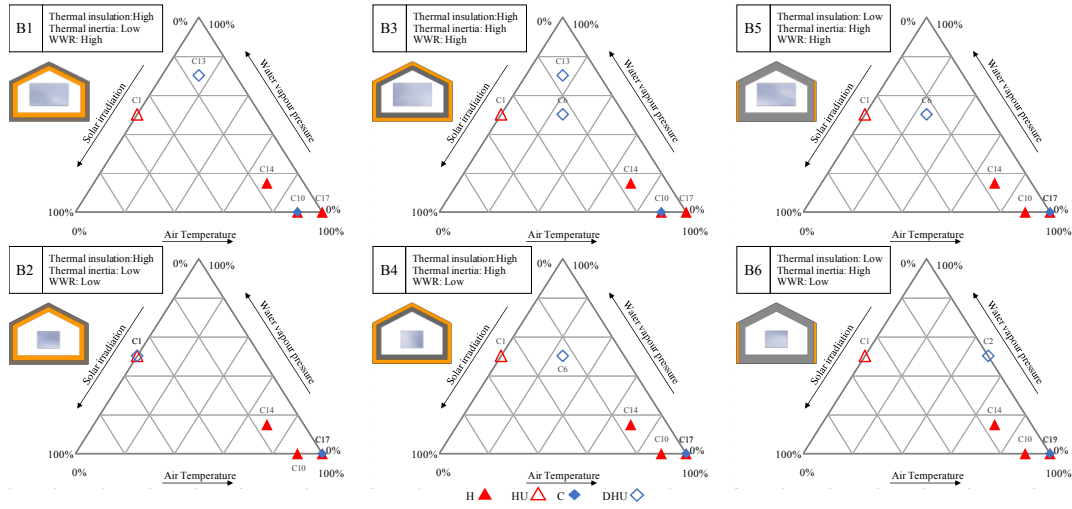


Figure 10: Ternary plot of optimum weighting coefficients for climate variables [46]

As shown in Table 9, the aggregation of the energy needs for the heating season (H+HU) presents the same best TMYs as for the only energy need for heating.

Regarding the cooling season, the situation is different. When evaluating aggregate services, for buildings with high WWR (B1, B3, and B5) and for poorly insulated building with low WWR (B6) the best TMY is C17 (1; 0; 0). For case studies B2 and B4 (very isolated buildings with low WWR), the greatest weighting coefficient is the one of solar irradiance.

For aggregated energy services, the TMY built according to the EN ISO 15927-4 standard provides greater representativeness both for winter and summer seasons (sensible and latent energy needs). The only exceptions are for case study B1 in the cooling season, B5 in the heating season, and case study B6 for both seasons. However, for these exceptions also the TMY constructed according to the ISO standard shows good representativeness.

The weakness of the TMY realized according to the standard consists in not being able to guarantee the representativeness of the single energy needs. The standard in fact provides representative results only for the energy needs for heating, but not for the others energy services.

Table 9: Optimum weighting coefficients for climate variables for single and aggregated energy services [46]

Case Study Energy Services	B1	B3	B4	B2	B5	B6
C	C10 [0.90; 0.10; 0]		C17 [1; 0; 0]			
DHU	C13 [0.15; 0.15; 0.70]	C6 [0.25; 0.25; 0.50]		C1 [0; 0.50; 0.50]		C2 [0.50; 0; 0.50]
C+DHU	C17 [1; 0; 0]		C5 [0.25; 0.50; 0.25]		C17 [1; 0; 0]	C1 [0; 0.5; 0.5]
H	C10 [0.90; 0.10; 0]		C14 [0.70; 0.15; 0.15]		C17 [1; 0; 0]	
HU	C1 [0; 0.50; 0.50]					
H+HU	C10 [0.90; 0.10; 0]		C14 [0.70; 0.15; 0.15]		C17 [1; 0; 0]	

3.4.8 Evaluation of TMYs based on primary energy

The case study was simulated with a technical building plant with the aim of verifying which TMY is the best approximation of average primary energy performance on long term. Observing the performance of buildings with energy

services of the previous section, for this study the research has been reduced to B1, B2, B5 and B6.

Heating system is active from 15th of October to 15th of April, in the complementary annual period the cooling system is activated. Heating and cooling is provided by an air-water heat pump. The fluid used to heat transfer is water and terminal units are fan-coil. The design temperature is 55 ° C in the heating period and 7 ° C in the cooling period. The regulation is through zone thermostat with set-point at 20°C in the heating period, in accordance with the DM, and 26°C in the cooling period.

The nominal energy consumption of the circulation pump is 140W with a motor efficiency of 0.9. The pump is with variable speed. The pump control type is intermittent, so the pump can shut down if there is no load.

The main features are listed in the **Table 10** and **Table 11**.

Table 10: Features heat pump

Feature	Air to water	Feature	Air to water
	heat pump coil		cool pump coil
Rated heating capacity [kW]	8 (B1 – B2) 12 (B5 – B6)	Rated cooling capacity [kW]	1.8
Rated COP [-]	3.66	Rated EE [-]	4
Rated evaporator inlet air dry-bulb temperature [°C]	27	Reference leaving chilled water temperature [°C]	18
Rated condenser inlet water temperature [°C]	55	Reference entering condenser fluid temperature [°C]	35
Set-point Manager	Outdoor Air Reset Set-point Manager	Set-point Manager	Outdoor Air Reset Set-point Manager

Table 11: Features recirculating pump and fan coil

Feature	Recirculating pump	Feature	Fan coil
Pump type	Variable speed	Fan total efficiency	0.7
Rated power consumption [W]	140	Motor efficiency	0.9
Pump motor efficiency	0.9		
Control type	Intermittent		

A photovoltaic system has been considered with characteristics shown in the table. Features come from technical sheet. Photovoltaic plant peak power is 2 kW and is in according to the Italian law on the use of renewable sources [92]. The photovoltaic solar collector performance is modelled as an equivalent one diode [22]. The inverter efficiency is 0.95.

Table 12: Photovoltaic panel features

Feature	Photovoltaic panel
Cell type	Amorphous silicon
Numbers Cells in series	75
Active area [m ²]	0.58
Transmittance absorptance product	0.9
Semiconductor bandgap [eV]	1.12
Reference temperature [°C]	25
Rated electric power [W]	500



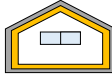
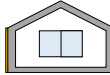
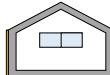
		B1			B2			B5			B6						
																	
EP Average [kWh·m ⁻²]		7.97	12.59	11.11	14.96	5.11	13.45	10.48	11.83	5.63	52.22	54.28	15.60	3.64	44.59	45.74	12.07
TMY	Weighting coefficients <i>T</i> <i>I</i> <i>WTP</i>	C	H	gl·ren	gl·ren	C	H	gl·ren	gl·ren	C	H	gl·ren	gl·ren	C	H	gl·ren	gl·ren
		[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
ISO	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
C1	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
C2	0.50	0.00	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
C3	0.50	0.50	0.00	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
C4	0.50	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
C5	0.25	0.50	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
C6	0.25	0.25	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
C7	0.75	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C8	0.25	0.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C9	0.40	0.40	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
C10	0.90	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C11	0.10	0.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C12	0.10	0.00	0.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C13	0.15	0.15	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
C14	0.70	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
C15	0.15	0.70	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
C16	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
C17	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C18	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C19	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Weighting coefficients		C	H	gl·ren	gl·ren	C	H	gl·ren	gl·ren	C	H	gl·ren	gl·ren	C	H	gl·ren	gl·ren
ISO	0.33	0.192	0.222	0.128	0.304	0.153	0.387	0.199	0.223	0.150	0.449	0.127	0.171	0.343	1.050	0.345	0.370
C1	0.00	0.118	0.135	0.095	0.170	0.098	0.204	0.119	0.127	0.081	0.288	0.101	0.087	0.176	0.688	0.290	0.184
C2	0.50	0.00	0.50	0.070	0.143	0.073	0.139	0.102	0.116	0.066	0.159	0.085	0.069	0.186	0.626	0.217	0.202
C3	0.50	0.50	0.00	0.090	0.130	0.076	0.080	0.074	0.114	0.061	0.098	0.083	0.072	0.179	0.272	0.188	0.194
C4	0.50	0.25	0.25	0.061	0.155	0.073	0.139	0.094	0.127	0.064	0.160	0.082	0.073	0.185	0.640	0.251	0.201
C5	0.25	0.50	0.25	0.084	0.152	0.080	0.131	0.102	0.118	0.068	0.160	0.085	0.077	0.183	0.559	0.230	0.195
C6	0.25	0.25	0.50	0.080	0.168	0.094	0.180	0.123	0.127	0.077	0.243	0.088	0.084	0.187	0.799	0.310	0.202
C7	0.75	0.25	0.00	0.093	0.131	0.070	0.105	0.085	0.108	0.058	0.119	0.094	0.068	0.194	0.338	0.209	0.213
C8	0.25	0.75	0.00	0.097	0.131	0.093	0.155	0.098	0.111	0.079	0.180	0.096	0.087	0.161	0.335	0.202	0.178
C9	0.40	0.40	0.20	0.104	0.093	0.093	0.152	0.106	0.119	0.060	0.180	0.091	0.077	0.190	0.654	0.257	0.212
C10	0.90	0.10	0.00	0.084	0.160	0.068	0.086	0.072	0.117	0.059	0.083	0.075	0.066	0.185	0.302	0.198	0.202
C11	0.10	0.90	0.00	0.128	0.123	0.123	0.189	0.131	0.144	0.111	0.235	0.147	0.111	0.199	0.640	0.238	0.211
C12	0.10	0.00	0.90	0.111	0.153	0.090	0.223	0.128	0.127	0.073	0.259	0.100	0.080	0.180	0.251	0.212	0.200
C13	0.15	0.15	0.70	0.119	0.097	0.090	0.212	0.135	0.127	0.073	0.270	0.092	0.084	0.180	0.858	0.305	0.201
C14	0.70	0.15	0.15	0.084	0.175	0.068	0.109	0.078	0.117	0.059	0.116	0.080	0.066	0.185	0.335	0.205	0.202
C15	0.15	0.70	0.15	0.101	0.116	0.100	0.191	0.132	0.116	0.090	0.238	0.145	0.091	0.175	0.637	0.237	0.187
C16	0.33	0.33	0.33	0.074	0.156	0.086	0.139	0.097	0.127	0.077	0.160	0.084	0.089	0.185	0.640	0.256	0.202
C17	1.00	0.00	0.00	0.060	0.131	0.068	0.076	0.068	0.117	0.059	0.096	0.080	0.066	0.185	0.348	0.213	0.202
C18	0.00	1.00	0.00	0.085	0.169	0.123	0.199	0.134	0.144	0.111	0.262	0.148	0.111	0.199	0.614	0.225	0.211
C19	0.00	0.00	1.00	0.103	0.158	0.090	0.219	0.125	0.127	0.073	0.305	0.106	0.081	0.180	0.581	0.234	0.200

Figure 11: TMY quality indicators for primary energy services and renewable and non-renewable energy

Concerning Figure 11, $\iota_{\Delta EP_S}$ and $\iota_{\Delta EP_S}$ indicators are calculated with previously equations based on primary energy services and renewable and non-renewable energy.

In **Table 13** optimum weighting coefficients are shown. TMYs C10, C14 and C17 provides high representative results for building types in cooling service with exception of B6, if the first and the second best values are considered. Same TMYs are selected for heating service and global non-renewable energy. This is due the fact that primary heating energy service is greater than primary cooling energy service. TMYs C7, C8, C10, C14 and C17 are representative of global renewable energy on long period. They have a more high coefficient for global solar irradiance than TMYs select for the global non-renewable energy. This is due to the considered renewable system.

Table 13: Optimum weighting coefficients for climate variables for primary energy services and renewable and non-renewable energy

Case Study Energy	B 1 	B2 	B5 	B6 
C	C 2 [0.5;0.;0]	C10 C14 C17 [0.90; 0.10; 0] [0.70; 0.15; 0.15][1; 0; 0]	C7 [0.75; 0.25; 0]	C8 [0.25; 0.75; 0]
H	C10 [0.90; 0.10; 0]	C17 [1; 0; 0]	C10 [0.90; 0.10; 0]	C12 [0.1; 0; 0.9]
gl,nren	C10 [0.90; 0.10; 0]	C17 [1; 0; 0]	C10 [0.90; 0.10; 0]	C12 [0.1; 0; 0.9]
gl,ren	C8 [0.25; 0.75; 0]	C7 [0.75; 0.25; 0]	C10 C14 C17 [0.90;0.10;0][0.70;0.15;0.15][1; 0; 0]	C8 [0.25; 0.75; 0]

Chapter 4

Models and data for energy efficiency measures of buildings on urban scale

4.1 Research question

Main building models, got from literature, are previously presented in in the Section 1.3. For the advantages highlighted in respective subsections, the white and gray models are the ones that are most used for analysis on an urban scale. For instance, Chen and T. Hong [93] investigated the impacts of building geometry modelling methods on the simulation results of urban building energy models by EnergyPlus simulations. Reinhart and Davila [31] made an ample review of urban building energy modelling case studies. They suggested to use dynamic thermal models using simulation engines (such as DOE2, EnergyPlus, IDA-ICE, TRNSYS) for evaluation of detailed urban design scenarios as well as urban-scale retrofit analysis.

The PhD candidate questioned himself about the following aspect to reply of the main question.

Which can models and data be used for EEMs of buildings on urban scale? In order to respond as completely as possible, case study is searched which would allow this investigation. The collaboration with Aachen University met this need. The PhD candidate collaborated in "EnEff: Campus RoadMap RWTH Aachen". The project was funded by the German Federal Ministry of Economic Affairs and

Energy (BMW) and it aims to provide energy analysis, modeling and energy efficiency measures of university campus. The final target of this collaboration is to identify the buildings, offering an efficient recommendation of measures for energetic retrofiting.

The question is faced as shows the fellow Figure 12.

Some section or part of them are citations or re-arrangends of the related paper.

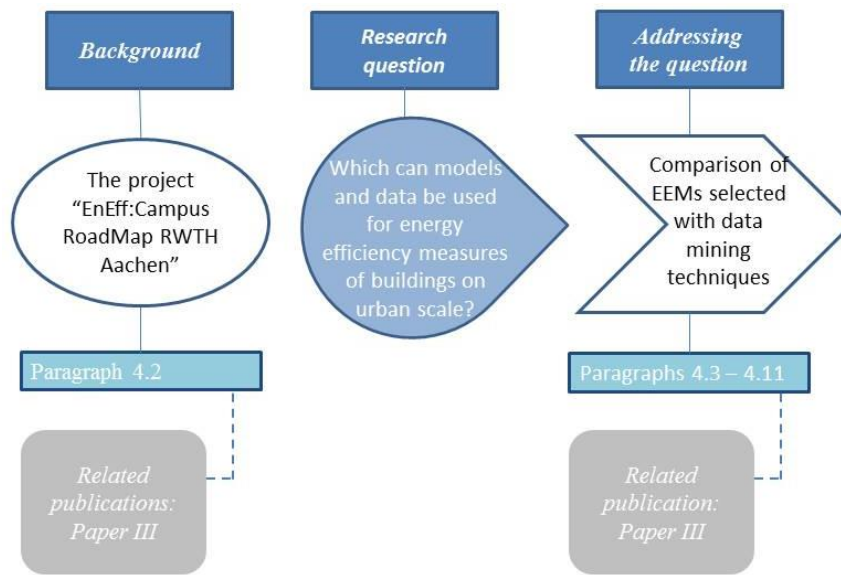


Figure 12: Scheme chapter 4

4.2 The project “EnEff:Campus RoadMap RWTH Aachen”

The central aim of the project is to develop a road map for the RWTH Aachen University which leads to a cost-effective reduction of specific primary energy consumption at RWTH Aachen University by 50 % until 2025, based on the energy consumption of 2013/14. The RWTH Aachen building stock counts about 300 buildings which differ for instance in the following characteristics: usage type, year of construction, and building structure typology.

To reach the central aim of the project, a city district performance simulation is applied and a systematic approach has to be followed, by using LOM and distribution network energy performance models. The city district performance simulation needs the LOM to calculate heating performance and

demand in satisfying computation time. The parametrization of the LOM is set up by archetype buildings. Lauster's investigations show that the used LOM leads to high accuracy compared to detailed simulation models [94]. Concerning the usage of statistical data for enriching LOM parameters, Schiefelbein describes the generation of archetype buildings by only five input parameters: "building type, year of construction, floor height, number of floors, net floor area" [95]. As the accuracy of statistical data depends on dataset, the parametrized LOM characterized by the five input parameters were investigated with respect to a similar building stock as the one of the RWTH Aachen Campus. Results achieved a corresponding compliance for the thermal city district simulation with respect to measurements [96]. All things considered, Lauster showed that the LOM is suitable for city district simulation due to the accurate estimation of heating load and energy demands [96].

4.3 Data mining technique

The aim of the investigation is to apply data mining methods for the determination of efficient energetic retrofit measures on a city district scale. Data mining methods enable the examination of a large number of parameters, for instance those, which influence the energetic behaviour of a building stock, like building construction parameters, such as U-Values, transmission heat loss coefficient, average efficiency ratio of the energy supply, and ventilation rate. In this investigation, two different approaches will be compared. The first one is a visualization method, which determines boundary sets in diagrams for filtering data, and the second one is the usage of CART algorithm. The different approaches are compared by LOM building performance simulation.

4.3.1 Visualization technique

When a large amount of data have to be analysed, there is a risk that they would become data dumps when there is not the possibility to adequately explore the data set. Information visualization focuses on data sets lacking inherent 2D or 3D semantics and therefore also lacking a standard mapping of the abstract data onto the physical screen space, as said Keim et al. [97]. More well-known techniques for visualizing of datasets are x-y plots, line plots, and histograms. These techniques are used for data exploration, but they are suitable with low-dimensional datasets. The data analyst can identify interesting subsets through the visualization technique which provides an overview of the data.

There are simple methods to determine energetic building retrofit measures with a potential of energy savings, however, they do not always provide high savings, as in previously work, Paper III [47], where the subset was realized with subjective value. In this study is used a standard 2D display x-y plot, where axis are the specific energy demand and the net leased area respectively. The x-y plot is divided in quartiles. In Table threshold limit values are shown which split data in 25 percent, 50 percent and 75 percent of the population.

Table 14: Threshold limits of specific energy demand

Specific energy demand	
Threshold limits	Value [kWh/m²]
1 st quartile	132
2 nd quartile	201
3 th quartile	323

Table 15: Threshold limits of net leased area

Net leased area	
Threshold limits	Value [m²]
1 st quartile	374
E,F, 2 nd quartile	1128
3 th quartile	2515

The visual information is to select subsets. The aim is to select a limited number of buildings that can provide high energy savings. In the plot x-y

buildings with high specific energy consumption and high net leased area are the most favourite buildings for the requalification. Doubts arise about which buildings will be object of renovation when buildings with high specific energy consumption and low net leased area are compared with buildings with opposite characteristics, low specific energy consumption and high net leased area.

Data sets that are taken into consideration are those shown in the following figure. Data set does not include the first quartile because an high number of buildings would be considered.

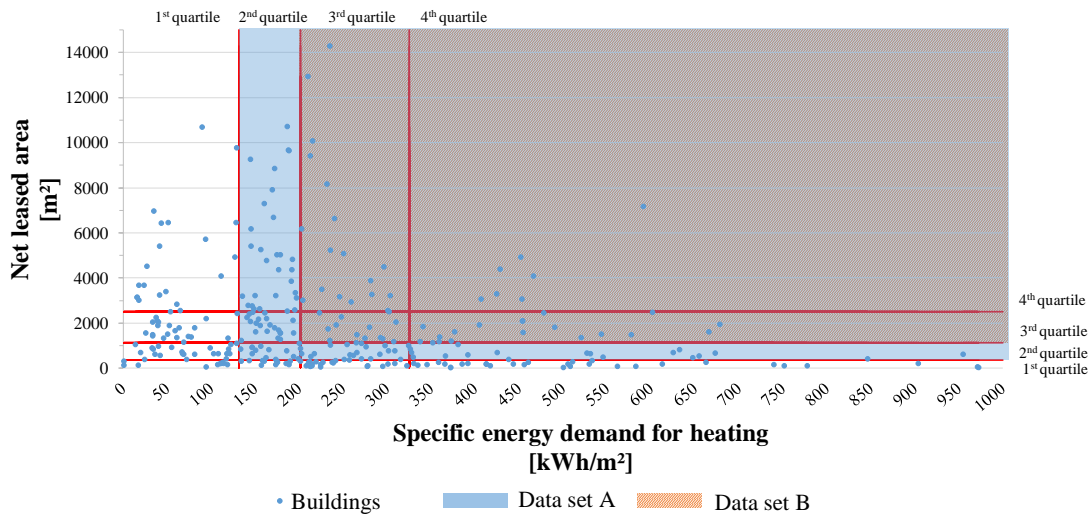


Figure 13: Considered data sets by visualization method

This visual illustration and analysis point out buildings, which could have a potential for retrofitting. Nevertheless, it has to be mentioned, that these are processes accounted by only two parameters, they hence represent a very simple way of filtering. On city district level, it is common that the energetic behaviour is influenced by more than these parameters. Thus, the data mining method will be applied to the building stock of the RWTH Aachen Campus.

4.3.2 Decision tre with CART algorithm

Data mining aims to determine models for decision making. In the energy context, the models used in this investigation represent two different types and depend on the scope: classification on the one hand and regression models on the other hand. The first kind of models try to assign a class for each observation (each line in a data set), considering information derived from a data set with classes which are already known (called learning sample). The second kind of models predict the attributes of a dataset which influence a given outcome

stronger than other attributes. Common techniques of classification are decision trees. The algorithms which are frequently associated with decision trees are: ID3, C4.5, CART, CHAID, SLIQ, SPRINT. In this work, a decision tree is chosen to show a group of rules of classification in a tree scheme and it is matched with the CART algorithm [98]. A regression tree is used to predict problems in case the response variable is numeric or continuous. This algorithm is adopted for a supervised multistage decision-making process to classify observations in a finite number of classes. In the literature, this approach has already been tested to rank flats based on calculated normalized primary energy demands calculated with a quasi-steady-state method, as show Capozzoli et al. [99][100].

The decision tree starts with root node which contains the complete data set and is used as learning sample. Successively, the decision tree sub-divides data set using a binary split in homogeneous subsets, considering $2k-1$ ways of creating a partition of k attribute values, and gives the origin to a new node. The Last nodes in the tree are called leaves and each node is labelled with the attribute's name. Tree branches show the path which respects a series of rules and classifies the samples. With a rising number of rules, the tree appears more and more complex which should be avoided to maintain the usability. For this reason, a so-called pruning can be applied. The criterion used is called Gini Index, which evaluates the degree of impurity of each node. The data are split for each node that maximizes the decrease of impurity.

Another element to characterize the tree is to evaluate the statistical performance of the model if a new dataset is used. In this investigation, a k -fold cross-validation is applied. This technique divides the dataset in equal k -parts and for each step; one part is used for the validation of data set, while the other one is used for training the dataset.

The models are developed with Rapid Miner 7.3.001.

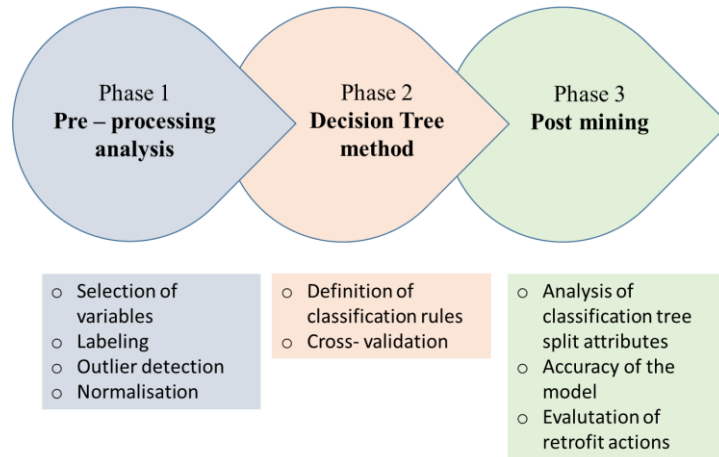


Figure 14: Scheme of the analysis with Decision Tree method

It is shown in Figure 14 the framework of analysis with Decision Tree method. Each phase is shown in following sections.

4.4 Low order building model

4.4.1 TEASER

TEASER uses statistical approaches based on the IWU [101] building typology [95]. The minimum required input data consist of the following five parameters: year of construction/ year of retrofit, building height, net leased area, number of storeys, and usage type.

These parameters are the basis to estimate envelope areas for exterior walls, windows, rooftops, and basement. Furthermore, the constructions of envelope structures are parameterized. This data enrichment provides a full dataset for the “MultizoneEquipped.mo” zone model of the Aixlib library. In this investigation, TEASER is applied to set up building models of the RWTH Aachen Campus building stock and is used to highlight differences of recommended estimated retrofit measures.

The mentioned LOM “MultizoneEquipped.mo” is an RC-Model based on the German Guideline VDI 6007-1 [94]. Lauster modified the guideline model by adding an extra resistance representing the thermal behaviour of window elements. To keep the information content low, a minimum number of zones should be the aim of low order modelling. Therefore, only a small number of zones represent the building in the thermal building performance model.

The accuracy of the TEASER tool chain for enriching the data by mentioned five parameters to set lumped parameters was evaluated by Lauster [96], and assessed to be suitable for city district energy performance simulation.

The applied low order models used for this investigation are supplied by the AixLib library version “The Modelica _Annex60_ library”. This library is currently still under development.

4.5 Data set

4.5.1 Origin of the data set

The building stock of the RWTH Aachen University campus consists of about 300 buildings. In Figure 15 is shown distribution of buildings for year of construction.

The specific value of the energy consumption (EC) or the campus’ total energy demand (ED) for heating amounting to approx.. 120,000 MWh [102].

Figure 16 shows the distribution of the EC of the RWTH Aachen building stock split into German energy efficiency classes (only 125 consumption values are available).

Figure 17 describes the distribution of the estimated ED by applying TEASER and LOM (299 data of ED are available); the estimated average of the yearly ED for heating is about 249 kWh/m² with respect to the net leased area

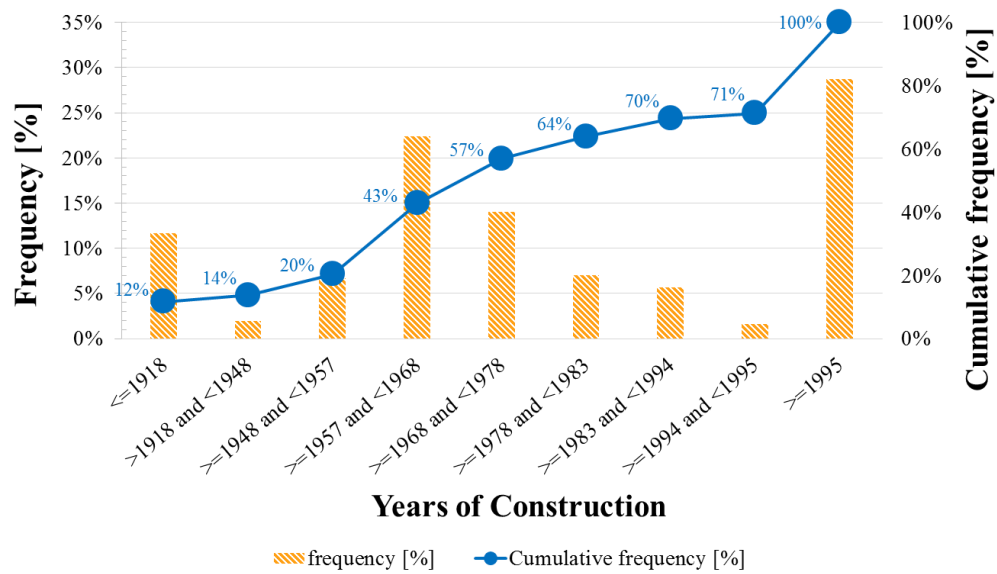


Figure 15: Distribution of the year of construction of the buildings

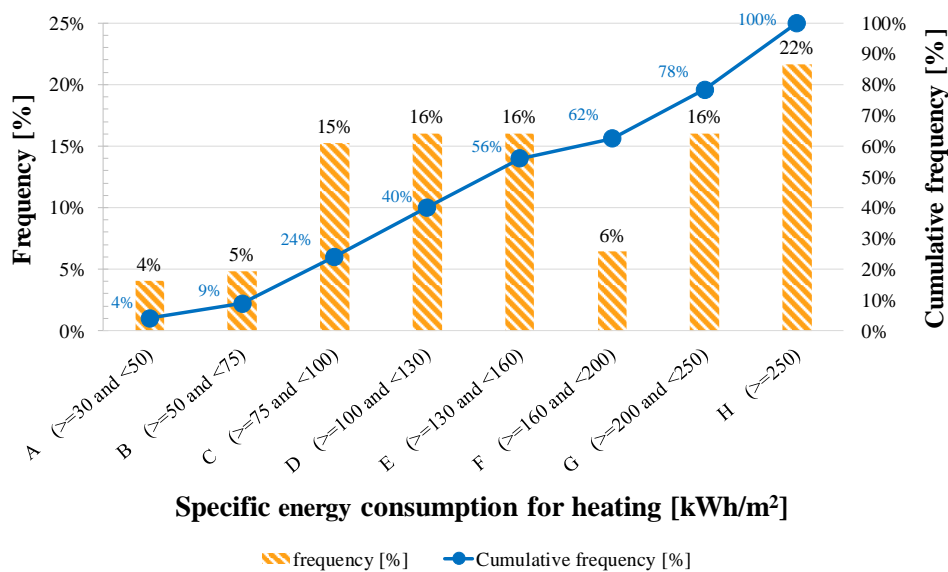


Figure 16: Distribution of the energy consumption of the buildings into German energy efficiency classes

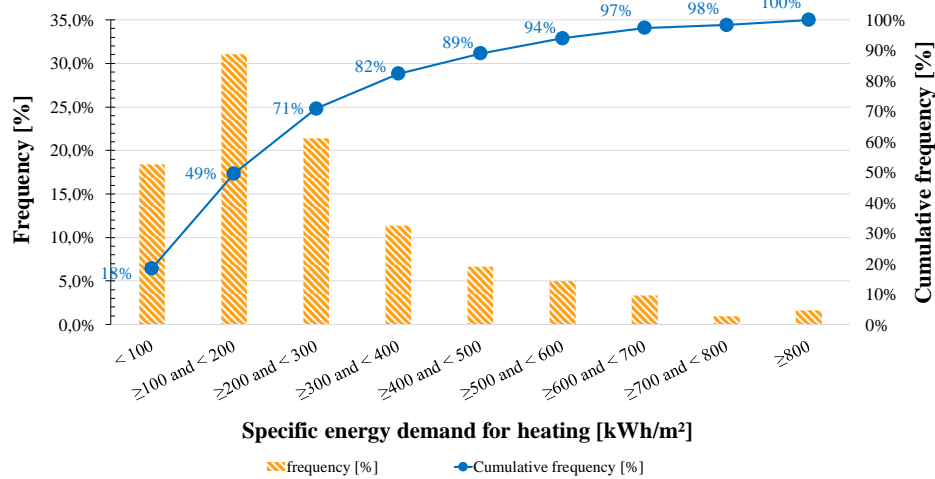


Figure 17: Distribution of the energy demand of the RWTH Aachen University Campus, estimated with TEASER and LOM

Figure 16 and Figure 17 illustrate that most of buildings have a high specific EC and ED for heating. This could yield to the assumption that a lot of buildings should have a high potential for energetic retrofitting. In the further reading, some characteristics of the data set are presented.

4.5.2 Characteristics of the data set

To show some important characteristics for the description of the energetic behaviour of the buildings, like U -values of the total vertical facade or opaque facade following histograms are illustrated in Figure 18 and Figure 19.

The distribution of the total mean U -value of facades is shown in Figure 18. The figure shows that there are 35 % of buildings with a U -value above 2.1 W/(m² K) and approximately 21 % above 2.4 W/(m² K). Hence, the focus of the investigation is indispensable and the main goal is the determination of facade retrofit measures. Furthermore, Figure 19 illustrates that the opaque U -values are for 32 % above 2.1 W/(m² K) and for 43 % under 0.9 W/(m² K). This leads to the allocation of window U -values. As mentioned before, the data set which describes the campus was emulated by TEASER; therefore, only two categories of windows are available.

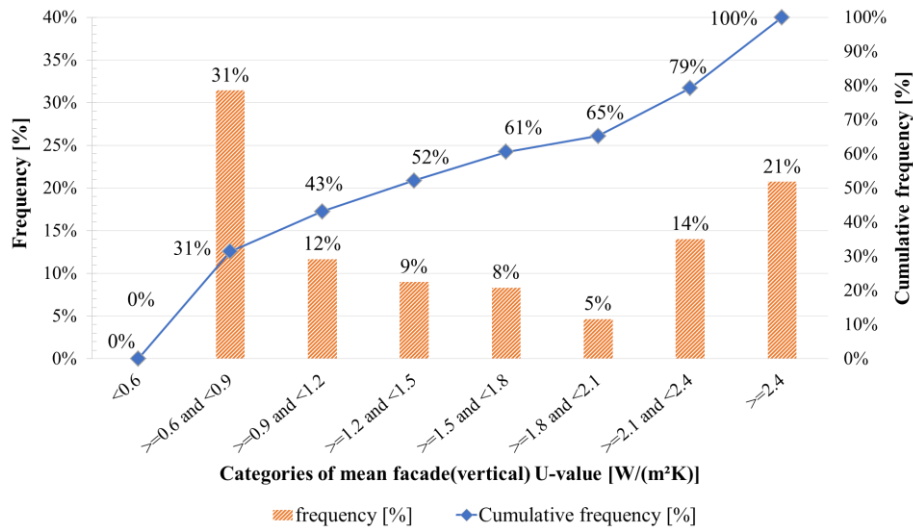


Figure 18: Distribution of the total mean U-value of the building facades, based on data estimated with TEASER

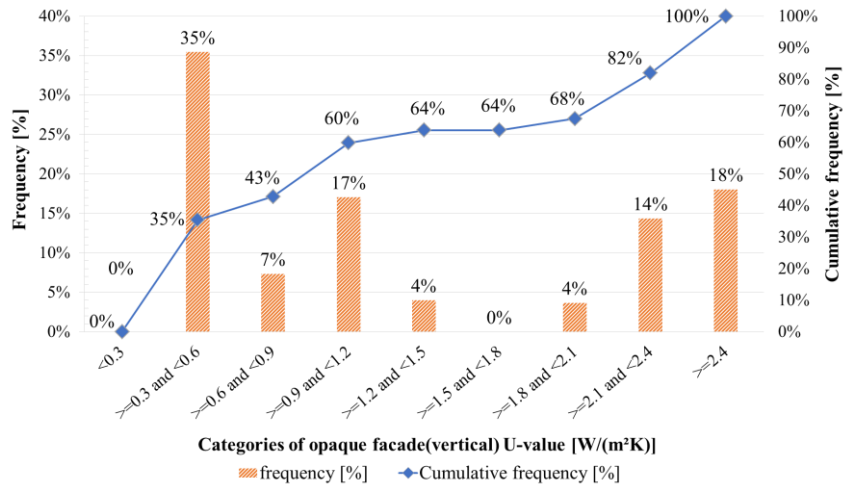


Figure 19: Distribution of the U-value of the opaque building facades, based on data estimated with TEASER

A category groups the window with thermal transmittance values between $1.5 \text{ W/(m}^2 \text{ K)}$ and $2.0 \text{ W/(m}^2 \text{ K)}$, and another with a thermal transmittance values above $2.8 \text{ W/(m}^2 \text{ K)}$.

Figure 20 deepens the correlation between average U-value [$\text{W/(m}^2 \text{ K)}$] and the transmission heat loss coefficient [W/K].

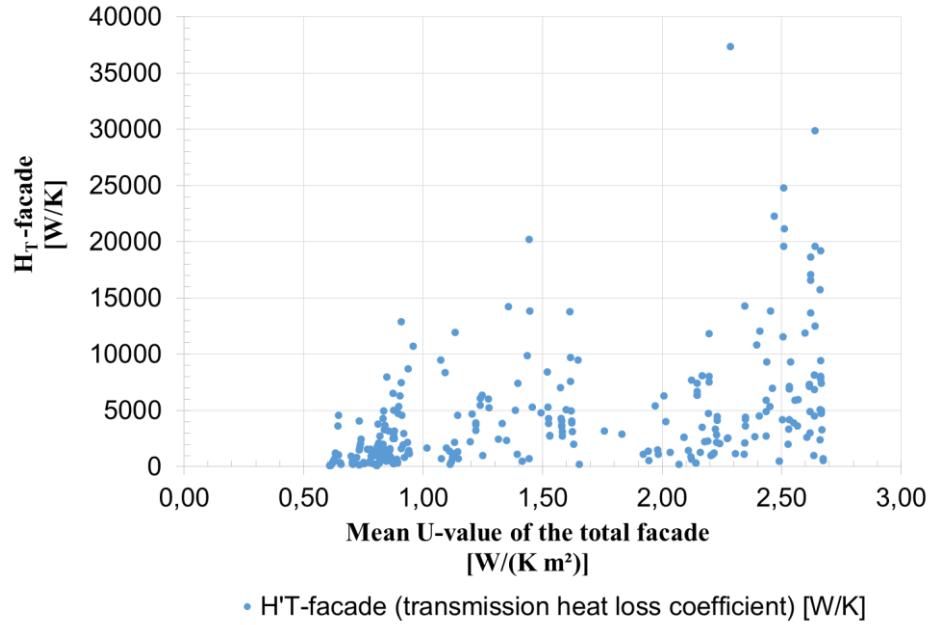


Figure 20: Qualitative overview of buildings with a high total facade U-Value and a high transmission heat loss coefficient H_T [47]

4.6 Determination of retrofit measures by the Visualization technique

As mentioned in section 4.3.1, the filter settings for determining the buildings which have to be retrofitted are indicated by the diagram in Figure 13. For this investigation two filters are set and applied on the data emulated with TEASER.

Table 14 and **Table 15** show boundaries of the first and the second visualization method filters. They subset the data set in Data set A and Data set B. The first set has specific energy consumption higher than 132 kWh/m^2 and net leased area higher than 374 m^2 . These boundaries selects 159 buildings. Data set B has specific energy consumption higher than 202 kWh/m^2 and net leased area higher than 1128 m^2 . The selected buildings are 57.

The energy renovation of these two data sets is carried out by energy efficiency measures both on the opaque and on the transparent envelope. This is due the fact that there are no information from the plot x-y on the envelope characteristics of the selected buildings.

4.7 Pre-processing of the data set

In this phase, different strategies are considered to prepare the data for an analysis. Firstly, outliers are detected and the values are normalized. Secondly, variables which influence attributes are selected. Finally, a data transformation is carried out.

To detect the outliers of the data set, a distance-based outlier detection algorithm is applied. Thereby, the Euclidean distance is calculated between the data points, and the ones with the greatest distance from other data points are marked as outliers. In order to grant equal consideration of the attributes, it is necessary to normalize the data set.

After the data analyses and the review of similar studies in literature [99][100], the following attributes are selected:

- *aspect ratio S/V ,*
- *heat transfer surface on heated volume in $[m^{-1}]$,*
- *U -value opaque, U -value of the vertical opaque envelope in $[W/(m^2 K)]$,*
- *H_T -value wall, the mean overall heat transfer coefficient by thermal transmission of the opaque components in $[W/K]$,*
- *U -value window, U -value of the vertical transparent envelope in $[W/(m^2 K)]$,*
- *H_T -value window, the mean overall heat transfer coefficient by thermal transmission of the transparent components in $[W/K]$.*

*The attributes are chosen based on the information gain they can give. For this reason, it is common that the attributes of the data set are independent and only the label attribute is clearly dependent of the other attributes. In this section, considered data sets are in **Table 16**.*

Table 16: Data set and corresponding attributes

Data set	Considered energy	S/V	U opaque	H_T wall	U window	H_T window
Data set C	EC	✓	✓		✓	
Data set D	EC	✓		✓		✓

Data set E	ED	✓	✓		✓	
Data set F	ED	✓		✓		✓
Data set G	ED	✓	✓	✓	✓	✓

ED: energy demand
EC: energy consumption
VM: visualization technique
CART: decision tree with CART algorithm

Sets C and E are used with all variables showed before with the exclusion of H_T . Data sets D and F take all shown variables into account with exception of U-values. Data set G takes all the previously variables.

Data transformation introduces criteria to label each building according to the “high”, “medium” or “low” category. These labels are necessary, as the classification tree is based on a categorical response variable. Each “high” category starts from the trimmed mean to the maximum value of energy performance. The thresholds between the categories “high-medium” and “medium”-“low” of the ED data set are 241.05 kWh/m^2 and 50.00 kWh/m^2 , respectively. The first threshold limit is the trimmed mean, which is calculated by excluding the 5% of the extreme values. The second threshold limit for the “low” category applying ED comes from the energy efficiency class of EnEv2014 [103].

The thresholds between the categories “high-medium” and “medium”-“low” of the EC data set are 171.52 kWh/m^2 and 74.00 kWh/m^2 , respectively. The first threshold limit is the trimmed mean, which is calculated by excluding the 5% of the extreme value. The threshold limit of the “low” category applying EC is based on a similar percentage of buildings as in the “low” category applying ED (the same percentage is impossible due to data set). The percentage of buildings in categories “high”, “medium”, “low” with the ED data set is 36 %, 54 % and 10 %. Categories with the EC data set have the following percentages 41 %, 50 % and 9 %.

Table 17: Energy demand categories

Consumption class	Energy demand	Percentile
Low	$0 < ED \leq 50.00$	10
Medium	$50.00 < ED \leq 241.05$	54
High	$ED > 241.05$	36

Table 18: Energy consumption categories

Consumption class	Energy consumption	Percentile
Low	$0 < EC \leq 74.00$	9
Medium	$74.00 < EC \leq 171.52$	50
High	$EC > 171.52$	41

4.8 Decision trees

Data set C, D, E, F and G are evaluated with CART algorithm. Three decision trees of three data sets are shown below. All showed values are normalized data. The first data set is determined with the input of the specific EC for heating. It is illustrated in Figure 21. All showed values are normalized data. For each subset is defined the number of classified buildings and the relative percent on total. Leaves show the category of classified buildings.

The decision tree of Data Set E with ED is shown in Figure 22. It classifies 221 buildings, thus, more buildings than the first one. Furthermore, in these decision trees, there aren't any attributes about transparent components and the root node is always the U opaque, but with different values. The Figure 23 show the decision tree of Data set G.

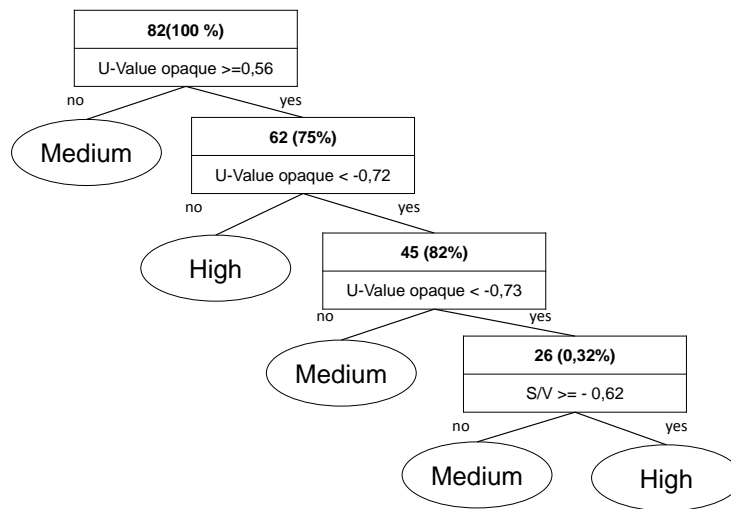


Figure 21: Decision tree based on EC with Data set C [47]

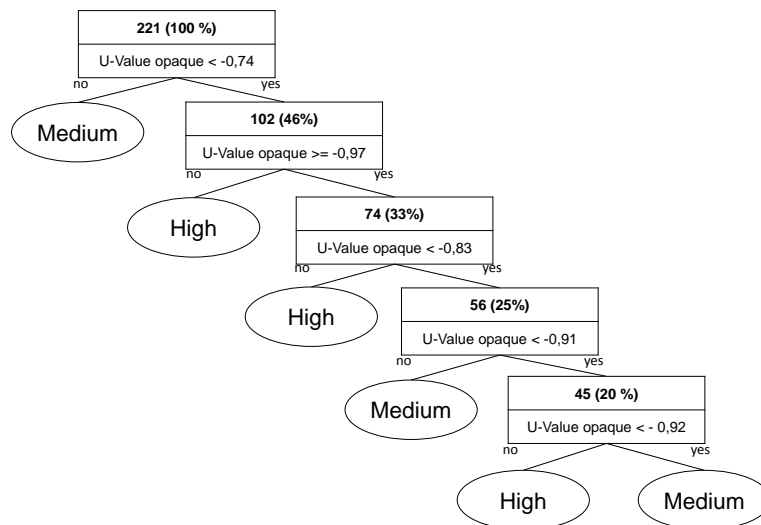


Figure 22: Decision tree, based on ED with Data set E [47]

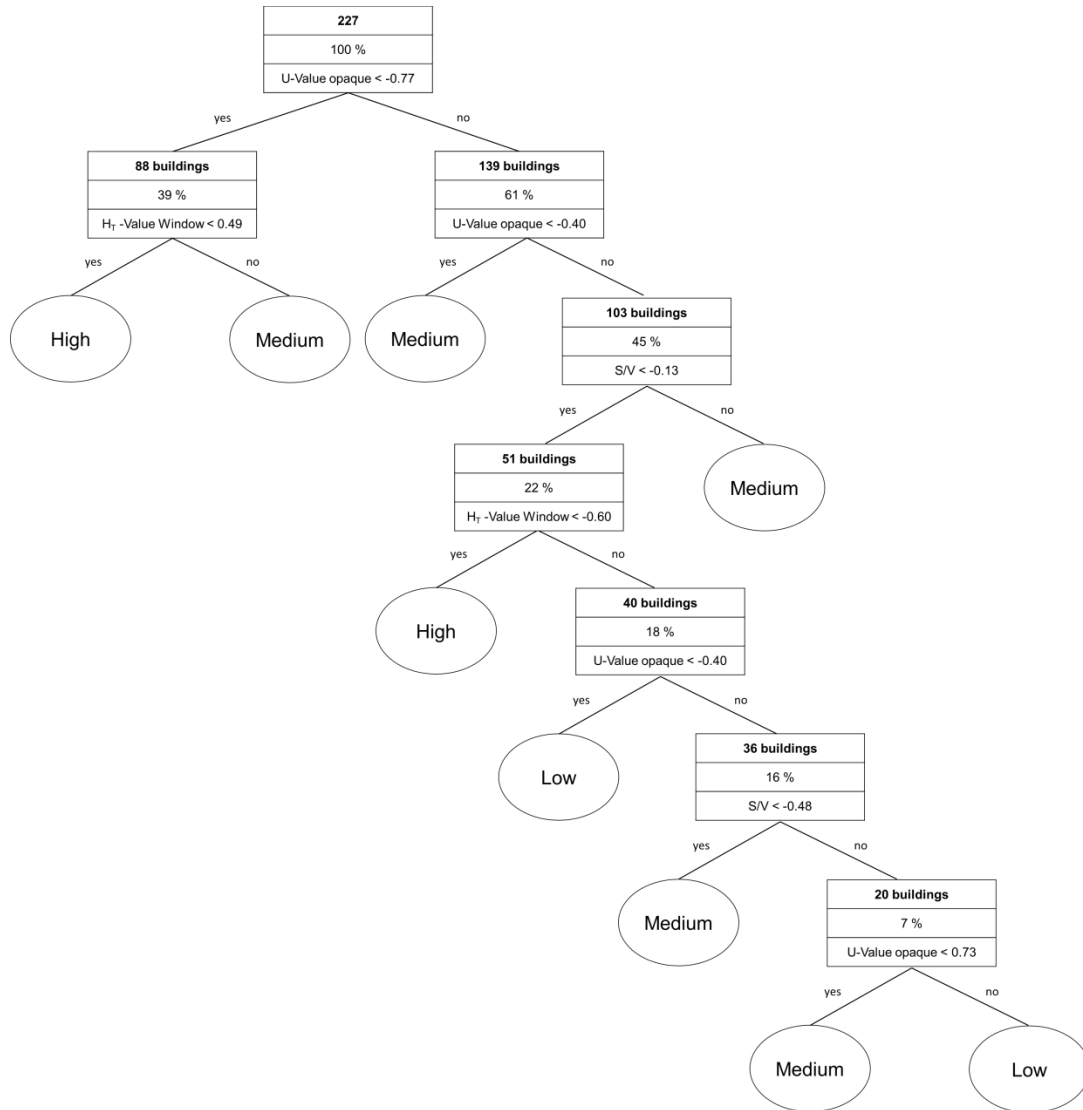


Figure 23: Decision tree, based on ED with Data set G.

4.9 Post mining

4.9.1 Analysis of classification tree split attributes

The first attribute enables us to split data in the Root Node, representing the one with the most influence on the energy consumption or demand.

The decision tree based on Data set C with EC has 5 leaf nodes and a tree size of 9. The main attribute is if the U-value of opaque facade is bigger or equal than 0.56. Furthermore, in this decision tree, there aren't any attributes about transparent components.

The decision tree, based on Data set E with ED, has 6 leaf nodes and the size of 11. The main attribute of this decision tree is if the U-value of opaque facade is smaller than 0.7 (with normalized data).

The decision tree, based on Data set G with ED show always the main node of other decision trees, but with different values. The graph show nine leaf nodes and his size is 17.

4.9.2 Classification accuracy

The training records which are correctly classified by the decision tree based on EC are about 66 % of all buildings. The accuracy of the same model is 52.97 % with 5 k- folders of cross validation.

Concerning training records of decision trees based on ED are about 78 % of the whole considered buildings, and the model accuracy about 70 % with 10 k-folders of cross validation. The accuracy of the whole classification of about 70-80 % [104] is considered acceptable. The lower number of buildings influences the model based on energy consumption negatively. The model of classification based on ED is recommended to evaluate retrofitting measures for higher accuracy.

4.9.3 Evaluation of retrofit actions

The decision trees visualize the main attributes which classify buildings and influence the energy consumption or demand. In the upper part of the tree, close to the Root Node, there are attributes that classify most of buildings. Each node could consider a retrofit action. In this study, for each building the following retrofit measures are considered: retrofitting of only transparent components or retrofitting of only opaque components. The retrofit actions are applied only in leaf nodes.

An attribute doesn't necessarily give the possibility of a refurbishment, such as in the case of the S/V-ratio (last node of the Figure 21). The retrofit actions are applied on all the buildings with the characteristics indicated by the attributes in the leaf nodes, including buildings not classified by the decision tree. The excluded buildings from retrofit actions belong to "low" categories (both with EC and ED). These are not considered, because priority is given to buildings which are classified as "high" and "medium".

If all buildings would be renovated, the specific energy demand would be approx. 72,540 MWh and the maximum saved energy would be about 39 percent of the pre-retrofit specific energy demand.

4.10 Comparison of the data sets

With the Visualization technique and the Decision Tree approach, six different data sets are evaluated. In **Table 19** are shown all the considered data sets. The main differences are the considered energy, demand or consumption, and the selection method, Visualization technique or Decision Tree with CART algorithm. Data set A and B are identify by visualization technique in section 4.3.1. Data set A suggests to renovate 159 buildings, whereas Data set B suggests to renovate 57 buildings. All the results of retrofit actions are analysed by applying a building performance simulation using LOM. The energy renovation of these two data sets is carried out by energy efficiency measures both on the opaque and on the transparent envelope.

Table 19: Considered data sets

Data set	Considered energy	Applied method
Data set A	ED	VT
Data set B	ED	VT
Data set C	EC	CART
Data set D	EC	CART
Data set E	ED	CART
Data set F	ED	CART
Data set G	ED	CART
ED: energy demand		

EC: energy consumption

VT: visualization technique

CART: decision tree with CART algorithm

Results are illustrated in Figure 24. Data Sets A and B do show large differences. The most energy save is with the Data set A. However, how was assumed in section 4.3.1, the Data set B have the most high potential of energy save. The prove is that the energy demand saving of Data set B is only about 14 percent less than the energy saved demand of Data set A, but without renovate 102 buildings.

Data Sets C and D with the Decision Tree select 73 and 72 buildings respectively. Estimated energy saves are low with Data Set C and D. They are of 11.0 percent and 11.4 percent respectively. This is due to Decision tree model with Data set C and D is not so accurate (approx. 53 percent).

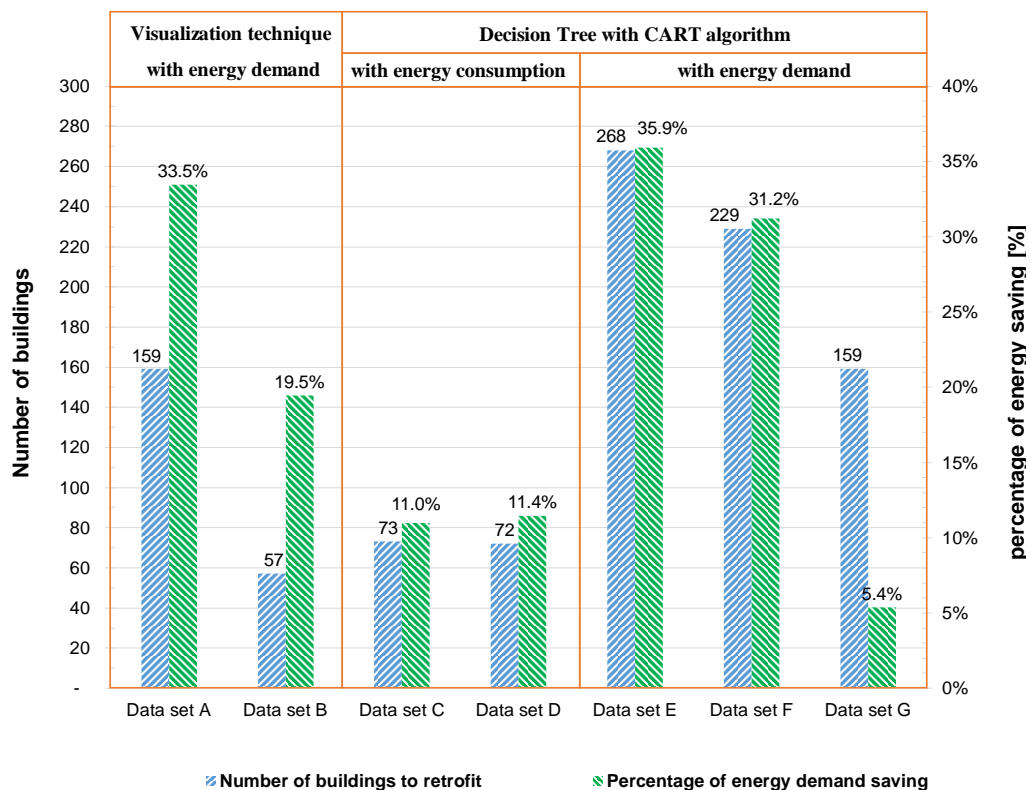


Figure 24: Comparison of different evaluated recommendations by the two different methods: visualization technique and decision Tree with CART algorithm

Data set E has the most energy saving potential but also the highest number of buildings to refurbish. The Data set G show the lower value of energy demand saving. This last result gives the opportunity to reflect if it is always correct to select retrofit action based on only leaf level.

4.11 Analysis of different levels of EEMs

Retrofit energy measures have been applied until now to buildings that end up in the leaf-level subset, as shown in the literature [99]. This approach saves energy, but the performance is lower than that with Visualization technique in this study. Since the root node also is the main attribute to classify the data set, it has to be considered for retrofit actions. In this section is investigated the possibility of applying EEMs in the leaf-level subset considering upper attributes. A diagram with considered levels is given in Figure 25.

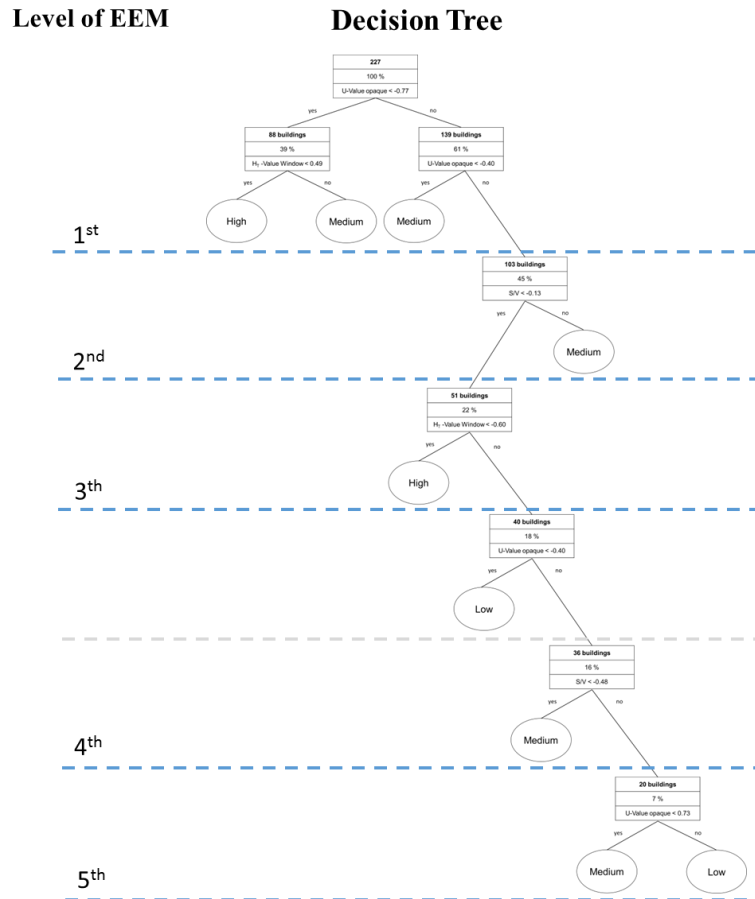


Figure 25: Levels of EEMs of decision tree based on Data set G

For instance the first level is applied at an High subset and two subsets labelled Medium. Buildings belong to High category are renovated with EEMs on opaque and transparent envelope because they are split by U_{opaque} and H_T window respectively. When the attribute is S/V, no retrofit action is applied for this attribute but only for those before of it.

The decision tree with Data set G show five level of EEMs. The results are plot in the following Figure 26.

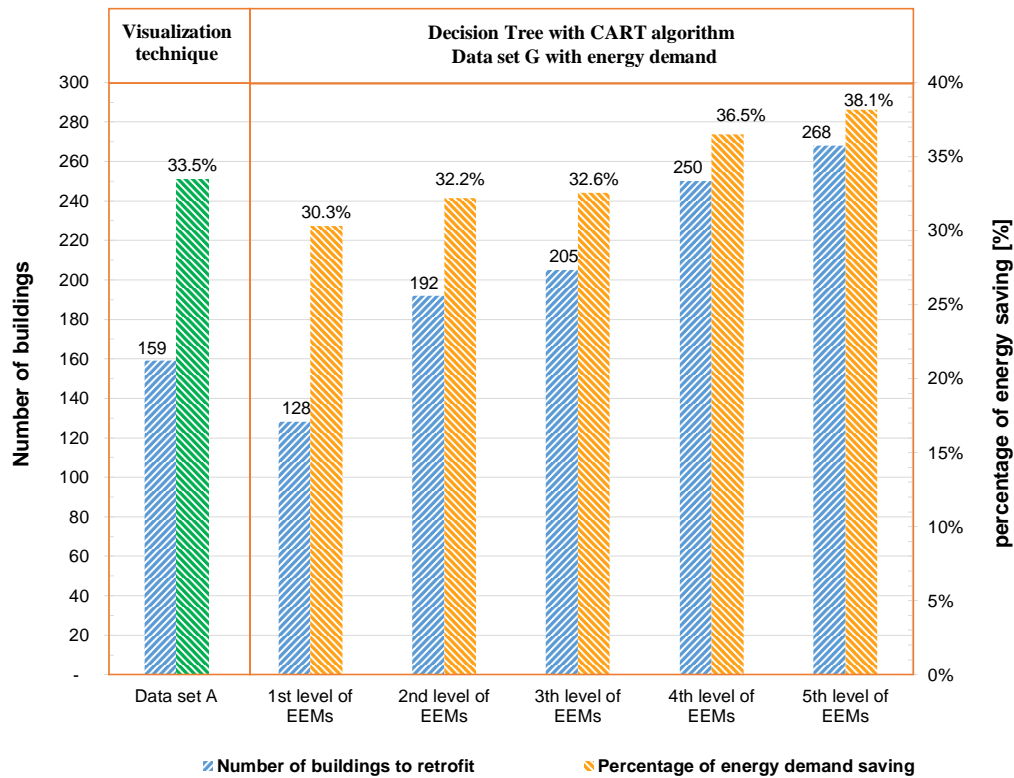


Figure 26: Levels of EEMs with Data set G

Levels of EEMs show increasing energy savings, as well as the number of buildings. The 1st level of EEMs show the 30.3 percent of energy demand saving with only 128 buildings. This saving with the first level of EEMs is less than with Data set A, however the difference is very closed. Moreover the Visualization technique with Data set A achieves the 33.5 percent of saving renovating both opaque and transparent envelope of 159 buildings, while the 1st level of EEMs suggests to renovate the whole envelope of 106 buildings and only the opaque envelope of 22 buildings. Finally, the Decision Tree show the priority of subset to renovate and how to do it.

Chapter 5

Definition of minimum building requirements

5.1 Research question

The building energy performance requirements in regulations are defined by means of a fixed value or a variable value defined through a formula or the notional reference building approach. The latter is the most promising to lead to nZEBs because it is more flexible than previous methods.

The secondary question leads the PhD research in the application field of the definition of minimum building requirements is the following (Figure 27).

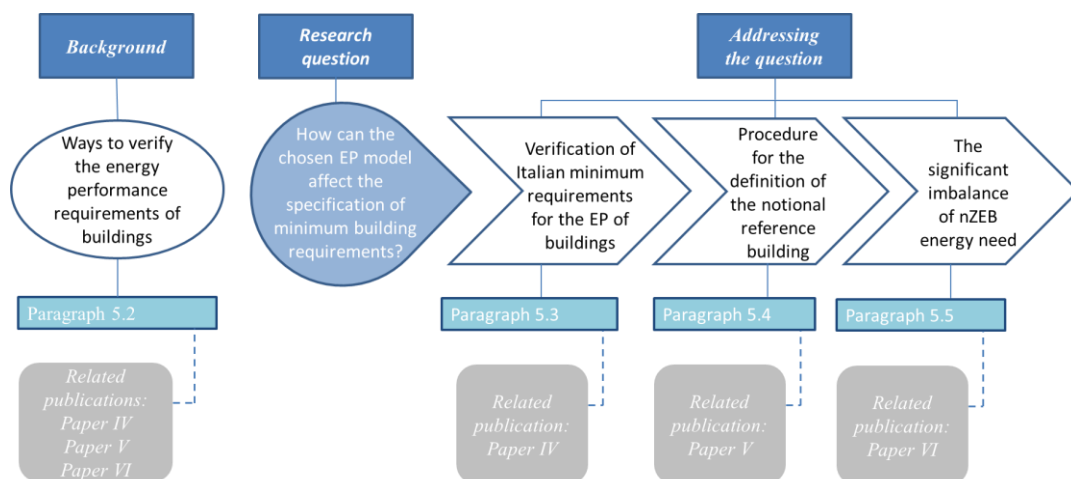


Figure 27: Scheme chapter 5

For addressing the question in a first phase is studied the Italian regulation which has been introduced the notional reference building on 2015 by the Italian Ministerial Decree 26/06/2015. It defines nZEBs requirements and demands that new building energy performance is compared with a notional reference building, which has the same location, function, size, but reference insulation level and technical building system efficiencies. The research aims both to investigate technical feasibility of design solutions complying with legislative requirements and to verify the notional reference building approach. The analysis is applied to a residential building in three Italian climatic zone and highlights limits of the notional reference building approach in the Italian legislation through the application of the standard quasi-steady-state calculation method (published in [48], Paper IV).

The aim of the second part of the work is to enhance the notional reference building approach application in the energy performance legislation. To this purpose, a detailed dynamic simulation is performed on an Italian residential nZEB located in two different climatic zones. The study highlights the need of more detailed reference parameters specifications in the notional reference building, especially when dynamic simulation is performed (study published in [49], Paper V). Compared to Paper V in this dissertation, a depth analysis is provided on the level of detail of technical building system requirements for heating.

The third part of the research starts from the observation that the Italian prescriptions for the notional reference building come into effect in two different steps. They aim of gradually increasing the building energy efficiency level through a reduction of reference building envelope components U-value. That causes a significant imbalance between the energy performance for different energy services, as for example, space heating and space cooling. The reduction of thermal transmittance determines the reduction of energy demand for space heating; by contrast, above all in warm climates, building super-insulation might cause higher energy demand for space cooling and indoor overheating. The finally objective of the research in this application field is to investigate in which conditions and extent a significant imbalance of energy needs for heating and cooling occur (published in [50], Paper VI). The analysis is performed on three different building types, i.e. single-family house, apartment block and office building, in two climatic zones (Milan and Palermo). The case studies energy performance is assessed by applying two steps of Italian energy efficiency

legislation sequentially and it is carried out by means of a detailed dynamic calculation tool (EnergyPlus).

5.2 Ways to verify the energy performance requirements of buildings

The Directive 2010/31/EU establishes that Member States define minimum energy performance requirements for building elements that have a significant impact on the energy performance with a view to achieving cost-optimal levels [4].

According to ISO 52003-1 [105] the requirements may be written as to modify (i.e. reduce, neutralize, correct or normalise) the impact of some parameters. For instance a requirement for an energy performance (EP) index may be expressed either (1) by a fixed value, or (2) by a variable value defined through a formula (or a table) as a function of some neutralising parameters (e.g. climate, building shape), or (3) by a variable value according to the notional reference building approach. In the last case, a reference EP is calculated for a building having the same location, building function, size etc. of the real building, but with parameters, such as thermal insulation level, heating system efficiency, activity schedules etc., replaced by reference values.

As highlighted by Pérez-Lombard et al. [80] in a review of benchmarking and rating concepts, the threshold value obtained through the formula approach should be dependent upon the parameters whose impact is to be reduced or neutralized. The authors suggest that the limit value should be discriminated at least by building category, climate, building shape, energy source and ventilation rate. In fact, the energy performance of different building categories cannot be comparable since they provide different energy services. In addition, especially in areas characterized by considerable geographic variations, the requirements should also take into account the climatic spatial variability. About that, some authors propose an increasing of the EP limit with the increasing of climate severity [106]. Pérez-Lombard et al. [80] suggest that a customised limit may be obtained by the self-reference (called notional reference building) approach.

The EU countries gradually abandoned the fixed limit approach in their regulations in favour of a more flexible approach [35].

For instance, the current building regulations of England require that the energy performance of new buildings, based on annual carbon dioxide emissions, must not exceed the Target CO₂ Emission Rate (TER), which is determined by means of the notional reference building. This building has the same size and

shape as the actual building, but with specified properties, such as thermal transmittance and thermal capacity of the envelope components, air permeability of enclosures, parameters for lighting, technical building system efficiencies, etc. [107] [108].

According to EnEV 2013 [109] the notional reference building is characterised by pre-determined values of some building parameters. They include envelope air tightness, thermal transmittance of envelope components, total solar energy transmittance of glazing, characteristics of the shading devices, thermal bridges effect, solar absorption coefficient of the external opaque surfaces, building automation, features of reference technical building systems.

The Greek regulations [110] provide the parameters of the notional reference building in function of the climatic zone. They include the maximum U-value for walls, windows, roofs etc., the average U-value of the whole building, at least 50% heat recovery in the central air-conditioning units, minimum levels of insulation of heating and cooling distribution networks, at least 60% of DHW production from solar panels, minimum requirements for lighting and minimum efficiency for heating generators.

In Italy, according to the Ministerial Decree (MD) 26/06/2015 [56], the notional reference building, also named reference building or target building, is characterised by reference values of the following parameters: thermal transmittance of the envelope components, total solar energy transmittance of windows in presence of shading device, efficiency of the heat utilization and of the generation subsystems of space heating, space cooling and DHW systems, and features of lighting and ventilation systems.

The choice of the reference parameters varies from one country to another; for instance, a reference thermal transmittance is common to all countries, while just some States use the envelope air tightness as reference parameter (e.g. Germany and England) and only some impose specific technologies for the technical building systems (e.g. Greece). The threshold values of the parameters can be different and can vary in function of the climatic zone, the building category, etc. For example, the reference U-values of the Italian and Greek notional reference buildings are provided in function of the climatic zone, while in Germany and in England the U-values differ in function of the envelope component types (e.g. cavity wall vs solid wall, vertical window vs skylight). In the European Union, the reference parameter values have been identified by each Member State through the cost-optimality comparative methodology framework [4].

As regards technical standards, ANSI/ASHRAE/IES Standard 90.1 [111] provides minimum energy efficient requirements for design and construction, and a plan for operation and maintenance of new buildings or portions of buildings and their systems, new systems and equipment in existing buildings. The standard also provides criteria for determining compliance with these requirements by using a notional reference building, the so-called baseline building. The baseline building approach is used for calculating the baseline building performance for rating above-standard design. The design building performance and the baseline building performance shall be calculated using the same simulation program, weather data, energy price, building model, space use and schedules. The baseline building differs from the design building for the U-value of the envelope components, the amount of glazing and its thermal properties, the type of lighting control, the HVAC system requirements.

5.3 Verification of the new Italian Ministerial Decree (MD)

The Italian Ministerial Decree 26/06/2015 on the “Application of the energy performance calculation methods and establishment of prescriptions and minimum requirements of buildings” [56](MD) entered into force in October 2015. It implements the national law no. 90/2013 [112] which transposes the Directive 2010/31/EU (EPBD recast) [4] in Italy, by modifying and integrating the legislative decree no. 192/2005. The MD sets the methodology for calculating the energy performance of buildings and establishes the minimum energy performance requirements of buildings and building units. It introduces new prescriptions, both for new buildings and for the energy refurbishment and renovation of existing buildings. It also specifies the requirements of nearly zero-energy buildings (nZEBs) that will be applied to new buildings and major renovations from 1st January 2019 for the public buildings and from 1st January 2021 for all the other buildings. As defined by the EPBD recast, a nearly zero-energy building is “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” [4].

In compliance with the decree, during the design phase many parameters must be checked, ranging from the features of single components to energy performance (EP) indicators regarding the whole building. In the latter case, the building energy performance requirements are based on the comparison between

the building and a notional reference building, which has the same location, function, size, but with parameters replaced by reference values Figure 28.

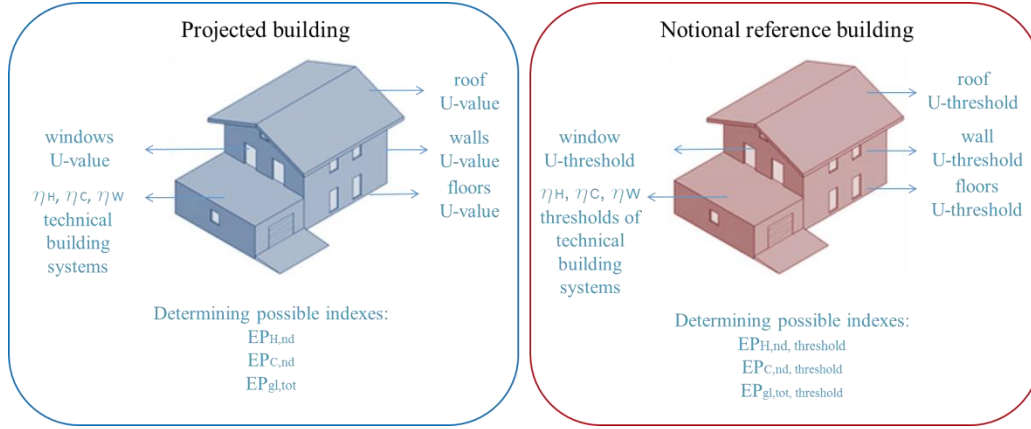


Figure 28: Notional reference building approach

The research aims to investigate the applicability of the MD for the verification of the nZEBs energy performance requirements, pointing out its limits and strengths.

In the present section, the following aspects related to the MD are discussed: (a) technical feasibility of the design solutions that comply with the legislative requirements set up for nZEBs, (b) issues concerning the reference building approach, (c) robustness of calculation methods in assessing low-energy buildings. To this purpose, the EP is assessed by the method prescribed by the MD (UNI/TS 11300) and by dynamic simulation (EnergyPlus).

The case study is a new residential nZEB located in three Italian cities (Milan, Rome and Palermo). The analysis focuses on different configurations of technical systems while a fixed package of solutions regarding the envelope has been assumed. All the energy services installed in the building are taken into account. Some high efficiency technical system variants are simulated, including technologies using renewable energy sources.

5.3.1 Energy performance requirements of nZEBs by Italian MD

The MD requires for new buildings to verify the following parameters concerning the building envelope:

- the mean overall heat transfer coefficient by thermal transmission (H'_T), calculated as:

$$H'_T = \frac{H_{tr,adj}}{\sum_k A_k} \quad (10)$$

where, $H_{tr,adj}$ is the overall heat transfer coefficient by thermal transmission of the building envelope calculated in accordance with EN ISO 13789 [113], and A_k is the area of the opaque or transparent envelope component k .

The maximum allowable value of H'_T is fixed by the MD 26/06/2015 in function of the climatic zone and of the compactness ratio of the building (A_{env}/V_g), as shown in **Table 20**.

Table 20: Maximum allowable value of the mean overall heat transfer coefficient by thermal transmission (H'_T) [$\text{W m}^{-2}\text{K}^{-1}$] [56]

Compactness ratio (A_{env}/V_g) [m^{-1}]	Italian climatic zone				
	Zone A and B	Zone C	Zone D	Zone E	Zone F
	(≤ 900 HDD)	($900 < \text{HDD} \leq 1400$)	($1400 < \text{HDD} \leq 2100$)	($2100 < \text{HDD} \leq 3000$)	($\text{HDD} > 3000$)
$A_{env}/V_g < 0.4$	0.80	0.80	0.80	0.75	0.70
$0.4 \leq A_{env}/V_g < 0.7$	0.63	0.60	0.58	0.55	0.53
$A_{env}/V_g \geq 0.7$	0.58	0.55	0.53	0.50	0.48

- the summer solar effective collecting area of the building ($A_{sol,sum}$), calculated as:

$$A_{sol,sum} = \sum_k F_{sh,ob,k} \cdot g_{gl,sh,k} \cdot (1 - F_F)_k \cdot A_{w,p,k} \cdot F_{sol,sum,k} \quad (11)$$

where, for each transparent envelope component k : $F_{sh,ob,k}$ is the shading reduction factor for external obstacles, $g_{gl+sh,k}$ is the total solar energy transmittance of the transparent part of the element in presence of a shading device, $F_{F,k}$ is the frame area fraction, $A_{w,p,k}$ is the overall projected area of the glazed element, and $F_{sol,sum,k}$ is the correction factor for the incident solar radiation, which is determined as the ratio between the solar irradiation of July, in the same site and orientation, and the mean annual solar irradiation in Rome on a horizontal plane.

According to the decree, the maximum allowable value of the summer solar effective collecting area related to the building conditioned net floor area ($A_{sol,sum}/A_f$) is 0.03 for the residential use and 0.04 for all the other uses.

The decree requires that opaque vertical external walls, except walls at North, North-West and North-East, must have surface mass not lower than 230

$\text{kg}\cdot\text{m}^{-2}$ or periodic thermal transmittance (Y_{ie}) not higher than $0.10 \text{ W}\cdot\text{m}^{-2}\text{K}^{-1}$. In addition, Y_{ie} of horizontal or tilted external walls must be not higher than $0.18 \text{ W}\cdot\text{m}^{-2}\text{K}^{-1}$.

The performance parameters concerning the whole building and its systems are the energy performance (EP) and the mean global seasonal efficiency of the thermal systems (η). In particular, the following variables must be determined for the building under design:

- $EP_{H,nd}$ and $EP_{C,nd}$ are the annual energy needs of the building for space heating and space cooling, respectively, divided by the building conditioned net floor area,
- $EP_{gl,tot}$ is the global total annual primary energy of the building divided the conditioned net floor area, where “global” means all the building services, “total” includes both renewable and non-renewable energy sources,
- η_H , η_C , η_W are the mean global seasonal efficiencies of the heating system, of the cooling system and of the domestic hot water system, respectively.

The limit values of the above listed parameters are not established a priori by the MD, but they are determined for a notional building, named notional or target or reference building. The notional reference building has the same location, building function, size of the building under analysis, but with parameters of the thermal envelope and of the technical systems replaced by reference values. The reference parameters are provided by the MD and consist of:

- thermal transmittance of the envelope components and of components between units or attached buildings,
- total solar energy transmittance of windows in presence of a shading device,
- heat utilization and heat generation subsystems efficiencies of space heating, space cooling and DHW systems,
- specific electricity need for mechanical ventilation in function of the air flow.

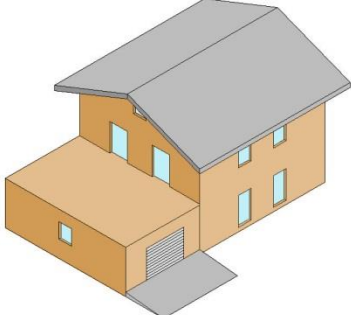
As concerns the first two bullet points, limits starting from 2019/2021 are applied in case of nZEBs.

According to the legislative decree no. 28/2011 [8] on the renewable energy sources (RES), 50% of energy demand for DHW and 50% of the sum of energy demands for DHW, space heating and space cooling must be covered by RES (from 1st January 2017). In addition, the minimum electrical power of a system fed by RES (like a PV system), calculated in function of the building footprint area on ground, is prescribed.

5.3.2 Case study description and energy performance assessment

The case study is a nZEB under design, a two-storey single-family house, supposed located in Milan (2404 HDD), Rome (1415 HDD) and Palermo (751 HDD). A picture of the building, the main geometric data and the thermo-physical parameters variants of the envelope components by climatic zone are reported in Table 21.

Table 21: 3D view and main data of the case study [48]

	Geometric data		Thermo-physical data of the envelope components*			
			Parameters	Location		
				Milan	Rome	Palermo
	A_f [m ²]	161	U_{wl} [W m ⁻² K ⁻¹]	0.22	0.22	0.37
	V_g [m ³]	651	$Y_{ic,wl}$ [W m ⁻² K ⁻¹]	0.04	0.04	0.08
	V [m ³]	429	$U_{f,attic}$ [W m ⁻² K ⁻¹]	0.20	0.24	0.40
	A_{env}/V_g [m ⁻¹]	0.72	U_g [W m ⁻² K ⁻¹]	0.16	0.18	0.37
	A_w [m ²]	25.6	U_w [W m ⁻² K ⁻¹]	1.43	2.23	3.11
	A_w/A_f [-]	0.16	g_{gl+sh} [-]	0.20	0.17	0.17

* The solar shading devices are not installed on the windows at North. $Y_{ic,wl}$ complies with the prescription (see Section 2).

Two heat generation system variants have been considered: (1) a biomass boiler for space heating and DHW plus a split air conditioner system for space cooling, (2) an air-to-water heat pump for space heating, space cooling and DHW. The heat emission subsystem consists of radiant heating panels in the former case and of fan-coils in the latter case. The features of the technical subsystems are listed in Table 22. For each system, both natural ventilation and controlled mechanical ventilation have been modelled in accordance with UNI/TS 11300-1 using the input data provided in Table 22. In case of mechanical ventilation, a heat recovery system is provided during the heating season, while mechanical ventilation is inoperative during the cooling season. All system variants include a thermal solar system for DHW and a PV system of 2 kW and 4 kW peak power (complying with the prescription of the legislative decree no. 28/2011 [92], in the variants of biomass and of heat pump respectively. The PV covers part of the electricity demand (i.e. system auxiliaries, heat pump and fan).

Table 22: Technical subsystem features of the system variants [48]

Thermal system variants	Energy services*													
	Space heating				Space cooling				Domestic hot water				Ventilation**	
	$\eta_{H,e}$ [-]	$\eta_{H,c}$ [-]	$\eta_{H,d}$ [-]	$\eta_{H,gn}$ or COP [-]	$\eta_{C,e}$ [-]	$\eta_{C,c}$ [-]	$\eta_{C,d}$ [-]	EER [-]	$\eta_{W,e}$ [-]	$\eta_{W,d}$ [-]	$\eta_{W,gn}$ or COP [-]	$A_{sol, coll}$ [m ²]	$\eta_{V,rc}$ [-]	$W_{V,fan}$ [W]
BIO+NV	0.99	0.99	0.97	0.75	0.97	0.98	1.00	2.50	1.00	0.99	0.75	3	-	-
BIO+MV	0.99	0.99	0.97	0.75	0.97	0.98	1.00	2.50	1.00	0.99	0.75	3	0.8	112
HP+NV	0.96	0.995	0.97	3.00	0.98	0.98	0.98	2.50	1.00	0.99	3.00	3	-	-
HP+MV	0.96	0.995	0.97	3.00	0.98	0.98	0.98	2.50	1.00	0.99	3.00	3	0.8	112

* Mean seasonal values of the efficiencies, except *COP* and *EER* that are declared at full load and reference temperatures of air/water.

** The external air flow in case of mechanical ventilation is 0.08 m³·s⁻¹.

5.3.3 Definition of the notional reference building

A notional reference building has been defined for each case study variant. It is characterized by the same parameters of the design building except those specified in the MD for a nZEB and listed in Table 23.

According to the MD, U-values of the notional reference building include the thermal bridges effect. In case of walls and floors attached to unconditioned spaces, the U-value is the ratio of the U-value for components facing outdoors to the heat transfer correction factor, as derived from UNI/TS 11300-1 in the form of pre-calculated values.

The utilization subsystems (u) include heat emission, control, distribution. The decree specifies that the efficiency of utilization and generation subsystems (Table 23) includes the effect of auxiliary electricity consumption.

Table 23: Main data of the notional reference building variants [48]

Parameters of the building envelope	Location			Parameters of the technical systems	Energy services			
	Milan	Rome	Palermo		Space heating	Space cooling	DHW	Ventilation
U_{wl} [W m ⁻² K ⁻¹]	0.26	0.29	0.43	η_u [-]	0.81	0.81	0.70	-
$U_{f,attic}$ [W m ⁻² K ⁻¹]	0.31	0.37	0.50	η_{gn} [-] (biomass)	0.72	-	0.65	-
U_g [W m ⁻² K ⁻¹]	0.26	0.29	0.44	η_{gn} [-] (thermal solar)	-	-	0.30	-

U_w [W m ⁻² K ⁻¹]	1.40	1.80	3.00	COP [-] (heat pump)	3.00	-	2.50	-
g_{gl+sh} [-] *	0.35	0.35	0.35	EER [-]	-	2.50	-	-
				E_v [Wh m ⁻³]	-	-	-	0.50
* does not apply at North, North-West, North-East				PV system efficiency			0.10	

5.3.4 Calculation methods and boundary conditions

According to the MD, the EP of the case study was calculated by means of the UNI/TS 11300 series [114], which specifies a quasi-steady-state calculation method based on EN ISO 13790 [62] and EN 15316 series [115]. The energy need and the primary energy for space heating, space cooling, DHW and ventilation were determined on monthly basis. An asset energy rating was performed by applying standard building use and climate input data. The primary energy conversion factors of the energy carriers have been derived from the MD and are listed in Table 24.

The dynamic simulation was conducted by means of EnergyPlus 8.3. The geometrical model of the building was developed in Design Builder 4.7. The modelling procedures were made consistent, according to a previous work of the authors [51]. The noteworthy consistency options are the following: (a) the internal heat gains and ventilation flow rate of the quasi-steady-state method are the mean values of the daily profiles of the dynamic method; (b) the same thermal system operation period was assumed in both models; (c) the same hourly operation of solar shadings and shutters is assumed both in EnergyPlus and in UNI/TS 11300-1.

Table 24: Total primary energy conversion factors of the energy carriers considered in the case study [48]

Energy carrier	$f_{P,nren}$	$f_{P,ren}$	$f_{P,tot}$
Solid biomass	0.20	0.80	1.00
Electricity from grid	1.95	0.47	2.42
Electricity from PV system	0.00	1.00	1.00
Thermal energy from solar collectors	0.00	1.00	1.00
Thermal energy from outdoor –	0.00	1.00	1.00

heat pump

5.3.5 Verification of the performance parameters

Performance parameters verified for the case study variants are listed in **Table 25**. The comparison between the design building and the notional reference building is presented in **Table 26** and in Figure 29 and Figure 30. All variants comply with the MD 26/06/2015 requirements for a nZEB, as presented in Section 5.3.1.

Table 25: Comparison of the case study performance parameters with the requirements of MD 26/06/2015 [48]

	Milan				Rome				Palermo			
	BIO+NV	BIO+MV	HP+NV	HP+MV	BIO+NV	BIO+MV	HP+NV	HP+MV	BIO+NV	BIO+MV	HP+NV	HP+MV
$H'_T [W m^{-2} K^{-1}]$		0.32				0.38				0.54		
$A_{sol, sum} / A_f [-]$		0.028				0.029				0.026		
% $E_{p,w}$ covered by RES	88	87	88	89	89	89	92	92	90	90	92	92
% $E_{p,H+C+W}$ covered by RES	79	79	70	71	80	80	79	80	78	77	76	76

Table 26: Comparison of the mean global seasonal efficiencies of thermal systems between the design building (D) and the notional reference building (R) [48]

	Milan								Rome								Palermo							
	BIO+NV		BIO+MV		HP+NV		HP+MV		BIO+NV		BIO+MV		HP+NV		HP+MV		BIO+NV		BIO+MV		HP+NV		HP+MV	
	D	R	D	R	D	R	D	R	D	R	D	R	D	R	D	R	D	R	D	R	D	R	D	R
$\eta_H [-]$	0.64	0.54	0.75	0.65	0.54	0.48	0.65	0.57	0.59	0.54	0.71	0.65	0.65	0.54	0.77	0.65	0.58	0.54	0.66	0.61	0.58	0.49	0.66	0.55
$\eta_C [-]$	1.96	1.10	1.96	1.10	1.65	0.99	1.65	0.99	1.97	1.11	1.97	1.11	1.64	1.02	1.64	1.02	1.82	1.05	1.82	1.05	1.47	0.91	1.47	0.91
$\eta_W [-]$	0.67	0.50	0.65	0.50	0.58	0.47	0.58	0.47	0.62	0.52	0.62	0.52	0.56	0.48	0.56	0.49	0.61	0.53	0.60	0.53	0.54	0.47	0.53	0.47

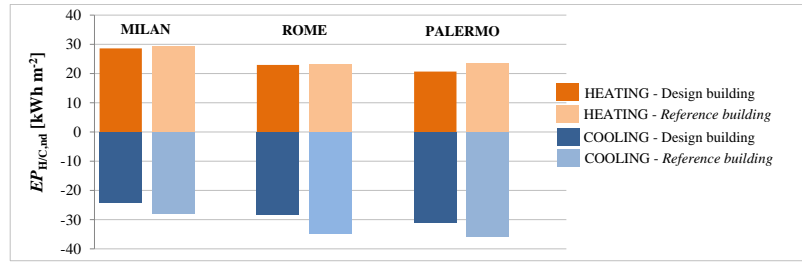


Figure 29: Comparison of $EP_{H,nd}$ and $EP_{C,nd}$ [kWh m^{-2}] between the design building and the notional reference building [48]

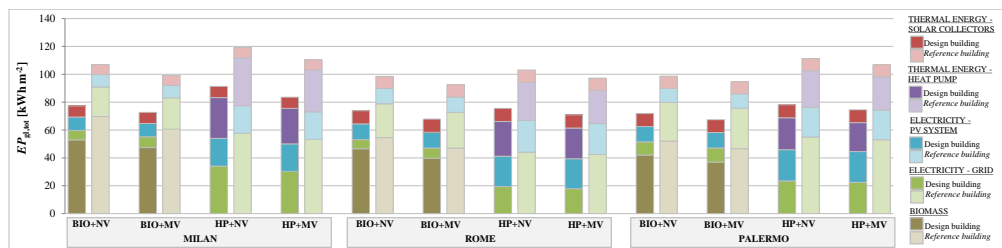


Figure 30: Comparison of $EP_{g,nd}$ [kWh m^{-2}] between the design building and the notional reference building, by energy carrier [48]

5.4 Improved procedure for the definition of notional reference building

Although the notional reference building approach is more flexible than the fixed value or the formula approach, some issues arise. They mainly concern: (1) the choice of the reference parameters of the notional reference building, and (2) the detail level used for its description. This last issue is strictly related to the adopted EP calculation model. Both issues are fully addressed in the Section 5.4.1.

The present section investigates the above aspects, aiming at enhancing the application of the notional reference building approach in the regulations and suggesting an effective procedure for its specification. The study is performed on a reference residential nearly zero-energy building (nZEB) located in Milan and Palermo, representative of different climatic zones. The analysis of the reference building is combined with a detailed dynamic simulation carried out using EnergyPlus.

Firstly, a sensitivity analysis of some thermal parameters, concerning both the thermal envelope and the technical building systems, is carried out. The aim is to verify to which extent these parameters, which are specified as reference features of the notional reference building by the MD 26/06/2015, influence the building energy performance and can be really considered as reference.

Secondly, the features of the building are described with different levels of detail; the final aim is to check whether the simplified reference parameters adopted in the legislation provide sufficient information to correctly determine the EP of the notional reference building even when a detailed dynamic simulation tool is used. The deviations in the results are pointed out and guidelines to give accuracy to the notional reference building approach are provided, as to improve its capability to handle different solutions with different degrees of complexity.

5.4.1 Theory and method

Notional reference building definition

The use of the notional reference building approach is finalised to verify the EP requirements of a given building, either under design or subject to renovation. According to this approach, the estimated energy use for the building is compared with the estimated energy use of a virtual building, usually named notional reference or baseline building. The notional reference building has some features as the actual building and other features characterised by predetermined parameters (reference values). If the estimated energy consumption of the given building is not higher than the estimated energy consumption of the notional reference building, the building requirements are met.

The use of the notional reference building approach is intended to reduce or neutralise the impact of some parameters on the compliance with the building energy performance requirements. In fact, the building parameters whose values are not replaced by reference values are excluded from the requirements: the effects of these parameters are neutralised. These parameters are usually known as neutralising parameters.

The neutralisation is aimed at, either:

- *cancelling the effect of the boundary conditions, as the driving forces of the building thermal behaviour (i.e. boundary factors), or*
- *promoting or penalising specific design choices (i.e. technical features).*

The boundary factors include climatic data and building use data (e.g. indoor air temperature, ventilation rate, occupancy profile). The technical features of the building include, for instance, the building type (e.g. shape, dimensions) and the energy carrier.

The modification of the impact of certain parameters is necessary to avoid excessive imbalances between the technologies used and consequent market disturbances. The technological level is adapted to climate, type of use, etc. as to achieve the technical and economic optimisation of the building.

According to van Dijk and Spiekman [116], the parameters are neutralised either intentionally or unconsciously. In the former case, the reasons of neutralisation are political or practical. An example of political reason is the neutralisation of the building size: if the size is not neutralised, the construction of smaller buildings might be discouraged. Other reasons for intentional neutralisation are either the small influence of certain parameters on the building energy performance or too complex effects to be taken into account (e.g. the effects of various control systems). The unconscious neutralisation includes cases in which the energy implications are not known.

Procedure for specifying the notional reference building

A structured methodology for specifying the notional reference building is suggested, as shown in Figure 31. The procedure follows four main phases.

I Choice of the calculation method. *The choice is influenced by the building typology, energy services (example space heating, space cooling, lighting) and by the boundary conditions (including building use and climate), in function of data availability, complexity level of the building, patterns of use, etcetera. Successively to definition of previous characteristics, a validation is performed combining characteristics in physical models with different calculation methods. These methods are quasi-steady-state calculation method (SS) according to the new technical standard ISO 52016-1, simplified hourly (SH) calculation method as specified by ISO 52016-1 and detailed dynamic (DD) method based on energy balances for building zones on hourly or sub-hourly time steps (as shown in Section 1.4).*

The choice of calculation method by the legislator should take into account results of validation of calculation methods.

II Distinction between reference and actual features. *The calculation method requires as inputs the building characteristics (geometry, thermo-physical*

properties, technical building systems features) and the boundary data (use, climate). According to the notional reference building approach, these inputs can be either reference features (i.e. described by predetermined parameters) or actual features (i.e. the same as the real building).

The appropriateness of setting a feature either as reference or actual firstly depends upon its effect on the building EP. In fact, if the influence of a certain building or boundary feature on the EP is negligible, setting it as a reference is meaningless. A sensitivity analysis is carried out to detect the most important features. The distinction between reference and actual features is also driven by political and socio-economic criteria. The actual features are directly described by means of neutralising parameters.

III Specification of the level of detail and simplifying assumptions.

The number of parameters describing the features generally depends on the complexity of the technological systems and is higher for advanced envelopes and technical building systems. It is necessary to define the level of detail to describe the reference features of the building. For instance, the wall properties can be simply described through a lumped parameter (e.g. the U-value) or in a detailed way, specifying the properties of the layers of the wall. The level of detail should be consistent with the calculation method and with the complexity of the building technology. A higher number of parameters is usually required by detailed calculation models, while lumped parameters are used in simplified methods

IV Setting of the reference parameters values. Finally, a value should be established for each reference parameter, taking into account specific aspects as for instance technical feasibility and economic viability. For the choice of the values multi-criteria optimization can be used.

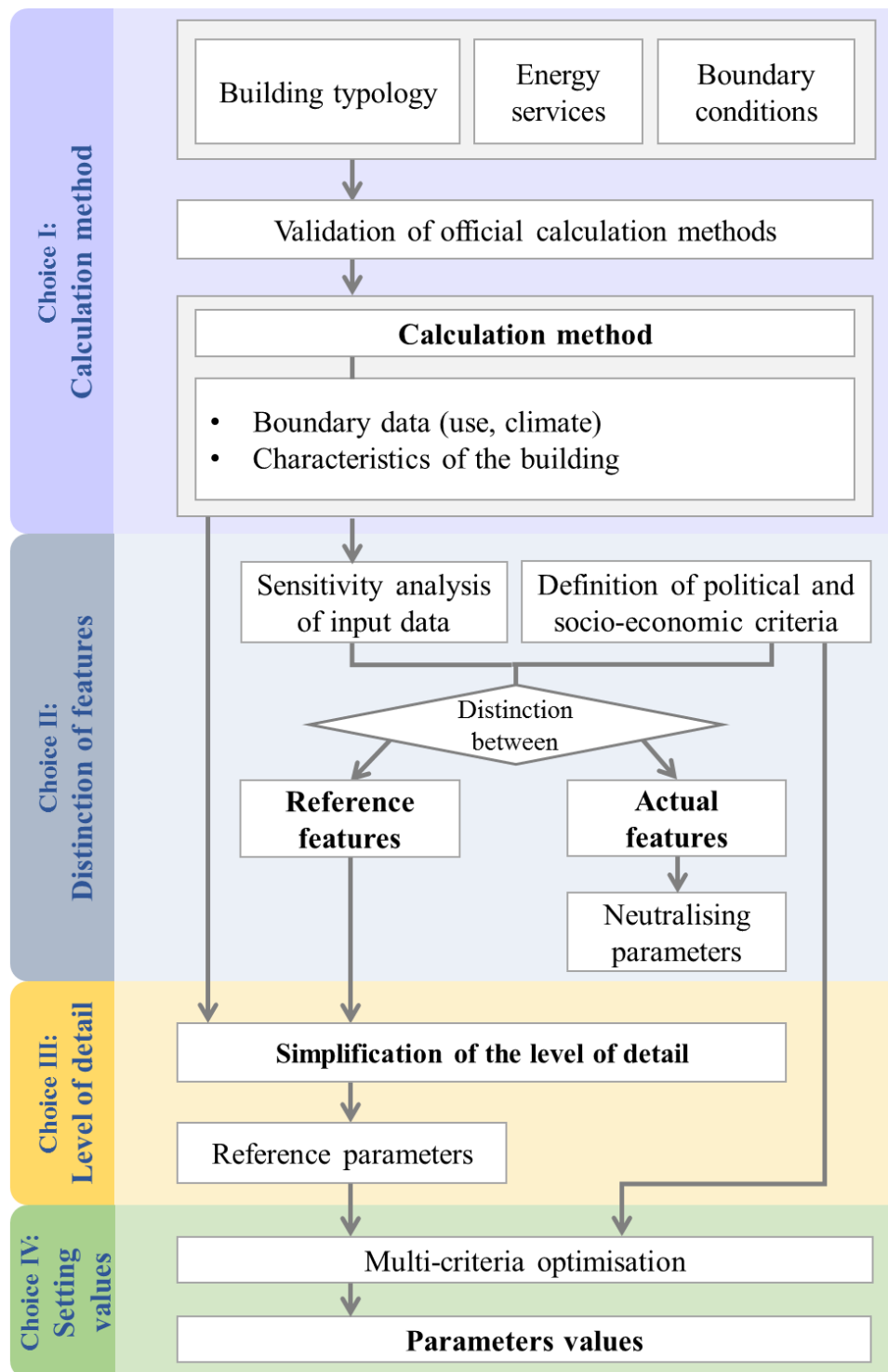


Figure 31: Flowchart of the improved procedure for specifying the notional reference building

Implementation of the notional reference building approach

The work provides an application of the above described methodology aimed at improving the notional reference building approach as used in the legislation on the energy performance of buildings, with specific focus on the Italian regulations.

The four steps of the methodology are applied as follows:

I Choice of the calculation method. *The dynamic numerical simulation is a way to enhance the modelling of the notional reference building. Compared with the quasi-steady-state method specified by the national regulations, a dynamic model better mirrors the real thermal behaviour of the building for the following main reasons:*

- it takes into account the high time variability of the thermal driving forces that can determine relevant thermal storage effects and overlap between opposite effects (e.g. heat gains vs. heat transfer, power demand vs. power on-site production),*
- it considers systems described by non-linear models (e.g. thermal plants, passive solar systems, advanced thermal control systems).*

The dynamic numerical simulation is also an effective instrument to carry out sensitivity analyses by means of different procedures and methodologies, as performed for instance by Ballarini and Corrado [117].

Anyway, the dynamic simulation can hardly be fit to a standard calculation, unless it includes many simplifications; this represents a disadvantage for its application in the notional reference building approach.

II Distinction between reference and actual features. *As a starting point, a sensitivity analysis should be carried out on the reference parameters already defined in the current legislation (i.e. U-value of the envelope components, g_{gl+sh} value of the windows, efficiency of the generators).*

III Specification of the level of detail and simplifying assumptions. *The default description of the reference building features should be based on a high level of detail as required by the dynamic simulation tool. If the national legislation provides lumped reference parameters, different technical*

solutions complying with the simplified reference parameter value set by the national regulation should be analysed and compared.

IV Setting of the reference parameters values. *The parameters values should be derived from cost-effective analyses. The parameters values used in this study are those fixed by the Italian regulations.*

5.4.2 Notional reference building case study

Description of the base case

The case study is a two-storey single-family house, located in two different cities, Milan (2404 HDD) and Palermo (751 HDD). The two locations belong to the climatic zones with the highest number of inhabitants, respectively dominated by the heating and by the cooling season. The main geometric data are reported in Table 27.

Table 27: Geometric data of the case study [49]

Symbol	Unit	Value
$A_{f,net}$	m^2	158
V_g	m^3	646
V_{net}	m^3	458
A_{env}/V_g	m^{-1}	0.74
A_w	m^2	25.3
$A_w/A_{f,net}$	-	0.16
A_w/A_{env}	-	0.054

The reference parameters values for the building envelope of the notional reference building are provided by the MD 26/06/2015 and listed in Table 28. They correspond to the requirements of a nZEB. The U-values are defined in function of the climatic zone (heating degree-days).

Table 28: Parameters of the building envelope of the notional reference nZEB (MD 26/06/2015). Base case [49]

Parameter	Unit	Climatic zone from 2101 to 3000 HDD (Milan)	Climatic zone up to 900 HDD (Palermo)
U_{wl}	$W \cdot m^{-2} K^{-1}$	0.26	0.43
U_r	$W \cdot m^{-2} K^{-1}$	0.22	0.35
$U_{fl,up,un}$	$W \cdot m^{-2} K^{-1}$	0.31*	0.50*
$U_{wl,un}$	$W \cdot m^{-2} K^{-1}$	0.43*	0.72*
$U_{fl,gr}$	$W \cdot m^{-2} K^{-1}$	0.26**	0.44**
U_w	$W \cdot m^{-2} K^{-1}$	1.40	3.00
g_{gl+sh}	-	0.35***	

* attached to an unconditioned space

** equivalent thermal transmittance (ISO 13370)

*** shading devices not installed on the north windows

The heating and cooling systems are composed of a generator, a circulation pump, the heating/cooling emitters and a temperature control system in each thermal zone. Two configurations of generator are investigated: (1) a biomass boiler for space heating and a split air conditioner system for space cooling, (2) a reversible air-to-water heat pump for space heating and space cooling. The emitters are radiators in case of biomass boiler and fan coils in case of heat pump. The components of the considered technical building systems are representative of the most widespread technologies available on the market.

The design parameters of the technical building systems (i.e. heating and cooling capacity, water temperature, etc.) are determined by calculating the heating and the cooling loads in design conditions. The inlet water design temperature is 70 °C for radiators and 55 °C for fan coils. The thermal flow supplied by the fan coil unit is controlled by varying the water flow rate in the coils. The circulation pump has a variable speed control and operates intermittently; so when there is no load on the loop the pump is stuck. The set-point air temperature is 20 °C for space heating and 26 °C for space cooling.

The MD 26/06/2015 requires that both the typology and the features of the technical building systems components are the same as those of the real building; however, reference mean seasonal efficiencies are given for the emission plus distribution subsystems and for the generation subsystem, which are listed in Table 29.

Table 29: Reference parameters of the generation subsystems (MD 26/06/2015).
Base case [49]

Parameter	Unit	Energy service	
		Heating	Cooling
η_{gn} (biomass boiler)	-	0.72	-
COP (heat pump)	-	3.00	-
EER (split system/heat pump)	-	-	2.50

The technical building systems are modelled according to DOE2 specifications based on manufactures extended ratings data for each component. As concerns the modelling of the non-generation components of the systems, the MD 26/06/2015 reference seasonal efficiency is disregarded, due to the impossibility of the simulation model to properly fit this numerical value. The distribution pipes are assumed adiabatic. The radiator model takes into account the convective and radiant heat transfer from the device to the zone.

*For each generator, the nominal efficiency value is set as to verify the mean seasonal efficiency of the MD 26/06/2015 **Table 29**.*

For the biomass boiler, the following main parameters are required: nominal power, nominal efficiency and flow temperatures. The performance curve, which is a bi-cubic function, uses, as input data, the load factor and the temperature in the water inlet into the boiler.

The main input parameters for the split system are the EER and the nominal power. The hourly power can be determined by means of two performance curves. The first one requests, as input, the wet-bulb temperature of the air entering in the cooling coil and the dry-bulb temperature of the air entering in the air-cooled condenser coil. The other curve requires the ratio of the actual air flow rate across the cooling coil to the rated air flow rate.

The air-to-water heat pump for the heating season is described with heating nominal power, nominal COP at reference inlet temperatures of air and water of the evaporator and the condenser respectively. The COP at each time step is determined taking into account the partial load ratio (PLR) and the inlet temperatures of evaporator and condenser. Concerning the heat pump cooling operation, the nominal power, the nominal EER at the outlet chilled water temperature and at the inlet condenser fluid temperature are needed.

Sensitivity analysis of the reference parameters

The whole analysis is performed through EnergyPlus v8.3.

The same neutralising parameters as established by the current Italian legislation (i.e. building geometry, use, location, types of technical building systems) are assumed in this study, because they derive from a political choice.

The sensitivity analysis of the reference parameters is based on the variation of the thermo-physical properties of the building envelope and of the technical building systems. The sampling method considers the technically achievable solutions available on the market, ranging from basic solutions widespread in existing buildings to the most advanced technologies.

The sensitivity analysis is carried out on the U-value of the envelope components, the g_{gl+sh} value of the windows and the efficiency of the generators. A total number of 30 simulations is carried out.

*The sensitivity analysis of the thermal transmittance consists in assuming, for each envelope component, a higher and a lower U-value compared to the actual reference value reported in **Table 28**. More specifically, for each component and location, the thermal transmittance reference values established by the MD 26/06/2015 for the two closest climatic zones are tested. In Palermo, as a closer climatic zone with a higher U-value does not exist, it is applied the same percentage increase as it occurs between the closest climatic zone with lower U-value and the U-value of the actual climatic zone. The analysed cases are listed in*

Table 30. *The case ID no. 00 concerns the base case **Table 28**.*

*A second sensitivity analysis concerns the total solar energy transmittance of glazing with a shading device. It consists in testing different g_{gl+sh} values got by considering various features of glazing and shading device as reported in **Table 31**. For each location, all variants allow the requirement on thermal transmittance value of windows to be met (see **Table 28**).*

*As regards the generation subsystem, the sensitivity analysis takes into account three levels of the nominal efficiency value of biomass boiler, split system and heat pump, as reported in **Table 32**. The upper and the lower nominal values are set with respect to the nominal value of the base case, as follows:*

- $\pm 2\%$ variation of the efficiency of the biomass boiler,
- ± 0.5 variation of the coefficient of performance (COP) of the heat pump in heating mode,

- ± 0.5 variation of the energy efficiency ratio (EER) of the split system and the heat pump in cooling mode.

Table 30: Sensitivity analysis of the envelope components thermal transmittance. Case studies [49]

ID case study	Description	$U \text{ [W} \cdot \text{m}^{-2} \text{K}^{-1}]$				
		U_{wl}	U_r	$U_{fl,up,un}$	$U_{wl,un}$	U_w
MI-00	Milan – base case (Table 28)	0.26	0.22	0.31	0.43	1.40
MI-SA-TT-01	Milan – higher U -value	0.29	0.26	0.37	0.48	1.80
MI-SA-TT-02	Milan – lower U -value	0.24	0.20	0.29	0.40	1.10
PA-00	Palermo – base case (Table 28)	0.43	0.35	0.50	0.72	3.00
PA-SA-TT-01	Palermo – higher U -value	0.52	0.37	0.53	0.87	3.80
PA-SA-TT-02	Palermo – lower U -value	0.34	0.33	0.47	0.57	2.20

Table 31: Sensitivity analysis of the total solar energy transmittance of glazing with shading device. Case studies [49]

ID case study	Description	g_{gl+sh} [-]	$g_{gl,n}$ [-]	$\tau_{sol,sh}$ [-]	$\rho_{sol,sh}$ [-]	Shading device position
MI-00	Milan – base case	0.35	0.67	0.15	0.70	internal
MI-SA-TST-01	Milan – lower g_{gl+sh} value	0.09	0.67	0.10	0.70	external
MI-SA-TST-02	Milan – higher g_{gl+sh} value	0.67	0.67	no shading device		
PA-00	Palermo – base case	0.35	0.75	0.15	0.70	internal
PA-SA-TST-01	Palermo – lower g_{gl+sh} value	0.05	0.75	0.00	0.70	external
PA-SA-TST-02	Palermo – higher g_{gl+sh} value	0.75	0.75	no shading device		

Table 32: Sensitivity analysis of the generator efficiency. Case studies [49]

ID case study	Description	Biomass boiler	Split system	ID case study	Description	Heat pump	
		η	EER			COP	EER
MI-00-BS	Milan – base case	0.73	2.59	MI-00-HP	Milan – base case	3.63	3.25
MI-SA-BS-01	Milan – higher efficiency	0.75	3.09	MI-SA-HP-01	Milan – higher efficiency	4.13	3.83
MI-SA-BS-02	Milan – lower efficiency	0.71	2.09	MI-SA-HP-02	Milan – lower efficiency	3.13	2.185
PA-00-BS	Palermo – base case	0.80	2.81	PA-00-HP	Palermo – base case	2.93	3.43
PA-SA-BS-01	Palermo – higher efficiency	0.822	3.31	PA-SA-HP-01	Palermo – higher efficiency	3.43	3.93
PA-SA-BS-02	Palermo – lower efficiency	0.78	2.31	PA-SA-HP-02	Palermo – lower efficiency	2.43	2.93

Table 33: Envelope components configurations with fixed thermal transmittance.
Case studies [49]

ID case study	Description	Envelope component	U [W·m ⁻² K ⁻¹]	Y_{ie} [W·m ⁻² K ⁻¹]	m_s [kg·m ⁻²]	κ_i [kJ·m ⁻² K ⁻¹]
MI-00	Milan - base case External insulation Heavy thermal mass	wall (EXT)	0.26	0.044	260	49.5
		roof (EXT)	0.22	0.049	249	63.5
		upper floor (UNC)	0.31	0.040	335	62.1
		wall (UNC)	0.43	0.084	258	50.1
MI-DE-TT-01	Milan Internal insulation Heavy thermal mass	wall (EXT)	0.26	0.057	260	24.5
		roof (EXT)	0.22	0.071	249	25.8
		upper floor (UNC)	0.31	0.031	335	24.2
		wall (UNC)	0.43	0.108	258	25.1
MI-DE-TT-02	Milan Internal insulation Light thermal mass	wall (EXT)	0.26	0.094	153	14.0
		roof (EXT)	0.22	0.071	249	25.8
		upper floor (UNC)	0.31	0.031	335	24.2
		wall (UNC)	0.43	0.178	152	16.6
PA-00	Palermo - base case External insulation Heavy thermal mass	wall (EXT)	0.43	0.085	257	50.1
		roof (EXT)	0.35	0.085	247	64.0
		upper floor (UNC)	0.50	0.076	333	62.4
		wall (UNC)	0.72	0.248	217	52.9
PA-DE-TT-01	Palermo Internal insulation Heavy thermal mas	wall (EXT)	0.43	0.109	257	24.8
		roof (EXT)	0.35	0.123	247	25.7
		upper floor (UNC)	0.50	0.058	333	25.1
		wall (UNC)	0.72	0.305	217	29.8
PA-DE-TT-02	Palermo Internal insulation Light thermal mas	wall (EXT)	0.43	0.177	152	16.6
		roof (EXT)	0.35	0.123	247	25.7
		upper floor (UNC)	0.50	0.058	333	25.1
		wall (UNC)	0.72	0.462	127	23.2

Table 34: Configurations of glazing and shading device with fixed total solar energy transmittance. Case studies [49]

ID case study	Description	g_{gl+sh} [-]	$g_{gl,n}$ [-]	$\tau_{sol,sh}$ [-]	$\rho_{sol,sh}$ [-]	Shading device position
MI-00	Milan - base case Low-e double glazing, white and medium translucent shading device	0.35	0.67	0.15	0.70	internal
MI-DE-TST-01	Milan Low-e double glazing, dark and high translucent shading device	0.35	0.67	0.45	0.25	external
MI-DE-TST-02	Milan Low-e triple glazing, pastel and semi-opaque shading device	0.35	0.46	0.10	0.50	internal
PA-00	Palermo - base case Uncoated double glazing, white and medium translucent shading device	0.35	0.75	0.15	0.70	internal
PA-DE-TST-01	Palermo Uncoated double glazing, black and translucent shading device	0.35	0.75	0.30	0.05	external
PA-DE-TST-02	Palermo Low-e double glazing, white and medium translucent shading device	0.35	0.67	0.15	0.70	internal

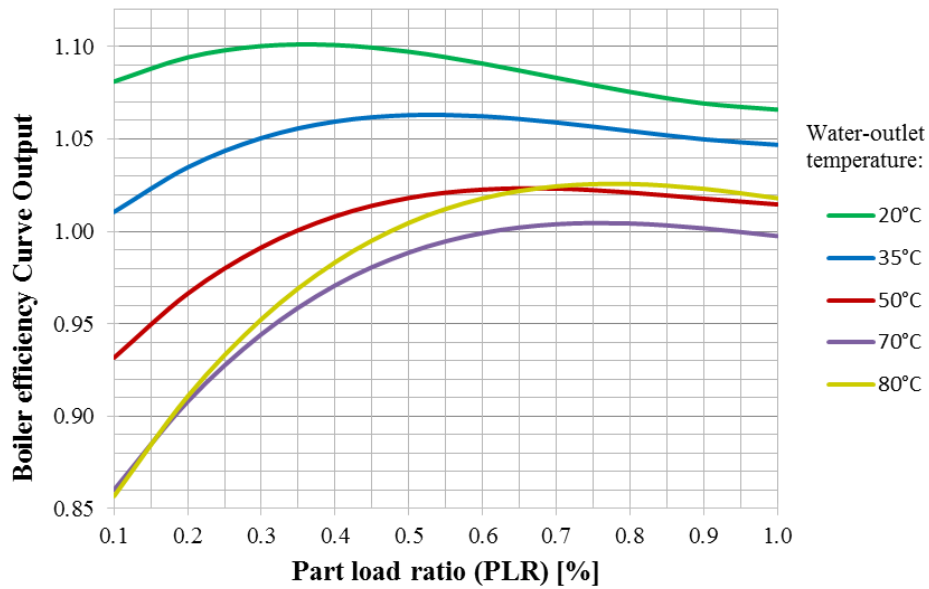


Figure 32: Efficiency curves by EnergyPlus for non-condensing boiler

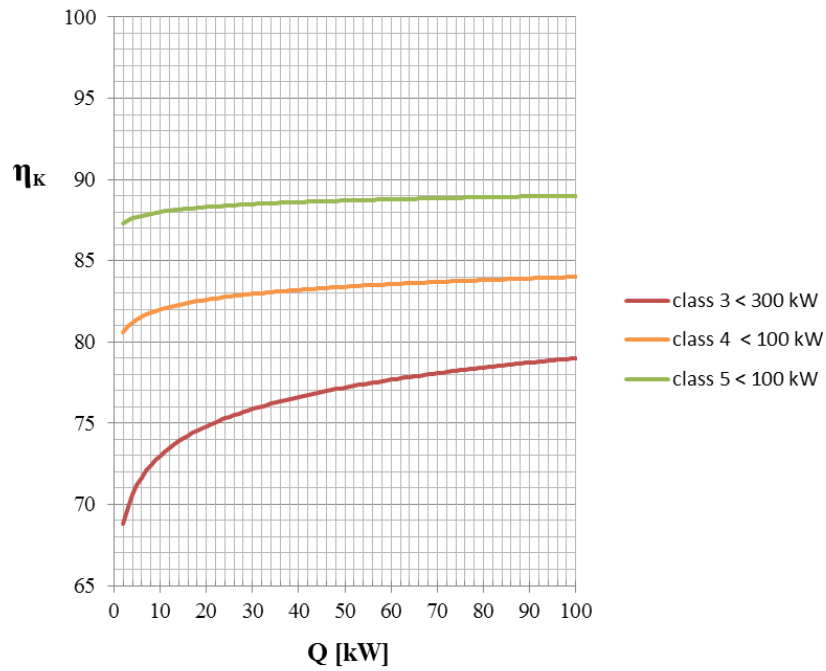


Figure 33: Biomass boiler performance curves by UNI EN 303-5 with η based on the lower heating value (LHV) of the fuel

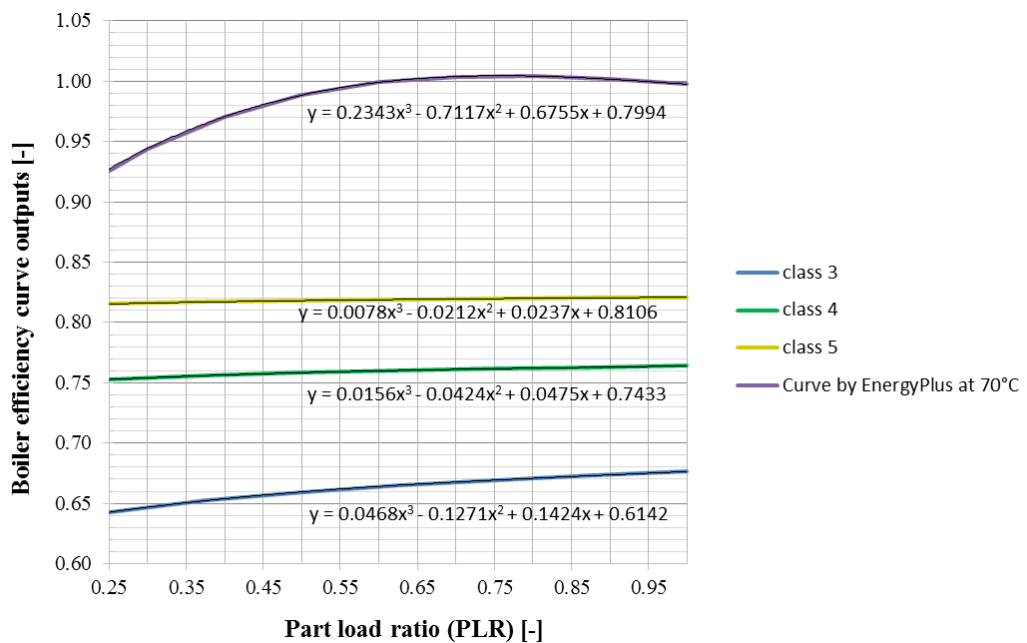


Figure 34: Considered biomass boiler curves after normalization (Milan case study)

Table 35: Configurations of the biomass generator with fixed generator performance.
Case studies

ID case study	Description	Efficiency related to water-outlet temperature	Biomass boiler performance	Boiler performance curve output		
			η	25% PLR for MI and 27% for PA	50% PLR	100% PLR
MI-00-BC	Milan – base case with curves by EnergyPlus	dependent	0.73	0.86*	0.99*	1.00*
MI-DE-BC-01	Milan – base case with curve by EnergyPlus	independent	0.73	0.86	0.99	1.00
MI-DE-BC-02	Milan – curve of class 3 by EN 303-5	independent	0.73	0.64	0.66	0.68
MI-DE-BC-03	Milan – curve of class 4 by EN 303-5	independent	0.73	0.75	0.76	0.76
MI-DE-BC-04	Milan – curve of class 5 by EN 303-5	independent	0.73	0.82	0.82	0.82
PA-00-BC	Palermo – base case with curves by EnergyPlus	dependent	0.80	0.86*	0.99*	1.00*
PA-DE-BC-01	Milan – base case with curve by EnergyPlus	independent	0.80	0.86	0.99	1.00
PA-DE-BC-02	Palermo – curve of class 3 by EN 303-5	independent	0.80	0.64	0.66	0.68
PA-DE-BC-03	Palermo – curve of class 4 by EN 303-5	independent	0.80	0.75	0.76	0.76
PA-DE-BC-04	Palermo – curve of class 5 by EN 303-5	independent	0.80	0.82	0.82	0.82

* Valued for plant loop set-point temperature equal to 70°C

Level of detail of the reference features

The detailed dynamic numerical simulation method requires a high level of detail in the description of the notional reference building features. For example, the building envelope components are described by the thermal properties of single layers. In such a way, various technical solutions for each envelope

component can lead to the same thermal transmittance value as established by the national decree (see **Table 28**).

As shown in **Table 33**, three different envelope configurations are tested for each location, taking into account a different position of the thermal insulation layer and a different thermal mass. It can be noted that a specific envelope component may have different dynamic thermal characteristics while achieving the same thermal transmittance value.

The MD 26/06/2015 provides all climatic zones with a unique reference value of the total solar energy transmittance of glazing with shading device (see **Table 28**). As for the thermal transmittance, different technical solutions using different types of glazing and shading devices would allow to achieve the same reference value of g_{gl+sh} . The configurations listed in **Table 34** are tested for the notional reference building.

Concerning the modelling of the generation subsystem, different real performance curves are compared and simulated.

EnergyPlus calculates the fuel used as the ratio between boiler load and product of nominal thermal efficiency for boiler efficiency curve output [22]. Latter derives from a performance curve which correlates the part load ration with the boiler efficiency curve output. Available curves are also correlated with the water-outlet temperature. The base case is performed with curves for boiler non-condensing available by EnergyPlus, shown in Figure 32. The first comparison curve is based on EnergyPlus curves, where only the curve for plant loop water set-point temperature is selected. The second, third and fourth curve are based on class 3, class 4 and class 5, respectively, of biomass boiler efficiency by EN 303-5 [118] (Figure 33). The provided η is transformed based on the higher heating value (HHV) of fuel and gets related to heating capacity of the boiler. Curves become as shown in Figure 34. Summary of considered configurations of the biomass generator with fixed generator efficiency are listed in **Table 35**.

5.4.3 Results and discussion

Energy performance of the notional reference building

The Italian MD 26/06/2015 requires to calculate the EP of the notional reference building by means of the UNI/TS 11300 series, which specifies a quasi-steady-state calculation method based on EN ISO 13790 and EN 15316 series. In Figure 35, a comparison between the results of the quasi-steady-state method and the detailed dynamic simulation (EnergyPlus) are shown for Milan and Palermo. The EP is expressed in terms of net energy need for space heating and space

cooling normalised on the conditioned net floor area of the notional reference building object of study.

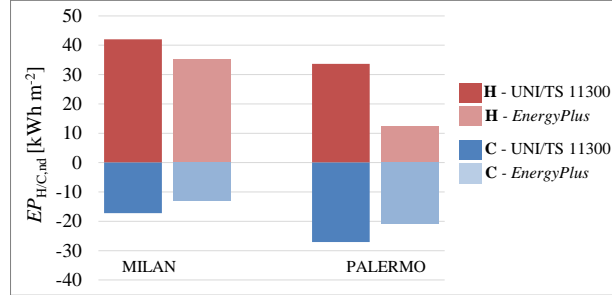


Figure 35: Comparison between UNI/TS 11300 and EnergyPlus [49]

The quasi-steady-state method overestimates the energy need both for heating and for cooling. The overestimation of space heating energy need significantly increases in Palermo, where higher outdoor air temperature and higher solar radiation occur. In addition, some critical points were identified, specifically concerning the effect of thermal bridges and of the technical building system auxiliaries in the reference building approach. The results reveal the limits of the simplified method in predicting the energy needs of low-energy buildings, as introduced in the Section “Theory and method”.

Therefore in the present work, a detailed dynamic simulation is chosen as reference calculation method to investigate the notional reference building approach.

Results of the sensitivity analysis

The results of the sensitivity analysis are reported in Figure 36, Figure 37 and Figure 38. Figure 36, the percentage variation of the EP in terms of annual net energy need for space heating and space cooling normalised on the building net floor area is plotted versus the percentage variation of the average U-value of the building envelope (U_{avg}), which is expressed through following equation:

$$U_{avg} = \frac{\sum_{k=1}^n b_k \cdot U_k \cdot A_k}{\sum_{k=1}^n A_k} \quad (12)$$

where, the sum includes all the building envelope components, b_k is the adjustment factor for heat transfer coefficient, A_k is the area of building envelope component k and U_k is its thermal transmittance. Considering a variation of $-9\div+14\%$ of U_{avg} (see Figure 36), the net energy need for space heating is more

sensitive ($-10\div+15\%$) than the net energy need for space cooling (below $\pm 2\%$) for the building located in Milan. In Palermo, a variation of about $\pm 17\%$ of U_{avg} determines a deviation of about $-22\div+20\%$ of the net energy need for space heating and of about $-7\div+9\%$ of the net energy need for space cooling.

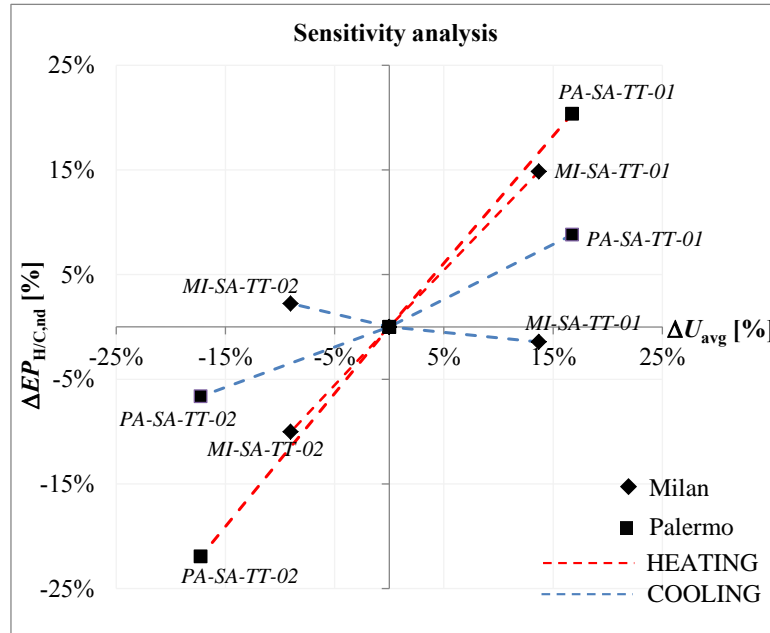


Figure 36: Sensitivity analysis of the thermal transmittance. Results for Milan and Palermo [49]

On the contrary, the total solar energy transmittance (Figure 37) affects more the energy need for space cooling ($-22\div+32\%$ in Milan and $-25\div+33\%$ in Palermo) than for space heating ($-10\div+7\%$ in Milan and $-15\div+13\%$ in Palermo). The influence of the g_{gl+sh} value on the building EP is however lower than the influence of the U -value.

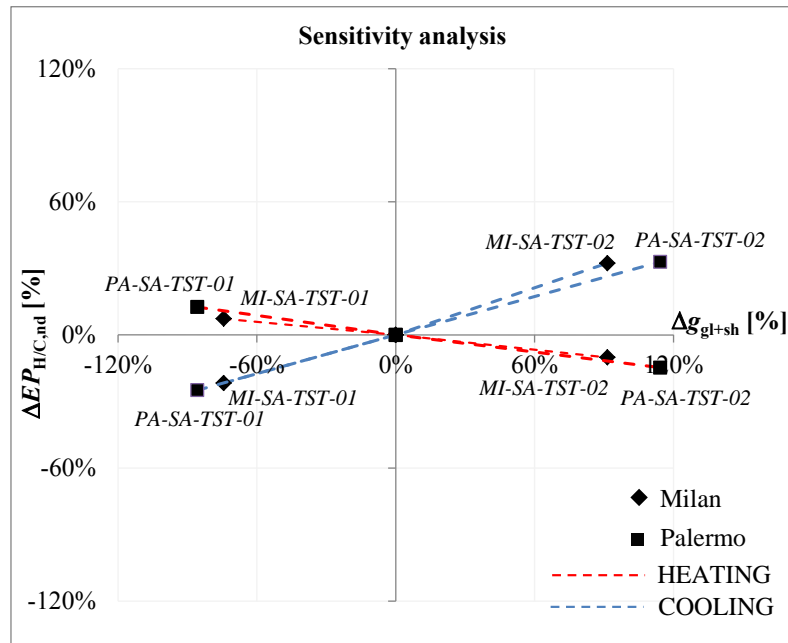


Figure 37: Sensitivity analysis of the total solar energy transmittance. Results for Milan and Palermo [49]

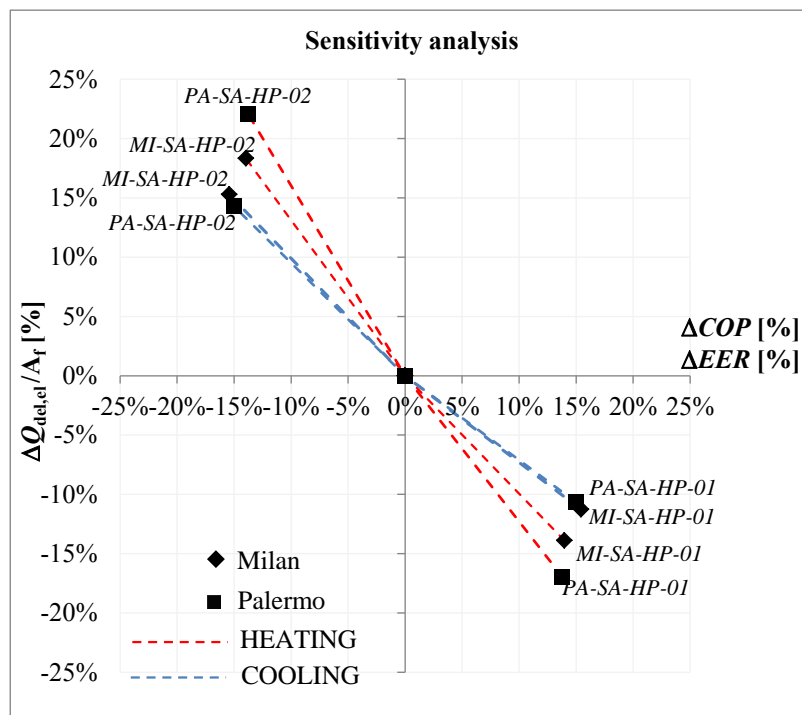


Figure 38: Sensitivity analysis of the generator efficiency, heat pump [49]

Table 36: Sensitivity analysis of the generator efficiency. Biomass boiler and split system [49]

ID case study	$\Delta\eta$ [%]	$\Delta Q_{\text{del,bio}}$ [%]	ΔEER [%]	$\Delta Q_{\text{del,el}}$ [%]
MI-00-BS	-	-	-	-
MI-SA-BS-01	3%	-3%	19%	-15%
MI-SA-BS-02	-3%	2%	-19%	22%
PA-00-BS	-	-	-	-
PA-SA-BS-01	2%	-1%	18%	-15%
PA-SA-BS-02	-2%	3%	-18%	22%

The sensitivity analysis of the generator efficiency (Figure 38 and **Table 36**) highlights the high influence of the COP on the delivered energy both in Milan and in Palermo. As regards the EER effect, there is not an appreciable difference between Milan and Palermo.

The analysed parameters of both building envelope and thermal systems prove to affect the building EP with considerable extent. Thus the related building features can be really considered as reference for characterising the notional reference building.

Results of the building features description

The analysed envelope configurations, which are characterised by the same thermal transmittance value and different thermal dynamic parameters, determine a variation of the EP as shown in **Table 37**.

In Milan, while the deviation in the annual net energy need for space heating is negligible, the space cooling presents an increment of about 12% in both configurations with the thermal insulation layer on the internal side. In Palermo, the variation of the energy need for space cooling is very high (about 45%) in both configurations.

The results of the analysed configurations of glazing and shading device, which determine the same $g_{\text{gl+sh}}$ value, are shown in **Table 38**. For the building in Milan, the EP is strongly affected by the type of glazing and by the shading device features. Specifically in this case, the variation of the total solar energy

transmittance of glazing affects the EP more than the position of the shading device.

Table 37: Results of the envelope components configurations [49]

ID case study	$EP_{H,nd}$ [kWh·m ⁻²]	$\Delta EP_{H,nd} / EP_{H,nd,base\ case}$	$EP_{C,nd}$ [kWh·m ⁻²]	$\Delta EP_{C,nd} / EP_{C,nd,base\ case}$
MI-00	31.74	-	12.77	-
MI-DE-TT-01	31.54	-0.63%	14.39	12.7%
MI-DE-TT-02	31.92	0.57%	14.34	12.3%
PA-00	13.86	-	14.65	-
PA-DE-TT-01	12.15	-12.3%	21.29	45.3%
PA-DE-TT-02	12.32	-11.1%	21.02	43.4%

Table 38: Results of the configurations of glazing and shading device [49]

ID case study	$EP_{H,nd}$ [kWh·m ⁻²]	$\Delta EP_{H,nd} / EP_{H,nd,base\ case}$	$EP_{C,nd}$ [kWh·m ⁻²]	$\Delta EP_{C,nd} / EP_{C,nd,base\ case}$
MI-00	31.74	-	12.77	-
MI-DE-TST-01	31.28	-1.46%	13.55	6.17%
MI-DE-TST-02	33.87	6.71%	9.46	-25.9%
PA-00	13.86	-	14.65	-
PA-DE-TST-01	14.02	1.17%	13.87	-5.37%
PA-DE-TST-02	13.51	-2.49%	14.65	0.01%

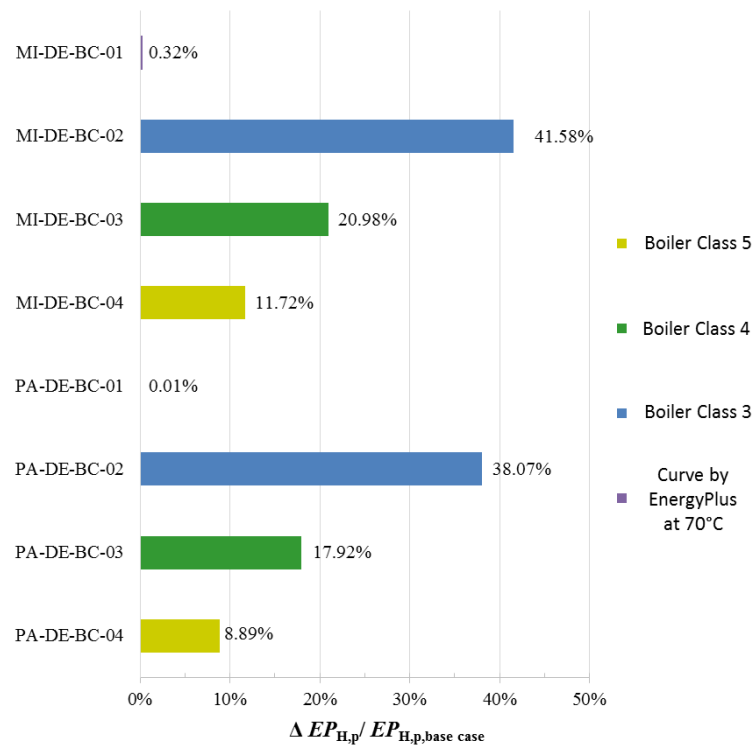


Figure 39: Results of the biomass generator configurations with fixed generator performance

Results of the biomass generator configurations, which are characterised by the same nominal generator performance and different performance curves, determine variations of the EP as shown in Table 36. The energy performance of the base case is used as reference to calculate deviations. In particular, the transition of biomass boiler performance from multi-curve in function of water-outlet temperature to single curve of plant loop set-point temperature gets differences less than 0.32%. If the curve of correlation between part load ratio and boiler efficiency curve output changes, great deviation of the energy performance is observed.

The results of the building features description highlight that significant deviations in the building EP may occur if an insufficient number of parameters is assumed for the notional reference building when using a dynamic simulation method. This aspect implies that the legislation should provide more detailed information to characterise the notional reference building.

With reference to the analysed case studies and building features, suggestions for improving the notional reference building approach are provided as follows.

- *Besides a lumped thermal transmittance value, one or more thermal dynamic features of the envelope components should be provided, either adopting neutralising parameters (e.g. the areal heat capacity of the notional reference building is the same of building under design), or fixing reference values.*
- *The total solar energy transmittance of glazing with shading device should be complemented with other parameters, as for instance the position of the shading device and the g_{gl} value. The former might be fixed as external, the latter might be considered a neutralising parameter.*
- Reference mean seasonal efficiencies of the heating building system is not sufficient to guarantee an high performance of the biomass boiler. The curve of correlation between part load ratio and boiler efficiency curve output is necessary to establish. For more accuracy in the estimation of energy performance of low energy buildings is suggested to define more than a curve.

5.5 The significant imbalance of nZEB energy need

In this section, a consequence of the selection of reference feature values is analysed (choice IV of Figure 31).

The present section aims to investigate in which conditions and extent a significant imbalance of energy needs for heating and cooling occurs by gradually reducing the U-values of the notional reference building up to 2020 limits as required by the Italian legislation. Despite the reduction of the heating energy need due to the limitation of the heat transfer through the envelope, there might be the risk that the cooling energy need increases and necessary measures for avoiding overheating should be adopted. The present work discusses the feasibility of technical solutions that comply with the legislative requirements set up for nZEBs. In addition, solutions aimed at reducing the summer energy needs and the cooling peak loads are investigated. The analysis is performed for three different building types, i.e. single-family house, apartment block and office building, in two different Italian climatic locations (Milan and Palermo). Although the MD 26/06/2015 requires that the building energy performance is calculated by means of a quasi-steady-state calculation method, in the present work a detailed dynamic numerical simulation is applied. Compared to the quasi-steady-state method, the dynamic method better mirrors the real thermal

behaviour of the building for the following main reasons: (a) it takes into account the high time variability of the thermal driving forces and the consequent thermal storage effects, (b) it correctly considers energy systems described by non-linear models. The dynamic method therefore allows to achieve a higher representativeness and quality of output data, especially in complex buildings; in addition, it can be an effective instrument to carry out sensitivity analyses through different procedures and methodologies, as done for instance by [119].

5.5.1 Energy performance requirements for buildings

The MD 26/06/2015 requires, through the notional reference building approach, to verify the annual net energy need of the building for space heating and space cooling, respectively, divided by the building conditioned net floor area ($EP_{H,nd}$ and $EP_{C,nd}$).

As regards the summer energy performance of the building, in order to limit the cooling peak loads and to maintain the thermal comfort conditions, the MD 26/06/2015 requires: (1) to evaluate the effectiveness of solar shading systems, (2) for locations with horizontal solar irradiance equal to or higher than $290 \text{ W}\cdot\text{m}^{-2}$ in the month with maximum solar irradiation, to carry out one of the following checks regarding the opaque envelope:

- *for vertical walls, except those at North, North-West and North-East, areal mass $M_s > 230 \text{ kg}\cdot\text{m}^{-2}$ or periodic thermal transmittance $|Y_{ie}| < 0.10 \text{ W}\cdot\text{m}^{-2}\text{K}^{-1}$ [120],*
- *horizontal and tilted roofs, periodic thermal transmittance $|Y_{ie}| < 0.18 \text{ W}\cdot\text{m}^{-2}\text{K}^{-1}$ [120].*

*According to standard guidelines [61], some Italian locations do not reach the threshold value of $290 \text{ W}\cdot\text{m}^{-2}$ for solar irradiance and therefore, despite having a predominant warm climate, are not subject to the second prescription listed above. Some of these locations are in South-Centre of Italy, as listed in **Table 39**. In such cases, the reference U-values can be achieved using various technical solutions, even with lightweight walls or placing the thermal insulation in different positions inside the wall, thus determining the risk of overheating in summer conditions. Some authors deeply investigated this issue. As reported by Corrado et al. [121] in case of lightweight components, an equivalent periodic thermal transmittance should be evaluated to take into account both the external surface solar absorbance and the exposure of the building components. To classify the envelope thermal quality, Di Perna et al. [121] also proposed to*

assign a threshold value to the internal areal heat capacity of the building envelope [120]

Table 39: Monthly horizontal global solar irradiance of some Italian locations.
Source UNI 10349-1 [61] [50]

Town	Agrigento (AG)	Jerzu (OG)	Palermo (PA)	Reggio Calabria (RC)	Siracusa (SR)	Iglesias (CI)	Decimomannu (CA)	Nocera Inferiore (NA)	Taranto (TA)	Mesagne (BR)
Alt [m]	230	13	14	31	17	111	6	17	15	13
Italian climatic zone	B	B	B	B	B	C	C	C	C	C
I_{\max} [$\text{W}\cdot\text{m}^{-2}$]	286	271	285	289	289	268	263	283	268	267
Month	Jul	Jun	Jul	Jun	Jun	Jun	Jun	Jun	Jun	Jun

Town	Luras (OT)	Otranto (LE)	Sassari (SS)	Samassi (VS)	Vibo Valentia (VV)	Nuoro (NU)	Teramo (TE)	Forlì del Sannio (IS)	Villa Fastigi (PU)	Luras (OT)
Alt [m]	15	49	225	135	476	549	432	423	11	15
Italian climatic zone	C	C	C	C	D	D	D	D	D	C
I_{\max} [$\text{W}\cdot\text{m}^{-2}$]	280	287	276	269	249	265	282	284	289	280
Month	Jul	Jul	Jun	Jul	Jul	Jul	Jul	Jul	Jun	Jul

5.5.2 Case studies

*The analysis was performed on three different building types: single-family house, apartment block and office building, supposed located in Milan (2404 HDD – Italian climatic zone E) and Palermo (751 HDD – Italian climatic zone B). The residential buildings have been selected among the representative building types of the IEE-TABULA research project [122]. The office is a reference office building analysed in [123]. The buildings have been chosen as to cover different compactness factors and use categories. The main geometric data of the case studies are shown in **Table 40**. The U-values of the building envelope components are those of the notional reference building, as reported in the MD 26/06/2015 [56]. They differ in function of two application steps – from 2015 to 2020 and from 2021 onwards – and of the climatic zones. For each building component, the thickness of the insulation layer was determined so as to comply with the thermal transmittance value including the effect of thermal bridges.*

Despite the legislative requirement related to the building thermal inertia is not mandatory for the considered locations, two opaque envelope solutions with different levels of areal thermal mass and periodic thermal transmittance were tested for each insulation level. The insulating material is placed either on the internal side or on the external side of each component.

*For each envelope configuration, two types of solar shading system have been considered, each one characterised by different position and performance level: (1) on the internal side of the window and g_{gl+sh} equal to 0.35, and (2) on the external side of the window and g_{gl+sh} equal to 0.15. **Table 41** summarises the properties of the building envelope components of the analysed configurations.*

The energy performance was assessed by means of EnergyPlus. The geometric model of the buildings was developed through the DesignBuilder software. The hourly climatic data were derived from the database of the Italian Thermotechnical Committee (CTI) [124]. Hourly profiles of the internal heat sources and the ventilation flow rate were modelled according to Part 1 of UNI/TS 11300 [85]. As specified by the Italian regulations, a continuous thermal system operation is considered during the heating and the cooling seasons. The set-point temperature was fixed at 20 °C and 26 °C for heating and for cooling respectively. For the solar heat gains evaluation, the solar shading devices are considered in function when the hourly value of solar irradiance exceeds 300 W·m⁻².

Table 40: Main geometric characteristics of the case studies [50]

Case study	Single-family house (SFH)	Apartment block (AB)	Office building (OB)
V_g [m ³]	584	8 199	6 100
V_n [m ³]	486	5 738	4 101
A_f [m ²]	162	2 125	1 519
A_{env} [m ²]	424	3 261	2 129
A_w [m ²]	20.3	275	434
A_{env}/V_g [m ⁻¹]	0.73	0.40	0.35
WWR [-]	0.097	0.123	0.591

Table 41: Characteristics of the building envelope components [50]

Application step	Parameter	Case study	Palermo				Milan			
	[Unit]		Zone B (751 HDD)				Zone E (2404 HDD)			
			from 2015 to 2020		from 2021 onwards		from 2015 to 2020		from 2021 onwards	
Thermal insulation position			INT	EXT	INT	EXT	INT	EXT	INT	EXT
Walls	U [W·m ⁻² K ⁻¹]	SFH, AB,OB	0.45	0.45	0.43	0.43	0.30	0.30	0.26	0.26
	κ_i [kJ·m ⁻² K ⁻¹]		17.1	50.2	16.6	50.1	14.4	49.6	14.0	49.5
	$ Y_{ie} $ [W·m ⁻² K ⁻¹]		0.19	0.09	0.18	0.09	0.11	0.05	0.09	0.04
	M_s [kg·m ⁻²]		152	258	152	258	153	259	153	260
Roof	U [W·m ⁻² K ⁻¹]	SFH, AB	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
	κ_i [kJ·m ⁻² K ⁻¹]		32.1	69.5	32.1	69.5	32.1	69.5	32.1	69.5
	$ Y_{ie} $ [W·m ⁻² K ⁻¹]		0.12	0.13	0.12	0.13	0.12	0.13	0.12	0.13
	M_s [kg·m ⁻²]		381	381	381	381	381	381	381	381
Roof	U [W·m ⁻² K ⁻¹]	OB	0.38	0.38	0.35	0.35	0.25	0.25	0.22	0.22
	κ_i [kJ·m ⁻² K ⁻¹]		14.1	68.7	13.9	68.6	13.7	68.4	13.8	68.4
	$ Y_{ie} $ [W·m ⁻² K ⁻¹]		0.04	0.04	0.03	0.04	0.02	0.03	0.02	0.02
	M_s [kg·m ⁻²]		632	632	632	632	634	634	634	634

Ground floor	U [W·m ⁻² K ⁻¹]*		0.46	0.46	0.44	0.44	0.30	0.30	0.26	0.26
	κ_i [kJ·m ⁻² K ⁻¹]	SFH	62.8	62.8	59.7	59.7	59.8	59.8	59.8	59.8
	$ Y_{ie} $ [W·m ⁻² K ⁻¹]		1.04	1.04	0.46	0.46	0.22	0.22	0.16	0.16
	M_s [kg·m ⁻²]		392	392	586	586	421	421	424	424
Floor vs. unconditioned space (attic)	U [W·m ⁻² K ⁻¹]		0.54	0.54	0.50	0.50	0.36	0.36	0.31	0.31
	κ_i [kJ·m ⁻² K ⁻¹]	SFH, AB	27.3	63.7	27.0	63.6	24.1	62.1	24.1	62.0
	$ Y_{ie} $ [W·m ⁻² K ⁻¹]		0.22	0.17	0.20	0.15	0.03	0.05	0.03	0.04
	M_s [kg·m ⁻²]		257	257	257	257	377	377	378	378
Floor vs. unconditioned space (cellar)	U [W·m ⁻² K ⁻¹]		0.73	0.73	0.67	0.67	0.48	0.48	0.43	0.43
	κ_i [kJ·m ⁻² K ⁻¹]	AB, OB	39.9	54.9	35.3	54.7	34.2	54.0	37.1	53.8
	$ Y_{ie} $ [W·m ⁻² K ⁻¹]		0.31	0.20	0.25	0.18	0.17	0.11	0.16	0.10
	M_s [kg·m ⁻²]		256	256	256	256	257	257	257	257
Windows	U [W·m ⁻² K ⁻¹]		3.20	3.20	3.00	3.00	1.80	1.80	1.40	1.40
	$g_{gl,n}$ [-]	SFH, AB, OB	0.75	0.75	0.75	0.75	0.67	0.67	0.67	0.67
	g_{gl+sh} [-] **		0.15 (e)	0.15(e)	0.15(e)	0.15(e)	0.15(e)	0.15 (e)	0.15 (e)	0.15 (e)
			0.35 (i)	0.35 (i)	0.35 (i)	0.35 (i)	0.35 (i)	0.35 (i)	0.35 (i)	0.35 (i)

(*) Equivalent thermal transmittance (EN ISO 13370).

(**) Solar shading devices are not installed on the windows at North. The solar shading is on the external side (e) or on the internal side (i).

5.5.3 Results

The results concern the net energy need (EP_{nd}) and the peak power (P) for heating and cooling, as shown in Figure 40. This study does not investigate the primary energy, since it focuses on the effects of the improvement of the building envelope features.

For all case studies, and for the different envelope configurations examined, the results indicate that the increase of the insulation layer thickness, corresponding to the reduction of U-values from 2015 to 2021 requirements, has a twofold and opposite effect. On the one hand, there is a reduction of the heating demand of the building and on the other an increase of the cooling energy need. The effect of higher insulation level on heating and cooling demands discloses an imbalance that emerges above all in relation to the energy needs rather than to the peak powers.

By increasing the envelope insulation, the space cooling demand grows about 5-6% without significant difference among the cases. By contrast, the

heating energy savings are more relevant and are estimated between -13% (SFH in Palermo with high thermal mass and g_{gl+sh} equal to 0.15) and -44% (OB in Palermo with high thermal mass and g_{gl+sh} equal to 0.35). Instead, installing more performant shading devices on the external side of the windows the energy need for cooling decreases about 10% in general, while the heating demand increases between 3% (SFH in Milan) and 25% (AB in Palermo). By improving the solar shading efficiency, the thermal mass level demonstrates to have no effect on the building energy need. Combining the insulation of the building envelope and the improvement of the solar shading performance simultaneously, the results reveal energy savings both for heating and for cooling in almost all cases, even if the variation of the heating energy need (between $+1\%$ and -28%) is less significant than considering the insulation option only. Similarly, the effects on the cooling demand is favourable (between -2% and -9%), although less convenient than the single improvement due to the shading devices.

Figure 41 presents two significant examples of imbalance between cooling and heating energy needs for two building types, i.e. office building in Milan and single-family house in Palermo, both insulated on the external side. For each case study, the axes origin represents the starting condition, i.e. thermal insulation level referred to the first application step (U_{2015}), g_{gl+sh} equal to 0.35 and internal shading device. The arrows identify three different efficiency measures applied to the starting condition (SC) and the consequent variation of the net energy needs for heating and for cooling is shown for each applied measure. The measures are: (M1) increasing of thermal insulation up to U_{2021} level, (M2) improving of the solar shading efficiency, and (M3) combination of M1 and M2. Four quadrants are highlighted: the red quadrant, encompassing measures with higher cooling and heating needs; the green quadrant with lower cooling and heating needs (as occurs by applying M3); the two white quadrants with an imbalance between the energy needs (higher cooling and lower heating needs, as the case of M1, or higher heating and lower cooling needs, as the case of M2).

For buildings located in climatic zones dominated by the heating season ($HDD > 2100$), it is preferable to increase the insulation of the building envelope than to improve the solar shading efficiency. In fact, by installing high performing solar shading devices, the heating energy demand would increase much more than the cooling would decrease, as emerges in the cases of apartment block and office building in Milan (see Figure 40).

Figure 40: Results of the analysed configurations: net energy need (EP_{nd}) for cooling and heating and peak power (P) of cooling and heating [50]

Figure 40: Results of the analysed configurations: net energy need (EP_{nd}) for cooling and heating and peak power (P) of cooling and heating [50]

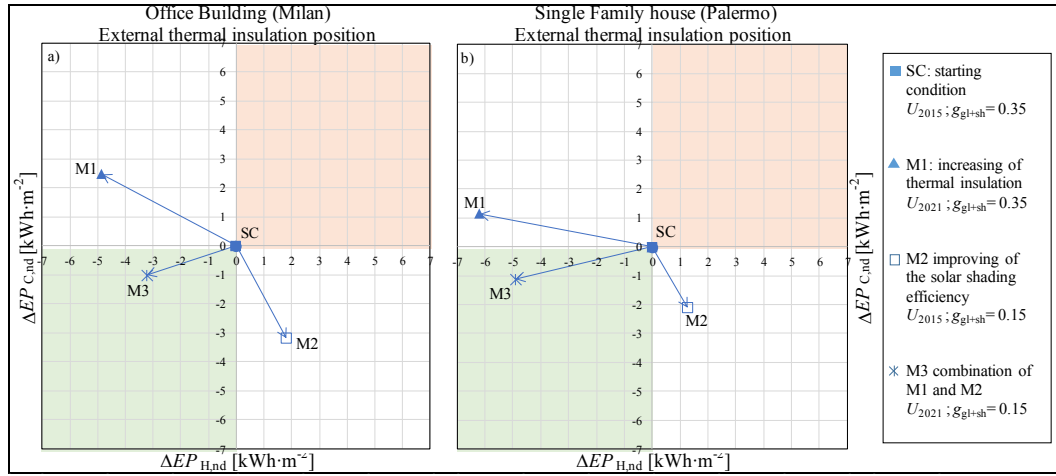


Figure 41: Variations of EP_{nd} for two case studies, office building in Milan (a) and single-family house in Palermo (b) [50]

As regards the peak power (see Figure 40), the reduction of the U -values of the building envelope causes a decrease of the heating load but negligible variations of the cooling load. The cooling peak power only lowers in combination with the installation of more performant solar shadings. For instance, it is reduced of about 12% in the single-family house both in Milan and in Palermo. The thermal inertia of the building influences the cooling peak power variation only for the case studies in Palermo and it is irrelevant for those in Milan. Considering both the solar shading solutions, the case studies with the insulation layer on the internal side of the opaque components present a cooling peak power of 9-10% higher than those with insulation on the external side. All the office buildings configurations highlight negligible variations on the cooling peak power because of the high influence of the internal gains on the building energy need. How can the chosen EP model affect to valuation methods?

Chapter 6

EP in valuation methods

6.1 Research question

How can the chosen EP model affect to valuation methods?

For addressing the question, two valuation methods are explored: the cost-optimal analysis and the Multi-Criteria Analysis. The Figure 42 shows the scheme of the chapter.

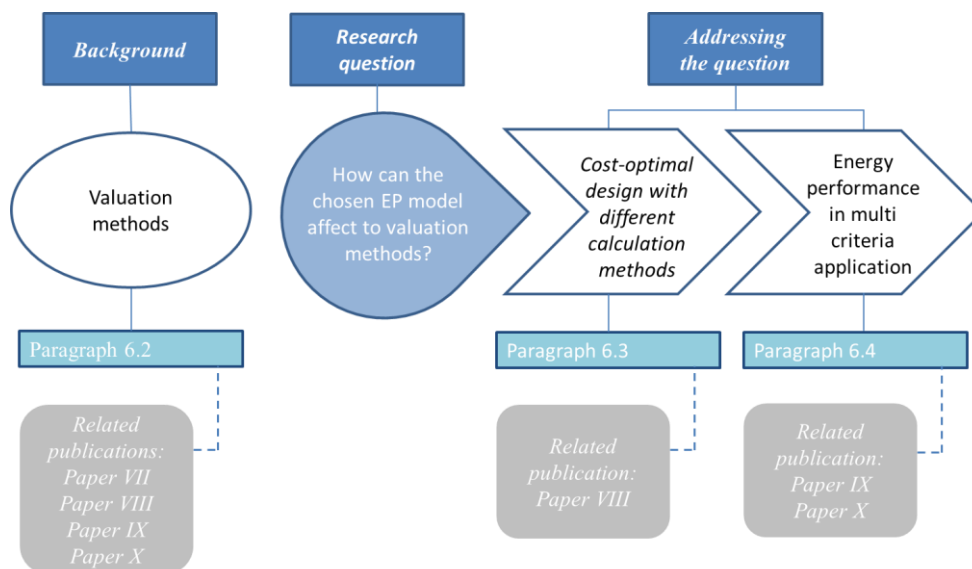


Figure 42: Scheme chapter 6

The first analysis is applied at a case study in Paper VII with quasi-steady-state calculation and the solution is compared with detailed dynamic calculation. Successively in Paper VIII, a comparison between cost-optimal analysis with quasi-steady-state model and simply hourly dynamic model is performed to highlight the difference. The PhD candidate followed the congruence between models from the side of quasi-steady-state calculation and successively the analysis of results.

A Multi-Criteria Analysis is performed to observe the role of energy performance when is used as criterion in this kind of analysis. The study is performed on both urban and building scale in Paper X and a sensitivity analysis is carried out in Paper IX.

Feedbacks and guide lines to building designers and planners which have to perform similar analysis, are provided on features of the energy performance and on criteria related to the EP.

6.2 Valuation methods

6.2.1 Cost-Optimal Analysis

European Directive 2010/31/EU on the energy performance of buildings, also known as EPBD recast [4], requires Member States to take the necessary measures to ensure that minimum energy performance requirements for buildings or building units are set with a view to achieve cost-optimal levels. Member States shall calculate cost-optimal levels of minimum energy performance requirements using a comparative methodology framework.

The comparative methodology framework has been established by the Commission Delegated Regulation No. 244/2012 [125] which supplements the Directive 2010/31/EU in order to provide the Member States with a common procedure to calculate cost-optimal levels of minimum requirements for the energy performance of buildings and building components.

A cost-optimal level is the energy performance (EP) level which leads to the lowest global cost during the estimated economic lifecycle, taking into account energy-related investment costs, maintenance and operating costs (including energy costs and savings, the category of building, earnings from energy produced), and disposal costs, where applicable.

The comparative methodology consists of the following activities:

- *definition of reference buildings (RBs), representative of the building stock according to specific criteria (e.g. building use, climatic conditions, age, size),*
- *definition of different packages/variants of energy efficiency measures (EEMs) for each reference building (RB),*
- *calculation of the primary energy demand resulting from the application of the EEM packages/variants to a RB,*
- *calculation of the global cost resulting from the application of the EEM packages/variants to a RB in its expected economic lifecycle,*
- *identification of the cost-optimal level of energy performance of and the related optimal EEM package/variant for each RB.*

The guidelines that accompany the Regulation [126] include information to help Member States to apply the comparative methodology at the national level.

The calculation of the energy demand of a reference building considering different energy efficiency measures consists in determining the annual total global energy use in terms of primary energy, including energy use for heating, cooling, ventilation, domestic hot water and lighting in non-residential buildings.

It is recommended that Member States use CEN standards for their energy performance calculations. In this regard, the energy balance of the building and its systems is the basis of the procedure. For instance, the main calculation procedure of the building energy need for space heating and cooling consists of the following steps, according to EN ISO 13790 [62]:

- *choice of the type of calculation method,*
- *definition of boundaries and thermal zones of the building,*
- *definition of internal conditions and external input data (e.g. climatic data),*
- *calculation of the energy need for each time step and thermal zone,*
- *consideration of the interactions between thermal zones and/or systems.*

A choice of three different methods is suggested in the CEN standards for the first step, as follows:

- *a fully prescribed monthly quasi-steady state calculation method,*
- *a fully prescribed simple hourly dynamic calculation method,*
- *calculation procedures for detailed dynamic simulation methods.*

For the purpose of the cost-optimal calculation, the guidelines accompanying the Regulation [126] give the following recommendations to achieve reliable results:

- *performing the calculations by using a dynamic method,*
- *defining boundary conditions and reference use patterns in conformity with the calculation procedures, unified for all the calculation series for each reference building,*
- *providing the climatic data used,*
- *define thermal comfort (e.g. indoor set-point temperatures for heating and cooling) for each reference building.*

Several studies have been carried out on this topic.

The cost-optimal calculations can be performed by means of several procedures; among these, the sequential search-optimisation technique is widely applied, as for instance in [127] and in [128].

As concerns the methodology for the energy performance calculation in the Cost-Optimal Analysis (COA), both quasi-steady state and dynamic simulation models are widely applied. For instance, the quasi-steady-state method has been applied both to the design of new nZEB [129] and to refurbishment of existing buildings [130]. In some cases, both of them are used for evaluating the behaviour of different building and system components [131].

Most of the national methods used in the Member States to enforce the Directive 2010/31/EU are based on monthly or seasonal models under stationary conditions [132]. Several research studies are instead based on the application of dynamic simulation tools, like the ones presented by Corgnati et al. [132], Ferrara et al. [133], Ganiç et al. [134], Becchio et al. [134], Ascione et al. [134].

The simple hourly dynamic calculation method has been used less than the other methods in COA studies; it is taken into account, for instance, when the analyses is focused on the energy delivered and the matching with renewable sources [134].

The Guidelines indicate two methods to deal the iterations between the building and its systems: holistic approach, where the heat gains from technical building system are considered in the calculation of the energy need, or simplified approach, where the recovered heat losses of the system are obtained by fixed conventional recovery factors. The holistic approach is more common in the dynamic models

6.2.2 Multi-Criteria Analysis

Most of the European building stock pre-dates the energy regulation and is responsible of 40% of energy consumption, with a potential of 90% emission reduction up to 2050 [135]. Lots of efforts are nowadays devoted to the definition of proper retrofitting strategies in the built environment sector. Wide ranges of solutions are available in order to reduce the energy consumption of a building [136] involving both the envelope and the energy system. Nevertheless, for either a citizen [137] or a municipality may be difficult select a proper retrofit option. When a decision needs to be taken, a set of sustainable aspects needs to be considered [138]. As discussed by [139], the energy planning of local systems is a very complex task and may be supported by Multi-Criteria Analysis (MCA). Principally, it represents a method that can support decision making when more than one criterion is involved [140]. MCA translates complex problems into simpler ones and it has been widely applied to the energy planning field [141], [142]. In the energy planning sector, MCA methods are classified in literature into four principal classes [143]: (i) Value measurement models (e.g., AHP, MAUT) (ii) Goal, aspiration and reference level models (e.g., TOPSIS) (iii) Outranking models (e.g., ELECTRE, PROMETHEE) (iv) Combination of methods.

Depending on the problem definition context, the appropriate MCA method should be selected. In particular, outranking methods are suitable for territorial analysis [144] Examples of outranking methods are ELECTRE, PROMETHEE and ORESTRE. More specific information on outranking decisions can be found in [145]–[147].

6.3 Cost-optimal design with different calculation methods

Comparisons of cost optimality results between the quasi-steady-state method and the detailed dynamic simulation are carried out in other works, as for instance in Paper VII [51].

This section studies how the calculation quasi-steady-state or dynamic methods of the energy needs for heating and cooling impacts on the final optimal design. This is done through the application of the cost-optimal procedure to a single-family house located in Milan. The building energy needs for space heating and cooling are calculated by means of the quasi-steady-state monthly method specified in the Italian standards and the simplified hourly dynamic model of ISO

13790 and EN 15316 series. The performance of the thermal systems is then assessed by means of the national standards (UNI/TS 11300), while the global cost is evaluated by means of EN 15459 [148]. Several design options with increasing levels of energy efficiency are applied to the case study.

The cost-optimal solutions derived from the application of the two methods are compared and the reasons for deviations are discussed.

6.3.1 Calculation methods

Quasi-steady-state method

The quasi-steady-state calculation method is presented in EN ISO 13790 [62], substitute by EN ISO 52016-1:2017 [11]. It is based on the monthly balance of heat losses (transmission and ventilation) and heat gains (solar and internal) assessed in monthly average conditions. The dynamic effects on the net energy needs for space heating and space cooling are taken into account by introducing a utilization factor for the mismatch between transmission plus ventilation heat losses and solar plus internal heat gains. The utilisation factor depends from the thermal inertia of the building, from the ratio of heat gains to heat losses and from the occupancy/system management schedules.

The energy need for space heating and cooling for each month is calculated as:

$$Q_{H,nd} = Q_{H,ht} - \eta_{H,gn} \cdot Q_{gn} \quad (13)$$

$$Q_{C,nd} = Q_{gn} - \eta_{C,ls} \cdot Q_{C,ht} \quad (14)$$

where, $Q_{H/C,nd}$ is the energy need for space heating/cooling, $Q_{H/C,ht}$ are the total heat transfer (transmission plus ventilation), Q_{gn} are the total heat gains (internal plus solar), $\eta_{H,gn}$ is the utilization factor of heat gains for heating mode, and $\eta_{C,ls}$ is the utilization factor of heat losses for cooling mode.

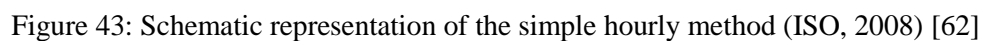
The quasi-steady-state monthly method specified in the Italian standards (UNI/TS 11300)[114] is applied in the present work.

Simple hourly method

The simple hourly dynamic method is described in Annex C of ISO 13790 [62]. It consists in a simplification of the heat transfer between outdoor and indoor environment based on a similarity between the thermal behavior of the analyzed building and a resistance – capacitance network made up of 5 resistance

The indoor air temperature (θ_{air}), at each time step, is calculated as:

Summing the $\Phi_{\text{H/C,nd}}$ per each time step adopted by the model (1 h), the heating/cooling energy needs during the analyzed period is obtained ($Q_{\text{H/C,nd}}$).



The case study

*The case study is a single-family house built in the period 1976-1990. It is a reference building selected within the IEE-TABULA project. The main geometric and construction data of the building are shown in **Table 42**, while the features of its thermal systems are listed in **Table 43**.*

Table 42: Main geometric and construction data of the case study [52]

Geometric data			Construction data		
V	[m ³]	725	U_{wl}	[W m ⁻² K ⁻¹]	0.76
$A_{f,n}$	[m ²]	199	$U_{fl,lw}$	[W m ⁻² K ⁻¹]	0.98
A_{env}/V	[m ⁻¹]	0.69	$U_{fl,up}$	[W m ⁻² K ⁻¹]	0.97
A_w	[m ²]	24.9	U_w	[W m ⁻² K ⁻¹]	2.80
No. storeys	-	2	$g_{gl,n}$	[-]	0.75

Table 43: Features of the thermal systems of the case study [52]

Space heating (H) and DHW (W) systems			Space cooling system		
Radiators	$\eta_{H,e}$	0.94	Heat terminal units	$\eta_{C,e}$	0.97
Central distribution	$\eta_{H,d}$	0.91	Zone temp. control	$\eta_{C,c}$	0.94
Gas standard boiler for H	$\eta_{H,g}$	0.85	Zone distribution	$\eta_{C,d}$	1.00
Gas standard boiler for W	$\eta_{W,g}$	0.80	Split system (100% load)	EER	2.35

The energy efficiency measures

The cost-optimal approach considered a whole renovation of the building. The energy efficiency measures (EEMs) concern both the fabric and the technical systems (see **Table 43**): EEMs from 1 to 5 consider the envelope; EEMs 6 and 7 stands for the replacement of the technical systems for space cooling and for combined space heating and domestic hot water preparation by means of different technologies (condensing boiler, biomass generator, district heating, air-to-water heat pump). The energy production from renewables is taken into account by EEMs 8 (solar collectors for DHW) and 9 (PV panels), while EEM 10 considers the heat recovery ventilation system. Finally, EEM 11 refers to the use of an advanced control for space heating. Several levels of performance (EELs) for each EEM were considered; for each level, the thermal parameter value and the referred specific cost are listed in **Table 44**; the data results from a market survey [149]. The costs exclude 22% VAT but include extra-costs for lathing and technical systems adjustment.

Table 44: Energy efficiency measures (EEMs) and related performance levels (EELs) and costs [52]

No.	EEM	Parameter	EEL			
			1	2	3	4
1	External wall thermal insulation	U_{wl}	0.30	0.26	0.20	
		$C/A_{f,n}$	25.75	28.86	35.10	
2	Upper floor thermal insulation	$U_{fl,up}$	0.30	0.25	0.20	
		$C/A_{f,n}$	11.70	15.60	21.06	
3	Lower floor thermal insulation	$U_{fl,lw}$	0.30	0.25	0.20	
		$C/A_{f,n}$	23.40	27.30	31.20	
4	Window thermal insulation	U_w	1.90	1.80	1.40	1.16
		$C/A_{f,n}$	113.88	119.57	124.21	150.50
5	Solar shading system	τ_s	0.40	0.35		
		$C/A_{f,n}$	50.00	70.00		
6	Chiller	EER_{7-35}	2.90	3.50	4.00	
		C	1638	1872	2028	
7	Combined generator for heating, DHW, and appropriate emission system	$\eta_{gn,Pn,H+W}$ OR COP_{7-35}	1.10	0.90	0.99	4.45
		C	2100	11700	3120	6000
8	Thermal solar system	A_{coll}	3.00	3.40	4.00	6.60
		C	3042	3354	3666	5148
9	PV system	W_p	1.00	2.00	3.00	4.00
		C	1716	3090	4680	6240
10	Heat recovery ventilation system	η_{ve}	0.90			
		C	1716			
11	Heating control system	$\eta_{H,c}$	0.995			
	* Cost computed in EEM 7	C	*			

Input data

The calculation was performed for the Milan location (2404 HDD). The weather database of the Italian Thermotechnical Committee was used [150].

Concerning the building energy performance evaluation: the values of the thermal transmittance of the opaque components already includes the effect of thermal bridges; the internal heat capacity of the building was calculated according to ISO 13786; the external obstacles were not considered; the heat transfer through the unheated spaces was calculated by means of the adjustment factors $b_{tr,U}$. Concerning the user behaviour, the following input data and assumptions were used:

- the sensible internal heat gains and the ventilation flow rate were defined by hourly schedule; the weekly mean values are respectively 4.5 Wm^{-2} and $0.04 \text{ m}^3 \text{ s}^{-1}$,
- the solar shadings were used when the incident solar radiation on the transparent components was higher than 300 Wm^{-2} ,

- *two different operational mode were considered for the heating season: a continuous and an intermittent schedule related to user's presence. In the first case the set-point was fixed at 20 °C; in the latter case 14 hours a day of operational time were set at 20 °C, and the set-back was fixed at 16 °C,*
- *the cooling set-point was constant at 26 °C.*

In the global cost analysis, a financial perspective calculation was adopted, without considering subsidies. The calculation was performed over 30 years, with a real interest rate of 3%. The energy costs as well as the energy trend scenarios, the annual maintenance costs and the technical lifespan of building components and systems used in the calculation process derived from previous studies [130].

The energy performance was calculated in accordance with ISO 52000-1 and it is expressed in terms of non-renewable primary energy (EP_{nren}). The renewable and non-renewable primary energy factors were assumed according to the Italian regulation. The electricity from PV panels is considered as a reduction of the monthly electrical energy demand, while the exported electrical energy is not considered.

6.3.3 Consistency options

In order to compare the two models, some consistency options were applied, as follows:

- *the monthly values of the outdoor air temperature and of the incident solar radiation derived from the correspondent hourly input data;*
- *in the quasi-steady-state method the use of the solar shadings was performed by means of the weighted fraction of the time $f_{sh,with}$, calculated from the hourly values of the simple dynamic method;*
- *the sensible internal heat gains and the ventilation flow rate in the monthly method were assumed equal to the mean value of the weekly profile used in the hourly method.*

Finally, the performance of the thermal systems was assessed by means of the national standards (UNI/TS 11300, parts 2, 3 and 4).

6.3.4 The cost-optimal approach

The cost-optimal solution consists of packages of energy efficiency measures characterised by the lowest global cost compared to a reference

package (starting point of the optimization). The global cost analysis was performed applying EN [148]. The global cost (C_{gl}) is expressed as in the following equation. It is directly linked to the duration of the calculation period t . The calculation, referred to the starting year t_0 , may be performed by a component or system approach, considering the initial investment (C_I), and, for every component or system j , the annual costs (C_a) and the discount factor (R_{disc}) for every year i (referred to the starting year), and the final value Val_F .

$$C_{gl}(t) = C_I + \sum_j \left[\sum_{i=1}^t (C_{a,i}(j) \cdot R_{disc}(i)) - Val_{F,t}(j) \right] \quad (16)$$

In the present work, the cost optimisation procedure was based on a sequential search-optimisation technique considering discrete options or levels of energy efficiency measures, as described in detail in [151] by Corrado *et al.* This procedure refers to the model developed by Christensen *et al.* [152]. The procedure allows to identify a sequence of “partial optimums”, each one obtained from the previous one by modifying all the parameters that characterize the levels of each energy efficiency measure one at a time.

As example is reported. It is concerning the optimization procedure of the simple hourly model in intermittent mode. Figure 44 and Figure 45 show partial optimum points related to different applications of the optimization procedure to the same model starting from different sets of EEMs with maximum and minimum level of Global cost.

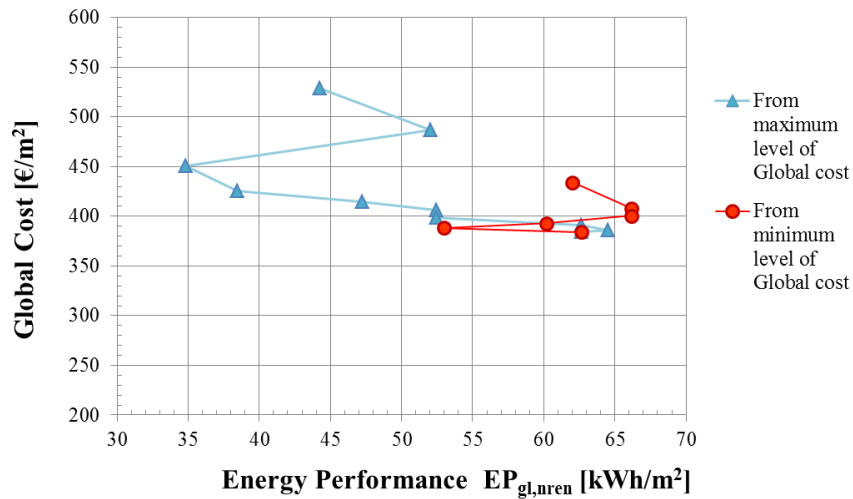


Figure 44: Optimization paths of simple hourly model in intermittent mode [52]

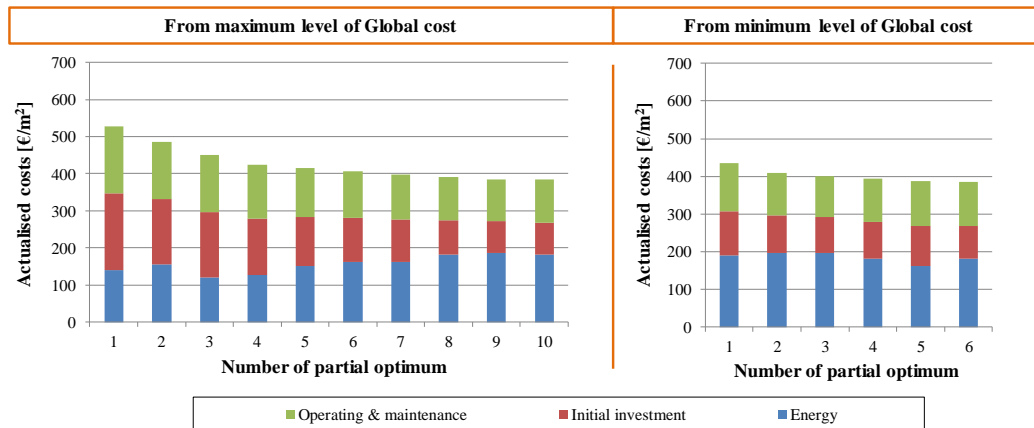


Figure 45: Actualised costs in optimization path of the simple hourly model in intermittent mode [52]

6.3.5 Comparison of cost optimal solutions

Figure 46 shows the energy needs for heating and cooling of the case study before retrofit, in case of continuous operational mode. As a general observation, it can be noted that the simple hourly method underestimates the energy use for heating and overestimates the energy use for cooling.

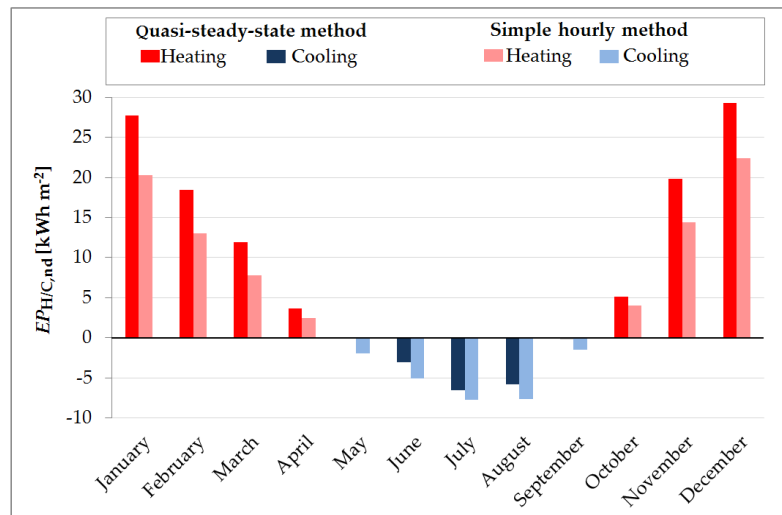
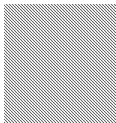


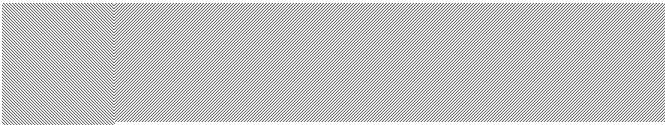
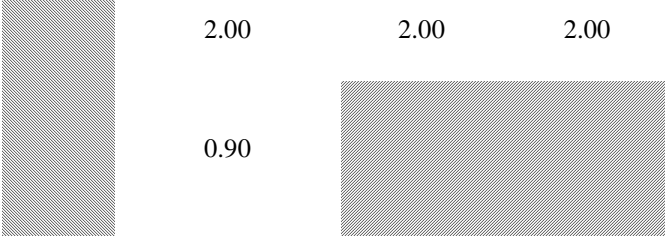
Figure 46: Building energy needs for space conditioning before the retrofit [52]

The results of the cost-optimization application are reported in Table 45, in terms of energy efficiency measures and performance levels.

As regards the monthly model, in case of intermittent heating the set-point temperature for the calculation is the same as for the normal heating mode, according to mode B of ISO 13790 (ISO, 2008); that is because the time constant of the building is greater than three times the duration of the longest reduced heating period. For that reason, the energy needs and consequently the cost-optimal solution do not change with the heating operational mode. In case of quasi-steady-state method, the optimal retrofit considers the thermal insulation of the opaque components by 0.08-0.10 m additional insulating material, the use of external movable shadings in tissue, the installation of thermostatic valves and of wall heat recovery ventilation units in combination with PV panels.

Table 45: Cost-optimal packages of measures [52]

Cost-optimal packages of measures						
No.	EEM	Parameter	Ante retrofit	Quasi-steady-state method	Simple hourly method	
				Continuous / Intermittent mode	Continuous mode	Intermittent mode
1	External wall thermal insulation	U_{wl}	0.76	0.26	0.30	0.30
2	Upper floor thermal insulation	$U_{fl,up}$	0.97	0.30	0.30	0.30
3	Lower floor thermal insulation	$U_{fl,lw}$	0.98	0.30	0.30	0.98
4	Window thermal insulation	U_w	2.80	2,80	2,80	2,80
5	Solar shading system	τ_s		0.40	0.40	0.40

6	Chiller	EER	2.35	2,35	4.00	4.00
7	Combined generator for heating, DHW	$\eta_{gn,Pn,H+W}$ or COP	0.85	0,85	0,85	0,85
8	Thermal solar system	A_{coll}				
9	PV system	W_p				
10	Heat recovery ventilation system	η_{ve}				
11	Heating control system	$\eta_{H,c}$	0.85	0.995	0.995	0.995

When the cost-optimal solution is investigated by means of the simple hourly method, it can be noticed that retrofit measures are generally oriented to the reduction of the energy use for space cooling: lower additional thermal resistance of the opaque wall in respect with the quasi-steady-state method, natural ventilation and substitution of the old splits with more efficient ones. Finally, the additional thermal resistance of the first floor facing the unconditioned space (EEM 3 of Table 45) is not considered an optimal retrofit measure when the intermittent operational mode is used in the simple hourly method.

Figure 47 shows the energy, the investment and the operating and maintenance costs of the building without retrofit and for the cost-optimal solutions. In case of no refurbishment, only the energy and the operating and maintenance costs occur. Results show that, despite different values of the global cost before the refurbishment (650 € m^{-2} in case of monthly evaluation, 567 € m^{-2} and 524 € m^{-2} for the hourly method with continuous or intermittent heating set-point respectively), the deviation of the cost-optimal solutions between the two calculation methods is negligible (maximum deviation of 5 € m^{-2} between quasi-steady-state and intermittent simple hourly model). In particular, the costs for operating and maintenance is similar for all the optimal solutions ($115\text{-}119 \text{ € m}^{-2}$), while the energy cost and the investment cost counterbalance each other.

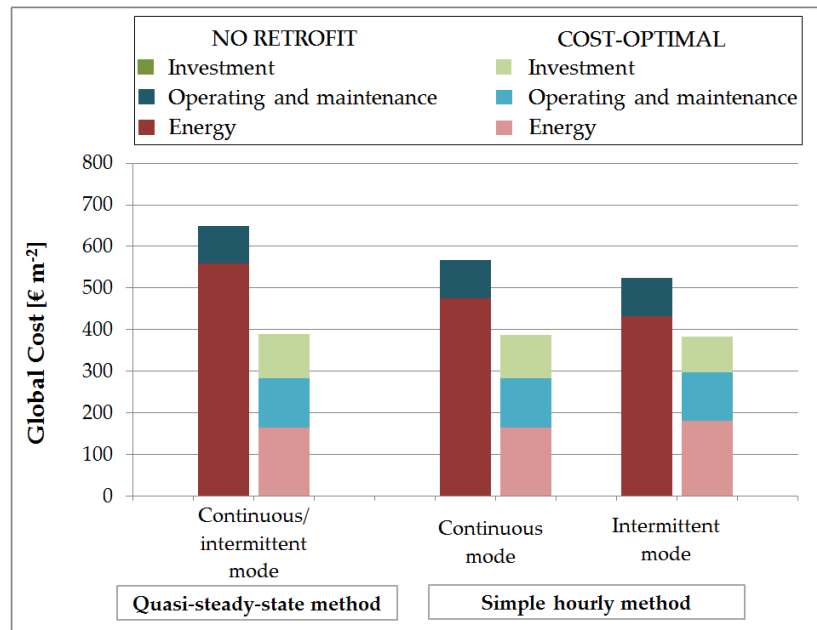


Figure 47: Global cost, no retrofit and cost-optimal solutions [52]

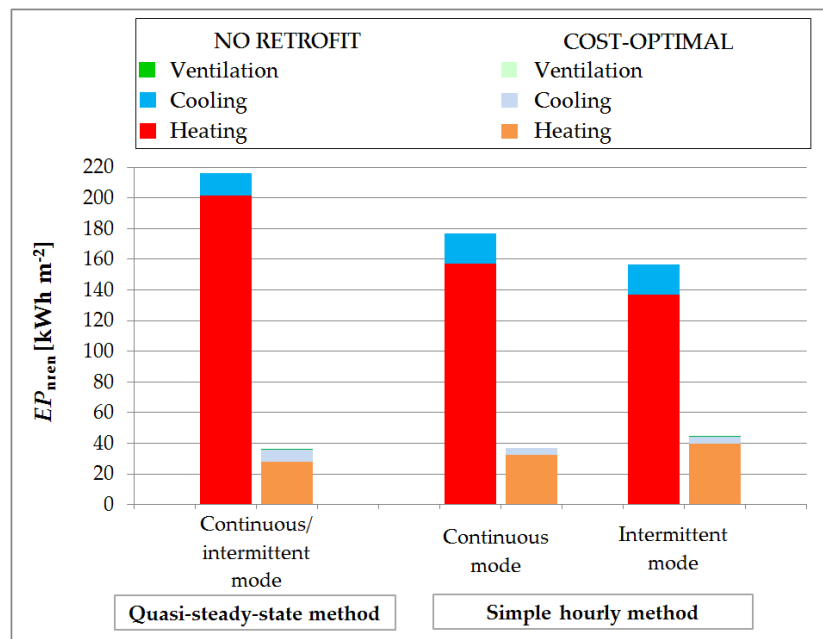


Figure 48: Non-renewable primary energy performance, no retrofit and cost-optimal solutions [52]

Figure 48 shows the non-renewable energy performance of the cost-optimal solutions compared with the building before the retrofit, calculated by means of the two methods. The cost-optimal approach allows to reduce the non-renewable primary energy use from 71% by the intermittent mode of the simple hourly method to 83% by the quasi-steady-state method.

Despite different values of the energy performance of the existing building (216 kWh m⁻² for monthly method, 177 kWh m⁻² and 157 kWh m⁻² for the hourly method with continuous or intermittent heating set-point respectively), the cost-optimal EP_{nren} is in between 37 kWh m⁻² of the monthly and the continuous hourly models, and 45 kWh m⁻² of the intermittent hourly model. The non-renewable energy use for heating is increased in the hourly method (especially with the intermittency mode) because minimization of the global cost. Thus, the higher energy cost in respect with the monthly model is counterbalanced by a lower investment cost (Figure 47) due to the choice of minor additional thermal insulation material and the absence of heat recovery ventilation systems. As well, the different EER values between the cost-optimal solutions of the quasi-steady-state and the simple hourly methods (EEM 6) justify the deviation in $EP_{C,nren}$.

6.4 Energy performance in Multi-Criteria Application

The work developed in Paper IX proposes a MCA model with PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation) for promoting the energy retrofitting of urban districts. It is applied to a study case in the city of Turin for outranking five different proposed alternatives for buildings refurbishment that allows to achieve 20% energy saving.

The study continues in Paper X to test the same procedure at the building level and to compare the results of two levels. In this dissertation methodology and results at district level are shown. Results at the building scale are analogous.

6.4.1 Method

The PROMETHEE method, developed by Brans *et al.* [153], has been chosen in this study due to its simplicity and because it has been used broadly in the field of energy planning and its applications, such as [154]. Therefore, PROMETHEE method fits the purpose of this study and it is used to outrank the proposed energy retrofit alternatives. Moreover, the presented methodology could be applicable in other similar urban areas.

PROMETHEE method is based on pairwise comparison that is able to rank a restricted number of alternatives characterized by conflicting criteria

[155]. *Criteria weights and decision-maker's preference function are the two-main necessary information in the implementation of this method. In this paper, PROMETHEE application follows the instructions provided in [53], which is summarized in Figure 49.*

The first step consists in defining problems and objectives of the analysis in the given planning context. Once the problem is clearly defined, data collection and analysis process can start. In case of a large database (e.g., urban context), Geographic Information Systems (GIS) tools can support data collection process [156]. Taking into account data availability, the previous literature [157] and the problem. The selection of a set of non-redundant criteria [158] and their relative weights represents the next step in the procedure.

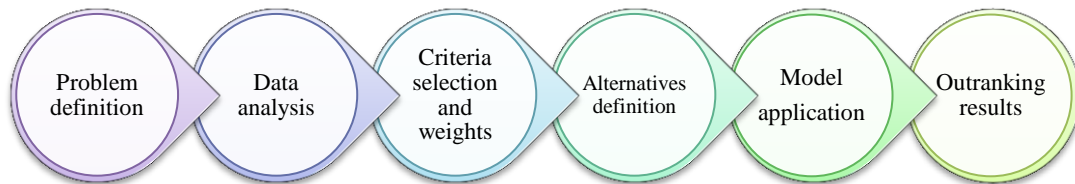


Figure 49: Conceptual framework of the methodology [53]

Afterward, a group of several stakeholders needs to be involved to select the final set of criteria based on stakeholders' preferences and knowledge. At this point, stakeholders assign a weight to each criterion. Since results are strongly affected by weights assignment, this step is particularly important. Furthermore, the alternatives to be outranked should be defined by analysts combining different retrofit measures involving buildings envelope or heating system. This step can also be performed with a participative approach. Finally, PROMETHEE method outranks retrofitting alternatives. Using this method, alternatives are pairwise compared based on the ϕ value. The ϕ is an indicator used to select the best alternatives. It is calculated as the difference between positive and negative outranking flows. The best alternatives are therefore the ones characterized by higher ϕ values.

6.4.2 Problem definitions

The work in this section simulates the specific case where a Municipality would like to invest part of his budget to finance energy retrofit of residential stock in order to improve the life quality of its inhabitants. This study applies the

MCA method to support the municipality deciding which energy retrofit alternative to promote (district scale analysis). [...] In this analysis it is assumed that the Municipality fixes its energy savings target to 20% compared to the actual performance. That the Municipality can invest a maximum of 17 M€ to finance the building energy retrofit. In this hypothetical situation, the budget of 17 M€ is intended as an economic incentive to citizens to finance up to 60% of the capital cost of the retrofit alternative. In this vision, the citizens will cover only 40% of the initial capital cost. This particular situation has been taken by authors in order to test a possible new policy in alternatives to the current tax deduction over 10 years.

Problems definition is therefore: “Which energy retrofit alternatives and strategies are best applied to generate both economic and socio-environmental benefits for the local community?”.

6.4.3 Data analysis

The study area involves 198 buildings sited in “District 3” of the city of Turin, Italy. The sample buildings have been classified into five building types as in Table 46.

Table 46: Buildings types sited in the relevant district [53]

Building Type	Family type	Year of Construction	Number of building
Type 1	MF	before 1980	132
Type 2	SF	before 1980	50
Type 3	MF	1981 to 2005	8
Type 4	SF	1981 to 2005	6
Type 5	MF	after 2006	2
MF= multi-family, SF= single family			

To match the total goal of 20% energy savings, a mix of different packages has been considered Table 47.

Table 47: Packages combination [53]

Packages	Strategies Description
1	standard envelope renovation
2	standard envelope renovation coupled with the installation of thermostatic valves
3	standard envelope renovation coupled with thermostatic valves and with heat pumps' installation

4	standard envelope renovation and the installation of mechanical ventilation
5	installation of heat pumps together with PV systems

Table 48: Alternative scenarios [53]

Alternative energy saving		Development of building refurbishment alternatives
1	Envelope	Package 1 Standard applied to 28 Building Type 1 and 8 Building Type 3 + Package 2 Standard applied to 15 Building Type 2 and 6 Building Type 4
2	Envelope+ Control system	Package 1 Standard applied to 24 Building Type 1 and 8 Building Type 3 + Package 2 Standard applied to 14 Building Type 2 and 6 Building Type 4 + thermostatic valves installed into 54 buildings including Building Type 5
3	Envelope+ Control system+ Plant system	Package 1 Standard applied to 19 Building Type 1 and 4 Building Type 3 + Package 2 Standard applied to 15 Building Type 2 and 6 Building Type 4 + thermostatic valves installed into 46 buildings including Building Type 5 + Heat Pumps installed into 19 Building Type 1 and 4 Building Type 3
4	Envelope+ Plant system	Package 1 Standard applied to 18 Building Type 1 and 4 Building Type 3 + Package 2 Standard applied to 14 Building Type 2 and 6 Building Type 4 + mechanical ventilation installed into 44 buildings including Building Type 5
5	Plant system +Renewable sources	HP + PV installed into 32 Building Type 1 and 8 Building Type 3 + 18 Building Type 2 and 6 Building Type 4 + 2 Building Type 5

*The first step consists in evaluating to which amount each options combination is contributing to energy savings with respect to different building types. Building features, package features and energy evaluations are referred to [159] and to TABULA project [40]. Considering volumes' distribution, the alternatives are thus described in **Table 48** and Figure 50.*

*As can be observed, it is not necessary to perform deep retrofit on the whole buildings. Accordingly, to options' combinations, the number of involved buildings in renovation works have changed from a minimum of 57 to a maximum of 113. In this case, five progressive scenarios have been supposed by researchers and experts starting from the envelope requalification to exploitation of renewable sources and comparing them (**Table 48**).*

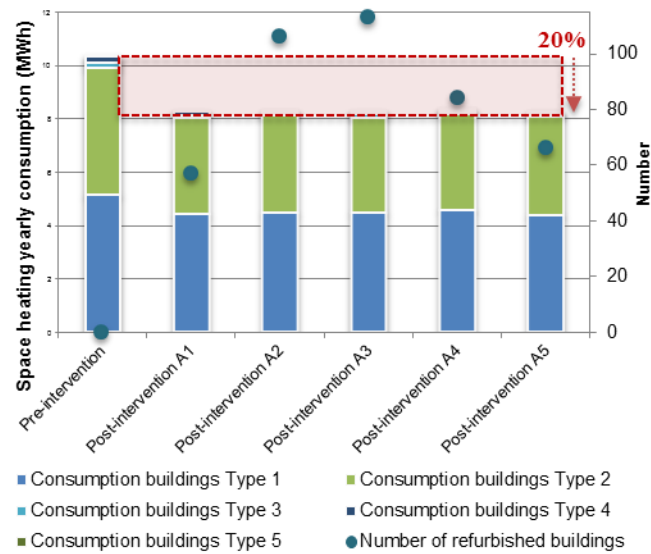


Figure 50: Energy savings and number of buildings on district scale buildings [53]

6.4.4 Criteria selection and weights

First, the criteria and alternatives were defined based on literature, and then, discussed during the focus group, involving three different stakeholders: an urban energy planner, an urban energy engineer and a built environment expert. Moreover, as a consequence of the focus group discussion, eight criteria have been defined with the aim at structuring the model.

Quantitative criteria are represented by:

- *Investment Cost C1 (M€): the capital cost of alternatives to be financed by the Municipality. Values of investment cost associated to each alternative has been evaluated by referring to Italian regional price list database [160],*
- *Replacement Cost C2 (M€): investment costs to be repaid by the citizen at present time to replace an alternative according to its technical life (when the calculation period is longer than the technical life of the alternative). These values are the same as in C1, discounted at present level with a discount rate assumed equal to 3.5% (present net value) [161],*
- *Maintenance Cost C3 (M€): fixed costs to be sustained by citizens during technical life of alternatives (evaluated with a discount rate assumed equal to 3.5% [161]). Operation and Maintenance (O&M) costs have been*

considered 0% of investment costs for envelope components and 2% of investment costs for energy system components,

- *Tax deduction C4 (M€): the amount of money that the Municipality is not giving to citizen for tax deduction over 10 years (in this paper the tax deduction option has been substituted by covering a 60% capital investment),*
- *Internal comfort C6: related to attended retrofit results in terms of comfort and to efficiency of technologies. This criterion has been considered proportional to the number of retrofitted buildings.*

Qualitative criteria are instead divided into:

- *Reliability C5: intended as presumed satisfaction with new internal thermal environment at the district level. The relative ordinal scale can be observed in **Table 49***
- *Built environment (BE) value C7: level of beautification of built environment. The relative ordinal scale can be observed in **Table 50**,*
- *Social image and awareness C8: how the choice of alternative rises the citizens' awareness to environmental benefits and their pro-active behaviour. The relative ordinal scale can be observed in **Table 51**.*

Criteria are divided into Economic (C1, C2, C3, C4) and Socio-Environmental (C5, C6, C7, C8) indicators.

The tax deduction criterion is intended as economic savings for the Municipality. In fact, the latter pays the 60% of initial investment to citizens instead of providing tax deduction in the next 10 years.

Table 49: Reliability ordinal scale [53]

Num.	Reliability	Description
1	failure	low efficiency of the technology (lower than 80%) and low probability of success of the measure (> 70%)
2	low probability of success	low efficiency of the technology (lower than 80%) or low probability of success of the measure (> 70%)
3	medium probability of success	high efficiency of the technology (higher than 80%) or high probability of success of the measure (> 80%)
4	high probability of success	high efficiency of the technology (higher than 90%) and high probability of success of the measure (> 80%)
5	success	high efficiency of the technology (higher than 1) and high probability of success of the measure (> 90%)

Table 50: Built environment ordinal scale [53]

Num.	Built environment value	Description
1	unacceptable built environment	degraded built environment
2	lower built environment	worsened built environment
3	medium built environment	the built environment doesn't change
4	improved built environment	built environment beautification
5	high built environment improvement	built environment consistent beautification

Table 51: Social Image and awareness ordinal scale [53]

Num.	Social image and awareness	Description
1	unacceptable to people	the solution is not in the cultural tradition of people and they are not aware about the benefits
2	low acceptability	the solution is not diffused in the area and people have low awareness about its benefits
3	medium acceptability	the solution normally adopted in the area and the related benefits are known
4	high acceptability	built environment beautification
5	extremely high acceptability	built environment consistent beautification

6.4.5 Alternatives definition

To apply PROMETHEE method, model parameters (i.e. indifference (q) and/or preference (p) thresholds) related to each criterion need to be defined. A certain level of uncertainties affects some evaluations, thus indifference and preference thresholds are presented to control the impact of a limited precision. Values associated to each criterion related to alternatives are proposed in **Table 52**.

Table 52: Performance Matrix [53][illegible]

Min Value	3.37	1.73	1.24	0.3	2	57	1	1
Max Value	10.1	3	3.7	3.3	5	113	5	5
Max Δ	6.73	1.27	2.46	3	3	56	4	4
Min Δ	0.3	0.07	0.1	0.1	1	7	1	1
A 1	8.1	1.8	3.0	3.3	3	57	5	4
A 2	7.4	2.5	2.7	3.1	4	106	4	5
A 3	7.1	2.8	2.6	2.6	5	113	3	2
A 4	10.1	3.0	3.7	2.5	2	84	2	1
A 5	3.37	1.73	1.24	0.3	2	66	1	3

As a first attempt (Baseline), the weight associated to each of n criteria has been considered equal to $1/n$ “Equal weights method”. The indifference value (q) associated to each of n criteria has been set equal to minimum values difference. In the Baseline, preference value (p) of each criterion has been assumed as double of q (Table 53).

Table 53: Thresholds selection [53]

	Indifference thresholds (q)	Preference thresholds (p)
C1	0.3	0.6
C2	0.07	0.14
C3	0.1	0.2
C4	0.1	0.5
C5	-	-
C6	7	25
C7	-	-
C8	-	-

6.4.6 Application of method and sensitivity analysis

Once the baseline model has been implemented in PROMETHEE, the tool provides result in form of ϕ ranking. It allows identifying strengths and weaknesses of alternatives respect the criteria and thresholds.

In Figure 51 the result of baseline model is showed.

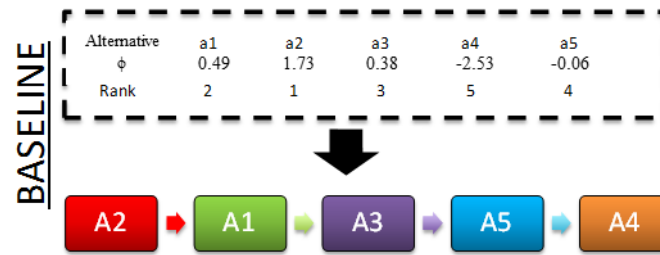


Figure 51: Baseline results [53]

As can be observed in Figure 51, the A2 Alternative is characterized by the highest ϕ value, and it is therefore identified as the best alternative. Alternatives A1 and A3 have ϕ values significantly lower compared to A2, but with closer values among themselves. Alternatives A5 and A4 have the lowest values of ϕ , in particular A4 that is the worst alternative.

		Inv. C 1	Main. C 2	Tax d. C 3	Rep. C 4	Built. C 5	Rel. C 6	Int. Com. C 7	Soc. Im. C 8
Baseline	Weight	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
	p	0.6	0.2	0.2	0.14	2	2	25	2
	q	0.3	0.1	0.1	0.07	2	2	7	2
Change 1 (Baseline + new weights)	Weight	0.17	0.11	0.11	0.11	0.15	0.10	0.10	0.15
	p	0.6	0.2	0.2	0.14	2	2	25	2
	q	0.3	0.1	0.1	0.07	2	2	7	2
Change 2	Weight	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
(Baseline + New lighter P thresholds)	p	1	0.77	0.5	1.36	2	2	30	2
	q	0.3	0.1	0.1	0.07	2	2	7	2
Change 3	Weight	0.17	0.11	0.11	0.11	0.15	0.10	0.10	0.15
(Change1 + New lighter P thresholds)	p	1	0.77	0.5	1.36	2	2	30	2
	q	0.3	0.1	0.1	0.07	2	2	7	2
Change 4	Weight	0.17	0.11	0.11	0.11	0.10	0.15	0.15	0.10
(Baseline + new socio- environmenta l weights)	p	0.6	0.2	0.2	0.14	2	2	25	2
	q	0.3	0.1	0.1	0.07	2	2	7	2
Change 5	Weight	0.17	0.11	0.11	0.11	0.10	0.15	0.15	0.10
(Change 4+ New lighter P thresholds)	p	1	0.77	0.5	1.36	2	2	30	2
	q	0.3	0.1	0.1	0.07	2	2	7	2

Figure 52: Changes for the sensitivity analysis [53]

A sensitivity analysis can be performed in order to visualize the robustness of the model. Therefore, different weights and threshold values have been

changed with respect to Baseline scenario. Five main “Changes” have been assumed by the focus group into the sensitivity analysis (Figure 52). In all the scenarios, indifference thresholds have not been changed.

In “Change 1”, “Change 3” and “Change 5” new weights with respect to Baseline of the criteria have been proposed. They have been indicated by considering the different perspectives of experts involved in the focus group. In all changes, the sum of weights relative to the economic and socio-environmental criteria have been maintained constant (0.5 for economic criteria and 0.5 for socio-environmental criteria). However, among weight Changes, economic criteria have constant weights while socio-environmental ones vary. Taking into account the relevance of Investment Cost, a higher weight has been assigned to this criterion. During the discussion of the focus group, any of Socio-economic criteria prevailed. Therefore, little weight variations (0.025) have been proposed in Changes respectively to the more technical criteria (Reliability and Internal Comfort) and to the more social oriented criteria (Built Environment Value and Social Image and Awareness). Moreover, in “Change 2”, “Change 3” and “Change 5”, new preference thresholds are proposed in order to increase the Investment preference and the Internal Comfort preference. This choice is justified by the possible intention of the Municipality in investing more for achieving a higher comfort level for citizens. All the preference and weight combinations are shown in Figure 52.

6.4.7 Outranking results

From model runs, by changing p and q thresholds as well as weights, the best alternative is always represented by A2 (coating + thermostatic valves), as it is shown in Figure 53. It allows raising a significant comfort improvement, it has acceptable costs and does not have a relevant built environment impact. Moreover, it is a well-known solution with high market availability. Instead, A4 (coating + mechanical ventilation) is always the worst alternative since the cost of technology is quite elevated and it is characterized by extremely low socio-environmental performances.

“Baseline”, “Change 1” and “Change 2” present the same outranking of alternatives, where A2 is followed by A1 (coating), A3 (coating + thermostatic valves + heat pumps), A5 (PV panels + heat pumps) and A4. In these three Changes, the rank position is not affected by the sensitivity analysis even if ϕ values vary for every Changes. A1 has best performances concerning the built environment and the social image, while A3 has lower costs and higher comfort

improvements. Instead, A5 can achieve the energy reduction goal at a lower price compared to all the other options, even if it has worst socio-environmental “Change 4” and “Change 5” show the same outranking, where the second position is reached by A3 instead of A1.

The proposed change of weights leads option A3 to be preferred to A1 since both Internal Comfort and Reliability of A3 are considerably higher compared to A1. The ranking of “Change 3” is different from previous results because the third position is covered by A5. This alternative has the lowest investment cost, whose role is amplified by a higher weight. Furthermore, changed preference for Internal Comfort decreases the difference (ϕ) between A5 and A3.

	New Weights 1	Baseline Weights	New Weights 2
Baseline Preferences	CHANGE 1 ϕ 1.73 0.55 0.25 0.11 -2.64 	BASILINE ϕ 1.73 0.49 0.38 -0.06 -2.53 	CHANGE 4 ϕ 1.73 0.65 0.09 0.03 -2.50
	CHANGE 3 ϕ 1.49 0.79 0.08 0.05 -2.40 	CHANGE 2 ϕ 1.53 0.68 0.21 -0.07 -2.35 	CHANGE 5 ϕ 1.46 0.43 0.35 0.02 -2.26

Figure 53: Outranking results [53]

6.4.8 Concluding remarks

This work demonstrates the suitability of applying the PROMETHEE method for the outranking analysis of different alternatives to improve energy efficiency in buildings at the district level.

The concluding remarks derived from this long process are outlined below.

- *The alternative scenarios should be characterized by different technological retrofitting choices to a different number of buildings in order to avoid a progressive evolution of alternatives with obvious results.*
- *It is suggested to consider a unambiguous odd ordinal scale for the definition of qualitative criteria performances in order to identify a neutral value.*
- *A sequence of changes (scenarios) in model parameters should be done in order to understand which are the model limitations and to restructure the model itself.*

- *The choice of thresholds is a very critical step of the MCA. The stakeholders' experiences and knowledge can help to reasonably choose these values.*
- *The weight values should be varied accordingly to the focus group preferences and not be defined a priori.*
- *The distribution of the importance of coefficients between the criteria (set of weights) should not be substantially diverse in different scenarios.*

For a possible future development of a real project, the following modifications in the proposed model are suggested.

- *Improving the actual criteria and evaluations procedures according to the local conditions.*
- *The weights should emerge from a broader number of stakeholders with different background.*
- *Unequal distributions of qualitative and quantitative criteria may be tested.*
- *Criteria need to be unambiguously defined by referring to actual laws, standards' targets, previous literature and stakeholders' experiences. For example, the values related to the useful life of technologies should derive from constructors' certificates. The lack of reliability of data makes difficult to assess with high precision the value of the specific criterion; such uncertainties may have an impact on the inclusion status of the criterion in the analysis.*

6.4.9 Considerations on EP

In this case study, as well as that of Paper X, different alternatives are compared. Each alternative considers different energy efficiency packages which achieve the 20% energy saving target.

However, changing the calculation method can change the EPs (as shown in Section 6.3 with Cost-Optimal Analysis) and therefore an higher number of retrofit actions may be needed.

For this reason and other consideration showed in this dissertation, the PhD candidate suggests the following recommendations for a future development of a real project with Multi-Criteria Analysis.

- If the objective of alternatives is to achieve a fix value of energy savings or of EP, this estimate have to realize through same calculation method for each package.
- p and q thresholds should be according to the calculation method and not fixed a priori. If the focus group doesn't have an expert of BES a variable value defined through a formula can be used (as assumed for criteria in this Section 5.5).
- Models used to estimate the energy saving must assume the same conditions as climatic data, internal inputs (internal gains, occupant behaviour), ventilation and operation (set-point and operating hours) for each energy efficiency packages.
- As analysed in Section, high values of insulation can have effects on space cooling energy, for this reason it is suggested to consider both energy services in an MCA analysis.
- Finally, a deterioration of the efficiency of energy package is recommended for long period of analysis (it may vary in function of the technology).

Chapter 7

Conclusions

7.1 Research questions

The main question of this thesis is: what is the role of the energy performance modelling with a view to low energy buildings?

The complexity of the BES and the wide use of energy performance modelling have made it necessary to delineate the boundaries of the research in order to be able to answer this question. The BES search field has been divided into four research fields. They are: climatic data versus energy performance, energy performance rating and ranking of buildings, definition of minimum building requirements and exploration of technologies, energy performance in valuation methods.

Secondary questions arose by exploring the aforementioned fields of research. Research boundaries are different depending on the field of application in order to better explore the field under examination. Proposed contributions in the thesis served to address the secondary questions.

The secondary questions are the following.

- i. What is influence of climatic data on energy performance? Are they reliable?

- ii. Which can models and data be used for Energy Efficiency Measures (EEMs) of buildings on urban scale?
- iii. How can the chosen EP model affect the specification of minimum building requirements?
- iv. How can the chosen EP model affect to valuation methods?

7.1.1 Question i

What is influence of climatic data on energy performance? Are they reliable?

The outdoor climatic data are an important factor in the assessments of the energy performance of buildings: they affect both the heat transfer through the building envelope, and the size and the efficiency of HVAC systems and of thermal and photovoltaic solar systems.

In order to evaluate the buildings that have a very low amount of energy covered to a very significant extent by energy from renewable sources (nZEB), detailed models under dynamic conditions and reliable and accurate climatic data are necessary. The analysis has showed that the sources of climate data currently available lead to results in terms of energy performance of a nearly zero-energy building that, in some cases, can be very different from each other [45].

$EP_{C,nd}$ and $EP_{H,nd}$ between the energy performance calculated using the climatic data of UNI 10349:1994 and UNI 10349-1:2016 with quasi-steady-state calculation model, could be as high as 50%. Furthermore in Section 3.3, it was possible to observe different trends of the variables in function of the climatic zones with quasi-steady-state model. $EP_{C,nd}$ calculated with the CTI TMY was always higher than the one calculated with DOE TMY with detailed dynamic model. The differences were between 28% and more than 200%. Countertrend the $EP_{H,nd}$ were higher with DOE except in Ancona where the values get close.

In Italy as intended by the national legislation, the design of nZEBs will take place with the use of the national standard UNI 10349-1:2016 [45].

The new climatic data can be used in hourly dynamic models. The building energy simulation will be always more wide used for forthcoming developments in energy design and evaluation. In particular for buildings with low energy consumptions will require TMYs that can guarantee reliable and realistic results. For this reason a research is addressed to study these aspects in Section 3.4.

The study took into account nineteen weighting coefficient configurations, four energy services, three types of building envelopes and two values of WWR.

An improvement of the EN ISO 15927-4 standard methodology was proposed, as to increase the estimation accuracy of the EP in the medium and long term.

Results highlight that different TMYs should be used for assessing EP for single energy services and, in some cases, for different types of buildings. At the opposite the EN ISO 15927-4 standard methodology provides greater representativeness for aggregated energy services.

*In the choice of optimal configuration (as shown in **Table 9** and **Table 13**) the influence of air temperature is generally dominant for heating and cooling services when they are expressed in terms of energy need and primary energy. Results highlight that different TMYs should be used for assessing EP for single energy services and, in some cases, for different types of buildings. At the opposite the EN ISO 15927-4 standard methodology provides greater representativeness for aggregated energy services [46].*

Representative TMYs of global renewable energy on long period have a more high weigh coefficient for global solar irradiance than TMYs select for the global non-renewable energy. This reinforces the suggested proposal that different TMYs should be used for assessing EP for single energy services.

7.1.2 Question ii

Which can models and data be used for Energy Efficiency Measures (EEMs) of buildings on urban scale?

In function of the scope of the study, the EP can be calculated with different calculation method (SS, SH or DD). If the aim is to estimate the energy needs of buildings that are connected to a district heating network, the most suitable models are the dynamic ones. The choice between the SH or DD models depends on the available data and the time available for analysis.

In chapter 4, the case study has energy demands estimated with SH method. The high number of buildings does not allow to analyse buildings individually to understand which retrofit allows the best energy saving. The study presented in chapter 4 suggests two different data mining approaches, namely the Visualization method and the Decision Tree with CART algorithm. Methods were analysed and evaluated. Deviations of compared techniques are shown in **Table 54**. The average percentage of energy demand saving data set is 26.5%. It is the ratio between the energy demand saving and the current energy demand. The maximum energy demand saving is approx. 39.4%. The average percentage of retrofitted buildings data set is 57.4%. It is the ratio between the number of retrofitted buildings and the total number of buildings. The total number of buildings is 299. Deviations in **Table 54** are the differences between percentage values of the data set or number

of retrofitted buildings of data set and respective averages. The table highlights as the 1st level of EEMs of Data set G has a high deviation percentage of retrofitted buildings (equal to -14.6%) and an low deviation percentage of energy demand saving 3.8%. Other data sets show couple of deviations with the same sign with exclusion of Data set A but it has a low percentage of deviation of retrofitted buildings (about -4.2%). The CART Method applied on data set with EC does not provide high performance. This highlights the limitation of this method when it is applied with real data. The risk is that correlations between identified variables and "labels" are not tight. Energy savings with the data sets A, B, E, F and G are more high than energy savings with data sets C and D because ED derives from the simulations through TEASER. The latter one obviously correlates the variables of the data set with used energy performance for labels of buildings. Moreover, ED of previously data sets is not influenced by the heating generation system, as happened for data sets with EC. In conclusion, the limitation of the applicability of Decision Tree with CART method is the quality of data sets, while Visualization technique is not sensible of this aspect. The latter one could be applicable without to know the ratio S/V, opaque and transparent thermal transmittances. On the other hand, the Visualization technique does not provide a priority of application of EEMs and which kind of EEMs (on opaque or transparent envelope).

Table 54: Deviations of compared techniques

Data set	Considered energy	Applied method	Application of EEMs to	Deviation of retrofitted buildings [%]	Deviation of energy demand saving [%]
Data set A	ED	VT	-	-4.2%	7.0%
Data set B	ED	VT	-	-38.4%	-7.0%
Data set C	EC	CART	Leaf-level	-33.0%	-15.5%
Data set D	EC	CART	Leaf-level	-33.3%	-15.0%
Data set E	ED	CART	Leaf-level	32.2%	9.4%
Data set F	ED	CART	Leaf-level	19.2%	4.7%
Data set G	ED	CART	Leaf-level	-4.2%	-21.1%

G					
Data set	ED	CART	1 st level of	-14.6%	3.8%
G			EEMs		
Data set	ED	CART	2 nd level of	6.8%	5.7%
G			EEMs		
Data set	ED	CART	3 th level of	11.1%	6.1%
G			EEMs		
Data set	ED	CART	4 th level of	26.2%	10.0%
G			EEMs		
Data set	ED	CART	5 th level of	32.2%	11.7%
G			EEMs		
Average				57.4%	26.5%

ED: Energy Demand

EC: Energy Consumption

VT: Visualization Technique

CART: Decision tree with CART algorithm

EEMs: Energy Efficiency Measures

7.1.3 Question iii

How can the chosen EP model affect the specification of minimum building requirements?

For addressing the question the first analysis was performed on the verification of the new Italian Ministerial Decree about minimum requirements for the energy performance of buildings. *In Section 5.3 the most feasible and wide spreading technical design solutions of nZEBs, concerning both the envelope and the technical systems, have been analysed. Results show the applicability of the MD for the design of the nZEBs.*

The following suggestions are provided to overcome the limitations of the notional reference building approach implemented in the Italian regulation: (a) the thermal bridge effect should be evaluated separately from the envelope component U-value; (b) the real technical system auxiliaries should be attributed to the notional reference building; (c) in addition to the average efficiency, other characteristics of the notional reference building thermal systems should be specified, possibly assumed as those of the design building.

The use of dynamic simulation as calculation methodology is advisable in the decree to accurately assess the energy performance of low-energy buildings [48].

The second analysis for addressing the question was an investigation of the notional reference building approach to verify the energy performance requirements of buildings through dynamic simulation. *The analysis, performed on an Italian single-family nZEB in two different climatic zones, demonstrates that the reference parameters established by the national regulations are correctly chosen, as they significantly influence the building EP. Anyway, the level of detail used to describe the notional reference building by the Italian legislation, even if suitable for a quasi-steady-state numerical method (with critical aspects listed previously), is not sufficient to fully characterise the building by means of a dynamic simulation tool. A more detailed information about the thermal envelope and the technical building systems would be necessary. An improved procedure for specifying a notional reference building was addressed in the Section 5.4 and consists of four main steps: (1) choice of the calculation method of the building EP, (2) distinction between reference and actual features, (3) specification of the level of detail and simplifying assumptions of reference parameters, (4) setting of reference parameters values [49] (See the Section 5.4 for the full implementation of procedure).*

The third analysis for addressing the question was to observe a consequence of the selection of reference feature values (choice IV of Figure 31) *The study was started from the Italian national legislation which establishes different levels of building envelope insulation for the notional reference building. The latter is used to verify the EP requirements. Different U-values are provided for the Italian climatic zones and types of envelope component, on the basis of two temporal steps of application. Even if these requirements aim to improve the energy performance of buildings by reducing the heating energy need, a consequent increase of the cooling energy need occurs. This phenomenon determines an imbalance of opposite energy demands. In Section 5.5, different building types have been considered.*

By reducing the U-value of envelope components, the imbalance between the cooling and the heating energy needs always occurred; the cooling need increased up to 5-6% in all the analysed cases. The cooling need could be effectively reduced by applying high performing shading devices. Anyway for apartment blocks and office buildings located in cold climatic zones, the reduction of the thermal transmittance was more effective on the annual energy performance of the building than the improvement of the solar shading. In fact, the super-insulation of the building envelope yielded to higher reduction of the heating need compared to the cooling energy savings that would result from the installation of more efficient solar shadings. The imbalance was less evident in

cases, like the office buildings, where the solar and internal gains have high influence on the building energy need. As concerns the peak load, the U-value reduction had negligible influence on the cooling power [50].

7.1.4 Question iv

How can the chosen EP model affect to valuation methods?

For addressing the question two valuation methods were taken into consideration, Cost-Optimal Analysis (COA) and Multi-Criteria Analysis (MCA).

Regarding the COA, the work in Section 6.3 presents the application of two different calculation methods for the heating/cooling energy needs in compliance with ISO 13790 to the cost optimization analysis. Analysed methods are the quasi-steady-state and simple hourly.

Results show that the cost-optimal set of energy efficiency measures is different if the quasi-steady-state or the simple hourly method is applied. Moreover, when the hourly model is used, a change in the operational schedule of the heating system (continuous or intermittent mode) entails a different set of cost-optimal retrofit solutions. Nevertheless, similar values of non-renewable energy performance and global cost among several refurbishment solutions, can be found despite the use of different calculation methods [52].

Regarding the MCA, *PROMETHEE methodology has been applied to a case study in the city of Torino for outranking five different proposed alternatives for buildings refurbishment that allows to achieve 20% energy saving. Three main phases characterize the study: i. analysis of buildings stock and alternatives identification; ii. criteria definition and quantification; iii. model implementation and result discussion.* Section 6.4 didn't compared two analysis with different calculation methods. The MCA is a time-consuming approach on data collection and analysis at district level, for this reason is not common to have EP from different calculation methods. However qualitative considerations of the role of EP can be gathered. The MCA can be based on EP, for this reason alternatives must to have same boundary conditions and input data (see Section 6.4.9 for the full details).

The Cost Optimality considers the Global Cost as the economic indicator for the evaluation of building energy retrofit and it is related with EP in COA. The COA method doesn't highlight the solution with the minor energy performance, as showed in Paragraph 6.3. Retrofit actions with lower energy consumption can be excluded from the final decision in COA. Other economic indicators could take

into account aspects which have impact on society and highlight advantages or disadvantages of building energy retrofit. This is called Cost-Benefit Analysis (CBA). The MCA gives the opportunity to take into account not necessarily economic aspects. As showed the research in section 6.4, criteria in MCA can consider economic aspects (as investment cost, replacement cost, maintenance cost and tax detraction) or socio environmental aspects (as internal comfort, built environment, social image and awareness). Two tricky points for application of MCA are the definition of criteria scales and of preference and indifference thresholds. Scale can be ordinal or cardinal, the choice depends from the criterion data. In case of ordinal scale, the division in steps have to through standard or objective rules, as shown in the case study. Thresholds depend of data quality and data distribution. MCA criteria are weighted thought the sensibility of the focus group, that is to say on a human-based structure. In summary, the MCA can constitute an alternative to CBA and COA to lead towards nZEBs when more criteria have to take into account.

7.2 Knowledge contributions and future work

Knowledge contributions of this dissertation and future work are shown for each chapter.

Chapter 3 - Climatic data versus energy performance

Detailed models under dynamic conditions and reliable, and accurate, climatic data are necessary to evaluate buildings which have a very low amount of energy covered to a very significant extent by energy from renewable sources. Different source of climatic data can lead to results in terms of energy performance of a nZEB that, in some cases, can be very different from each other, as the study shown in Section 3.3.

Results of the study of Section 3.4 suggest to implement the procedure specified in the EN ISO 15927-4 standard, as to differentiate the choice of each TMY month according to the predominant energy service in that month and to the building type.

Since each month has a specific dominant energy service (or group of energy services), the proposal consists of constructing a representative TMY by applying a different weighing combination for each month.

The procedure has been checked for residential buildings and for a locality where space-heating service prevails on the other energy services. Nevertheless, the building energy simulations have shown that the energy impact of dehumidification service is not negligible. In other locations, the impact of this energy service could be even more relevant. In particular, for building categories characterized by higher water vapour mass production such as dance halls, bars, restaurants, cinemas, theatres and meeting rooms for conferences the dehumidification service could become dominant. For this reason, the impact of humidification and dehumidification services on the building energy performance has been considered in this work and it represents a main novelty of this study.

Moreover, as the examined case studies are buildings with natural ventilation, the wind speed and wind direction have been assumed as having a secondary role; however for buildings that incorporates techniques of passive ventilation these variables might have a different impact.

Future research will enlarge the analysis of weighting coefficients in the TMY in different climatic zones, with other building types and technical building systems [46].

Chapter 4 - Models and data for energy efficiency measures of buildings on urban scale

Two methods of selection of EEMs have been investigated. In literature, Decision Tree method was already suggested to select individual EEMs on an urban scale at the level of tree leaves. However it has not been applied yet. In this Dissertation this approach was applied to a case study where energy saving could be calculated by applying EEMs and comparing it with those deriving from another less time-consuming method. The author of the dissertation suggests to apply EEMs in each splitting node. With this approach same building can be object of more retrofit actions and it is possible to achieve maximum saved energy.

Another consideration concerns the used data set. Data set G includes all available attributes and not only attributes which are clearly independent. Results show that, in this case study, the CART model find anyway a satisfying correlation between attributes of Data set G and the classification label (even if the accuracy of the model decrease). This is due to the same origin, TEASER, of attributes and energy demands.

In further investigations, other algorithm can be tested and more retrofit measures can be taken into consideration.

Chapter 5 - Definition of minimum building requirements

Building energy performance requirements are usually expressed by means three mode in national regulations: fixed value, variable value defined through a formula or the notional reference building approach. The aim of the research was to know how the chosen EP can model affect the specification of minimum building requirements. It led to analyse the application of the notional reference building approach in the energy performance legislation. Successively, for enhance it, an improved procedure (Figure 31) for specifying a notional reference building was addressed and a case study was implemented in each phases.

The research highlights the need of more detailed specifications of reference parameters in the notional reference building, especially when dynamic simulation is performed. The realm of validity of results was affected by the choice of the case study, as regards its geometry and its use category. A future research can enlarge the analysis by investigating more building features and their level of detail.

Concerning the analysis of the imbalance of nZEB energy need for heating and cooling, the study provided guidelines to support professionals in building design optimization. Future research will enlarge the analysis of imbalance by investigating the effect of technical building systems, identification of an indicator of imbalance, deepening of the parametric analysis, analysis of single energy efficiency measures applied to building units.

Chapter 6 - EP in valuation methods

When assessing the cost optimal levels of energy performance, the calculation of the energy needs is usually carried out by means of CEN standards or equivalent national calculation methods, which are based either on steady-state or on dynamic simplified models. However, many research studies have pointed out the limitations of the steady-state approach, especially for high performance buildings.

The work in Section 6.3 showed how the calculation method – SS or SD - of the energy needs for heating and cooling impacted on the final optimal design. This was done through the application of the cost-optimal procedure to a single-family house located in Milan. The performance of the thermal systems was then assessed by means of the national standards (UNITS 11300), while the global cost was evaluated by means of EN 15459. Several design options with increasing levels of energy efficiency were applied to the case study.

The cost-optimal solutions derived from the application of the two methods were compared and the reasons for deviations are discussed [52].

The MCA in Section 6.4 intended to provide an academic exercise of MCA application to support the definition of energy retrofit choices. This exercise has been developed by the authors in the role of decision-makers. The study in Section 6.4 gives the possibility to have a qualitative idea of the EP role in MCA. A guidelines was provided to help building designers and planners for select the most energy savings retrofitting scenario. For a possible future development, the following modifications are suggested: increasing the number of criteria for both the building and district levels, applying the model to different case studies in order to validate and test the robustness of the model, improving the evaluation of energy retrofit options.

References

- [1] IPCC Intergovernmental Panel on Climate Change, ‘Climate Change 2014: Summary for policy makers, Synthesis report, IPCC, Geneva, Switzerland, 2014’, 2014.
- [2] European Commission, *Europe 2020. A European strategy for smart, sustainable and inclusive growth*. OJEU, 2010.
- [3] European Commission, ‘Buildings - European Commission’, 2018. .
- [4] European Commission, ‘Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast)’, *Off. J. Eur. Union*, pp. 13–35, 2010.
- [5] G. Augenbroe, ‘Trends in building simulation’, *Build. Environ.*, vol. 37, no. 8–9, pp. 891–902, 2002.
- [6] J. A. Clarke and J. L. M. Hensen, ‘Integrated building performance simulation: Progress, prospects and requirements’, *Build. Environ.*, vol. 91, pp. 294–306, 2015.
- [7] M. I. Farouk, ‘Check the comfort of occupants in high rise building using CFD’, *Ain Shams Eng. J.*, vol. 7, no. 3, pp. 953–958, 2016.
- [8] W. Tian, X. Han, W. Zuo, and M. D. Sohn, ‘Building energy simulation coupled with CFD for indoor environment: A critical review and recent applications’, *Energy Build.*, vol. 165, pp. 184–199, 2018.

- [9] Y. Toparlar, B. Blocken, B. Maiheu, and G. J. F. Van Heijst, 'A review on the CFD analysis of urban microclimate', *Renew. Sustain. Energy Rev.*, vol. 80, no. September 2016, pp. 1613–1640, 2017.
- [10] S. Pinheiro *et al.*, 'MVD based information exchange between BIM and building energy performance simulation', *Autom. Constr.*, vol. 90, no. February, pp. 91–103, 2018.
- [11] European Committee for Standardization (CEN), *EN ISO 52016-1:2017 on Energy performance of buildings — Energy needs for heating and cooling, internal temperatures and sensible and latent head loads*. 2017.
- [12] S. Citherlet, J. A. Clarke, and J. Hand, 'Integration in building physics simulation', *Energy Build.*, vol. 33, no. 5, pp. 451–461, 2001.
- [13] ASHRAE, *ASHRAE Standard 209-2018 on Energy Simulation-Aided Design Standard*. 2018, p. 2018.
- [14] D. B. Crawleya, J. W. Hand, M. Kummertc, and B. T. Griffith, 'Contrasting the capabilities of building energy performance simulation programs', *WSEAS Trans. Environ. Dev.*, vol. 10, pp. 264–273, 2014.
- [15] F. Roberti, U. F. Oberegger, and A. Gasparella, 'Calibrating historic building energy models to hourly indoor air and surface temperatures: Methodology and case study', *Energy Build.*, vol. 108, pp. 236–243, 2015.
- [16] J. Hensen and S. Wang, 'Building Performance Simulation for Sustainable Building Design and Operation', *Proc. 60th Anniv. Environ. Eng. Dep. Prague, 14 Sept.*, p. 8, 2011.
- [17] S. Royer, S. Thil, T. Talbert, and M. Polit, 'Black-box modeling of buildings thermal behavior using system identification', *IFAC Proc. Vol.*, vol. 19, no. 3, pp. 10850–10855, 2014.
- [18] M. Killian, B. Mayer, and M. Kozek, 'Effective fuzzy black-box modeling for building heating dynamics', *Energy Build.*, vol. 96, pp. 175–186, 2015.
- [19] P. Bacher and H. Madsen, 'Identifying suitable models for the heat dynamics of buildings', *Energy Build.*, vol. 43, no. 7, pp. 1511–1522, 2011.
- [20] S. Wang and X. Xu, 'Simplified building model for transient thermal performance estimation using GA-based parameter identification', *Int. J. Therm. Sci.*, vol. 45, no. 4, pp. 419–432, 2006.
- [21] M. Filippi and E. Fabrizio, 'Introduzione alla simulazione termoenergetica

- degli edifici', *Guid. AiCARR, Ed. Delfino*, p. 2012, 2012.
- [22] U.S. Department of Energy, *Engineering Reference of EnergyPlus 8.8.0*. 2017.
- [23] L. Mazzarella and M. Pasini, 'Integration time step issue in Mediterranean Historic Building energy simulation', *Energy Procedia*, vol. 133, pp. 53–67, 2017.
- [24] A. Gasparella, G. Pernigotto, M. Baratieri, and P. Baggio, 'Thermal dynamic transfer properties of the opaque envelope: Analytical and numerical tools for the assessment of the response to summer outdoor conditions', *Energy Build.*, vol. 43, no. 9, pp. 2509–2517, 2011.
- [25] European Committee for Standardization (CEN), *EN ISO 52017-1:2017 on Energy performance of buildings - Sensible and latent heat loads and internal temperatures Generic calculation procedures*, vol. 2016. 2016.
- [26] J. A. Clarke, *Energy simulation in building design, 2nd edition*, Butterworth. Oxford, 2001.
- [27] J. L. M. Hensen and R. Lamberts, *Building performance simulation for design and operation. London: Taylor & Francis.*, Taylor & F. London, 2011.
- [28] A. J. Chapman, 'Heat Transfer', 1984.
- [29] J. H. Lienhard, 'A Heat Transfer Textbook'. Englewood Cliffs, N.J.: Prentice-Hall, 1981.
- [30] T. G. Theodosiou and A. M. Papadopoulos, 'The impact of thermal bridges on the energy demand of buildings with double brick wall constructions', *Energy Build.*, vol. 40, no. 11, pp. 2083–2089, 2008.
- [31] C. F. Reinhart and C. C. Davila, 'Urban building energy modeling - A review of a nascent field', *Build. Environ.*, vol. 97, pp. 196–202, 2016.
- [32] C. Cartalis, A. Synodinou, M. Proedrou, A. Tsangrassoulis, and M. Santamouris, 'Modifications in energy demand in urban areas as a result of climate changes: An assessment for the southeast Mediterranean region', *Energy Convers. Manag.*, vol. 42, no. 14, pp. 1647–1656, 2001.
- [33] K. F. Fong and C. K. Lee, 'Investigation of climatic effect on energy performance of trigeneration in building application', *Appl. Therm. Eng.*, vol. 127, pp. 409–420, 2017.

- [34] M. Zinzi, E. Carnielo, and B. Mattoni, 'On the relation between urban climate and energy performance of buildings. A three-years experience in Rome, Italy', *Appl. Energy*, vol. 221, no. March, pp. 148–160, 2018.
- [35] Concerted Action EPBD (2015), 'Implementing the Energy Performance of Buildings Directive (EPBD recast), featuring country reports', 2015.
- [36] V. Corrado, I. Ballarini, S. Paduos, and L. Tulipano, 'A new procedure of energy audit and cost analysis for the transformation of a school into a nearly zero-energy building', *Energy Procedia*, vol. 140, pp. 325–338, 2017.
- [37] European Committee for Standardization (CEN), *EN 16247-(series) Energy audits*. 2012, p. 16247.
- [38] S. Robinson, 'Conceptual modelling for simulation part I: definition and requirements', *J. Oper. Res. Soc.*, no. 59 (3), pp. 278–290, 2008.
- [39] International Energy Agency, 'Transition to Sustainable Buildings', 2013.
- [40] I. Ballarini, S. P. Corgnati, and V. Corrado, 'Use of reference buildings to assess the energy saving potentials of the residential building stock: The experience of TABULA project', *Energy Policy*, vol. 68, pp. 273–284, 2014.
- [41] T. Loga, B. Stein, and N. Diefenbach, 'TABULA building typologies in 20 European countries-Making energy-related features of residential building stocks comparable', *Energy Build.*, vol. 132, pp. 4–12, 2016.
- [42] I. Delponte, I. Pittaluga, and C. Schenone, 'Monitoring and evaluation of Sustainable Energy Action Plan: Practice and perspective', *Energy Policy*, vol. 100, no. May 2016, pp. 9–17, 2017.
- [43] P. Bogetoft and P. Pruzan, *Planning with Multiple Criteria: Investigation, Communication and Choice, (2nd edition)*. 1997.
- [44] J. Dodgson, M. Spackman, A. Pearman, and L. Phillips, 'DTLR Multi-Criteria Analysis Manual, UK Dept. for Transport, Local Government and the Regions', 2001. .
- [45] G. Murano, V. Corrado, and D. Dirutigliano, 'The new Italian Climatic Data and their Effect in the Calculation of the Energy Performance of Buildings', *Energy Procedia*, vol. 101, pp. 153–160, 2016.
- [46] G. Murano, D. Dirutigliano, and V. Corrado, 'Improved procedure for the

- construction of a typical meteorological year for assessing the energy need of a residential building', *J. Build. Perform. Simul.*, pp. 1–30.
- [47] D. Dirutigliano, M. A. Brüntjen, C. Fliegner, J. Frisch, V. Corrado, and C. van Treeck, 'Case Study for Energy Efficiency Measures of Buildings on an Urban Scale', *Press Conf. Proc. 3rd BSA Conf.*, 2017.
- [48] V. Corrado, I. Ballarini, D. Dirutigliano, and G. Murano, 'Verification of the New Ministerial Decree about Minimum Requirements for the Energy Performance of Buildings', in *Energy Procedia*, 2016, vol. 101.
- [49] D. Dirutigliano, I. Ballarini, G. Murano, and V. Corrado, 'Reference Building Approach Combined with Dynamic Simulation in Designing nZEBs', 2009.
- [50] G. Murano, I. Ballarini, D. Dirutigliano, E. Primo, and V. Corrado, 'The significant imbalance of nZEB energy need for heating and cooling in Italian climatic zones', in *Energy Procedia*, 2017, vol. 126.
- [51] V. Corrado, I. Ballarini, D. Dirutigliano, and S. Paduos, 'Cost-optimal analysis of Italian office buildings through the application of a quasi-steady state model validated by detailed dynamic simulation', *14th Int. Conf. IBPSA - Build. Simul. 2015, BS 2015, Conf. Proc.*, vol. 13790, pp. 2043–2050, 2015.
- [52] I. Ballarini, A. Costantino, D. Dirutigliano, E. Fabrizio, S. Paduos, and V. Corrado, 'On the cost-optimal design: comparison of quasi-steady-state and dynamic simplified methods of calculation of H / C energy needs', no. 2015, 2016.
- [53] D. Dirutigliano, C. Delmastro, and S. Moghadam, 'Energy efficient urban districts: A multi-criteria application for selecting retrofit actions', *Int. J. Heat Technol.*, vol. 35, no. Special Issue1, pp. S49–S57, 2017.
- [54] D. Dirutigliano, C. Delmastro, and S. T. Moghadam, 'A multi - criteria application to select energy retrofit measures at the building and district scale', no. i.
- [55] I. Ballarini, S. Pichierri, and V. Corrado, 'Tracking the energy refurbishment processes in residential building stocks. The pilot case of Piedmont region', *Energy Procedia*, vol. 78, pp. 1051–1056, 2015.
- [56] Italian Republic, *Decree of the Italian Ministry of Economic Development 26 June 2015 "Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli*

- edifici" (in Italian).* pp. 1–8.
- [57] Italian Organisation for Standardisation (UNI), ‘UNI 10349:1994, Heating and cooling of buildings - Climatic data’, p. 10349, 1994.
 - [58] G. Sorrentino, G. Scaccianoce, M. Morale, and V. Franzitta, ‘The importance of reliable climatic data in the energy evaluation’, *Energy*, vol. 48, no. 1, pp. 74–79, 2012.
 - [59] WMO, *Guide to Meteorological Instruments and Methods of observation*, vol. I & II, no. 8. 2008.
 - [60] European Committee for Standardization (CEN), *EN ISO 15927-4:2005, Hygrothermal performance of buildings - Calculation and presentation of climatic data - Part 4: Hourly data for assessing the annual energy use for heating and cooling (ISO 15927-4:2005)*. 2005, p. 15927.
 - [61] Italian Organisation for Standardisation (UNI), *UNI 10349-1:2016, Heating and cooling of buildings - Climatic data - Part 1: Monthly means for evaluation of energy need for space heating and cooling and methods for splitting global solar irradiance into the direct and diffuse parts and for calculate th.* 2016, p. 10349.
 - [62] European Committee for Standardization (CEN), *EN ISO 13790:2008. Energy performance of buildings - Calculation of energy use for space heating and cooling, 2008.* 2008, pp. 1–24.
 - [63] A. Argiriou *et al.*, ‘Comparison of methodologies for tmy generation using 20 years data for athens, Greece’, vol. 66, no. 1, pp. 33–45, 1999.
 - [64] I. J. Hall, R. R. Prairie, H. E. Anderson, and E. C. Boes, ‘Generation of typical meteorological years for 26 SOLMET stations. In: Sandia Laboratories Report, SAND 78-1601. Albuquerque, NM.’, p. 1978, 1978.
 - [65] H. Zang, Q. Xu, P. Du, and K. Ichiyangi, ‘A modified method to generate typical meteorological years from the long-term weather database’, *Int. J. Photoenergy*, vol. 2012, 2012.
 - [66] D. S. E. 40: 405-411 Pissimanis, G. Karras, V. Notaridou, and K. Gavra, ‘The generation of a “Typical Meteorological year” for the city of Athens ’’, *Sol. Energy*, vol. 40, pp. 405–411, 1988.
 - [67] S. and W. M. Wilcox, ‘Users Manual for TRY3 Data Sets’, 2008.
 - [68] J. M. Finkelstein and R. E. Schafer, ‘Improved goodness-of-fit tests’,

- Biometrika*, vol. 58, pp. 641–645, 1971.
- [69] J. Taylor *et al.*, ‘The relative importance of input weather data for indoor overheating risk assessment in dwellings’, *Build. Environ.*, vol. 76, pp. 81–91, 2014.
- [70] Y. Arima, R. Ooka, and H. Kikumoto, ‘Proposal of typical and design weather year for building energy simulation’, *Energy Build.*, vol. 139, pp. 517–524, 2017.
- [71] S. Kim, D. Zirkelbach, H. M. Künzle, J. H. Lee, and J. Choi, ‘Development of test reference year using ISO 15927-4 and the influence of climatic parameters on building energy performance’, *Build. Environ.*, vol. 114, pp. 374–386, 2017.
- [72] G. Pernigotto, A. Prada, A. Gasparella, and J. L. M. Hensen, ‘Analysis and improvement of the representativeness of EN ISO 15927-4 reference years for building energy simulation’, *J. Build. Perform. Simul.*, vol. 7, no. 6, pp. 391–410, 2014.
- [73] I. A. Rahman and J. Dewsbury, ‘Selection of typical weather data (test reference years) for Subang, Malaysia’, *Build. Environ.*, vol. 42, no. 10, pp. 3636–3641, 2007.
- [74] J. L. . Hensen, ‘Hensen, Jan L.M. 1999. Simulation of Building Energy and Indoor Environmental Quality - some Weather Data Issues. Paper presented at the International Workshop on Climate Data and Their Applications in Engineering , Prague, Czech Republic, October 4-6’, *Proc. Int. Work. Clim. Data Their Appl. Eng.*, p. 1999, 1999.
- [75] T. Kershaw, M. Eames, and D. Coley, ‘Comparison of multi-year and reference year building simulations’, *Build. Serv. Eng. Res. Technol.*, vol. 31, no. 4, pp. 357–369, 2010.
- [76] M. Grudzińska and E. Jakusik, ‘Energy performance of buildings in Poland on the basis of different climatic data’, *Indoor Built Environ.*, vol. 26, no. 4, pp. 551–566, 2017.
- [77] R. Dogniaux and R. Sneyers, ‘Méthodologie d’analyse statistique des données météorologique en vue de la constitution de périodes- types pour l’application à des problèmes spécifiques. (in French)’, Liège, 1977.
- [78] A. L. S. Chan, ‘Developing future hourly weather files for studying the impact of climate change on building energy performance in Hong Kong’, *Energy Build.*, vol. 43, no. 10, pp. 2860–2868, 2011.

- [79] M. Bhandari, S. Shrestha, and J. New, ‘Evaluation of weather datasets for building energy simulation’, *Energy Build.*, vol. 49, pp. 109–118, 2012.
- [80] P. Baggio, V. Corrado, G. Murano, and G. Riva, . ‘2010. “Definizione degli Anni Tipo Climatici delle Province del Nord Italia [Definition of the typical weather years in the North Italy provinces].” (9): 61-68. (In Italian)’, *La Termotec.*, no. 9, pp. 61–68, 2010.
- [81] T. Huld, E. Paietta, P. Zangheri, and I. P. Pascua, ‘Assembling typical meteorological year data sets for building energy performance using reanalysis and satellite-based data’, *Atmosphere (Basel)*., vol. 9, no. 2, p. 9020053, 2018.
- [82] S. Petrarca, F. Spinelli, E. Cogliani, and M. Mancini, *Profilo climatico dell’Italia (in Italian)*, Edizioni E. 1999.
- [83] Italian Thermo-technical Committee Energy and Environment, ‘Site of CTI’, 2018. .
- [84] EnergyPlus, ‘Weather Data – EnergyPlus’, *US Deparment of Energy*, 2016. .
- [85] Italian Organisation for Standardisation (UNI), *UNI/TS 11300-1, Energy performance of buildings. Part 1: Evaluation of energy need for space heating and cooling (in Italian)*. 2014, p. 11300.
- [86] K. Pagh, P. Blanc, F. Vignola, L. Ramírez, and M. Blanco, ‘Discussion of currently used practices for: Creation of Meteorological Data Sets for CSP/STE Performance Simulations’, 2017.
- [87] J. Boland and B. Ridley, ‘Models of Diffuse Solar Fraction, in Modelling Solar Radiation at the Earth’s Surface”. Springer-Verlag Berlin Heidelberg . 8:193-219.’, p. 2008, 2008.
- [88] T. Kusuda and P. R. Achenbach, ‘Earth temperatures and thermal diffusivity at selected stations in the United States’, vol. 71, no. 1, pp. 61–74, 1965.
- [89] H. T. Ceylan and G. E. Myers, ‘Long-time solutions to heat- conduction transients with time- dependent inputs’, *ASME J. Heat Transf.*, vol. 102, no. February, pp. 115–120, 1980.
- [90] J. E. Seem, ‘Modeling of Heat Transfer in Buildings ”. Ph.D. Thesis , University of Wisconsin’, *Ph.D. Thesis , Univ. Wisconsin*, p. 1987, 1987.

- [91] K. Ouyang and F. Haghighat, 'A procedure for calculating thermal response factors of multi-layer walls-State space method', *Build. Environ.*, vol. 26, no. 2, pp. 173–177, 1991.
- [92] Italian Republic, *Law 3 March 2011 no.21 'Attuazione della direttiva 2009 / 28 / CE sulla promozione dell ' uso dell ' energia da fonti rinnovabili , recante modifica e successiva abrogazione delle direttive 2001/77/CE e 2003/30/CE' (in Italian)*. 2011.
- [93] Y. Chen and T. Hong, 'Impacts of building geometry modeling methods on the simulation results of urban building energy models', *Appl. Energy*, vol. 215, no. November 2017, pp. 717–735, 2018.
- [94] M. Lauster *et al.*, 'Improving a low order building model for urban scale application', *Proc. BAUSIM 2014, Ger. – Austrian IBPSA Conf. (in Ger.)*, p. 2014, 2014.
- [95] J. Schiefelbein *et al.*, 'Development of a tool chain for complex city district energy system modeling and simulation', *Proc. Build. Simul. 2015 Hyderabad, India*, 2015.
- [96] M. Lauster, J. Teichmann, M. Fuchs, R. Streblow, and D. Mueller, 'Low order thermal network models for dynamic simulations of buildings on city district scale', *Build. Environ.*, vol. 73, pp. 223–231, 2014.
- [97] D. A. KEIM, M. SIPS, and M. ANKERST, 'Visual data mining techniques', *Vis. Handb.*, pp. 831–843, 2004.
- [98] L. Breiman, J. H. Friedman, R. A. Olshen, and C. J. Stone, *Classification Regression Trees*, Chapman an. 1984.
- [99] A. Capozzoli, G. Serale, M. S. Piscitelli, and D. Grassi, 'Data mining for energy analysis of a large data set of flats', *Proc. Inst. Civ. Eng. - Eng. Sustain.*, vol. 170, pp. 3–18, 2016.
- [100] A. Capozzoli, D. Grassi, M. S. Piscitelli, and G. Serale, 'Discovering knowledge from a residential building stock through data mining analysis for engineering sustainability', *Energy Procedia*, vol. 83, pp. 370–379, 2015.
- [101] T. Loga, N. Diefenbach, J. Knissel, and R. Born, 'Entwicklung eines vereinfachten statistisch abgesicherten Verfahrens zur Erhebung von Gebäudedaten für die Erstellung des Energieprofils von Gebäuden - Kurzverfahren Energieprofil (in German)', 2005.

- [102] F. Management, ‘Energiebericht 2013 (in German)’, 2014. .
- [103] Federal Ministry for Economic Affairs and Energy (BMWi), ‘Energieeinsparverordnung -EnEV 2014 (in German)’, 2014. .
- [104] Y. Gao, E. Tumwesigye, B. Cahill, and K. Menzel, ‘Using data mining in optimisation of building energy consumption and thermal comfort management’, *Softw. Eng. Data Min.*, pp. 434–439, 2010.
- [105] International Organisation for Standardisation (ISO), *ISO 52003-1 - Energy performance of buildings — Indicators, requirements, ratings and certificates. Part 1: General aspects and application to the overall energy performance*. 2017, p. 52003.
- [106] F. J. Sánchez de la Flor, J. M. Salmerón Lissén, and S. Álvarez Domínguez, ‘A new methodology towards determining building performance under modified outdoor conditions’, *Build. Environ.*, vol. 41, no. 9, pp. 1231–1238, 2006.
- [107] HM Government, *L1A Conservation of fuel and power in new dwellings*. London, 2014.
- [108] HM Government, *L2A Conservation of fuel and power in new buildings other than dwellings*. London, 2014.
- [109] German Federal Ministry for the Environment Nature Conservation Building and Nuclear Safety (2013), *Energieeinsparverordnung (EnEV)*. 2013.
- [110] E. and C. C. (2010) Greek Ministry of Environment, *Regulation on the Energy Performance of Buildings’ (KENAK)*. 2010.
- [111] American Society of Heating Refrigerating and Air-Conditioning Engineers, *ANSI/ASHRAE/IES Standard 90.1: Energy Standard for Buildings Except Low-Rise Residential Buildings*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers. 2010, p. 2010.
- [112] O. of the I. Republic, *Law 3 August 2013 no. 90 “Conversione in legge, con modificazioni, del decreto-legge 4 giugno 2013, n. 63, recante disposizioni urgenti per il recepimento della Direttiva 2010/31/UE del Parlamento europeo e del Consiglio del 19 maggio 2010, sulla prestazi.* 2013, pp. 1–12.
- [113] European Committee for Standardization (CEN), *EN ISO 13789 ‘Thermal*

- performance of buildings. Transmission and ventilation heat transfer coefficients. Calculation method*'. 2007.
- [114] Italian Organisation for Standardisation (UNI), *UNITS 11300 (series) 'Energy performance of buildings' (in Italian)*. .
- [115] European Committee for Standardization (CEN), *EN 15316 (series) 'Heating systems in buildings. Method for calculation of system energy requirements and system efficiencies' (in Italian)*. 2007.
- [116] H. A. L. van Dijk and M. E. Spiekman Eds, 'Energy Performance of Buildings; Outline for Harmonised EP Procedures. Final report of EU SAVE ENPER project, Task B6', 2004.
- [117] I. Ballarini and V. Corrado, 'A new thermal analysis by numerical simulation to investigate the energy performance of buildings', *Proc. Build. Simul. 2011, 12th Conf. Int. Build. Perform. Simul. Assoc. Sydney, Novemb. 14-16, 2011*.
- [118] European Committee for Standardization (CEN), *UNI EN 303-5:2012 on Heating boilers – Part 5: Heating boiler for solid fuels, manually and automatically stoked, nominal heat output of up to 500 kW – Terminology, requirements, testing and marking*. 2012, p. 2012.
- [119] I. Ballarini and V. Corrado, 'A new thermal analysis by numerical simulation to investigate the energy performance of buildings', *Proc. Build. Simul. 2011 12th Conf. Int. Build. Perform. Simul. Assoc.*, no. November, pp. 2225–2232, 2011.
- [120] European Committee for Standardization (CEN), 'EN ISO 13786 Thermal performance of building components — Dynamic thermal characteristics — Calculation methods (ISO 13786:2007)', p. 22, 2007.
- [121] V. Corrado and S. Paduos, 'New equivalent parameters for thermal characterization of opaque building envelope components under dynamic conditions', *Appl. Energy*, vol. 163, pp. 313–322, 2016.
- [122] I. Ballarini, V. Corrado, F. Madonna, S. Paduos, and F. Ravasio, 'Energy refurbishment of the Italian residential building stock: energy and cost analysis through the application of the building typology', *Energy Policy*, vol. 105, no. January, pp. 148–160, 2017.
- [123] F. Margiotta, 'Metodologia per la determinazione delle caratteristiche strutturali ed impiantistiche di "Edifici Tipo" del Parco Edilizio Nazionale ad uso ufficio e Valutazione del Potenziale di Risparmio energetico sulla

- base della fattibilità degli interventi di riqua', 2010.
- [124] Italian Thermotechnical Committee (CTI), 'Test reference years for thermotechnical applications'. .
- [125] European Union, *Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council*. 2012.
- [126] European Union, 'Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council', 2012.
- [127] C. Christensen, G. Barker, and S. Horowitz, 'A Sequential Search Technique for Identifying Optimal Building Designs on the Path to Zero Net Energy', *Proc. Sol. 2004, Am. Sol. Energy Soc. Portland, Oregon*, 2004.
- [128] M. Hamdy, A. Hasan, and K. Siren, 'A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010', *Energy Build.*, vol. 56, pp. 189–203, 2013.
- [129] J. Kurnitski, A. Saari, T. Kalamees, M. Vuolle, J. Niemelä, and T. Tark, 'Cost optimal and nearly zero (nZEB) energy performance calculations for residential buildings with REHVA definition for nZEB national implementation', *Energy Build.*, vol. 43, no. 11, pp. 3279–3288, 2011.
- [130] V. Corrado and I. Ballarini, 'Refurbishment trends of the residential building stock: Analysis of a regional pilot case in Italy', *Energy Build.*, vol. 132, no. March 2013, pp. 91–106, 2016.
- [131] C. Baglivo, P. M. Congedo, D. D'Agostino, and I. Zacà, 'Cost-optimal analysis and technical comparison between standard and high efficient mono-residential buildings in a warm climate', *Energy*, vol. 83, pp. 560–575, 2015.
- [132] E. Maldonado, *Implementing the Energy Performance of Buildings Directive (EPBD)*. Brussels, Belgium, 2013.
- [133] M. Ferrara, E. Fabrizio, J. Virgone, and M. Filippi, 'A simulation-based optimization method for cost-optimal analysis of nearly Zero Energy Buildings', *Energy Build.*, vol. 84, pp. 442–457, 2014.
- [134] N. Ganiç and A. Z. Yilmaz, 'Adaptation of the cost optimal level calculation method of Directive 2010/31/EU considering the influence of

- Turkish national factors', *Appl. Energy*, vol. 123, pp. 94–107, 2014.
- [135] U. Persson, B. Möller, and S. Werner, 'Heat Roadmap Europe: Identifying strategic heat synergy regions', *Energy Policy*, vol. 74, no. C, pp. 663–681, 2014.
- [136] J. Ma and J. C. P. Cheng, 'Estimation of the building energy use intensity in the urban scale by integrating GIS and big data technology', *Appl. Energy*, vol. 183, pp. 182–192, 2016.
- [137] E. Lo Cascio, Z. Ma, D. Borelli, and C. Schenone, 'Residential Building Retrofit through Numerical Simulation: A Case Study', *Energy Procedia*, vol. 111, no. September 2016, pp. 91–100, 2017.
- [138] P. Zhou, B. W. Ang, and K. L. Poh, 'Decision analysis in energy and environmental modeling: An update', *Energy*, vol. 31, no. 14, pp. 2604–2621, 2006.
- [139] M. D. Catrinu, 'Decision Aid for Planning Local Energy Systems: Application of Multi-criteria decision analysis', 2006.
- [140] P. Bogetoft and P. Pruzan, *Planning with Multiple Criteria: Investigation, Communication and Choice*. 1997.
- [141] A. Giaccone, G. Lascari, G. Peri, and G. Rizzo, 'An ex-post criticism, based on stakeholders' preferences, of a residential sector's energy master plan: the case study of the Sicilian region', *Energy Effic.*, no. July, 2016.
- [142] P. Lombardi and S. Giordano, 'EVALUATING THE EUROPEAN SMART CITIES VISIONS OF THE FUTURE', *Int. J. Anal. Hierarchy Process*, vol. 4, no. 1, Jun. 2012.
- [143] E. Løken, 'Use of multicriteria decision analysis methods for energy planning problems', *Renew. Sustain. Energy Rev.*, vol. 11, no. 7, pp. 1584–1595, 2007.
- [144] M. Bottero, V. Ferretti, J. R. Figueira, S. Greco, and B. Roy, 'Dealing with a multiple criteria environmental problem with interaction effects between criteria through an extension of the Electre III method', *Eur. J. Oper. Res.*, vol. 245, no. 3, pp. 837–850, 2015.
- [145] J. Jin and Y. M. Wei, 'Generalized intelligent assessment methods for complex systems and applications.', *Beijing Sci. Press.*, 2008.
- [146] Y. Guo, 'System synthetical evaluation theory, methods and application.',

- Sci. Press*, 2007.
- [147] J. Xu and W. Wu, 'Multiple attribute decision making theory and methods.', *Beijing Tsinghua Univ. Press*, 2006.
- [148] European Committee for Standardization (CEN), *EN 15459, Energy performance of buildings - Economic evaluation procedure for energy systems in buildings*, vol. 3. 2007.
- [149] V. Corrado, G. Murano, S. Paduos, and G. Riva, 'On the Refurbishment of the Public Building Stock Toward the Nearly Zero-energy Target: Two Italian case studies', *Energy Procedia*, vol. 101, no. September, pp. 105–112, 2016.
- [150] CTI, 'Typical Meteorological Year', 2012.
- [151] V. Corrado, I. Ballarini, and S. Paduos, 'Assessment of cost-optimal energy performance requirements for the Italian residential building stock', *Energy Procedia*, vol. 45, pp. 443–452, 2014.
- [152] C. Christensen, R. Anderson, S. Horowitz, A. Courtney, and J. Spencer, 'BEoptTM Software for Building Energy Optimization: Features and Capabilities', 2006.
- [153] J. P. Brans, P. Vincke, and B. Mareschal, 'How to select and how to rank projects: The Promethee method', *Eur. J. Oper. Res.*, vol. 24, no. 2, pp. 228–238, 1986.
- [154] D. Diakoulaki and F. Karangelis, 'Multi-criteria decision analysis and cost-benefit analysis of alternative scenarios for the power generation sector in Greece', *Renew. Sustain. Energy Rev.*, vol. 11, no. 4, pp. 716–727, 2007.
- [155] A. De Montis, P. De Toro, B. Droste-franke, I. Omann, and S. Stagl, 'Assessing the quality of different MCDA methods', *Altern. Environ. Valuat.*, pp. 99–184, 2000.
- [156] S. Torabi Moghadam, C. Delmastro, S. P. Corgnati, and P. Lombardi, 'Urban energy planning procedure for sustainable development in the built environment: A review of available spatial approaches', *J. Clean. Prod.*, vol. 165, 2017.
- [157] J. J. Wang, Y. Y. Jing, C. F. Zhang, and J. H. Zhao, 'Review on multi-criteria decision analysis aid in sustainable energy decision-making', *Renew. Sustain. Energy Rev.*, vol. 13, no. 9, pp. 2263–2278, 2009.

- [158] P. Lombardi, F. Abastante, and S. T. Moghadam, ‘Multicriteria Spatial Decision Support Systems for Future Urban Energy Retrofitting Scenarios’, 2017.
- [159] C. Delmastro, G. Mutani, and S. P. Corgnati, ‘A supporting method for selecting cost-optimal energy retrofit policies for residential buildings at the urban scale’, *Energy Policy*, vol. 99, pp. 42–56, 2016.
- [160] Regione Piemonte, ‘Prezzi di riferimento per opere e lavori pubblici nella Regione Piemonte. Italia: Regione Piemonte’, 2012. .
- [161] S. Copiello, L. Gabrielli, and P. Bonifaci, ‘Evaluation of energy retrofit in buildings under conditions of uncertainty: The prominence of the discount rate’, *Energy*, vol. 137, pp. 104–117, 2017.