Politecnico di Torino, Energy Department
Ph.D Course in Technological Innovation for Built Environment

SCALABLE DYNAMIC SIMULATION-BASED METHODOLOGY FOR THE ENERGY RETROFIT OF EXISTING BUILDINGS

Valentina Monetti

Alla piccola
ma già grande Sofia

TABLE OF CONTENTS

Preface

This thesis would not have been possible without the support, patience and encouragement of many people.

Foremost, I would like to thank my supervisor Marco Filippi who supported me with insightful advice and encouragement, starting from my M.Sc. and following through to the Ph.D. I am also thankful for him for supporting my period of study in Belgium.

I am sincerely grateful to Enrico Fabrizio for being a qualified, bright and friendly supervisor. He supported me with constructive suggestions and constant supervision during the last three years. Without his advice and experience, this Ph.D. project could not have been completed.

I would also like to thank Stefano Corgnati for allowing me to participate to the IEA ECBS Annex 59 and especially, for his advice and suggestions during the first year of my Ph.D.

I would like to express my gratitude to Philippe André for giving the opportunity to work with the BEMS group at the Arlon Environment campus. The period spent in Arlon revealed to be of high importance for my Ph.D. project. I am really grateful to Philippe, Elisabeth and all the other members of BEMS for the support received.

This research would not have possible without the support of my office colleagues at TEBE group and IEEM. I especially would like to thank Cristina, Mara and Valeria for being real good friends.

I thank Alessandra, Chiara, and Rossella and all my friends for supporting me.

Finally, I want to thank Stefano for standing on my side for the good and the hard times during these years.

Last but definitely not least, a very special thank goes to my sisters Daniela and Simona, and to my mum for their patient and unconditional support over the years.

Summary

It is widely recognized that the building sector largely contributes to the total European energy consumption with a 40% influence on the total assessed energy uses. To this regard many energy efficiency targeted policies and projects have been launched. In particular, the EPBD recast Directive promotes nearly zero energy buildings (nZEB) for the public and the private sector as a mandatory requirement by 2020.

Nonetheless, by the time this “energy efficient” approach will become the standard best practice for buildings design, energy consumption will increase even more. To this regard, given the low energy efficiency of old buildings, concerns about the state of the existing building stock should be seriously considered as most of the energy consumption is attributable to the existing buildings. Additionally, residential buildings are often seen as long-term assets, setting thus a low replacement rate, approximately 1% per year in Europe, of old buildings by new ones. To this regard, larger energy savings can be achieved with the energy retrofitting of the existing building stock, rather than with the construction of relatively small proportion of new high performing buildings. Therefore, the refurbishment of the existing building stock has to be primarily planned and accomplished in order to achieve a timely reduction on the buildings energy consumption. According to the EBPD, a building undergoes a “major renovation” when the total cost of the renovation is higher than 25 % of the value of the building or more than 25 % of the surface of the building envelope undergoes renovation. The renovation does not have to compulsorily concern the whole building but it can also regard only those parts that are most relevant for the energy performance of the building and that are considered cost-effective.

Concerning this, the EPBD recast, as policy driver for reducing European energy use in buildings, has been representing the first and main legislative reference. In particular, the Directive stipulates that “Member States must ensure that minimum energy performance requirements are set with a view of achieving at least cost-optimal levels for buildings, building units and building elements” by means of a comparative methodology framework applied to new constructions and existing buildings undergoing major renovations. The methodology specifies how to compare energy efficiency measures in relation to their energy performance and to the cost attributed to their implementation, and how to apply these to selected reference buildings with the aim of identifying cost-optimal levels of minimum energy performance requirements. A cost optimal level is defined as the energy performance level, which leads to the lowest cost during the estimated economic lifecycle of the building. A measure is considered cost-effective when the cost of implementation is lower than the achievable benefits, during the expected life of the measure. This type of analysis allows defining energy renovation scenario based on their energy and economic optimum.

Within the complex scenario described above, this Ph.D. thesis aims to provide a scalable methodology for the definition of energy retrofit scenarios to be applied to existing buildings, based on the use of dynamic building simulation models. The methodology targets the existing building stock given the large energy savings that can be achieved from existing buildings. It builds on an energy and economic assessment of energy efficiency measures applied to different building typologies. The energy and economic assessment are respectively carried out by means of dynamic building simulation and a cost-optimality approach. The cost optimal analysis was chosen for the aim of this study for its systematic approach in defining energy retrofit interventions based on their energy and economic optimum.

The term “scalable” is used for defining the methodology as the studied energy retrofit scenarios can vary depending on the “scale” of the study. Two main scales of buildings can be distinguished: building stock or single buildings. When retrofit interventions are studied to be applied to wide portion of the building stock, as for example at national level, representative building models are used. They correspond to reference buildings representative of a certain building typology, construction age and geographic location. Within this thesis, a methodology for their definition was defined and various reference buildings for the Italian context were created.

On the contrary, when it is necessary to study specific and customized retrofit measures, a single existing building is modelled. In this case, compared to the case of the reference buildings, larger quantity of data and a higher degree of detail are necessary. These building models are customized based on the existing buildings characterization (e.g. building envelope, system, etc) and when applicable, based also on data from monitoring. To this regards, when detailed information about the building real operation from monitoring is available, the building model need to be calibrated based on measured data. For a model to be calibrated, the building energy consumption predicted by the simulation program, has to match the consumption measured from monitoring. Calibrated models can be used for comparing the baseline situation of the building (calibrated and not retrofitted) with other simulation results relative to the application of building renovation interventions. To this regard, within this Ph.D. thesis, a literature review on the most common calibration techniques currently in use for the calibration of building models was conducted. Additionally two case studies were calibrated by means of two different approaches: a trial and error approach and an optimization-based calibration.

For both scale of buildings (building stock and single buildings), dynamic building simulation was employed for the energy assessment. Building simulation application has expanded since mid-‘70s building simulation as an attempt to emulate reality. To date, it is much more common to employ building simulation in post construction or advanced building design phases rather than in early phases. In particular building simulation is frequently used for the prediction of energy savings by assessing energy retrofit interventions on existing buildings. To this regard, given its wide application and the high level of detail of the analysis performed (dynamic analysis), building simulation was chosen within this thesis, as a tool for the energy assessment of buildings and of the relative energy renovation interventions.

Finally, the economic assessment of the energy retrofit measures was carried out by means of the cost optimal methodology, as defined by the EPBD recast. The methodology allowed defining energy renovation interventions based on their economical and energy optimum. The Directive requires to define different packages of energy efficiency measures, which can be applied to reference representative buildings but also to single and existing building for energy and economical assessments. The energy assessment of a building can be carried out with analytical or simplified methods, but dynamic building simulation is strongly suggested, as performed within this thesis. For the economic assessment, the global cost method was employed based on the calculation method of the Standard EN 15459 as advised by the EBPD. The global cost method considers, for each energy efficiency measure, the initial investment, the sum of the annual costs for every year (including energy costs) and the final value, all with reference to the starting year of the calculation period.

In order to define different energy retrofit solution and set the minimum energy performance requirements, within the Ph.D. thesis, the cost optimal approach was applied to both the considered scale of buildings: to the building stock scale with three reference buildings, and to the single buildings scale with two calibrated buildings. A set of energy efficiency measures was defined and applied to the case studies for evaluating the financial and energy performance gap between the cost-optimal solutions and nZEB levels, respectively. For the building stock, different energy retrofit solutions are defined as final outcomes. Given the use of representative models (reference buildings), the retrofit solutions can be replicated to several buildings, among the same building typology. In this sense, different energy retrofit solutions can be established. On the other hand, for single buildings, the energy retrofit solution studied is specific and customized barely to the analyzed case study.

Sommario

A livello europeo il settore delle costruzioni è responsabile del 40% del consumo totale di energia. A tale riguardo, tra le molteplici misure attuate a livello legislativo, la Direttiva europea 2010/31/EU sulla prestazione energetica degli edifici, nota come EPBD recast, prescrive in particolare l'elaborazione da parte di tutti gli Stati Membri di un piano per lo sviluppo di edifici ad energia quasi zero (nZEB), vale a dire di edifici ad altissima prestazione energetica, con un fabbisogno netto di energia primaria molto basso, coperto in forte misura da fonti rinnovabili. Secondo quanto stabilito dall'EPBD recast, entro la fine del 2020 tutti gli edifici, sia pubblici che privati, di nuova costruzione o soggetti a interventi di riqualificazione energetica importante dovranno essere nZEB.

Tuttavia, in considerazione dei tempi previsti affinché la progettazione di nZEB diventi l'ordinaria procedura progettuale, non sarà possibile registrare una concreta contrazione nei consumi energetici del patrimonio edilizio ancora per lungo tempo. Per questa ragione, alla luce dello stato dell'arte degli edifici esistenti, caratterizzati da basse prestazione energetiche e da epoche di costruzione mediamente anteriori al 1960, la ristrutturazione del patrimonio edilizio esistente racchiude in se un alto potenziale di risparmio energetico. Inoltre gli edifici, in particolar modo quelli a destinazione residenziale, sono spesso percepiti come beni di lunga durata. Il 75 ed il 17% degli italiani vive infatti in edifici costruiti rispettivamente prima del 1990 e del 1950. Pertanto, considerando che a livello europeo il flusso di edifici di nuova realizzazione è pari circa all'1%, la vera opportunità di risparmio energetico è rappresentata dal retrofit del patrimonio edilizio esistente rispetto ai risparmio conseguibile con la costruzione di ridotte porzioni di nuovi ed energeticamente performanti edifici.

In maniera conforme a quanto stabilito dall'EPBD, per "riqualificazione energetica importante" di un edificio si intende un intervento di riqualificazione il cui costo supera del 25% il valore dell'edificio o che riguarda più del 25% della superficie dell'involucro edilizio. Non è necessario che l'intero edificio sia oggetto di riqualificazione energetica, ma bensì solo alcune parti dell'edificio possono essere soggette ad interventi di retrofit, selezionati in quanto economicamente vantaggiosi e maggiormente influenti sul miglioramento della prestazione energetica dell'edificio.

A tale riguardo l'EPBD recast ha stabilito che ciascuno Stato Membro debba fissare, a livello nazionale o regionale, i requisiti minimi di prestazione energetica degli edifici e dei componenti edilizi e la predisposizione di misure, per il miglioramento della stessa prestazione per gli edifici esistenti e per quelli di nuova costruzione, che siano efficaci anche sotto il profilo dei costi, corrispondenti cioè al cost optimal level. Quest'ultimo rappresenta il livello di prestazione energetica che comporta il costo globale più basso durante il ciclo di vita economico dell'edificio stesso. Esso deve essere calcolato in conformità al quadro metodologico comparativo definito "Cost optimal analysis" nelle linee guida della EPBD recast, il quale descrive come selezionare e confrontare tra loro interventi di efficientamento energetico in funzione della loro prestazione energetica e del costo relativo alla messa in opera. Per questo motivo a ciascuno Stato Membro è inoltre demandata la creazione di una serie di edifici di riferimento, denominati Reference Buildings, ai quali, come edifici rappresentativi di determinate categorie edilizie a livello nazionale o regionale, verranno applicate le misure di efficientamento e per i quali sarà calcolato il livello ottimale della prestazione energetica in funzione dei costi. Una misura

di efficientamento o un pacchetto di misure è definito cost-effective quando il suo costo globale è inferiore al valore dei risparmi che derivano dalla sua messa in opera. E' definita cost-optimal la misura con il costo globale inferiore all'interno delle misure cost-effective individuate. L'analisi di tipo cost optimal permette la definizione di scenari di interventi di retrofit energetico degli edifici, basato sul loro valore ottimale sia a livello economico che energetico, e che possono essere applicati su larga scala a livello di patrimonio edilizio nazionale.

All'interno del complesso scenario appena descritto, la presente tesi di dottorato persegue la definizione di una metodologia multi-scala per lo sviluppo di scenari di riqualificazione energetica del patrimonio edilizio esistente, attraverso l'impiego della simulazione termoenergetica dinamica. Il patrimonio edilizio esistente è stato scelto come oggetto di studio poiché risparmi energetici più elevati possono essere conseguiti attraverso il retrofit di edifici esistenti. La metodologia di studio proposta si è basata sull'analisi a livello energetico (consumi e prestazione energetica) ed a livello economico (costi) di edifici ai quali sono applicati misure di efficientamento energetico. A tale riguardo, l'analisi della prestazione energetica dell'edificio è stata conseguita attraverso strumenti di simulazione energetica dinamica. L'analisi economica degli interventi di efficientamento energetico è invece condotta attraverso l'analisi di tipo cost optimal descritta in precedenza.

La metodologia descritta all'interno della presente tesi di dottorato è stata definita multi scala in quanto può essere "scalata" in funzione della scala dell'oggetto dell'intervento di riqualificazione studiato. A tale riguardo, possono essere individuate due scale principali: quella del patrimonio edilizio esistente, o *building stock*, e quella di singoli edifici.

Quando gli interventi di riqualificazione sono studiati al fine di essere generalizzabili e conseguentemente applicati ad un'ampia scala, quale quella del patrimonio edilizio esistente (ad es. su scala nazionale), allora per la definizione degli stessi interventi di riqualificazione è necessario usare modelli di edifici rappresentativi. Questi ultimi corrispondono ad edifici di riferimento (*reference buildings*), caratterizzati dalla loro funzionalità e posizione geografica, comprese le condizioni climatiche interne ed esterne, e rappresentativi di dette caratteristiche. Essi sono pertanto edifici con caratteristiche medie che rispecchiano il patrimonio edilizio esistente. All'interno della presente tesi è stata illustrata una metodologia per la loro definizione e creazione, sulla base della quale sono successivamente stati presentati diversi edifici di riferimento, per tipologie edilizie residenziali e non.

Quando è necessario studiare interventi di riqualificazione specifici per determinate condizioni di calcolo e quindi non generalizzabili, si è soliti creare un modello "customizzato", che rispecchi il più verosimilmente il singolo edificio oggetto di studio. Per questa ragione, una maggiore quantità di dati di input ed un più alto livello di dettaglio sono requisiti fondamentali nel processo di definizione del modello dell'edificio. Quest'ultimo deve infatti essere modellato in funzione delle reali caratteristiche dell'edificio, sia a livello di involucro edilizio e configurazione impiantistica che, quando noto, dell'effettivo utilizzo dell'edificio. A tale riguardo, quando attraverso campagne di monitoraggio energetico ed ambientale, sono disponibili informazioni dettagliate sull'effettivo uso dell'edificio, è necessario che il modello dell'edificio sia calibrato sulla base dei dati monitorati. Un modello viene definito calibrato quando i consumi energetici "previsti" dal programma di simulazione sono corrispondenti a quelli misurati e reali dell'edificio. Lo sviluppo di modelli calibrati di edifici è necessario per la valutazione di interventi di retrofit energetico di edifici esistenti. Il modello calibrato può infatti essere usato come modello di riferimento dell'edificio esistente attraverso il quale studiare differenti soluzioni progettuali di retrofit energetico ed dal quale ottenere risultati dall'accuratezza ed attendibilità più alta rispetto a quelli raggiungibili con modelli non calibrati. Al fine di delineare un attento quadro delle tecniche di calibrazione attualmente in uso da parte della comunità scientifica, un'analisi bibliografica è stata condotta all'interno della presente tesi. Sulla base di tale analisi, due differenti approcci alla calibrazione di edifici sono stati rispettivamente applicati a due casi studio: una calibrazione di tipo empirico, "trial and error", di un edificio multifamiliare, ed una calibrazione di un edificio di prova, basata su un processo di ottimizzazione.

Per entrambe le scale di edifici considerate, vale a dire la scala del patrimonio edilizio e quella di singoli edifici, sono stati creati modelli di edifici attraverso programmi di simulazione energetica dinamica. Tale scelta è stata motivata dalla crescente importanza che la simulazione energetica dinamica degli edifici sta guadagnando come strumento per la valutazione e l'ottimizzazione della prestazione energetica dell'edificio. Essa è infatti sempre più ricercata ed applicata come strumento di analisi non solo nelle fasi "tradizionali" e preliminari della progettazione dell'edificio ma anche in processi successivi alla costruzione dell'edificio e che riguardano il monitoraggio energetico dell'edificio, quali ad esempio il "Commissioning", mirato ad verificare e documentare le prestazioni dell'edificio, o il "fault detection and operation diagnosis", finalizzato all'individuazione di problemi di gestione e di non ottimale funzionamento dell'edificio, o ancora l'Audit energetico degli edifici.

Come anticipato, l'analisi economica degli interventi di riqualificazione energetica è stata condotta conformemente con l'analisi di tipo cost optimal suggerita dalla Direttiva europea EBPD recast. Molteplici pacchetti di misure di efficientamento sono stati definiti ed applicati sia ad una serie di edifici di riferimento (in totale tre) che ad un singolo edificio esistente oggetto di monitoraggio energetico. Il metodo del costo globale, come indicato dalla Direttiva e sulla base della norma EN 15459, è stato impiegato per la valutazione economica dei diversi interventi di efficientamento. Nel caso degli edifici di riferimento, diversi interventi, replicabili su scala nazionale sulle medesime tipologie edilizie, sono stati analizzati. Nel caso dell'edificio singolo monitorato, la soluzione studiata è specifica e customizzata per il caso studio.

List of publications

This Doctoral thesis is based on the results presented in six papers, four of which have been published in a scientific peer-reviewed journal, one is an international conference and one has been submitted to an internal peer-reviewed conference (February 2015). They are listed as follows:

Paper I	S.P. Corgnati, E. Fabrizio, M. Filippi, V. Monetti, *Reference buildings for cost optimal analysis: Method of definition and application*, Applied Energy, Volume 102, February 2013, Pages 983-993 (ISSN 0306-2619).
Paper II	C. Becchio, E. Fabrizio, V. Monetti, M. Filippi, *Cost optimal levels of energy requirements for nearly-ZEB: application to an Italian reference building for existing offices*, CLIMA 2013 11th REHVA World Congress "Energy efficient, smart and healthy buildings", Prague, 16-19 June 2013 (ISBN 978-80-260-4001-9).
Paper III	P. Dabbene, C. Becchio, E. Fabrizio, V. Monetti, M. Filippi, *Cost optimality assessment of a single-family house: building and technical systems solutions for the nZEB target*, Energy and Buildings, Volume 90, March 2015, pages 173-187 (ISSN 0378-7788).
Paper IV	V. Monetti, Fabrizio, M. Filippi, *Impact of low investment strategies for space heating control: application of thermostatic radiators valves to an old residential building*, Energy and Buildings, Volume 95, 2015, pages 202-210 (ISSN 0378-7788).
Paper V	V. Monetti, E. Fabrizio, *Methodologies and advancements on the calibration of building energy models*, Energies, Volume 8, Issue 4, April 2015, 2548-2574.
Paper VI	V. Monetti, E. Davin, E. Fabrizio, P. André, M. Filippi, *Calibration of building energy simulation models based on optimization: a case study*, 6th International Building Physics Conference, Turin, 14-147 June 2015 (Paper accepted 22/05/2015).

Others

Other papers, developed during the Ph.D., are reported below:

Papers in international conference proceedings:

A. V. Monetti, E. Fabrizio, M. Filippi, *Influence of different temperature control patterns through TRV on district heating loads*, Proceedings of the 8th International Symposium on Heating, Ventilation and Air Conditioning ISHVAC 2013, Xi'an (China), 19-21 October 2013, Lecture Notes in Electrical Engineering, ISSN 1876-1100, vol. 262 (2014), pp. 251-258.

B. Becchio, S.P. Corgnati, E. Fabrizio, V. Monetti, F. Seguro (2014), *Application of the LEED PRM to an Italian existing building*. In: Proceedings of International Conference on Sustainability in Energy and Buildings 2014, Cardiff, Wales, UK, 25-27 June 2014, ENERGY PROCEDIA, vol. 62, pp. 141-149. (ISSN 1876-6102).

C. V. Monetti, E. Fabrizio, M. Filippi, *Impact of low investment strategies for space heating control: application of thermostatic radiators valves to an old residential building*, in 49th International Conference AICARR, Roma, 26-28 February 2014.

D. Becchio, S. P. Corgnati, E. Fabrizio, G. Nese, V. Monetti, *Cost Optimal Levels of Minimum Energy Requirements for Retrofit Measures on Exemplar Office Buildings: a comparison between two European case studies*, in 49th International Conference AICARR, Roma , 26-28 February 2014;

E. C. Becchio, S.P. Corgnati, V. Monetti, E. Fabrizio, *From high performing buildings to nearly zero energy buildings: potential of an existing office building*, Climamed '13 Proceedings Book, VII Mediterranean Congress of Climatization, Istanbul, 3-4 October 2013, Secil Ofset, pp. 72-81. (ISBN 978-975-6907-17-7).

F. C. Becchio, P. Cantamessa, E. Fabrizio, P. Florio, V. Monetti, M. Filippi, *Dynamic simulation of BACS (Building Automation and Control Systems) for the energy retrofitting of a secondary school*, in E. Wurtz (editor), "Proceedings of BS2013: 13th Conference of the International Building Performance Simulation Association"IBPSA, Chambéry, 2013, pp. 2060-2068 (ISBN 978-2-7466-6294-0).

G. C. Becchio, S.P. Corgnati, E. Fabrizio, V. Monetti, *The cost optimal methodology applied to an existing office in Italy*, The REHVA European HVAC Journal, ISSN 1307-3729, Volume 50, Issue 5, August 2013, pages 18-22.

H. E. Fabrizio, D. Guglielmino, V. Monetti, *Italian benchmark building models: the office building*, in V. Soebarto, H. Bennetts, P. Bannister, P.C. Thomas, D. Leach (eds), "Driving better design through simulation", IBPSA Australia & AIRAH, Melbourne, 2011, pp. 1981-1988 (ISBN 978-0-646-56510-1).

Papers in national conference proceedings:

I. S.P. Corgnati, E. Fabrizio, M. Filippi, V. Monetti, *Livelli di prestazione energetica ottimali per edifici a energia quasi zero: creazione degli edifici di riferimento*, 67° Congresso Nazionale ATI, Trieste, 11-14 settembre 2012, paper 02.068, pp. 1-7 (ISBN 978-88-907676-0-9).

J. Becchio, E. Fabrizio, V. Monetti, *Livelli di prestazione energetica ottimali per edifici a energia quasi zero: il caso di un edificio multifamiliare*, in 67° Congresso Nazionale ATI, Trieste, 11-14 settembre 2012, paper 02.100, pp. 1-9 (ISBN 978-88-907676-0-9).

K. Becchio, P. Cantamessa, E. Fabrizio, P. Florio, V. Monetti, M. Filippi, Smart schools: previsione dei risparmi energetici conseguibili, 31° Convegno AICARR “La gestione energetica del patrimonio edilizio pubblico: strategie ed esperienze”, Bologna, 17 ottobre 2013.

0.

The thesis: aims and outline

The main goal of this Ph.D. thesis is to define a scalable dynamic simulation-based methodology for developing energy retrofit scenario of existing buildings. The methodology targets existing buildings and intends to assist professionals in the definition of energy retrofit scenario for existing buildings, as they constitute the sector where larger energy savings can be achieved.

The methodology builds upon an energy and economic assessment of energy efficiency measures applied to different building typologies (e.g. residential buildings, tertiary buildings, etc.). Dynamic building simulation was chosen for performing the building energy assessment for the high level of detail achievable (detailed building model, dynamic state for the analysis) and for its recognized and increasing worldwide application in the design process. The economic assessment was indeed carried out by means of the cost-optimality approach prescribed by the EBPD recast.

The term scalable is used for characterizing the methodology as different scales can be defined depending on the objective of the study. The “scale” of the objective of the study can hence range from the building stock to single buildings. Renovations can be defined for large sample of buildings, such as portions of the existing building stock or rather be devoted to the study of single buildings. On one hand, when the scale of the building stock is considered, it may be possible to define energy scenario for estimating the impact of energy retrofit measures at national level. Several energy retrofit solutions can thus be defined replicated on a large portion of the building stock. On the other hand, when a smaller renovation scale is considered, single buildings become the objective of the study and the energy retrofit scenario selected cannot be replicated as they are specific and customized for the studied building. Given this latter consideration, single retrofit interventions are set.

Consequently, the scale of the energy models associated to the buildings studied, may vary. To this regard, for the building stock scale, representative models are employed. In particular, reference buildings should be used in order to achieve reliable and building stock benchmark outcomes. Indeed, building models customized based on the studied single building should be used when a smaller scale is considered. When monitoring data about the building real operation are available, the model of the single building has to be calibrated based on measured data. Calibration is the process that tunes the building input data for reducing the energy performance gap between the simulated building energy consumption and the measured energy consumption. Calibrated building models are necessary for comparing the baseline situation of the existing building before the application of renovation strategies.

In order to achieve the ultimate objective of the Ph.D. study, interim goals were pursued and are listed as follows:

- Firstly, a picture of the European Union (EU) building stock and of the current EU policy targeting energy renovation strategies was provided within Chapter 1.
- Secondly, the building stock scale was depicted starting from a literature review on the state of the art. Following to this, a methodology proposal for creation of reference buildings was set up, with special reference to Paper I. Based on the methodology, different typologies of Italian reference building models were created and presented within Chapter 2, with special reference to Papers II and III.
- In Chapter 3, a picture on the role and application of building simulation during the different phases of the design process was provided.
- Within Chapter 4, the scale of single models was investigated. These models are usually defined based on specific and customized data about the studied building. In particular within this thesis, the case of single buildings which energy consumption and real operation are noted from monitoring, was studied. In order to obtain reliable results about the application of energy retrofit project, these building models needed to be calibrated based on data from monitoring. A literature review on the most common calibration techniques currently in use for the calibration of building models was carried out, as depicted in Paper V. Two case study were calibrated based on two different approaches: a trial and error approach (Paper IV) and an optimization-based calibration methodology (Paper VI). This latter approach aimed to simplify and automate the calibration process of dynamic simulation models and define a hierarchy of the input parameters that mostly impact on the calibration process.
- Finally, in Chapter 5, the economic assessment of the energy retrofit measures was carried out by means of the cost-optimal methodology, as defined by the EBPD. The methodology allowed defining energy renovation interventions based on their economical and energy optimum. The economic assessment was applied to both scale of building: on a selection of the RBs presented previously in Chapter 1 for the building stock scale; on calibrated building models for monitored single buildings. In general, the case studies considered were both residential and non-residential buildings.
- In the final chapter, some general recommendations and critical observations with reference to the methodology proposed and the results achieved were presented. Some remarks about future works and improvements were also provided.

1.

Introduction

1.1 EU building stock: defining the problem

The building sector holds a pivotal role in the European sustainable future as the greatest energy saving potential lies in buildings. It in fact represents the first EU (European Union) energy consumer with approximately 40% of energy consumption [1] and the main contributor to GreenHouse Gas (GHG) emissions, with 36% of $C0_2$ emissions [2]. Moreover, buildings experienced an increase on the total energy consumption by around 1% per year since 1990 (1.5% per year for non-residential buildings and 0.6%/year for households) [3], with an average annual energy consumption of 220 kWh/m2 in 2009, (residential around 200 kWh/m^2 and non-residential buildings around 300 kWh/m^2) [3].
Notwithstanding the building stock represents the second-largest opportunity, after the energy sector, for EU to comply with the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) [1] and to reduce by 2020 GHG emissions by at least 20% below 1990 levels. With the undertake of concrete actions aimed at improving the buildings energy efficiency, it is possible to reduce EU energy consumption by 5-6% and to lower CO_2 emissions by about 5% [2]. In this framework, the building industry would be one of the key enablers of the 2050 decarbonisation agenda for the European economy.
In EU a real engagement has been carried out on new buildings with law obligations and requirements for them to be constructed in compliance with high energy performing standards and new thermal regulations. Since their first implementations in the 1960s, new regulations on the building energy efficiency have been often updated in many countries. Buildings constructed in 2009 consume 40% less than dwellings built in 1990 [3]. However the low volume of new construction hinders the potential related to the introduction of these regulations. The annual rate of new constructions was hence reported to be around 1%, between 2005 and 2010 [4]. Moreover, the construction sector has also been experiencing a significant downward trend due to the global financial and economical crisis. With regard to that, because of the low incomes, residential energy consumption recorded a reduction of around 1.6%.
This clearly indicated that acting on the existing buildings, is the only way to pave the way for a concrete reduction of the building energy demand. Approximately 35% of European buildings are 50 years old [2] and many other buildings, today in use, are hundreds of years old. With specific regard to Italy, according to the most recent census survey [5], national building stock amounts approximately to 14.5 millions of buildings, of which more than 84% are residential (12.2 millions). With

respect to the previous census, it has been recorded a decrease of approximately 5% in overall amount of buildings not in use for refurbishment undergoing or for unsafe conditions.

First of all, it is important to define the term "renovation". Renovation is an umbrella term generally used for indicating a variety of improvement-oriented interventions in an existing building: from modernization, retrofit, restoration and rehabilitation to simple maintenance, repairs and routine upgrades [6]. In particular, energy renovations/retrofits target, by means of single or multiple measures, the energy improvement of the building energy performance[7].

From art.2 of the Energy Performance of Building Directive (EPBD) [1], a building undergoes a "major renovation" when:

a. the total cost of the renovation relating to the building envelope or the technical building systems is higher than 25 % of the value of the building (excluding the value of the land upon which the building is situated);
b. or more than 25 % of the surface of the building envelope undergoes renovation.

The EPBD also specifies that the improvement of the overall energy performance of an existing building does not necessarily mean a total renovation of the building but can also regard only those parts that are most relevant for the energy performance of the building and that are considered cost-effective [8].

Another definition of renovation, compliant with the one of the EPBD, is that presented within the Energy Efficiency Directive [9]. It specifies that deep renovations can also be undertaken in stages and more importantly, that cost-effective deep renovations, aiming to very high energy performance, should bring to a significant reduction (typically more than 60% [10]) in the delivered and final energy consumption of a building. A deep renovation is also assessed as a refurbishment that brings to at an improvement of at least 75% in the building energy performance and primary energy consumption inferior to the 60 kWh/m^2 per year [11].

However, different distinctions can be made with regard to different levels of building renovation, from single measures to packages of measures based on a holistic approach. As described in Table 1, BPIE identified four different levels of renovation (Minor, Moderate, Deep and nZEB renovation), depending on the energy savings achievable [%] and the cost estimate of the retrofit project [€/m^2] [12].

Table 1 – Renovation levels. Table adapted from [7]

Renovation Level	Total Energy Savings [%]	Cost Estimate of the Project [€/m^2]
Minor	0-30 %	60
Moderate	30-60 %	140
Deep	60-90 %	330
nZEB	90 %+	580

Minor Renovations are retrofit projects based on the implementation of a single measure for the improvement of the building energy performance and that can reach an overall reduction on the building energy consumption up to 30%, with a cost estimate of 60 €/m^2. Moderate renovations can reach energy reduction from 30% up to 60% and involve from 3 up to 5 measures for the building energy performance improvements. Package of different measures, based on a holistic approach and with an achievable energy reduction from 60 up to 90%, characterize deep renovation indeed. Finally, the highest renovation level is represented by those renovations that pursue improvement of building energy performance for reaching performance levels of nearly Zero Energy Buildings (nZEB).

Notwithstanding, depending on the target and on type of the retrofit measures (e.g. aiming to improve the energy performance of the building envelope), different renovations can be distinguished, as reported in Table 2. Undoubtedly if a single measure is undertaken, the renovation can be considered "minor", as stated previously.

Table 2 – Renovation classes depending on the measure typology. Retrieved and adapted from [6].

Target of renovation measure	Description
Building envelope	- Insulation of external walls, roofs, lofts, floors; replacement of windows, doors; - Draught proofing; - Installation of solar shading systems; - Employment of natural ventilation techniques; - Passive solar heating or cooling techniques.
Building technical systems	- Replacement of inefficient boilers with condensing gas boilers; - Improvement of mechanical ventilation; - Air-conditioning, lighting, auxiliary systems; Installation of heat recovery system; - Improvement of emission/distribution systems of technical systems; - Installation of buildings controls; - Installation of micro cogeneration systems.
Renewable heat generation systems	- Biomass boilers; - Thermal solar systems; - Ground, water, air source heat pumps.
Renewable electricity generation systems	Photovoltaic systems, micro wind generation systems, micro-hydro systems.
Connection to district heating	Upgrades or new connection to a district heating network.
Other Energy-related measures	Measures aiming to improving the energy efficiency of electrical appliances.

In order to fully understand the real potential of energy regulations and how renovations strategies can affect and impact, it is important to have a wide picture of EU building stock EU is characterized by a remarkably varied building stock in terms of function type, location and size. BPIE conducted a large survey to give some figures about the EU building stock in 2010[7]. It estimated that buildings area is equivalent approximately to the Belgium size, around to 25 billion m^2 of useful floor space (30 528 km^2).

With particular regard to the residential sector, 40% of the building stock was constructed before the introduction of any policy and regulation for the building energy efficiency and conservation, which started to be implemented only in the 1960s [12]. As depicted in Figure 1, looking at the housing stock, the proportion of the building age is quite homogeneous in all Europe.

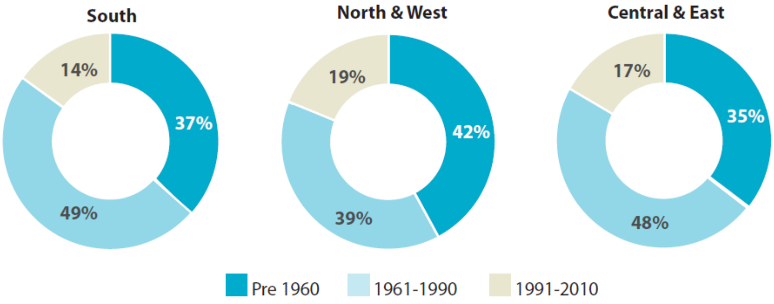


Figure 1. Age of Housing building stock (Adapted from [7]).

However, considering that approximately 50% of the EU floor space is located in the North and South, and 36% and 14% respectively in the South and in the Central and East area, more than half of the total buildings sited in Northern and Western Europe was built before 1960s.

With special attention to the Italian context, residential buildings are often seen as long-term assets. Approximately 75% and 17 % of Italians live hence respectively in buildings built before 1990 and before 1950, confirming and even intensifying EU trend [13]. For this reason more than 60% of residential buildings are over 45 years old and were built before the first Italian law on building energy savings, Law No 376 of 1976. Figure 2 gathers the Italian residential buildings distribution based on eight different construction ages, from "before 1919" up to "after 2001".

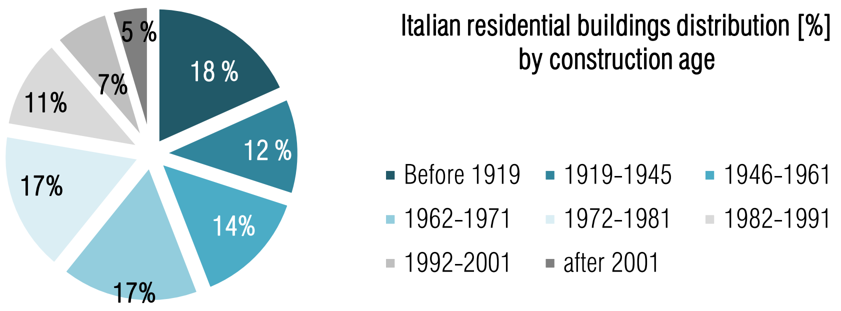


Figure 2- Italian residential buildings distribution [%] by construction age in 2009. Adapted from [10]

The residential stock has a great relevance on the total building stock and on the overall EU final energy consumption [14]. It is responsible for the 68% of the building sector final energy consumption in 2009 [7]. Moreover, as stated previously, since 1990 a tiny increase (0.6%) has been experienced in the household's energy consumption due the higher use of gas and electricity (around 50%) rather than solid fuels and oil, which recorded a reduction of 75% and 27% respectively [10].

Residential buildings represent the biggest segment of European buildings, covering 75% of total EU floor area, 64% of which is composed of single family houses, that is the most frequent typology, as reported in Figure 3. In 2009 (Figure 4) 42% of the EU-27 population lived in flats, 34% in detached houses and 23% in semi-detached/terraced houses [10]. Confirming EU trend, also Italian residential buildings hold the highest incidence (84%) on the total building stock, 52 % of which is composed of single family houses [5].

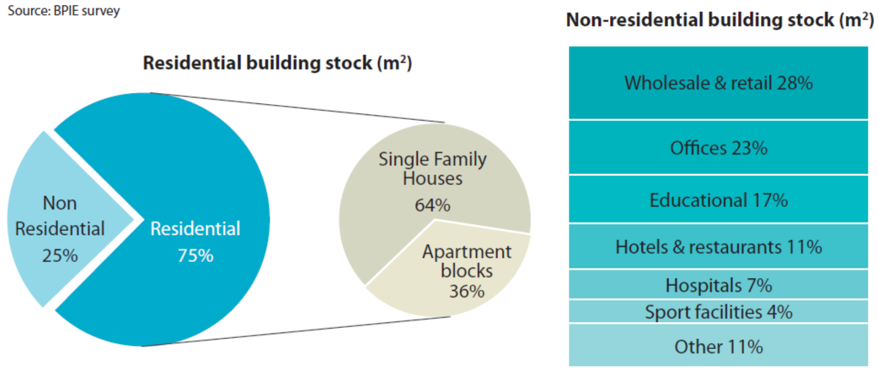


Figure 3 – Residential and non-residential building stock composition in Europe. Retrieved from [7]

Typically, the residential building stock is more homogeneous, in terms of size and usage patterns, than the non-residential building stock. With regard to the ownership and tenure status (Figure 4), in 2009 around 70% of European population owned and occupied their homes, by means of mortgage and loan (approx. 37%) or without any loan (around 50%), while the remaining 25% of residential population was composed of tenants [10]. In particular most of residential buildings are owned by private households and only a limited extend (from approx. 5% up to 30%) is constituted by public and mixed owners. On the contrary, as depicted in Figure 5 [12], public sector holds the greatest amount of the total non-residential buildings stock.

Furthermore, the non-residential sector represents a quarter of European building stock (see Figure 3) and it is mainly constituted by retail and wholesale buildings (28%) and by offices (23%). For non-residential buildings a more heterogeneous ownership profile is reported, with private owners varying from 10% to 90%, as reported in Figure 5.

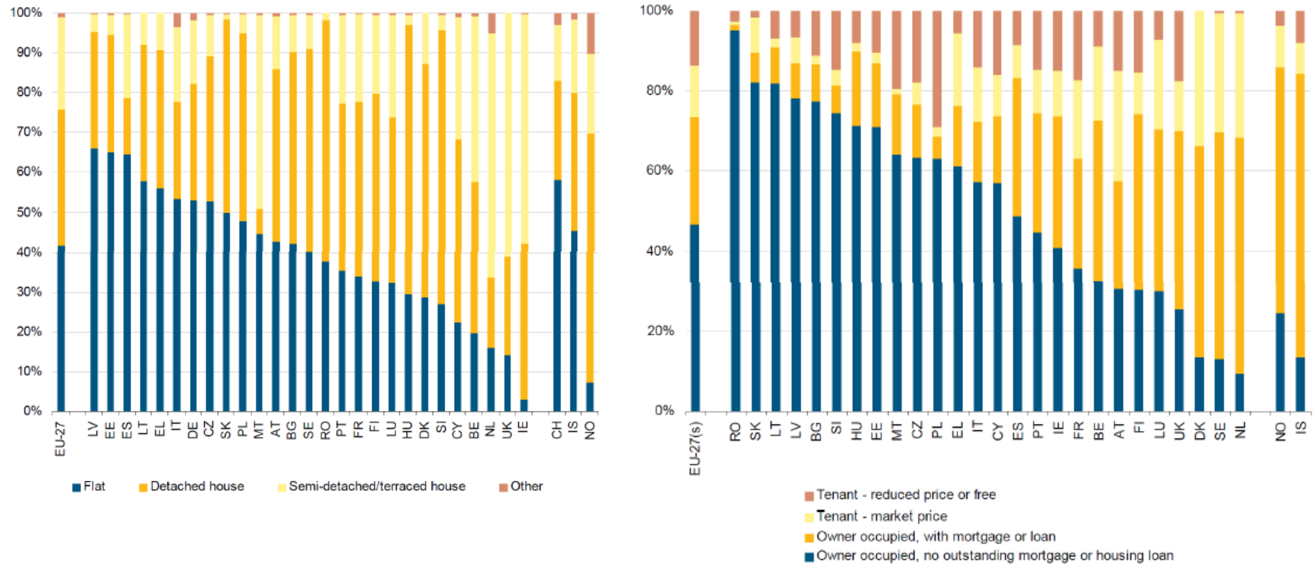


Figure 4 - EU-27 population distribution [%] by dwelling type (on the left) and residential population distribution by tenure status in EU-27(on the right). Retrieved from [10]

In general, either for residential and non-residential buildings, the tenure/ownership profile has direct implications on the ability and interest to embark into renovation investments. Conflicts regarding the split benefits and expenditures can be faced indeed.

With regard to energy consumptions, an average energy consumption of 300 kWh/m^2 is attributed to non-residential buildings [3]. Especially, due to the enhanced application of technological devices and in general technological advances, a remarkable increase (74%) has been recorded over the last 20 years in non-residential buildings. While hospitals and educational buildings hold 12% of the overall energy consumption, more than half of the energy consumptions is hence attributable to offices (26%) and to retail and commercial buildings (28%) [12].

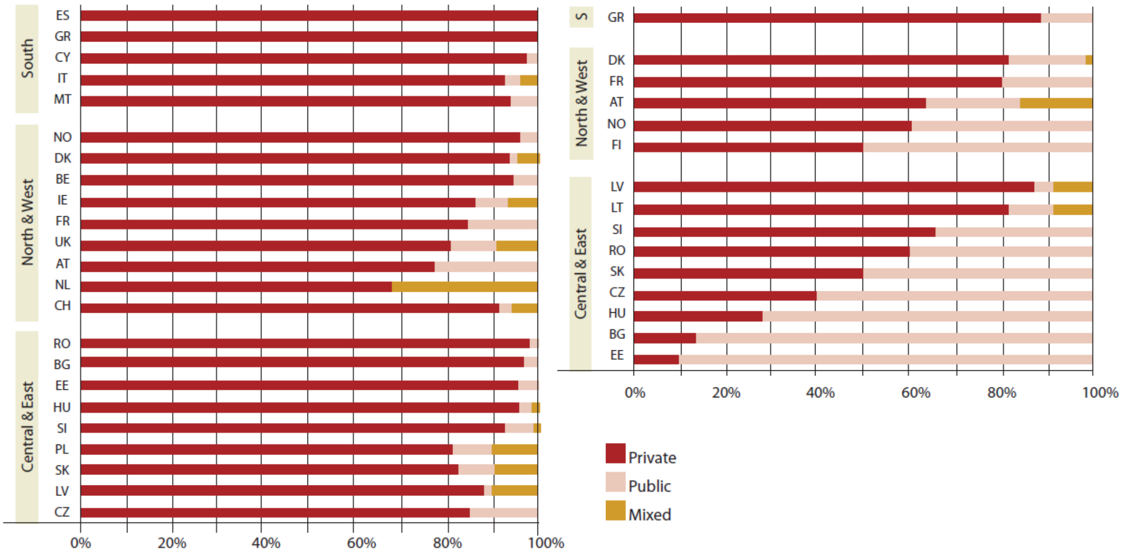


Figure 5 - Ownership/tenure profile in residential and non-residential buildings in EU [4] .

With special regard to Italy, the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) conducted a detailed report on the energy retrofit projects conducted in Italy in 2012 over the existing building stock, by means of tax incentives [15]. The most common typology of renovation devoted to the improvements of the buildings energy efficiency and performance in Italy in 2012 can be identified in the replacement of building envelope transparent components, like windows. From 2009 to 2012, an upward trend in the application of this type of measure was recorded, from a 48% up to a 64%. On the other hand, a reduction in the refurbishment of the opaque building envelope components, from 6% to 3%, was observed. Despite that, if looking in absolute terms at the size of the buildings surface engaged in renovation, approximately 1200000 m^2 and 2400000 m^2 respectively of opaque and transparent building envelope components, were subjected to energy retrofit. With regard to the construction age, most of renovations were carried out in buildings constructed before the 1983 and mostly to residential buildings (96%). In particular, approximately 37% of interventions concerned buildings built before the 1960, 46% buildings built between the 1961 and 1982, 9% buildings built between the 1983 and 1991, and only 8% for the most recent building stock (constructed after 1991). Moreover, buildings with a floor surface inferior to 250 m^2 were the most subjected to renovations, even if larger energy savings, compared to the investment cost, were achieved in building with a surface area superior to 750 m^2.

1.2 Barriers and benefits to renovations in EU

A reflection on the barriers to be addressed and on the achievable benefits, is necessary before introducing the state of European policy and regulations concerning the renovations of buildings.

Many benefits can directly and indirectly be achieved with a wide renovation of the building stock. Generally monetized benefits are the first ones that come up to mind. They represent the benefits directly impacting on individual investors.

However considering only these benefits can bring to an underestimation of the full and wide impact of building stock renovation.

Other indirect impacts and co-benefits, beyond the usually most referred economic and environmental ones, should be also considered. BPIE identified four main classes of benefits and impacts [4]:

- Economic Benefits. This class includes all benefits easy to read and to monetize, such as savings on the energy bills or the improvement of the building envelope performance or of the building system. Buildings with higher energy performance increase their market value indeed. Therefore, while trying to maintain the value of the existing stock in the short-term period and increasing the long-term value of the portfolio, real estate companies also started to focus on the retrofit of existing buildings [16]. Furthermore, the construction sector holds an important position for EU economy, as the largest EU single activity, accounting for about 10% of EU-27 GDP in 2011[10], and the biggest EU industrial employer with 15 million of people employed and 3.1 millions of enterprises [17]. Given the financial and economic crisis that affected also the construction industry, the building sector has a great potential to be a leader and one of the most capable sectors for reacting quickly to underpin the re-launch of the economy [18]. The building retrofit can hence generate new construction-related job opportunities and stimulates the local economical growth, bringing to an increase of the EU GPD. Moreover the renovation of buildings towards nearly zero energy buildings or energy positive buildings, will bring to a reduction of the energy import dependency, for each Member State, and thus to a reduction of the national energy bills related to the energy import of oil and gas;
- Societal Benefits. This class is constituted by widespread benefits that are not easy to read and not directly and immediately quantifiable but with a wide impact on the society. The most relevant benefit is the reduction of fuel poverty, a problem that affects between 50 and 125 million people in Europe [19]. Fuel poverty can be defined as a household's difficulty, sometimes even inability, to adequately heat its dwelling at a fair, income indexed price [19]. It is very sensitive to the energy price trend, as picture in Figure 6. Many countries, like UK and Ireland, took concrete actions to combat fuel poverty. Considering the enduring economic and financial crisis, many household with low incomes are at risk of poverty. In particular elderly people (whose incidence is forecast to double up to 2050) are the most exposed to fuel poverty because of low incomes, need of higher indoor temperatures and social assistance, higher predisposition to diseases, and higher unwillingness to invest in their homes.

  Three causes can be identified as main drivers of fuel poverty: low household income, cost of energy, and low energy efficiency of buildings. Many solutions can be detected to cope with the problem of fuel poverty (like subsidies and grants), but the most recognized and effective one is acting on the reduction of households'/tenants' energy bills, by reducing the energy demand of buildings with retrofit actions. Beyond the reduction of the energy bills, buildings renovation can generate indirect and societal benefits, like cutting the demand for medical assistance (due to a higher indoor thermal comfort). Moreover with regards to working environment, thermal comfort can also bring to higher productivity levels [4];

- Environmental Benefits. A more efficient use of energy, including a reduction of the building energy demand, can have a direct impact on the reduction of carbon emissions and air pollutions, as widely illustrated in various studies ([4],[20]).
- Energy system benefits. The reduction and better management of the building energy demand has implication on the national energy security supply, limiting peak loads and thus avoiding high demand and the need of new generation capacity. In particular, it can influence the global energy market and thus the security of energy supply in the medium and long term [1].

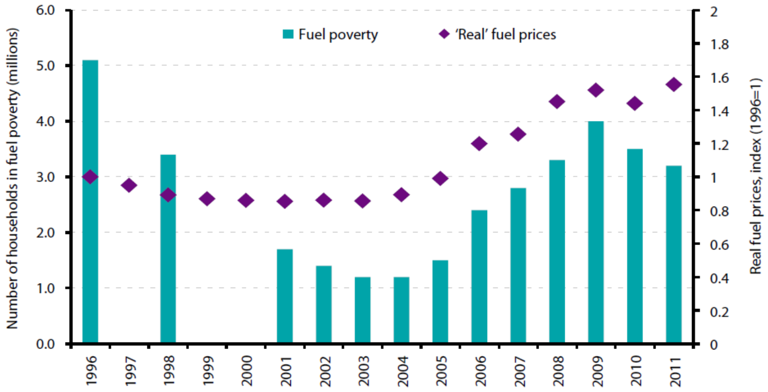


Figure 6 – Fuel poverty and Real fuel prices in United Kingdom [21].

The real potential of retrofitting the existing building stock, in terms of achievable benefits, has not been understood and its implementation is pretty limited; the renovation rate of the existing building stock rates barely above 1% per annum in most EU countries [10]. Moreover, despite the efforts of some EU Member States to spur the investment in building retrofitting, the extent of renovation is still limited. In order to understand the causes affecting such a low renovation rate, it is necessary to comprehend the factors that affect renovation decisions and identify the corresponding barriers. According to FIEC (European Construction Industry Federation), the market barriers are strongly related to the access to finance (e.g. low mobilization of the available funds and difficulty to access to credit) and to the low awareness of the achievable long-term benefits brought by renovation (prefer to spend money on more tangible benefits, low willingness to invest, split incentive) [22]. Based on a literature review ([6][12][23]), five main class of barriers, can be identified as follows:

- Financial. This class concerns financial barriers, which hold a direct impact on the investments for renovation and have a crucial weight on retrofit projects. The lack of funds to secure finance, tighten up by the current financial crisis, is generally one of the most important barriers. A lack of confidence towards the financial benefits achievable from renovations characterizes also the financial institution, closing tight the limited funds availability. Given the large quantity of buildings owned, the public sector, together with large housing providers, can be the first potential leaders in the undertaking of 'deep renovations'. On the contrary single households are not willing to consider renovation a priority investment as the energy running costs account only for 3-4% on the total disposable incomes and generally the short payback expectations are not fulfilled. Moreover, due to the perception by single households of the fast acquisition of higher "societal benefits, other investments (e.g. electronic gadget, etc) are hence preferred to renovations that are indeed hindered by up-front costs and dispersed benefits. In addition, the uncertainty surrounding the stability of energy price does not encourage investing money in retrofit actions for achieving energy savings in building energy demand.

- Information and awareness. A lack of clarity around why renovation should be undertaken usually characterized the market, decreasing customers' motivation and causing "potential" customers to be discouraged towards renovation. In particular, if it is not strictly urgent (equipment failures or serious operation problems), households chose to not undertake renovation measures. A low awareness about the cost-effective energy saving solutions is also caused by a lacking and poor quality knowledge that should be given by professionals.
- Institutional and administrative. This class regards barriers that have a direct impact on the rate and ambition of renovation in EU countries. The fragmentation of the different energy regulations and their "late" implementation by Member States hinder the real improvement of the buildings energy efficiency. Moreover, the lack of stability into energy tariffs reduces motivation and interest towards investments in energy retrofit projects.
- Separation of expenditure and benefit (Investor/User barrier). The class regards barriers originated by the structure of the buildings ownership/tenure (e.g. often the building owner and the tenant do not correspond). Barriers are often represented by the split incentives can be encountered: for instance, this is the case where the owner of a building makes an investment to improve the energy performance of the building but the only tenant gets the resulting financial savings from the reduced energy bills [10]. For this reasons, public owners are usually more willing and have greater financial means to invest in building renovations than private owners. Moreover, as public ownership is quite extended in non-residential buildings, great potential lies in large-scale renovation strategies [7].
- Technical. Technical barriers should also be considered. They concern the lack of feasible energy efficiency technologies and skills shortage identification, implementation and maintenance of adequate retrofit measures. Skill shortages may be identifies in professionals and market contractors [6].

As stated previously, financial barriers represent the first and greater obstruction to a wide renovation of the building stock. Despite this, EU has been slowly promoting different economic and financial instruments to support the renovation of the existing building stock. Among these, grants and subsidies are the most commonly employed in EU28, followed by loans and tax incentives. The renovation measures mostly supported by these economic instruments are those aiming at improving the energy efficiency of the building technical systems and of the building envelope [6].

1.3 Where we stand now: EU energy policy framework

Since the agreement to Kyoto protocol in 2007, European Union has been taking part to the international commitment for preventing climate change. With the agreement to keep the climate change below 2°C (below pre-industrial levels) as endorsed in Copenhagen and within the Kyoto Protocol, Europe drives for becoming a "low carbon economy" by 2050. In fact, in order to reduce GHG emissions a detailed roadmap, known as "Roadmap for moving to a competitive low-carbon economy in 2050", has been defined as a long-term pathway for achieving a 80% cut in domestic emission by 2050, compared to 1990 [24].

For reaching the ultimate goals of 2050, intermediate targets, for the 2020, the 2030 and 2040, were set. With special regard to the closest ones of the 2020 roadmap, usually referred as "Europe 2020 strategy for smart, sustainable and inclusive growth", adopted by the EU Council on 17 June 2010[25], the EU set out a specific headline goal related to climate and energy. In particular, under the climate and energy umbrella three main targets, known as "20-20-20 targets", were defined to be reached from each Member State. Table 1 reports the key priorities for the sustainable growth with its targets and flagship initiatives. Europe is currently on track to meet two of those targets, but it will not meet its energy efficiency target unless further efforts are made.

Table 3 - Europe 2020 Strategy for the sustainable growth (Table adapted from [25])

	TARGETS	FLAGSHIP INITIATIVES
Sustainable growth	Reduce greenhouse gas emissions by 20% compared to 1990 levels; Increase the share of renewables in final energy consumption to 20%; Reduction of energy consumptions of 20% by improving energy efficiency.	Resource efficient Europe An industrial policy for the globalization era.

Moreover other specific targets are set within the Framework Programme for Research and Innovation 2014-2020, set within the Horizon 2020 initiative. In particular, Horizon 2020 shall play a central role in the delivery of the Europe 2020 strategy for a smart, sustainable and inclusive growth ("Europe 2020 strategy") by providing a common strategic framework for the Union's funding of excellent research and innovation [26]. It will act as a vehicle for leveraging private and public investment, creating new job opportunities and ensuring Europe's long-term sustainability, growth, economic development, social inclusion and industrial competitiveness, as well as addressing societal challenges across the Union.

In addition, the EU commission, with the recent "climate and energy policy framework 2030", has set a package of new ambitious pillars for tightening up EU's progress towards a low-carbon economy and for making EU's economy and energy system more competitive. The most cost-effective and central milestone of the framework consists in a 40% reduction on the greenhouse gas emissions (below 1990 levels), ensuring EU to be on track towards its objective of cutting emissions by at least 80% by 2050. Moreover, a target of at least 27% for renewable energy and energy savings by 2030 has been set.

Over the years, since its first commitment, Europe has doubtless made positive steps to drive forward the improvement of the building sector energy efficiency, introducing several pieces of legislation. In particular, the Energy Performance of Buildings Directive (EPBD) [1], the Energy Efficiency Directive (EED) [9] and the Renewable Energy Directive (RED) [27] directly address to public buildings by setting specific targets or requirements for focusing resources on sustainable energy in buildings and for mobilizing investment [10]. *Table 4* overviews the most relevant rules and requirements of these directive. The EPBD, as policy driver for reducing energy use in buildings, has been representing the first and main legislative reference. Based on a methodological framework for calculating the energy performance of buildings, it has allowed Member States (MS) to set minimum energy performance requirements for both new and existing buildings (>1000 m^2), undergoing major renovations. The introduction of the energy certification system, as an informative tool about the building energy class for both new and existing buildings (to be rented or to sell), is one of the core features of the Directive. Due to difficulty related to the implementation of the directive, the large energy savings potential of the EPBD was not exploited. For this reason, the EPBD, originally formulated in 2002 (2002/91/EC) was recast in 2010 (2010/31/EU) with new amendments, to strengthen buildings minimum energy efficiency requirements and to push them towards cost-optimal levels by means of a comparative methodology framework. In particular the EPBD recast set up new requirements for nearly Zero Energy Buildings, to be met for all new buildings by the end of 2020 (for 2019 for public authorities) and requires MS to define ad hoc National plans to stimulate the number of nZEB buildings.

Table 4 – Main rules and requirements of the principal EU Directives. Adapted from [28] and [16].

EPBD **Directive 2010/31/EU**	**EED** **Directive 2012/27/EU**	**RED** **Directive 2009/28/EC**
MS have to develop and apply a methodological framework for calculating building energy performance.	MS have established a long-term strategy for mobilizing investment in the renovation of the national stock of residential and commercial buildings, both private and public.	MS have to set-up sector-specific targets for renewable heating and cooling.
Minimum energy performance requirements, at MS level, for building and building component, to be applied and verified, in new and existing building undergoing major renovations, for achieving cost-optimal level of energy performance.	MS have to ensure a refurbishment rate of 3% per year related to the total floor rate of all heated and/or cooled buildings (>500m^2) owned and occupied by their central governments.	MS have to adopt policies for RES-H (project to help MS evaluating heating and cooling in light of renewable energy sources) at least for new buildings and existing buildings that are subject to a major renovation.
MS have to take measures aim at optimizing the performance, installation, dimensioning, adjustment and control of the technical building systems installed in existing buildings.	MS have to establish energy efficiency obligation scheme (White Certificates Schemes) or alternative measures with equivalent effect, aiming at providing efficiency measures that achieve averagely 1.5% energy savings per year.	Specific technology restrictions (in view of target accounting) for heat pumps and bio-liquids
All new public and private buildings have to be nZEB (nearly-zero Energy Buildings) respectively by 2018 and 2020; National plans and ad hoc policies have to be developed aiming at increasing the number of nZEB	MS have to promote the availability of independent high-quality energy audits to all final customers.	MS have to ensure that new public buildings, and existing public buildings subjected to major renovation, hold an exemplary role in the context of the use of RES-H, at national, regional and local level.
Member States shall ensure that all parts of the heating and air-conditioning systems are regularly inspected and that heating installations older than 15 years are assessed with respect to their energy performance.		

Implementation of EPC schemes
according to a number of minimum
requirements defined by the Directive.

Moreover, in order to apply the minimum energy performance requirements to a large extend of the existing building stock, the limit of 100m^2 for major renovations was cancelled, as it excluded approximately 72% of buildings.

The EED has been launched at the end of 2012, replacing the Energy Services Directive (2006/32/EC), in order to help MS to get the 2020 goals. With article 4, EED requires MS to "establish long-term strategies for mobilizing investment in the renovation of the national stock of either public and residential and commercial buildings public and private". In Article 5, the EED explicitly requires central governments to renovate at least 3% per year of public buildings, both owned and occupied, from 2014 onwards. Energy efficiency obligations constitute another important tool that leverages investments from companies in the energy sector. Energy providers are requested to reduce energy use among their customers by the equivalent of 1.5% of final energy consumption per year. Member States are obliged to adopt an indicative national energy efficiency target in 2020, where significant savings are expected to accrue from the building sector. Promotion of the energy services market through the provision of model contracts, exchange of best practice and guidelines, in particular for the public sector, are also included. Moreover, MS must define long-term national building renovation strategies, specifying the planned energy efficiency measures and the improvements that each MS expect to achieve, within ad hoc created National Energy Efficiency Action Plans (NEEAPs) every three year [2].

The RED is an important piece of legislation that promotes the use of energy from Renewable Energy Sources (RES) and targets the coverage of at least 20% of EU total energy needs with RES by 2020(Art. 3).

Two additional important EU Directives, as far as the building sector is concerned, are the following:

- Ecodesign Directive (2005/32/EC) and its recast (2009/125/EC);
- Energy Labelling Directive (1992/75/EWG) and its recast (2010/30/EU).

The Directives 2009/125/EC and 2010/30/EU address mandatory minimum energy efficiency and labelling requirements for energy-related products, with a special focus for technologies used in the building sector and related to building electricity, heating and hot water consumption. In particular, the Ecodesign Directive 2009/125/EC establishes a framework for setting eco-design requirements for energy-related products aiming to increase their energy performance throughout their lifetime, while the Energy Labelling Directive sets out energy labelling requirements for helping consumers choose more energy-efficient products.

According to David Myers of Johnson Controls, although EU energy efficiency laws distinguished themselves from other international regulations for being considered extremely progressive, they lack in implementation [16]. Therefore, even if theoretically they could reach high-rated targets, because of a patchy and delayed implementation of the regulations, EU policy has acted ineffectively, missing the expected targets. The introduction of the building energy performance certificate in 2002[8] represents a clear example; a vague definition brought to an inconsistent implementation at national level and a difficult comparison at EU level. Moreover, concerning the EPBD recast and the EED directives two aspects clearly arise as ambiguous. First, within the EPBD recast, more understanding is required concerning the definition of" nearly zero-energy building". A nZEB, within the EPBD recast, is defined as a building with a high energy performance. However, this definition cannot be considered fully comprehensive, lacking of common rules for MS to stimulate nZEB development. Second, within the EED, the deep renovation of building stock is presented as a requirement to be accomplished at national level by MS. Still no time plan horizon is defined and mostly a definition of deep retrofit is not given within the Directive.

In order to achieve the projected energy savings and spur buildings refurbishment, a full and fast execution of the regulations in force is required. Therefore, a more clear and effective regulation strictly devoted to the renovation of the existing building stock, is necessary. As frankly stated in [16] "Europe needs to stop hiding behind vague concepts. It is fundamental for the market to get clear on common rules for nearly zero-energy buildings and on what constitutes a deep retrofit". Indeed, most buildings present today in the EU will still be standing in 2050. Yet, renovation rate across the EU is low, standing at approximately 1% of the building stock. Moreover, only a minority of retrofit interventions can be regarded as deep renovations. Most of renovations recently undergone have hence achieved energy savings characteristic of minor renovations (as defined in Table 1).

With these regards, in 2011, the Buildings Performance Institute Europe's (BPIE) conducted an interesting study over EU ambition and real potential of achieving 2050 decarbonisation target with reference to the building stock renovation. It especially draws different potential scenarios for achieving the 2050 roadmap targets [7]. All the scenario were distinguished based on the renovation rate (the speed at which buildings are retrofitted) and the type of renovation undergone (renovation level as defined in Table 1). It comes as no surprise that for reaching the decarbonisation goals, the rate and the level of renovations on the existing building stock have to be definitely increased. A renovation rate of around 2.5-3 % per year (compared to the current 1%) should be recorded. Moreover as reported in Figure 7, also the level of renovation should change, reducing the number of minor renovations and increasing deep and nZEB ones.

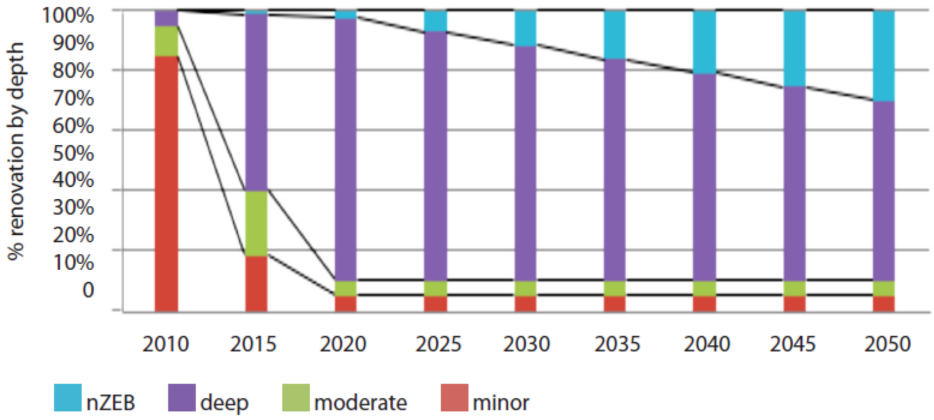
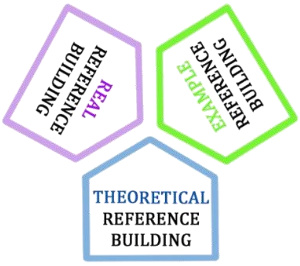


Figure 7 – Scenario for reaching the 90% Co2 saving of the 2050 roadmap based on the renovation level undergone.



2.

Reference Buildings [RBs]

This Chapter deals with the topic of Reference Buildings. As stated in the previous chapter a scalable dynamic simulation-based methodology for developing energy retrofit scenario for existing buildings is proposed. The first scale of building tackled within this thesis is that of the building stock by means of reference buildings (RBs). The overarching goal of using reference buildings is to draw widespread representative renovation scenarios and strategies that can be applied to wide portion of the existing building stock. To this regard, for instance for the development of energy retrofit strategies at national level, being representative building models, reference buildings could be employed. They represent a concrete tool to take action to save energy in the existing building stock. Accomplishing to the EED requirements, at least 3% of public buildings (>500m^2) have to be refurbished each year. However, carrying on energy retrofit analyses on every single existing building does not represent a manageable solution due to an endless and unreasonable computing time. The use of representative models, such as reference buildings, is thus necessary to optimize the time employed and, mostly, to make general considerations to be applied to both the existing and new buildings stock. This is also the case of private companies with a large real estate, which need to renovate and improve their building stock for reducing the energy consumption and, when applicable, for acquiring white certificates. The use of RBs can thus provide a consistent baseline for the definition of benchmark retrofit strategies and accelerate the retrofit uptake on the existing building stock. Furthermore, they can serve as instrument to gain knowledge about the relevance and impact that energy renovation can play on the existing buildings.

First, a literature review on the use and application of RBs at national and international level is provided. Second, a methodology proposal for the creation of the reference building models is presented (**Paper I**). Based on this methodology, a set of Italian RBs were created covering different building typologies, like residential and non-residential buildings and considering different construction ages, including also new constructions. Finally, a descriptive summary sheet is reported for each RB defined.

2.1 Reference Buildings: use and definition

Reference buildings are worldwide used for carrying out analysis that can deliver benchmark calculation results. In particular, they aim to characterize the energy performance of typical building categories under typical operations. When considering for instance a sample of similar buildings (e.g. single-family houses), due to high and not manageable computational time, it is not possible to conduct the same study/analysis on every individual building. For this reason, RBs are used as representative buildings to carry out analysis scenario on wide portion of the building stock. For instance, they can be used for studying the impact of new policies and regulations, such as the overall achievable energy savings, on the national existing building stock. Moreover, they can be used for obtaining benchmark results [29], such as energy consumption, to be further employed for comparison with specific case study. For example, during the energy assessment and design of an office building, reference buildings can provide first input data for the modelling process and benchmark results to employ in further comparisons.

To this regard, their application is explicitly required at EU level for the purpose of the cost-optimal methodology, by the EPBD recast [1]. The regulation hence asks MS to identify at least 9 RBs: one RB for new buildings and at least two for existing buildings, subjected to major renovation, for each of the following categories (single-family buildings, multi-family buildings, office buildings; and other non-residential buildings)[1]. The RBs have to be defined as models for applying measures aimed at improving the buildings energy performance. The process for their establishment is described in detail within the Guidelines accompanying the Regulation [6].

Despite their wide application, no harmonized and recognized definition has been indicated to refer to them yet. The EPBD recast specifies that RBs are *"buildings characterized by, and representative of, their functionality and geographic location, including indoor and outdoor climate conditions"*[1]. Since it is not possible to calculate cost optimal levels of energy performance for each building, either existing or new, RBs aim to provide a realistic picture of the typical and average building stock for each MS. The EPBD recommends that RBs have to cover residential and non-residential buildings. Considering the variety characterizing EU building stock in terms of climate, buildings styles and usage, the creation of sub-categories, even if not mandatory by the regulation [1], can help MS into the definition of RBs. To this regard, specific remarks are reported by the European Commission (EC). The suggested sub-categories are listed as follows:

- <u>Age.</u> The identification of different age groups can be significant for the characterization, in a specific MS, of an heterogeneous building stock. The construction age of the building reflect directly the construction technologies and customs typical of the time period the building has been built in, as well as the energy saving requirements in the building construction (e.g. thermal insulation), if applicable. For this reason for a better sampling of the building stock, the building age should always be considered.
- <u>Size.</u> Size categories can represent subcategories for both energy and cost-related characteristics.
- <u>Location.</u> This sub-category is fundamental especially in countries where sensible climatic conditions can be observed in different area of the same country (e.g. South and North). This difference usually drives different national requirements in the building construction (e.g. energy savings requirements), having a direct impact on the buildings characterization.

- Orientation and shading. This sub-category may be used for defining "average" situation of shading and orientation for buildings located in a urban context and in a countryside. This average situation may be used to define, at national level, some recommendation regarding the building design.
- Construction products in load carrying and other structures. The distinction of massive and lightweight buildings should be considered for MS where this difference can be clearly observed in the existing building stock.
- Heritage protected buildings. MS with a relevant number of heritage protected buildings, the creation of an hoc category of RBs should be strongly considered.

The definition of a reference building, and consequently the creation of the corresponding building model, is a complex task. It originates from the collection of all data necessary for the building characterization. Data like the year of construction, the building size, the type and age of the energy system, as well as the features of the building envelope are necessary for the creation of RB. Based on this data, once the modelling process is completed, the assessment of the building energy performance can be performed. Both the quality and the quantity of data, to be used for creating the RB model, play an equally relevant role on the accuracy and level of detail pursued in the building definition. It is not always possible to rely on high quality and large quantity of data. The lack of information is a constant issue in the creation process of building models, together with the commonly observable low quality data. For this reason, the source to rely on for the data collection, during the definition of the RB, is of high relevance. In particular, depending on the type of model used for the energy assessment of the building energy performance within the study, the quantity of data to be implemented in the model may vary. Simplified models require a low level of detail than more complex model, like those created with dynamic building simulation programs. As stated in the previous chapter, this study aims at using dynamic energy models created by means of building simulation programs for the high level of detail that can be achieved. Moreover, the EPBD recast suggests MS to perform calculation based on a dynamic method.

2.2 RBs application: national and international experiences

Different experiences of RBs creation and use can be found in the literature, both at national and international levels. At international level the most recognized one is the database of commercial reference building models of the U.S. DOE [30]. They represent the outcome of the collaboration of the U.S. DOE with the National Renewable Energy Laboratory, the Pacific Northwest National Laboratory, and the Lawrence Berkeley National Laboratory. They were developed to serve as starting point for conducting energy efficiency research. These models represent fairly realistic buildings and typical construction practices in the U.S. This database consists of 16 RBs (15 commercial buildings and one multi-family residential building), selected as the most common building typologies and representative of approximately 70% of the commercial building stock in the U.S., across 16 locations (from Alaska to California), which represent all U.S. climate zones. For each RB, three different construction ages are considered: new construction, post-1980 and pre-1980. New construction building models are defined based on the current normative/standard requirements (e.g. ASHRAE Standard 90.1), while the post-1980 and pre-1980 models refer to the law requirements relative to their construction period. They are modeled and used within the building simulation program EnergyPlus for whole building energy analysis. Therefore, for each RB in each climate location, an EnergyPlus input file is available. Overall, the database is composed of 256 models, that are available to download from the website portal [31]. Spreadsheet scorecards document the model parameters (used as input data for modeling) and annual energy performance for each building type and location.

As stated previously, they were created for energy efficiency research, taking advantage of the potential of simulation studies and improve the value of computer energy simulations using software such as EnergyPlus. In particular, they have been used for conducting analysis, for the ASHRAE, to estimate the energy savings achievable with selected Standards (e.g. 90.1, 189.1) and, based on the outcomes of the simulation studies review the targets sought [29].

At European level, consistent efforts towards the definition of an EU database of RBs were made within the two IEE (Intelligent Energy Europe) projects TABULA and ASIEPI. The first one aimed to fill the gap of data availability about the energy performance and the state of refurbishment of the EU building stock, which directly affects the reliability of building stock models and of scenario calculations [32]. TABULA main objective was to create a harmonized structure of the European building typologies and to identify representative building types, with a special focus to the residential typologies, across 13 European countries. The set of representative buildings created within TABULA could be used as a basis, at national level, for carrying out scenario analysis on the building energy demand and on potential energy retrofit savings, and at EU level, to conduct a cross-country comparison. Unlike dynamic building simulation used in U.S. DOE commercial reference buildings, in TABULA, simple energy performance calculation procedure, based on the respective CEN standards, were used for assessing the energy demand of the RBs. Each national typology consists of a classification scheme grouping buildings according to their size, age and further parameters and a set of exemplary buildings representing the building types. A WebTool was also created to disseminate the general idea of national building typologies to building experts from all European countries. The TABULA project was also recommended in the EPBD recast as a source of RBs for cost-optimal studies. Moreover, a new project, EPISCOPE, has acquired TABULA legacy to further developing it with new typologies, for including examples of new buildings meeting current national requirements or targeting the nZEB level [33].

On the other hand, the ASIEPI (Assessment and Improvement of the EPBD Impact) project developed, as a subtask within its project, a set of possible RBs [34] to be used in pilot comparison studies. A variety of typical single-family houses (from row house to detached house) were defined for 12 European countries, including Italy.

Another EU project worth of consideration with regard to the definition of building typologies or reference buildings, is the DAMINE project, which main objective was to learn from data collection and analysis of large scale EP building certificates, across 12 EU countries, and to draw conclusions for establishing harmonized monitoring systems. The first step towards monitoring the energy performance of the building stock is to get a systematic overview of its structure. For this reason different building typologies were defined based on the information coming from the Energy Performance certificate [35].

An ad hoc Rehva Task Force “Reference Buildings for energy performance and cost optimal analysis”, which the author of this Ph.D. thesis participated to, was also created. The Task Force aims to develop, on the basis of the national experiences, a set of European Reference Buildings/benchmark buildings in order to suggest European wide harmonized database of building types which could be used for cost optimal calculations according to EPBD recast at European level by technicians and researchers. So far, ongoing activities on the definition of national RBs are being developed and they are still far from being closed. Due to this fact, TF is now focusing in conducting cost optimal analyses and comparing the results of these between different MS in order to give some useful information to policy makers and investors.

BPIE also defined two RBs, across three representative European climates (Copenhagen, Stuggart and Madrid), in a simulation study about nZEB implementation. A single-family house and a multi-storey office building house were defined as RBs for new construction, based on experts' assumption [36].

With specific regard to Italy, a quantitative and qualitative analysis of Italian commercial building stock, with special focus on the tertiary sector, was conducted by ENEA (Italian National Agency for New Technologies Energy and Sustainable Economic Expansion) for evaluating energy retrofit scenario on the existing building stock [37]. This research considered approximately 65'000 Italian office buildings, defining two office RBs as the most representative for the existing stock.

The projects and researches reported above are examples of studies aiming at assessing the energy performance of the existing building stock, and at the same time at calculating the energy savings achievable with specific retrofit scenario, on large portion of national and international (U.S. or EU) building stock. Beyond this type of research, reference buildings are also defined on a "smaller" scales as representative buildings like for instance at the municipality level.

Dall'O et al [38], for instance conducted a study on the analysis of the energy savings achievable from the building envelope retrofitting of the existing residential building stocks in five different municipalities in the province of Milan. Through a survey, they created a buildings cadastre classifying each building by typology and age of construction. Based on the buildings characterization observed in the survey, the potential area of the components surfaces, both opaque and transparent, to be subjected to retrofit was assessed.

Similarly, Fracastoro and Serraino [39] performed a study for assessing the energy performance of large-scale building stocks, at Regional level (Piedmont and Lombardy regions in North Italy). They developed an analytical methodology to determine the statistical distribution of residential buildings according to primary energy consumption for heating purposes, to be used, within regulations, to introduce mandatory measures and incentives for building energy retrofits, as well as to evaluate the potential of new technologies. For this reason, they analyzed the existing building stock, based on statistical available surveys, for defining the average features of the building residential sample in Piedmont and evaluating the impact of large-scale energy retrofit measures.

2.3 Focus on PAPER I: A methodology proposal

Creating a reference building means to model a building that can be considered representative of a sample of buildings. The data used for its definition should be reliable and “adequate”; this means that a reference building has to include average and typical characteristic of the “sample of buildings analyzed” for the RB to be considered representative.

Several pieces of information are necessary to properly define a RB. Data concerning program, form, fabric and equipment of a building have to be gathered together for creating a reference building model. Four main data sub-categories/levels, during data collection can be identified, as pictured in

Figure *8*. They can be described as follow:

1. Form. This sub-category includes all data concerning the building form. This means data about main typology (e.g. detached house, office building), the size and general features about the geometry of the building (e.g. floor, dimensions, volume, aspect ratio, orientation, etc).
2. Envelope/Fabric. All data regarding the construction types and the thermo physical proprieties of building envelope components (exterior walls, roof, floors, windows) belong to this sub-category. Depending on the data source, this data may be defined based on design manuals and on the national minimum requirements with respect their construction age.

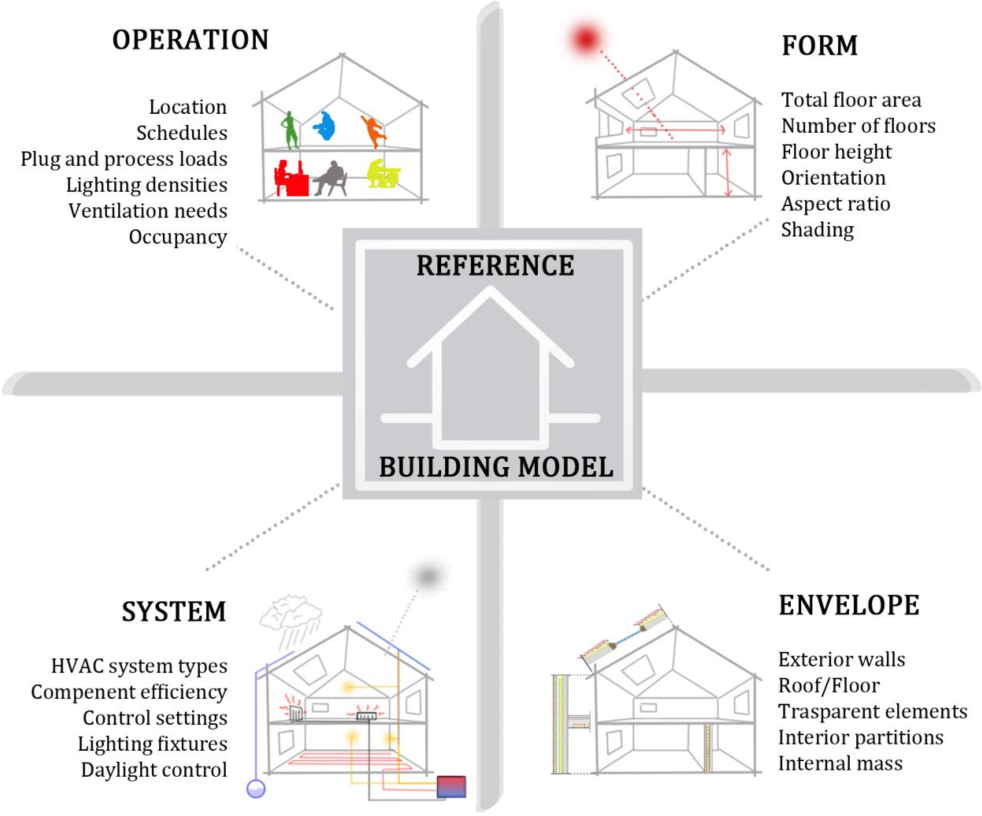


Figure 8 – Main data sub-categories for the creation of reference building model.

3. <u>Operation</u>. This sub-category set the operational parameters affecting the usage of the building. It includes data about the activity performed, location coordinates, occupancy rate, lighting and equipment loads, ventilation needs and a each schedule for each building action affecting the operation (i.e. lighting schedule, equipment schedule, heating temperature schedule, etc).
4. <u>System</u>. The data about the system that serves the building and regards. It includes heating and cooling systems, mechanical ventilation systems and refrigeration systems (when applicable) and system for the energy production from renewable sources.

The structure of these four main sub-categories was adapted from the approach followed for the creation of the commercial reference building by the Department of Energy (DOE) of United States [30].

After collection, data have to be gather together based on their source. The source of each piece of data should be clearly distinguished during the definition of the reference building model. The data used could be retrieved from statistical documentation, such as survey and analysis on the building stock, or also from energy performance certificates, or design manuals and standards, or it could also be the final results of experts' assumption based on their building design experience. It is important to take into account the source of the data used for RBs modeling, as based on the typology of the data (statistical, based on experts' experience, standard and design manuals) and on its processing, different typology of RB models can be defined. A methodology for their definition, based on the findings of the TABULA project, has been described in **Paper I** and Figure 9.

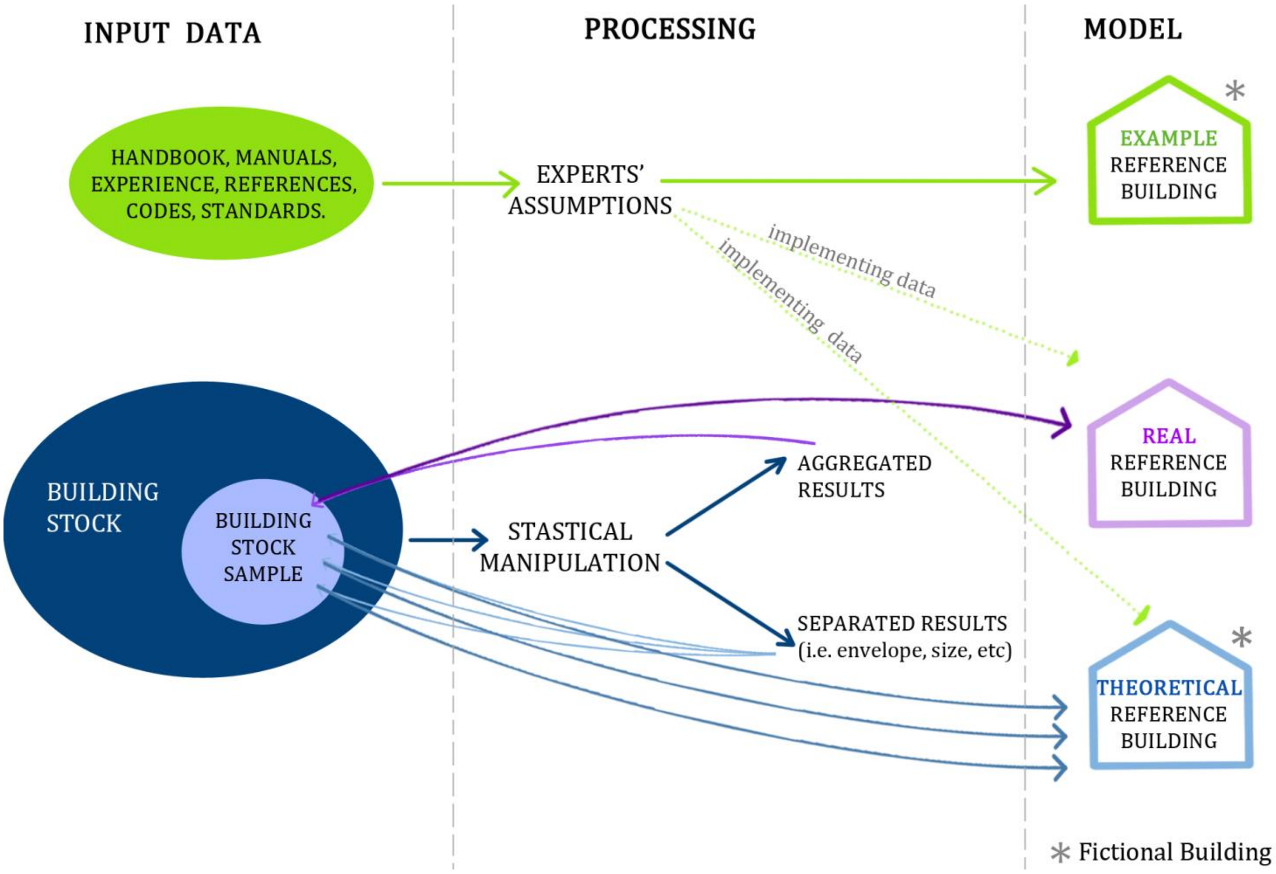


Figure 9 – Process for the creation of reference building depending on the starting input data.

For its high reliability and for the large portion of building stock that it allow to consider, statistical documentation represents the most valued and claimed source for the creation of a reference building. Even if statistical analyses cannot be carried out on the whole building stock, it can provide a fairly realistic picture of the current state of a sample of the existing building stock investigated. Notwithstanding, it may also occur that the statistical data used is not sufficient for a complete characterization of a building model; for instance it does not provide information about the building occupancy and operation. Therefore, when statistical surveys are not sufficient or available, they should be used in conjunction or replaced by other typology of data. This is the case of design manuals and handbooks concerning the design of the building typology studied. Often used as a second choice data for the RBs definition, they supply information about the building construction and system that are considered traditional of a specific building typology (e.g. office buildings). Standard and regulations are also used as "reliable" source of data to fill in possible lack of information in the RBs definition. The last category of data to which appeal is the experts' assumptions that is used when there are any other data available is based on the experts' experience. Depending on the approach followed for data processing and considering the data source, three different typology of reference buildings can be created, as clearly picture in Figure 9.

When statistical information is not available, information from different sources (design manuals, standards, handbooks, etc) are thus used and processed together based on the experts' assumptions to provide a building that is the most probable of a group of buildings, within a selection location and construction age. This RB is referred as *Example Reference Building* and is a fictional building. The reference building created based on this approach do not represent real buildings and their definition strongly depends on the experts' judgment and assumption.

On the other hand, when statistical analyses are available, the data is processed with statistical tools for obtaining a synthetic representation of it. However, the building stock cannot be studied in its entirety but, even by means of statistical analyses, only a sample of it can be observed. As depicted in Figure 9, data coming from statistical sources, can be processed in two different ways: as aggregated data or as separated results. After statistical manipulation, a single violet arrow can be drawn or a series of blue arrows are traced for indicating the use of aggregated or separated results respectively. In the first case, when data are treated aggregately, only a single arrow is represented as an existing building, among those analyzed in the sample considered, is selected as representative. This is the case of an existing building with average characteristic and it is referred as *Real Reference Building*. The building model is thus created based on the selection from the sample data of the building stock, as it is the most close to the statistical results.

In the second case, when data are treated separately, the building model created is a statistical composite of the building features which are defined based on a statistical manipulation. For instance, the average U-value of each building envelope component, such as the exterior wall or the window, is defined based on the statistical analysis of the sample data studied. Looking at Figure 9, after the statistical manipulation, different arrows can be observed, representing each one an average value of the features necessary for the RB characterization. The RB model created based on this approach is identified as a *Theoretical Reference Building*. It is created based on the summation of the features (operation, form, system and envelope) of real buildings observed within the statistical analysis, but it is not a real building itself. It is thus a fictional building that is considered representative of the most common features used in the building typology studied.

As previously stated, statistical data are not always sufficient for a full definition of a RB. For this reason, data from manuals and standards, manipulated by experts, may be used (dotted arrow in Figure 9) for integrating the lack of data in the building model creation.

2.4 RBs for Italy

Based on the methodology previously presented and described in **Paper I**, some examples of reference buildings for Italy were created and are hereafter presented. The set of RBs reported covers different building typologies, such as residential and non-residential buildings and considers either existing buildings and new constructions. A few of the RBs defined were also used for the purpose of cost-optimal studies, as it is further presented in Chapter 4 of this Ph.D. thesis. The selection of the RBs was based on the building typology (residential and non-residential), on the building stock distribution and composition and on the construction age. The set created aimed at providing a sufficiently systematic and representative picture of the buildings stock in Northern Italy, taking into account the most common observable building typologies.

Before listing the RBs, it is necessary to disclose the main normative references in Italy (depicted in Figure 10) that impact on the building construction, with concern to the buildings energy performance, since the beginning of the XX century. As stated in the introductory chapter, EU and also Italian building stock is quite old, with 60% of Italian residential buildings being over 45 years old. As can be observed in the timeline pictured in Figure 10, the law no. 373 is the first normative reference that ruled over buildings energy performance and savings, setting specific requirements on the design heating load.

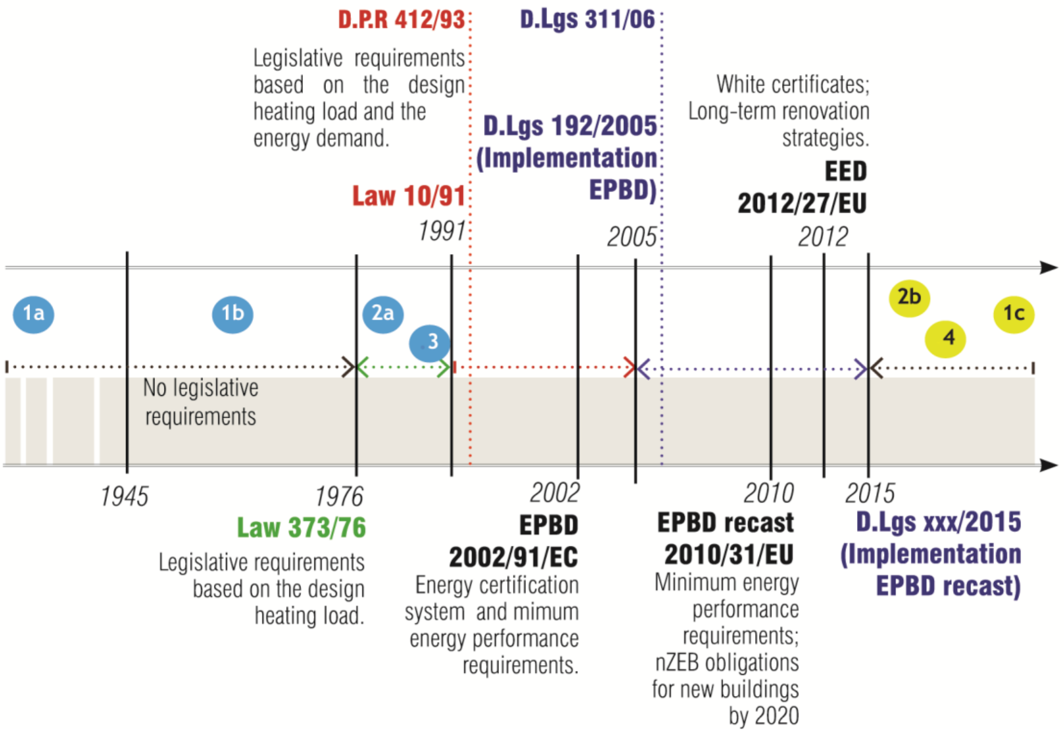


Figure 10 – Timeline for the selection of the RBs

Following to Law 373, new additional normative requirements regarding the building energy demand were defined with the Law 10 in 1991 and its accompanying Legislative Decree 412 of 1993. The legislative Decree 192 of 2005 and Decree 311 of 2006, as direct implementation of the first EPBD (Directive 2002/91/EC), introduced the limit to the building heating energy demand (the decree for its actuation in the Law 10/911 was missing) and the building energy performance certificates. In July 2015 it is expected to be issued the Italian Implementation of the EBPD recast (Directive 2010/31/EU) about the minimum requirements on the building energy performance and the nearly zero energy buildings.

RBs were created and selected to be representative of different construction period: each reference building describes in fact a different context in terms of construction technologies used and also in terms of energy policy and normative requirements in Italy. Therefore for instance, two real RBs (1a and 1b in Figure 10), belonging to different decades before and after the First World War, were created: RB#01a is multi-family and protected building for its cultural heritage, being built at the beginning of the XX century, while RB#01b is a multi-family building representative of the major reconstruction of the post-World War II and characterized by construction technologies with no thermal insulation. The multi-family houses typology was selected as was observed to be, from statistical analysis, the second most common residential buildings in Italian context, after single-family houses, which are represented with the RB#01c. This latter RB, representative of new constructions, refers to the coming decree implementing the EBPD recast in Italy. On the other hand, the RB #02a, an existing medium office building, can be attributed to a more recent construction age, from 1991 until now. It is thus characterized by thermally insulated building envelope constructions. Finally, RBs for new construction, placed at the end of the timeline, are representative of the current design approach and of the minimum legislative requirements in terms of energy efficiency and performance in buildings.

Hereinafter a complete list of the RBs modelled, based on their typology, is reported:

Residential buildings:

1. Multi-family buildings/Apartments block:
    1a. Multi-family building built at the beginning of the XX century;
    1b. Multi-family building built after the 2nd World War;
    1c. Single-family house for new construction.

Non-residential buildings:

2. Office buildings:
    2a. Existing medium office building;
    2b. New large Office building;
3. Secondary school;
4. Supermarket.

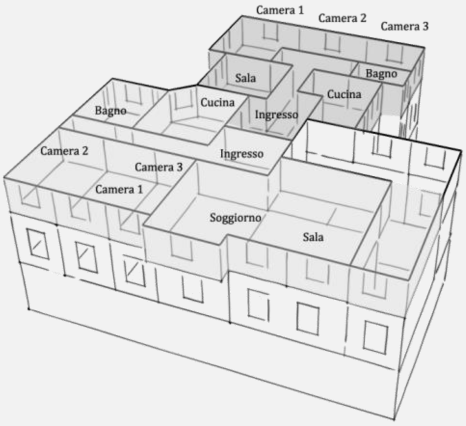
In general, the RBs modelled are all representative of North Italy (climatic zone E), with the only exception of the medium office RB, which was also modelled for Central Italy, specifically for Rome (climate zone D), as further described in **Paper I**. With regard to the building structure, light-structure buildings are not so frequently used in Italy; all RBs have hence massive structure. For each RB a summary data sheet is compiled and an energy model is created within the dynamic building program EnergyPlus, for the energy assessment of the building energy performance. The data used for defining the buildings are gathered in terms of geometry, technical systems and usage patterns. For the creation of the RBs, different sources for the data collection were used. Therefore different typology of RBs, as defined in **Paper I**, are identified; some are real RBs, others theoretical and others exemplar.

Moreover a large office reference building model was created within the IEA ANNEX 59 project, which the author of this Ph.D. thesis took part to. In particular the RB was defined within the Sub-Task A, with the cooperation of the Italian team of TEBE group and the Belgium team of the Université de Liege. This RB aimed to be representative of the European large office building typology and to be used for testing, based on simulation studies, building systems based on Low temperature heating and High temperature cooling.

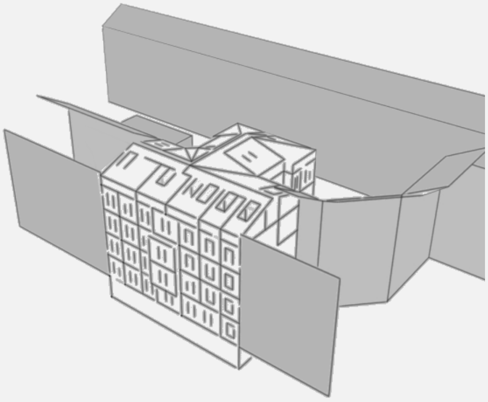
RB#01a	MULTI-FAMILY BUILDING	EXisting
Typology	**Real existing RB**	
Data source	Building main characterization: Energy performance Certificate, IREN research contract Other assumptions: National Standard [40], U.S. DOE [30]	
Construction Age	Beginning of 1900	
Reference paper	Paper IV	
Benchmark energy consumption	Primary Energy: Heating energy: 152 kWh/m^2	

Building	**Description**	The building consists of 12 equal apartments and 4 floors, with conditioned attic studios and a not conditioned basement.		
		Total conditioned floor area		2114 m^2
		Apartments average gross floor area		73.45 m^2
		Room height		4 m
		N Façade	Exterior wall area	322 m^2
			Window area	76 m^2
		S Façade	Exterior wall area	412 m^2
			Window area	65 m^2
		W Façade	Exterior wall area	275 m^2
			Window area	34
		E Façade	Exterior wall area	275 m^2
			Window area	34 m^2
	Envelope Components	Opaque elements	Exterior Wall	1.9 W/m^2K
			Roof	2.17 W/m^2K
			Slab towards not conditioned basement	2.1 W/m^2K
		Transparent Elements	Window	4.90 W/m^2K
System	**Heating system**	District heating sub-stations. Apartments are equipped with radiators. The system operates from 5 a.m. until 10 a.m., and from 12 a.m. to 9 p.m. The temperature set point is 20.5°C, 21° and 21.5° respectively on the ground, intermediate and upper floors.		
	Ventilation	The infiltration rate is 0.5 ACH and is constant during all days.		
Operation	**Internal Gains**	People		0.04 person/m^2
		Lighting		3.88 W/m^2
		Appliances		5.38 W/m^2

RB typical floor plan



3d view of the energy model.

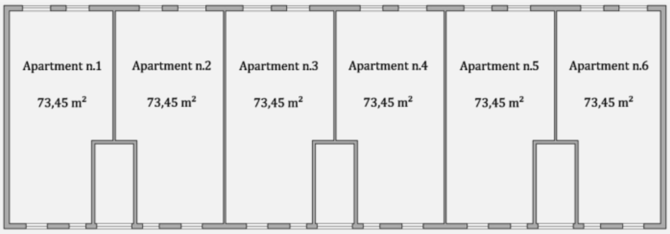


RB#01b	MULTI-FAMILY BUILDING	EXisting

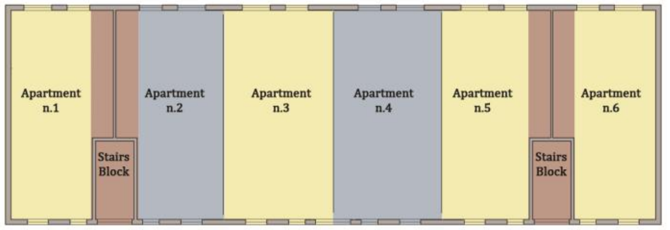
Typology	**Real existing RB**
Data source	Building main characterization: **IEE TABULA** [41] Other assumptions: National Standard and design manuals [40]
Construction Age	1946-1960
Reference paper	Paper J
Benchmark energy consumption	Primary Energy: Heating energy: 178 kWh/m^2 (including aux) Lighting and Appliances:114 kWh/m^2 Total energy consumption: 286 kWh/m^2

Building	Description	The building is a residential apartment block S-E oriented. It consist of 24 equal apartments and 4 floors above grounds. It has also either a basement and an attic not conditioned.		
	Geometry	External dimensions		12.6 x 37.5 m
		Total Gross Floor Area		1890 m^2
		Apartment gross floor Area		73.45 m^2
		Room height		3.10 m
		N-E Façade	Exterior wall area	170.10 m^2
		S-E Façade	Exterior wall area	383.70 m^2
			Window area	122.58 m^2
		S-O Façade	Exterior wall area	170.10 m^2
		N-O Façade	Exterior wall area	326.30 m^2
			Window area	94.06 m^2
	Envelope Components	Opaque elements	Exterior Wall	1.15 W/m^{2}K
			Flat ceiling under the roof	1.65 W/m^{2}K
			Slab towards non conditioned basement	1.30 W/m^{2}K
		Transparent Elements	Window	4.90 W/m^{2}K
System	Heating system	Gas boiler with radiators. The set point temperature is 20°C from 7 a.m. until 8 p.m., and 18°C during the remaining hours.		
	Ventilation	The infiltration rate is 0,5 ACH and is constant during all days.		
Operation	Internal Gains	People	0.04 person/m^2	
		Lighting	5.35 W/m^2	
		Appliances	8 W/m^2	

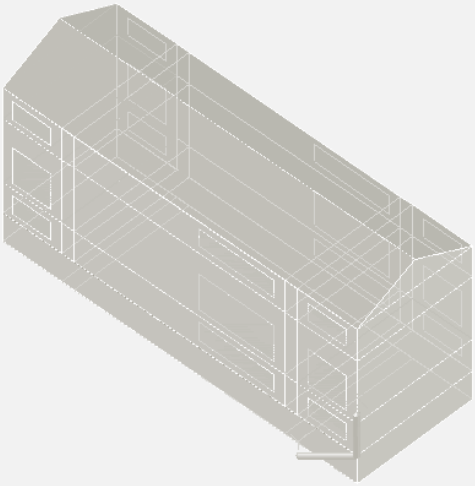
RB typical floor plan.



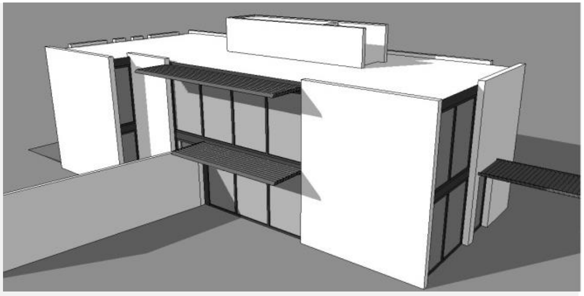
Energy model plan: thermal zones.



3d view of the energy model.



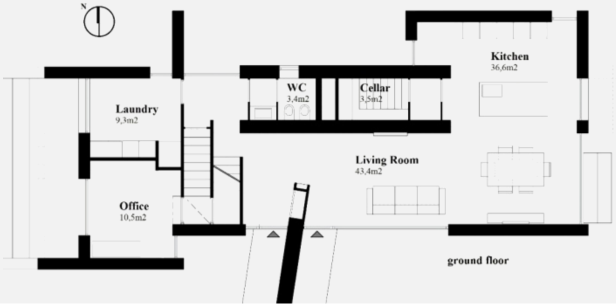
RB#01c SINGLE-FAMILY HOUSE NEW



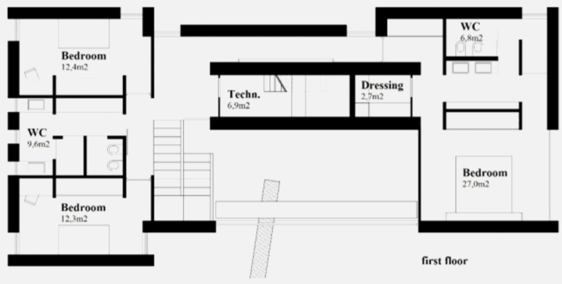
Typology	Example new RB
Data source	Building main characterization: architecture firm “GOOD-FOR” Other assumptions: National Standard and design manuals
Reference paper	Paper III
Benchmark energy consumption	Primary Energy: Heating: 63.2 kWh/m^2 (incl. HDW) Cooling: 20 kWh/m^2 Auxiliaries: 9.8 20 kWh/m^2 Lighting and Appliances: 50.3 kWh/m^2 Total energy consumption: 123.3 kWh/m^2(incl.production from Renewables)

Building	Description	The building has 2 floors above ground. The interior layout is defined by daytime area on the ground floor and a nighttime area on the first floor.		
	Geometry	External dimensions		19.6 x 9.2 m
		Gross Floor Area		248 m^2
		Conditioned Net Floor Area		174 m^2
		Floor to floor height		3 m
		Northern Façade	Exterior wall area	101.3 m^2
			Window area	19.8 m^2
		Southern Façade	Exterior wall area	86.4 m^2
			Window area	37.4 m^2
		Western Façade	Exterior wall area	45.4 m^2
			Window area	23.4 m^2
		Eastern Façade	Exterior wall area	35.3 m^2
			Window area	25.8 m^2
	Envelope Components	Opaque elements	Exterior Wall	0.32 W/ m^2 K
			Roof	0.297 W/ m^2 K
			Slab	0.29 W/ m^2 K
		Transparent Elements	Window	2.00 W/ m^2 K
System	Heating system and DHW	Condensing gas boiler with radiant heating floor and radiators. Dedicated gas boiler for the DHW production. The se tpoint temperatures are 21 °C from 7 a.m. until 8 p.m., and 18°C in remaining hours, during week days.		
	Cooling system	Multi-split air conditioner with direct-expansion units. The set point temperature is 26°C from 7 a.m. until 5 p.m., 18°C in the remaining hours.		
	HVAC	4 pipes fancoils with outside air.		
	Ventilation	0.3 ACH		
	Renewables	Photovoltaic system with 1.6 kW$_p$. Solar thermal system with hot water storage (coverage 80% of DHW).		
Operation	Internal Gains	People	The occupancy rate for offices is 0.04 person/m^2.	
		Lighting	4.5 W/m^2	
		Appliances	2.98W/m^2	

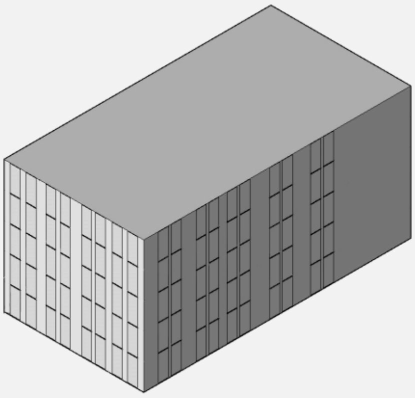
RB ground floor plan.



RB first floor plan.

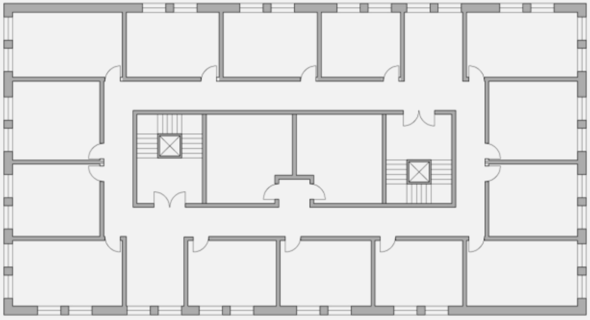


RB#02	MEDIUM OFFICE BUILDING	EXisting
Typology	Theoretical existing RB	
Data source	Building main characterization: **ENEA** and **CRESME statistical survey** [42]. Other assumptions: National Standard and design manuals[43],[40][44]	
Construction Age	From 1971 up to date.	
Reference paper	Paper II	
Benchmark energy consumption	Primary Energy: Heating: 49.6 kWh/m^2 Cooling: 20 kWh/m^2 Lighting and Appliances: 83.7 kWh/m^2 Total energy consumption: 165.6 kWh/m^2	

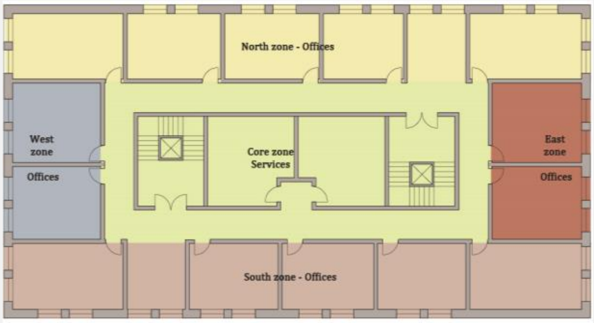


Building	Description	The building has 5 floors above ground. The interior layout is defined by cellular offices on the perimeter area and by a central core for the distributive elements (stairs and elevators) and service areas.		
	Geometry	External dimensions		16x30 m
		Typical Floor Gross Area		480 m^2
		Total Gross Area		2400 m^2
		Height		2.9 m
		Northern Façade	Exterior wall area	278 m^2
			Window area	157.50 m^2
		Southern Façade	Exterior wall area	278 m^2
			Window area	157.50 m^2
		Western Façade	Exterior wall area	232 m^2
			Window area	140 m^2
		Eastern Façade	Exterior wall area	232 m^2
			Window area	140 m^2
	Envelope Components	Opaque elements	Exterior Wall	0,761 W/ m^2 K
			Roof	0,828 W/ m^2 K
			Underground slab	0,516 W/ m^2 K
		Transparent Elements	Window	3,19 W/ m^2 K
System	Heating system	Gas boiler (80°C). The setpoint temperatures are 21,5°C from 5 a.m. until 6 p.m., and 15°C in remaining hours, during week days.		
	Cooling system	Water-cooled chiller. The setpoint temperature is 26°C from 5 a.m. until 6 p.m. during week day. The system does not operate during the remaining hours.		
	HVAC	4 pipes fancoils with outside air.		
	Ventilation	11 l/s per person, Air flow is assumed to be constant from 5 a.m. until 6 p.m. during week days.		
Operation	Internal Gains	People	The occupancy rate for offices is 0.06 person/m^2.	
		Lighting	13 W/m^2 during working days. A 0.5 percentage is assumed during weekends and night time for security systems.	
		Appliances	10 W/m^2 during working days.	

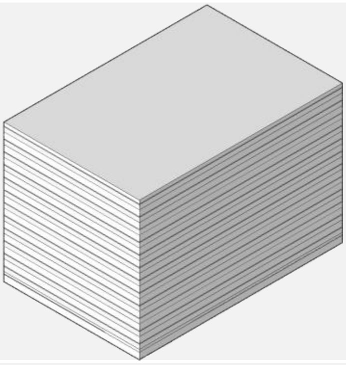
RB typical floor plan.



Energy model plan: thermal zones

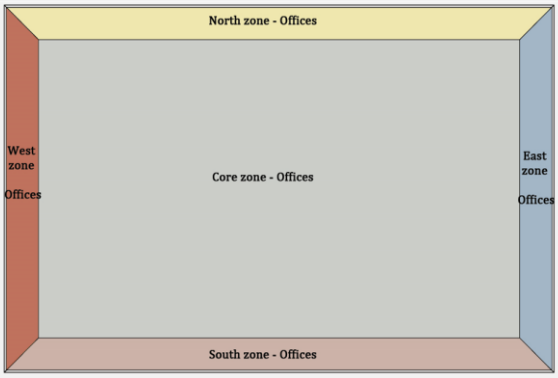


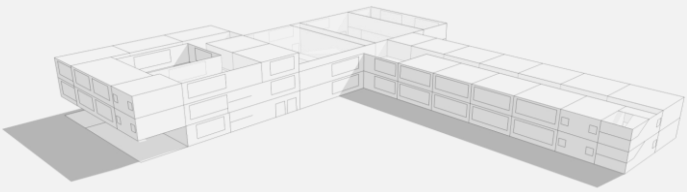
RB#02b	LARGE OFFICE BUILDING	NEW
Typology	Theoretical new RB	
Data source	Building main characterization: U.S. DOE RBs [30] Other assumptions: National Standard and design manuals [43],[40][44]	
Benchmark energy consumption	Primary energy: Heating: 49.6 kWh/m^2	Cooling: 20 kWh/m^2
	Lighting and Appliances: 83.7 kWh/m^2 Total energy consumption: 165.6 kWh/m^2	
Reference paper	Paper I and H	



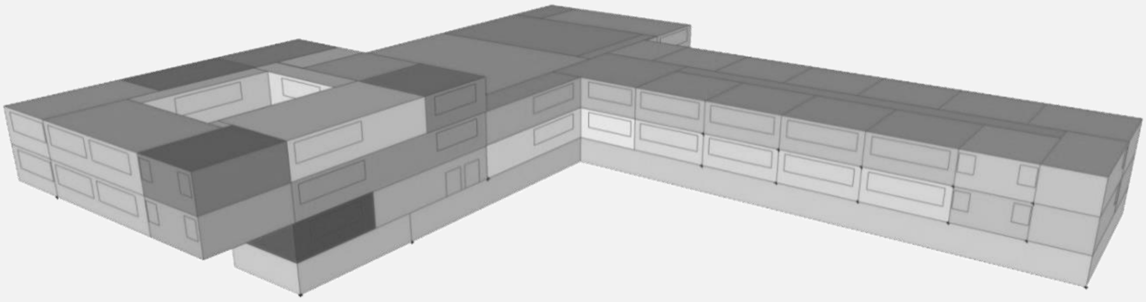
Building	Description	The building has 12 floors, plus a not conditioned basement. Its interior layout is defined by open offices on the perimeter areas and a central core for service areas, and offices as well.		
	Geometry	External dimensions		48x73 m
		Gross Floor Area		3563 m^2
		Total Gross Area		46’320 m^2
		Floor to Floor Height		2,74 m
		Northern Façade	Exterior wall area	2090 m^2
			Window area	1391 m^2
		Southern Façade	Exterior wall area	2090 m^2
			Window area	1391 m^2
		Western Façade	Exterior wall area	1389 m^2
			Window area	927 m^2
		Eastern Façade	Exterior wall area	1389 m^2
			Window area	927 m^2
	Envelope Components	Opaque elements	Exterior Wall	0,309 W/ m^2 K
			Roof	0,248 W/ m^2 K
			Underground slab	0,638 W/ m^2 K
		Transparent Elements	Window	1,1 W/ m^2 K
System	Heating system	Gas boiler (80°C). The setpoint temperatures are 21°C from 5 a.m. until 7 p.m., and 15.6°C in remaining hours, during weekdays.		
	Cooling system	Two Water-cooled chillers. The setpoint temperature is 24°C from 5 a.m. until 6 p.m. and 30°C during the remaining hours, during weekdays,.		
	HVAC	Multi-zone VAV with fancoils		
	Ventilation	0,10 ACH. Air flow is assumed to be constant from 6 a.m. until 10 p.m. during weekdays.		
Operation	Internal Gains	People	The occupancy rate for offices is 0.06 person/m^2.	
		Lighting	15 W/m^2 during working days.	
		Appliances	10 W/m^2 during working days.	

Energy model plan: thermal zones.



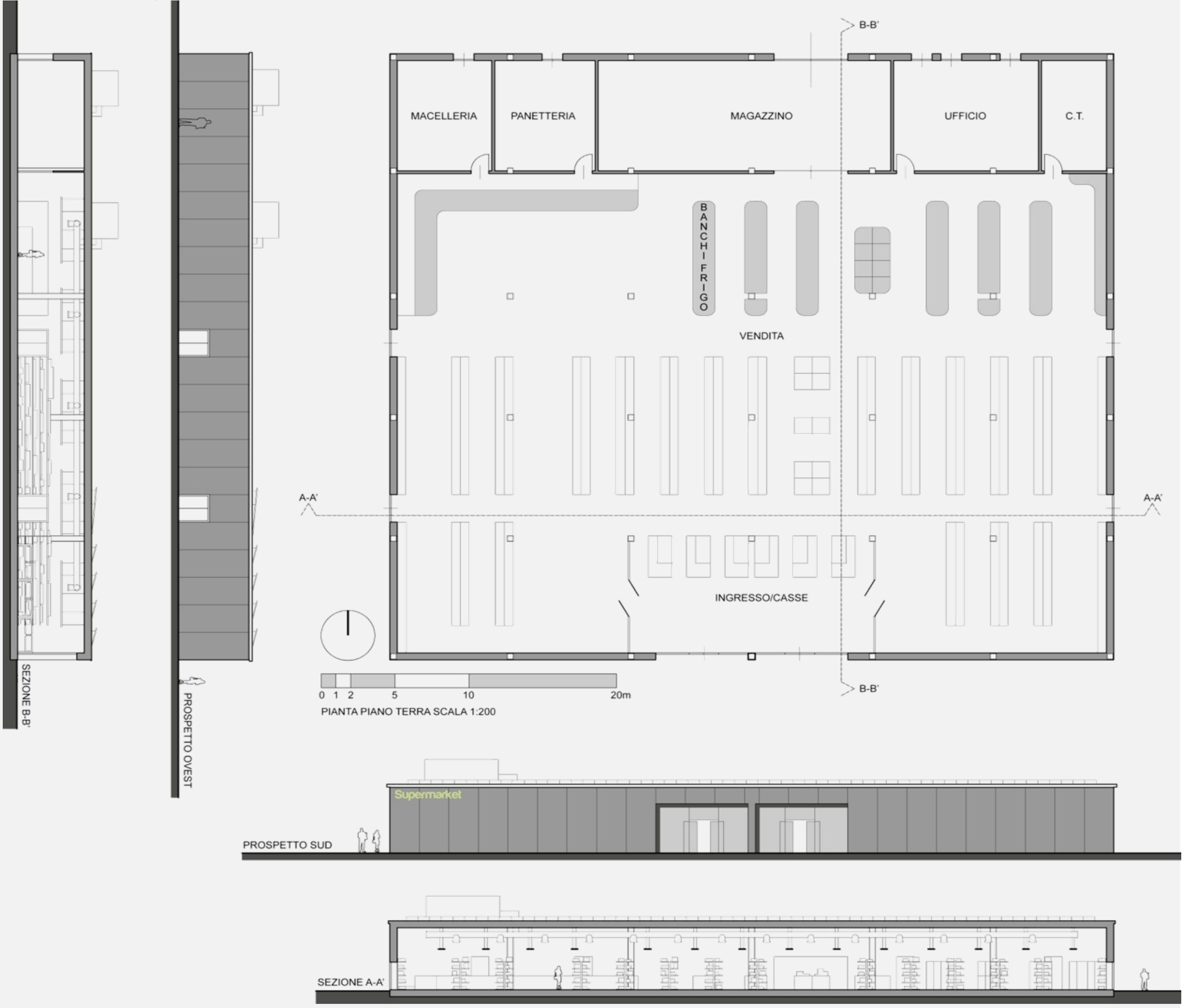
RB#03	SECONDARY SCHOOL			EXisting
Typology	Theoretical existing RB			
Data source	Building main characterization: [45][46] Other assumptions: National Standard and manuals[43],[40][30]			
Construction Age	after 1970			
Reference paper	Paper F and K			
Benchmark energy consumption	Heating: 99 kWh/m^2 Lighting and Appliances: 47 kWh/m^2		Auxiliaries: 9 kWh/m^2 Total energy consumption: 155 kWh/m^2	
Building	Description	The building has 3 floors above ground.		
		Total Gross Floor Area		6007 m^2
			Classrooms	960 m^2
			Laboratories	410 m^2
			Library	144 m^2
			Gym	390 m^2
			Office, Central Desk	6 m^2
			Service area	1353 m^2
		Floor to floor Height (Classrooms, Office, service area)		3 m
		Floor to floor Height (Laboratories, Gym, Library)		5 m
		Northern Façade	Exterior wall area	403 m^2
			Window area	133 m^2
		Southern Façade	Exterior wall area	437 m^2
			Window area	99 m^2
		Western Façade	Exterior wall area	358 m^2
			Window area	175 m^2
		Eastern Façade	Exterior wall area	370 m^2
			Window area	164 m^2
		Opaque elements	Exterior Wall	1.1 W/ m^2 K
	Envelope Components		Roof	1.41 W/ m^2 K
			Underground slab	2.78 W/ m^2 K
		Transparent Elements	Window	5.8 W/ m^2 K
System	Heating system	Gas boiler with radiators. The setpoint temperature is 20°C during the school operation.		
	Cooling system	Water-cooled chiller. The setpoint temperature is 26°C from 5 a.m. until 6 p.m. during week day. The system does not operate during the remaining hours and school holidays.		
	HVAC	4 pipes fancoils with outside air.		
	Ventilation	0.6 ACH.		
Operation	Internal Gains	People	The occupancy rate depends on the room typology and students' agenda.	
		Lighting	9 W/m^2	
		Appliances	10 W/m^2 during working days.	

Energy model: thermal zoning



RB#04	THE SUPERMARKET			NEW
Typology	Example RB			
Data source	Building main characterization: [47][48] Other assumptions: National Standard and design manuals[43],[40],[49],[50],[30].			
Benchmark energy consumption	Gas energy consumption: 69.6 kWh/m^2 (Heating and DHW) Electrical energy consumption: 218.9 kWh/m^2 (Cooling, Refrigeration, Lighting, Appliances, Fans and Pumps) Total energy consumption: 516.4 kWh/m^2 (including production from Renewables)			
Building	Description	The commercial building consists of a large open space intended to sell self-service, some assisted-sales zones with laboratory and technical rooms.		
	Geometry	External dimensions		49 x 44 m
		Total Gross Area		2156 m^2
			Sales Area	1730 m^2
			Laboratory	268 m^2
			Offices	87 m^2
			Warehouse	93 m^2
			Technical Room	43.5 m^2
		Floor to floor height		5 m
		North Façade	Exterior wall area	245 m^2
			Window area	3,92 m^2
		South Façade	Exterior wall area	245 m^2
			Window area	184,8 m^2
		West Façade	Exterior wall area	220 m^2
		East Façade	Exterior wall area	220 m^2
	Envelope Components	Opaque elements	Exterior Wall	0,33 W/m^{2}K
			Roof / Slab	0,30 W/m^{2}K
		Transparent Elements	Window	1.91 W/m^{2}K
System	Air conditioning system	Sales Area- Rooftop Air handling Unit with heat-recovery. Warehouse – Condensing gas boiler heating system with air heaters. Offices – Cooling and Heating air-to-air heat pump. Laboratories - 4 pipes fancoils with outside air.		
	Set point (SP)	Sales Area - Heating SP= 18°C; Cooling SP= 26°; R.U. SP: 60%. Warehouse - Heating SP= 14°C. Offices- Heating SP= 20°C; Cooling SP= 26°. Laboratories - Heating SP= 18°C; Cooling SP= 26°.		
	Ventilation	Sales Area and Warehouse - 0.0065 m^3/s person Office - 0.011 m^3/s person Laboratories - 0.0165 m^3/s person		
	Refrigeration system	Direct expansion centralized system		
	Renewable energy system	Photovoltaic system installed on the roof, 27kW$_p$ Thermal solar system for the DHW production.		
Operation	Internal Gains	People	Sales Area = 0.2 person/m^2. Laboratories = 6 persons	Warehouse = 0.1 person/m^2. Offices = 0.06 person/m^2.
		Lighting	Sales Area = 15 W/m^2 Laboratories = 15 W/m^2 Technical Room =10 W/m^2	Warehouse = 15 W/m^2 Offices = 15 W/m^2
		Appliances	Sales Area = 3.5 W/m^2 Laboratories = 15 W/m^2	Warehouse = 3.5 W/m^2 Offices = 10 W/m^2

RB floor plan, façades and sections.



2.5 Critical discussion

Several and different positions have been held, in the literature, with regard to the effectiveness and utility of RBs. Their application is also common for delivering benchmark outcomes on the building stock characterization and energy consumption.

Some people reckon that reference buildings can hold an important role in the definition of energy saving scenarios at national levels. With regard to this, the U.S. DOE database of reference building models is a clear example of it. On the other hand, others assert that RBs are unrealistic model and therefore they cannot provide a realistic picture of the building stock that they aim to represent indeed.

However, despite their recognized use and application for drawing wide energy saving scenarios and impact at national level or on a large portion of a building stock, there is no consensus methodology to refer to for their creation. Indeed, a methodology is of high relevance as it can guide users through this complex process, highlighting also the limits of RBs. To this regard, undoubtedly the accuracy achieved during the creation of reference building constitutes a major issue. Consequently, the data used for their creation, depending on both its quality and quantity, play an important role and therefore, employing reliable data sources is fundamental for obtaining fine results. The methodology presented within this Ph. D. thesis aimed thus to provide some guidelines, based on the data typology and source availability, for the definition of reference buildings. In particular, it focused on three different approaches that drives towards the definition of three different typologies of reference buildings. When statistical data are not applicable, an example reference building is created. On the contrary, when data from statistical analyses are available, a real or a theoretical reference building can be defined.

At this point, it is important to dwell on the concept of representative as applied to RBs. *Are RBs actually representative? To what extend can they be asserted as representative models*? Reference Buildings are defined based on the characteristics of the building stock and the research purpose they are intended for. On one hand, it is true that they cannot provide an accurate and realistic description of the building stock. Even when large statistical analyses are employed, RBs cannot enclose the building stock as a whole but only a portion of it. Analyses able to provide similar results may be extremely time consuming and based on national updated census, which often do not include all the necessary information. When these latter studies are not available, especially for the definition of RBs for existing buildings, data from literature review on manuals and architectural journals is manipulated by experts, based on their experience and skills. On the other hand, due to the limited statistical knowledge about the building stock, the selection and definition of a Reference Buildings has a more arbitrary nature, that can be regarded as a source of deviation and inconsistency in the representativeness final outcomes of the study using RBs, such as cost optimal analyses.

Therefore, it is important to bear into mind that RBs can provide a fair picture of a rather small sample of existing buildings. The term representative should not be intended in absolute terms as applied to the whole building stock, but rather in relative terms, to a portion of it. Moreover, representativeness-in a narrow sense cannot be achieved if only one reference building is selected per building category. When carrying out studies with a wide spread impact on the building stock, such as cost optimal analyses, an accurate selection of reference buildings is a prerequisite to reach realistic results. To this regard, if, in a given country, where an extensive building stock with various construction solutions is observed, it is recommended to define enough reference buildings in order to represent the reality as faithfully as possible.

Moreover, beyond the quantity of data, which is for sure of high relevance during the process of definition of RBs, an adequate data quality is essential in order to obtain fine and accurate results. The availability of fine data from statistical analyses cannot be always observed, therefore RBs are often defined based on experts' assumptions, especially for reference buildings for new construction. To this regard, in order to define simple and realistic geometry, consultations with architects and contractors should be considered.

When data quantity is lacking but a statistical analysis is available, the most preferred approach is that of the Real Reference Building, in particular for new construction. This approach, that is described within this thesis, is to select a "future" existing building, based on its design project, as representative of a sample of new buildings. This solution is applicable when, based on a statistical analysis over the recent building construction trends, the "new building" has average characteristics, which are consistent with the typical characterization of the building typology investigated (e.g. new multi-family building). This means that the new building is depicted as it actually is or will be constructed: it reflects thus the design project of the new building. With regard to the existing buildings, the reference building is a real existing building, defined with as-built data. This approach has been thus widely employed for the residential RBs definition of the harmonized structure of the European building typologies within the TABULA project.

Furthermore, going through critically the concept of "representative", the RBs application, based on the previous statements, should be limited to early design stages or to benchmark investigations. If RBs are thus defined based on the methodology and approaches just depicted, it is fair to admit that their use cannot be widespread during the whole design process. Given hence that not every project can be assimilated to a RB, designers should rather consider RBs as starting building models and use them during the first phases of the design process. In particular, they should take advantage of the RBs features for a first characterization of the "designed building" during energy assessment studies by means of dynamic building simulation. At this stage of the process, the building concept is well defined but the whole building definition is not complete. To this regard, RB can be employed as a valuable source of standard information and data about a certain building typology. Especially during this early stage of the design process, data for the building definition are usually missing and RBs input data can be taken as first reference data (e.g. rules of thumb data) to be further customized based on the proposed design project. For instance, data about the building use and operation are usually not noted but RBs are defined with ad hoc schedules about the building occupancy and operation (e.g. lighting schedule, occupants schedule, equipment schedule, etc), correlated with occupancy rate, installed power, etc., defined depending on the building typology (residential, tertiary, etc.). Moreover, this same set of data can be used for testing different building envelope and system solutions during early design stages, on the proposed designed building.

The RBs use should be thus enhanced and especially better exploited in the professional building design practices, as a valuable tool for assisting and guiding designers during these early stages of new buildings projects or retrofit interventions on existing buildings.

To this regard, another use of RBs that has found large application and it expected to increase, it that of employing RBs as baseline buildings, talking of which the definition process is built on different assumptions with respect to the methodology depicted within this thesis. A baseline building is a reference building consistent, in its characterization, with the geometry, location, typology and generation system of a new "proposed" and designed building. The other features for completing the definition of the baseline building, such as the building envelope and other systems settings, are se in compliance with standard prescriptive requirements of the regulation in force. For instance, the U-value of the baseline building envelope components will have to fulfil the U-value limits set by the regulation in force. The use of baseline buildings can undoubtedly regard the design of new buildings but also the retrofit of existing one. Baseline buildings are already well known for their definition and application in the Building Performance Rating Method described within the ASHRAE Standard 90.1. The ASHRAE 90.1 (Energy Standard for Buildings Except Low-Rise Residential Buildings) is a US standard that provides minimum requirements for the energy efficient buildings design. In addition to being used for code compliance, Standard 90.1 is often used as a baseline for energy efficient and green building programs, such as the U. S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) program. Baseline buildings are used within performance paths for defining the threshold limit of primary energy consumption for the proposed designed building: the proposed building is demonstrated (through building energy simulation) to use less energy than the baseline building defined fulfilling the ASHRAE 90.1 specifications.

With reference to Italy, this special use of reference buildings as baseline buildings is to come next within the end of 2015 and to become the common standard RBs application. The use of baseline building will thus be similar to that of the Standard 90.1. The new legislative decree 90/2013, in force starting from the 1st July 2015, will replace the Italian republic President's decree 59/2006 and the legislative decree 192/2005 for the implementation of the EBPD recast in Italy. One of the main innovation of this decree is thus the use of reference buildings for establishing of the minimum energy requirements of energy performance for new buildings and existing building subjected to major renovations. The normative check of the minimum requirements will thus be based on the comparison of the new building (or the retrofitted existing building) energy performance with that of the reference building. With this approach, the building energy performance will be investigated depending on the actual building characterization (in terms of services), and not in absolute terms as in the past regulations.

In conclusion, the use of RBs can vary depending on the purpose of the study, as depicted above. Moreover, their application can also serve for promoting building simulation applications. As occurred for U.S. DOE commercial reference buildings, they should be especially employed within building simulation programs, for exploiting fully heir potentiality (estimation of energy savings with different building design solutions).

Generally speaking, if on one hand, their application should be better promoted and exploited, not only within research and academic contexts, but in particular by professionals due to the new upcoming regulation (e.g. Italian legislative decree 90/2013). On the other hand, it is of high relevance to bear in mind that their application should be performed with caution as they are not representative building models of the building stock in absolute terms.

3.

Building Simulation

This chapter provides an overview about the role and application of building simulation in the design process. In particular, the integration of the building energy design is depicted during the different phases of the design process. A bit of history of building simulation from its first applications to the current uses, is presented together with the some remark about pros and cons of employing building simulation.

3.1 Building Energy Design in the design process

For much of the last century energy has typically been addressed at the building systems level, taking a back seat to many other drivers of the design and construction process [51]. Traditionally the design of the building form by the architects and design of the building systems by the engineers occurs in sequence.

To date, high-performing and sustainable buildings are becoming the new standard in architecture and technology development has driven towards more complex buildings and systems. The design of high performing buildings pushes designers towards unprecedented challenges due to the need of fulfilling many requirements and taking consideration of many dynamic processes around the building (e.g. climate, occupants' comfort and needs, etc.). For instance, if compared to the traditional design practice in the design of an nZEB, architects need to achieve high levels of energy performance. Additionally, higher indoor environment requirements are demanded.

These new challenges, together with those defined by the current sustainability goals (e.g. 20-20-20 targets in EU), requires models and tools for the consideration of interoperating domains in order to optimize buildings energy consumptions. An approach capable of considering the dynamic interaction of the different sub-systems (building, people, HVAC system, equipment and outdoor environment) is thus necessary [52].

To this regard, the traditional long-accepted approach to the building design cannot be accepted anymore. A more holistic and collaborative approach to design is necessary. Energy has to be addressed as a design problem to deal with in an iterative process with the design and performance design.

Given their mono-disciplinary approach, traditional engineering design tools are considered largely unsuitable to tackle these energy challenges. The traditional and sequential approach of the design process is not suitable as well.

To this regard, the integration of the energy design by means of energy models is needed to validate and support the design of high-performing buildings. Moreover, the use of energy models for the building energy design and assessment is growing to the alignment of energy policies and codes on the use of performance base paths. The building energy design through energy models is thus being integrated in the architectural services as requested by Standard and also by customers for achieving sustainability certifications (e.g. LEED). Prescriptive compliance approaches are slowly being replaced by performance-based approach based on the use of energy models for the achievement of outstanding buildings energy performance, beyond code compliance requirements.

Usually the term "energy model" is used to refer to the creation of a building model, within a building simulation program, that is composed by several input data such as the building geometry, the system features, the operation schedules and that produces outputs for the building energy assessment. However, in order to exploit the full capability of building energy models, it is necessary to transform the current design approach from a sequential process to a collaborative and iterative process, where all of the disciplines (included building physics) are involved in the building design and construction and work as a team from the beginning. In particular, it is essential that the energy design is perceived as a recognized and meaningful part of each stage of the design process.

To this regard, the American Institute of Architects has distinguished four different stages of the energy design during the design process, as depicted in Figure 11. To each stage, it corresponds to a specific type of energy modelling:

- Design Performance Modelling. Typically performed during the early staged of the building design, it provide a first and fast assessment of the building energy performance based on the first concept ideas of the building.
- Building Energy Modelling. During this stage, the building project is verified in compliance with national energy codes. The building energy performance is calculated based on Typical Meteorological Year data, as well as many assumptions about the building operation and maintenance.
- Building Operations Modelling. In this stage, utility bills and data about the real building operation as well as real weather conditions are integrated in the building energy model (BEM). The comparison of actual energy use with the predicted use is performed, bringing usually to the observation of disagreements between actual and predicted. The process of tuning the building energy model is known as "calibrated simulation". At this stage, the building energy model is also used in commissioning with post-occupancy monitoring.
- Project Resource Modelling. It is usually performed during construction and operation stages. It assesses multiple resource issues that affect and are affected by the development of a project, including energy, water, material selection, and solid waste. It may also include transportation, primary growth issues, manufacturing, social and agricultural elements, embodied energy, carbon emissions, health, and other factors. This type of extensive study typically addresses the interrelationships among resources, their consumption, efficiencies, and conservation.

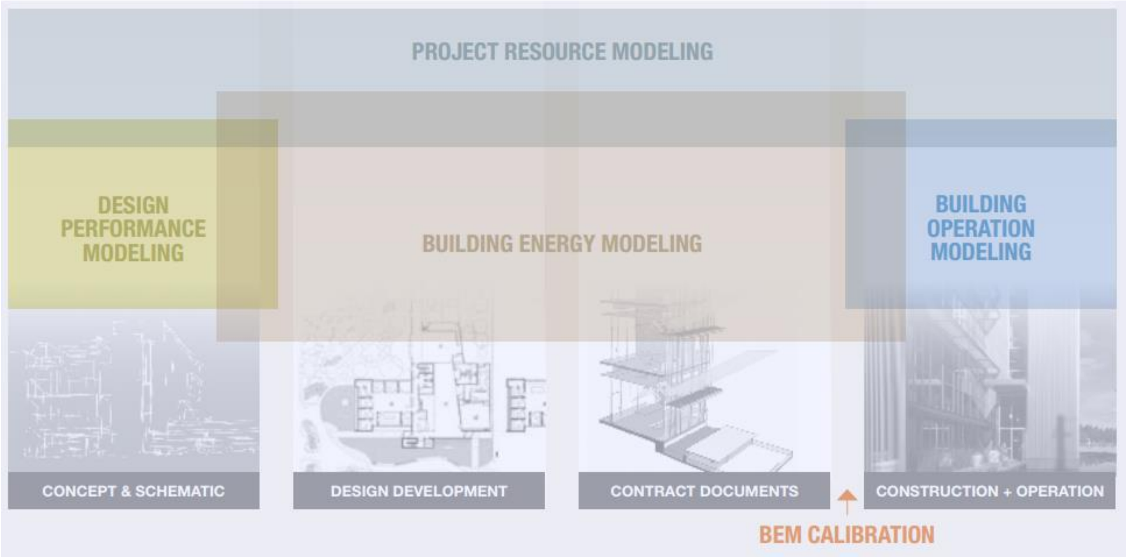


Figure 11 – Stages of the design process and types of energy modelling. Retrieved from [51].

The use of Energy Modelling throughout the design process, from early stages to construction ones, enables benefits and offers add values to the development of the building design. First, it assists the achievement of high-energy performance requirements with the evaluation of different building envelope solution, building orientations or shading solutions and the optimization of the use of renewable energy and passive systems. Moreover, with the use of energy models, professionals and designers acquire new technical expertise. Designers can effectively understand how design decisions can impact on the building energy use since early staged of the design process. The potential information that can be acquired, even if not quite specific, are of high relevance for considering different performance options and not missing important design opportunities. Furthermore, the ability to use energy models can drive more collaborative relationships among team members with different skills and can reflect on a higher client's and project team's satisfaction [51].

Some examples of the development of integrated approach in the design process are also encountered at academic level. For instance, beyond specific studies conducted by single researchers, the Solar Decathlon competition represents a formative event, held between universities from different countries around the world, for the future experts of the building environment. It thus pushes students towards an integrated design process, where all the disciplines are involved at each design stage. The university multi-disciplinary design team are hence usually composed of students from different faculties or departments (e.g. civil, mechanical, electrical, engineering, architecture, interior design).

3.2 Energy Modelling through Building Simulation

The energy modelling process is accomplished through building simulation. A mathematical model is constructed within building simulation programs, aiming to provide a realistic representation of the real world.
Building simulation is one of the most powerful analysis tools used today in almost every field (from games to engineering). It is problem-oriented that does not provide solutions or answers but it aims to emulate reality [53]. With reference to the

energy design, an energy model is created and assessed by means of building simulation programs. The use of simulation drives designers towards a more energy conscious design, with better comforts levels and energy performances [53].

As pictured in Figure 12 the building energy model should be perceived as composed of “n” nodes that contributes to the model complexity. The interaction of each nodes with the others defines the building energy demand and impact on the occupants’ comfort.

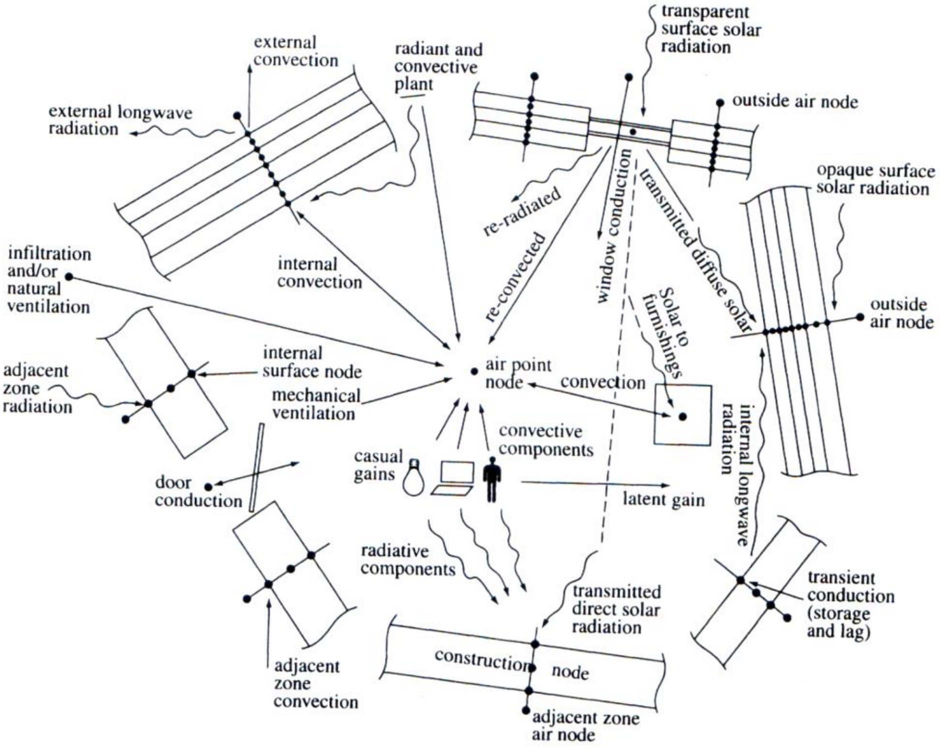


Figure 12 – Building energy flowpaths. Retrieved from [53].

Over the time, the building simulation (BS) domain has grown richer, due to the development of new softwares and to the increase of the models robustness and fidelity [52].

Clarke identifies up to four generation of design tools for supporting the building energy assessments.

The first generation corresponds to analytic calculation techniques based on simplifying and fragmented assumptions. They provide indications about the building energy performance, which is overall difficult to interpret and translate to real buildings. The second generation of tools, emerged from the mid-‘70s, was based on standard theories, stressing the dynamics of building construction components, except for systems which were modelled in steady state. The models created with this tool generation are less simplified but still based on analytical calculations.

A first attempt towards the integrated design was achieved with the third generation of tools from the mid-‘80s. A shift towards numerical methods characterized the third generation. A higher integration is then achieved from the fourth generation of programs, that in order to promote the use of building simulation, are more easy to use and interpret and pursued the development of more friendly user interfaces.

Moreover, if in the past the major focus was especially on the software features, now great attention is paid over the effectiveness of building performance simulation in the building life cycle process [52]. The great widespread involvement in the design of sustainable and green buildings, has also extended the application of BS to well-known performance rating systems such as LEED (Leadership in the Energy and Environmental Design) or as BREEAM (Building Research Establishment Environmental Assessment Method). For instance, within LEED, the use of BS is promoted for achieving additional points in the Energy and Atmosphere Credit 1.

According to Clarke "Simulation represents a paradigm shift of vast potential" that can make the design process "cheaper, better and quicker" [53]. Notwithstanding simulation potential is still untapped. Its application is in fact mostly restricted to the final phases of the building design process, to a few key areas (like the building envelope design) and to the analysis of single solutions rather than to combination of solutions for optimization studies or during earlier design stages for a better enhancement of BS application and potential [52].

One of the greatest barriers of BS is the creation of the building model. The capabilities of building simulation are improving but there is still a lot to work on. Creating and simulating an energy model is not as simple as pushing a button and getting an energy number [54]. Probably the most fundamental challenge of creating an energy model, it the collection of the several input data and assumptions to be made. The modelling process represents hence the most complex task of building simulation as several assumptions have to be made through the modelling process [55]. The more accurate the assumptions are, the better the predicted outcomes will be. Nevertheless, given this, a building energy model is not a guarantee of building performance. Especially for post-construction applications, it will not exactly replicate actual building operations and energy use. Due to construction, operations and maintenance, seasonal weather variations, and occupancy, the actual building performance will inevitably depart from the modelled conditions.

Moreover, creating a building energy model does not means only constructing a building in a program but being experienced with building physics and in the BS domain for making the "right" assumptions that will result in an accurate energy model. A high expertise in the building physics domain is thus required for handling building simulation; also long-time users of BS cannot pretend to be claimed omniscient in the domain.

It is a false belief that a complex and detailed building model is the better solution for achieving the expected findings. The chance of making errors in the performance prediction grows with the increase of the level of detail and complexity in the model [56]. Therefore, it is better to keep the model as simple as possible to clearly address the objectives of the study [57].

Another barrier to diffusion of BS, is represented by the difficulty and expertise required for using BS programs. This hence definitely impact on still not fully exploited BS application, causing hence its low use within professionals and its restriction to the domain experts.

3.3 Building simulation as an instructive tool

Recent energy policies have driven building design more and more towards performance requirements. BS is hence used for assessing the building performance in a dynamic state, evaluating and optimizing the design solution implemented, either at the building envelope level and at the system level.

Currently, its most prevalent uses are for code compliance or sustainable-design rating system compliance (e.g., LEED) [51]. In particular performance based approaches, coupled with prescriptive approaches, are becoming more common in energy policies, such as the ASHRAE Standard 90.1. For instance, this latter standard sets, within its Appendix G, a performance-based compliance path for the design of new and renovated commercial buildings, which assessment should be performed based on an hour-by-hour analysis of the whole building energy performance, by means of dynamic building simulation. This path has also been undertaken by the LEED program by the U.S. Green Building Council and by the Green Building Council Italia.

However, BS can also play an important role in the definition of renovation interventions. It can hence be used as a tool for testing energy retrofit solutions on single buildings, blocks of buildings or even a district. Actually BS use for energy saving prediction studies has already diffused with Measurements and Verification (M&V) studies. They correspond to the comparison of measured energy use before and after the implementation of a retrofit project. In particular, with an official endorsement by the U.S. International Performance Measurements and Verification protocol (IPMVP), the use of building simulation is suggested for the commissioning or assessment of energy retrofit scenario of existing buildings.

In EU the use of BS for similar application has also been suggested by the Energy Performance of Buildings Directive (EPBD) for the investigation of energy efficiency solutions to be applied to either existing and new buildings in the definition of the cost optimal level of energy performance. The use of BS is strongly suggested during the design of nearly zero energy buildings for the optimization of the building energy performance in dynamic calculation conditions.

As stated previously, the application of building simulation has also expanded due to the integration of the energy design from early stages of the design process to construction and post-construction stages. With this regard, the recent interest into the optimization and verification of the building real performance, has amplified the use of BS in post-construction stages pursuing the detection and diagnostic of system failures in the building operation. The disagreement between the predicted (during simulation) building energy performance and the measured building energy performance (during real operation) has earned a great attention and started to be tackled with a specific application of BS, called calibrated simulation (CS). CS hence aims at tuning the building model input data for making the simulated energy performance match the measured one [58]. Calibration plays two main roles; adjusting the model using actual occupancy and operations patterns and identifying areas for operational improvement [51]. The calibrated building models correspond to building energy models subjected to calibration using measured data. This building energy models are the most accurate models as they pretend to recreate past energy use performance of existing buildings.

Based on the wide range of capabilities and despite the “difficulties” that can be faced when using it, BS was chosen as tool for the buildings energy assessment within this Ph.D. study.
First dynamic building simulation was selected for the high level of detail and of accuracy that can be reached with it.
Second, building simulation represents an instructive tool for supporting the building energy design with a view of an integrated design process. Given this, considering its still limited application in the professional community, its use within

this research aims to highlight the potential of this new expertise and to share it as valuable and assisting tool for the building design.

Building simulation was employed for the energy assessment of both scale of buildings (building stock and single buildings). In particular, it was used for the prediction of the energy savings achievable from the application of retrofit interventions to reference buildings. Moreover, it was employed in post-construction stages, for the calibration of building energy models. The creation of this high-level accuracy building energy models was necessary to obtain more reliable results concerning the energy savings achievable from the application of renovation solutions on real existing buildings.

4.

Calibrated Simulation [CS]

This chapter presents the second "scale" of buildings analyzed within this Ph.D. thesis for the definition of energy renovation interventions. As opposed to reference buildings, this scale of buildings is used when the aim pursued is to study a specific building. The degree of knowledge about the building use and definition is thus higher than that of the RBs. This second scale considers buildings which energy performance is assessed by means of a tailored energy rating, under user-specific conditions. This means that, in order to assess the building energy performance, standard input values are replaced by data customized based on the actual building use, climate and occupancy. With respect to reference buildings as representative models of the building stock, this scale of models regards single buildings indeed. This building models are created to further carry on specific optimisation and retrofit studies.

When available, data from monitoring is used for the definition of the actual building model. It represents an essential requirement, within retrofit analyses, for obtaining reliable results about the achievable energy savings. To this regard, monitored data are used to calibrate the building energy models for reflecting the building real construction and operating conditions. This means that the simulated energy consumption of the building has to match the measured energy consumption for comparing the baseline situation of the building (not retrofitted) with other simulation results relative to the application of building renovation interventions. This process of "matching" simulated and measured data, is known as calibration. It is a complex procedure, that is of growing importance and which application has recently been extended in the building simulation domain.

Single buildings, which energy models need to be calibrated based on data from monitoring, constitute thus the second scale of buildings presented in this Ph.D. thesis. In particular, the building energy models created are detailed building energy models, based on hourly values and created by means of dynamic building simulation programs, such as EnergyPlus. Simplified building energy models are most frequently used in the building simulation domain and, due to their lower complexity, are also preferred for calibration applications. Notwithstanding dynamic building energy models were selected for the aim of this thesis for their higher degree of detail in the building definition and the dynamic state of the calculations performed for the building energy assessment.

After a short description of the aim and use of calibration, and a literature review on the most common techniques currently in use for the calibration of building models, in this chapter, two different approaches to the process of calibration, applied to two different case studies, are presented.

4.1 Calibration in the building energy assessment: aims and role

As stated in Chapter 1, since mid-‘70s building simulation (BS) has emerged as an attempt to emulate reality [53]. Traditionally it was used as assisting tool throughout the design process, from early stages to detailed construction phases. To date, addressing the current high and ambitious sustainability goals, BS is of growing importance. It has thus started to being considered as an integral part of the building design, targeting to reduce the buildings energy demand and optimize their energy performance. With regard to this latter purpose, recently a great application of BS has been observed in post-construction stages [52]. As, buildings do not perform as well as predicted in simulation design analyses, an extensive interest into building real monitoring and operation diagnostic has aroused and the disagreement between measured and simulated data is thus become a top-issue to deal with in BS. In this kind of scenario, the process of fine-tuning the building model input data, for making simulated building energy consumption match with real monitored consumption, has spread out under the name of Calibration. Especially, this particular application of building simulation is customarily called calibrated simulation (CS).

Reddy et at [58], to give a proper definition, refers to calibrated simulation applied to building energy simulation computer programs, as the “*process of tuning or calibrating the various inputs to the program so that observed energy use matches closely with that predicted by the simulation program”*.

A boost in the use of calibration has been given when whole building simulation has started to be used not only for design purpose but also for the optimization of building operation in post-design phases. Usually referred as Commissioning, the most common optimization concerns the functionality of buildings partial or whole HVAC system. Most of existing buildings in fact do no operate properly and this procedures aims at solving problems and failures in the building operation.
Moreover, new levels of interest have thus aroused around calibration and new potential uses of it have spread out, making applications of calibration more amplified. The current main applications of calibrated simulation can be listed as follows [52]:

- energy audits, to determine the potential savings from proposed retrofit measures;
- energy savings estimation, to explore the potential savings from changing building operational strategies (“what-if” analysis);
- existing building and new construction commissioning;
- fault detection and diagnostics;
- model-based optimization;
- program evaluation.

A constant issue encountered during modeling, unconditionally of the BS program used, is the selection and definition of the building input data. That phase in the process of building model creation, can be considered one of the most crucial and important one as the building accuracy and definition will depend on that. This is also why large disagreements between real energy consumptions and simulated ones are usually encountered and why models need to calibrated based on monitoring. Moreover, one of the main drawback of building and calibrated simulation, is to be an highly time consuming activity. The large quantity of input parameters to be "tuned" for calibrating the building model and required by building simulation program, could make the calibration process very tedious. For this reason, given the large number of parameters involved, the process of calibrating a detailed energy model represents a highly undetermined problem that brings to a non-unique solution [59], [60].

The assumptions made for the building definition are thus directly responsible for those differences. Input data generally comes from as-built data and design documents, and when applicable, from energy audit or detailed monitoring. The model accuracy especially relies on the ability of the user to input the parameters that results in a good model of the actual building energy use [61]. Consequently, in order to hopefully achieve good agreements in the results, accomplished and specialized simulation experts are required. M&V protocol strongly suggests to follow option D for calibration only on projects where great energy savings can be achieved (e.g. enough savings to justify the use of a such time-intensive and highly-specialized approach) [62].

When talking about performing calibrated simulation, it is also important to distinguish different levels of calibration based on the input data availability, as depicted in Table 5. Level 1 is the first level of calibration based on incomplete and split information due to the availability of nothing but as-built data. For this reason, it represents the weakest calibration level as the information about the building definition and operation is not detailed and cannot be cross-checked with on-site visits. Utility bills data represent the minimum requirements, in terms of measurements and history data, for CS. The period of availability of measured data or utility bills should be at least one-year-long in order to provide reliable results.

Table 5 – Calibration levels on the building input data. Retrieved from [60] and [58].

CALIBRATION LEVELS	**BUILDING INPUT DATA AVAILABLE**					
	Utility bills	As-built data	Site visit or inspection	Detailed audit	Short-term monitoring	Long-term monitoring
Level 1	X	X				
Level 2	X	X	X			
Level 3	X	X	X	X		
Level 4	X	X	X	X	X	
Level 5	X	X	X	X	X	X

In addition to the information of level 1, Level 2 is characterized by visits or inspections which allow to verify as-built data and collect extra information about the whole building. Level 3, based on detailed audit of the case study, allows to collect on-spot measurement of the building operation and energy consumptions. Level 4 and 5, based respectively on short-term and long-term monitoring, are the most detailed levels of calibration. Data loggers are thus installed in the building to collect all the required information. Building models, in these two levels, are created based on detailed data about the whole building system and its real operation. Moreover, depending on the monitored data availability, calibration can be performed hourly, or monthly. To this regard, it is important to consider that for hourly calibration not every type of building simulation program can be used, such as for instance those BS programs which weather file are composed of average daily data and a peak weather day for each month. For this reason, only BS programs that use hourly weather data files (composed of 8760 hours data) can be accepted for calibration purpose according to the ASHRAE guidelines 13 and the M&V protocol. Additionally, the type of in-deep analysis on the building model, can regard only the building system or the whole-building [62].

Weakness and limitations of calibration are well balanced by strength and opportunities as described in Figure 13. Three main strengths can be identified as the drivers of the recent increasing use of calibration, especially within the building simulation domain, as reported in the top square on the left in Figure 13. It is thus frequent to observe the use of calibrated building models for carrying out energy retrofit solutions and estimating the achievable energy savings. To this regard, faults detection and diagnostic have recently emerged as common outcomes of calibration processes, aiming at solving malfunctioning in the building operation and at reducing unexpected increases in the building energy consumption. Moreover, calibration studies are often performed targeting the improvement and optimization of the building real operation, also based on the results of the previously cited faults detection studies, by simulating different operating scenarios on the calibrated building model.

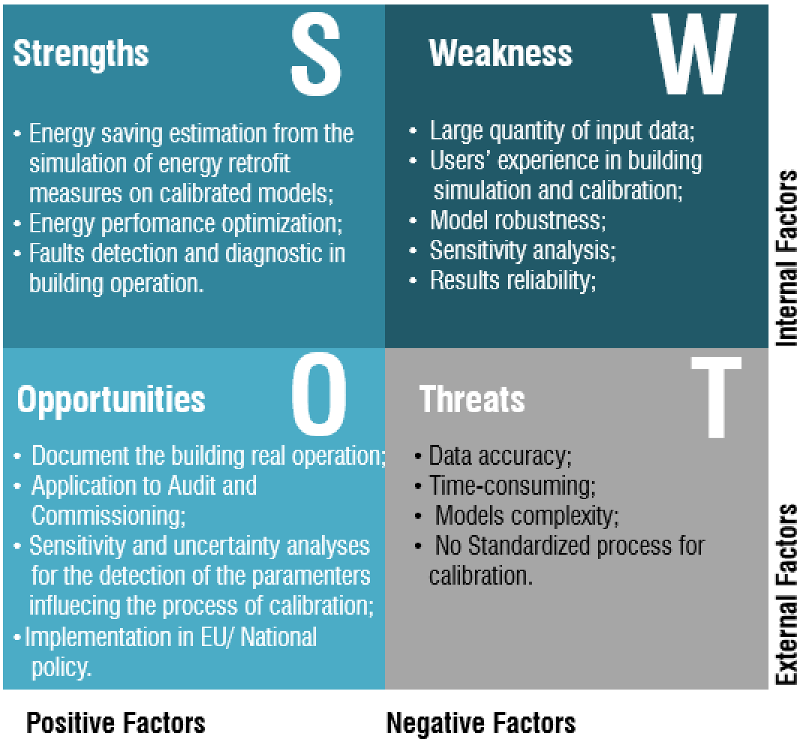


Figure 13 – Calibration SWOT Analysis

Additionally, the use of calibration can also pave the way to different opportunities, as external factors, as depicted in the bottom left square in Figure 13. Calibrated models, based on data from monitoring, can thus constitutes a concrete chance for providing more information about the building operation, that constantly represents a missing piece of information during the building characterization. The introduction of calibration procedures in audit reports, as well as in EU and national policies, should be closely accounted as a profitable and assisting tool in the energy assessment of single monitored buildings.

On the other hand, many other issues characterize calibration negatively, with the label of a complex procedure that requires high-level expertises. The data accuracy and the model complexity represent the main threats usually faced during calibrating, together with the lack of a formal and recognized standard methodology to support the process of calibration. Moreover, as anticipated, calibration is a highly time-consuming procedure, due to large modeling time and, mostly to even larger computational time for the tuning of the building model input data. In particular, the process of tuning can be regarded as an endless process as it is not possible to define a unique "calibrated" solution, but many other calibrated combinations can be found. To this regard, the role of an expert user acquires higher relevance for the process definition and constitutes a clear weakness of calibration. Reddy et al [58] claim hence that "calibration is highly dependent on the personal judgment of the analyst doing the calibration". Experienced users may be able to detect the underlying causes of the mismatch between simulated and measured consumption, based on their building simulation skills and expertise. However, these kind of disagreements may also be linked to a chain of causes or imputation errors in the building model definition or also to measurements errors. For instance, the large quantity of input data required for the building model definition can affect the model robustness and thus the process of calibration. The assumptions for their definition should be made carefully and driven by sensitivity and uncertainty analyses.

4.2 Focus on Paper V: Review on Calibration methodologies and applications

Notwithstanding the recent common applications of calibration, still no universal consensus guidelines have been presented yet. Standards criteria for validating a calibrated model are used as a reference, but a formal and recognized methodology still lacks. **Paper V** reviews the state of the art in the domain of calibrated simulation, pointing out criticalities and lacks of CS recent applications. A focus on the techniques and methodologies generally used for calibrating building models is hereafter provided.

So far, statistical indices are the most used criteria for evaluating the accuracy of calibration and whether or not a model should be considered calibrated. These criteria determine how well simulated energy consumption matches the measured utility data at the selected time interval. They do not constitute a methodology for calibrating buildings models but rather a measure of the goodness-of-fit of the building energy model, recognized at international level by the ASHRAE Guidelines 14 [63], the International Performance Measurements and Verification protocol (IPMVP) [62] and M&V guidelines for FEMP [64]. The Mean Bias Error (*MBE*) and the Coefficient of variation of the Root Mean Square Error (*Cv(RMSE)*) are the statistical indices generally used for calibration purpose. Their combined application is recommended for preventing any calibration errors. In fact the use of only MBE as statistical index is discouraged as can bring to erroneous values due to compensation effects (positive and negative values contribute to reduce *MBE* final value). MBE is a measure of how closely the simulated data corresponds to the monitored ones. It is calculated, as reported in equation (1), as the total sum of the difference between measured energy consumptions and simulated ones at the calculation time intervals (e.g. month) of the considered period. The difference is then divided by the sum of the measured energy consumptions.

$$MBE\ (\%) = \frac{\sum_{Period}(S-M)_{Interval}}{\sum_{Period} M_{Interval}} \times 100\%\ \text{(1)}$$

where

- M is the measured energy data point during the time interval;
- S is the simulated energy data point during the same time interval.

The Root Mean Squared Error (RMSE) is a measure of the sample deviation of the differences between the measured data and the values predicted by the model. The *Cv(RMSE)* is the Coefficient of Variation of RMSE and is calculated as the RMSE normalized to the mean of the observed values. This is a normalized measure of the variability between measured and simulated data and a measure of the goodness-of-fit of the model. It indicates the overall uncertainty in the prediction of the building energy consumption, reflecting the errors size and the amount of scatter. It is calculated as follows (2) - (4):

$$Cv(RMSE_{Period}) = \frac{RMSE_{Period}}{A_{Period}} \times 100\ \text{(2)}$$

$$RMSE_{Period} = \sqrt{\frac{\sum (S-M)^2_{Interval}}{N_{Interval}}}\ (3)$$

$$A_{Period} = \frac{\sum_{Period} M_{Interval}}{N_{Interval}}\ (4)$$

where $N_{Interval}$ is the number of time intervals considered for the monitored period.

In order to consider a model calibrated, the threshold limits of the MBE and Cv(RMSE) are ±5% and 15% for monthly calibration and ±10% and 30% for hourly calibration, according to [63] and [62]. These thresholds represent a first guidance for the building calibration and should not be taken as definite values. The compliance with the thresholds may be achieved with different models as the solution is not-unique and may not guarantee that all the model input data are correctly tuned. As stated before, calibration is an underdetermined problem. Moreover it is important to note that this validation approach does not take into account uncertainties in the model and may drive users to take no notice of other influent parameters, such as indoor condition, temperature trend and occupancy.

According to Clarke et al [65] and Reddy [66] four main categories of calibration methodologies can be listed, as reported in Table 6. The first three category represent techniques that are considered user driven. Indeed manual approaches do not require a systematic procedure but are strongly based on the users' experience. To this regard the trial and error approach is thus based on an iterative manual tuning of the input parameters until the model is considered calibrated. Graphical-based techniques are generally based on the use of time series, comparative displays of the simulation results with the measured data, for calibrating the models. They are often used in combination with manual approaches. Calibration techniques based on analytical and test procedures are assisted by measurement tests, such as short or long monitor periods, or also blower door tests or wall thermal transmittance measures. The latter category is composed by all techniques based on sort of automated procedures that usually employ mathematical procedures. Different methods, from the four main categories above, may be used during the same calibration process. For example, both graphical and mathematical/statistical methods may be used in synergy to improve the calibration of a building model. Moreover, manual and automated calibration may be both based on analytical procedures. For additional details on the different techniques belonging to the categories outlined above, a more exhaustive description can be found in Paper V.

Table 6 – Main categories of calibration techniques

CATEGORY OF CALIBRATION METHODOLOGY	TECHNIQUES
Manual techniques	Trial and error approach (iterative)
Graphical-based methods	3D comparative plots; Calibration signature.
Analytical procedures	PSTAR method; Procedures based on measurements, audit, etc.
Automated techniques	Bayesian calibration; Meta-modeling; Optimization-based method.

When calibration is carried out, a deterministic approach is usually adopted. However, as not all input data affect the investigated energy consumption in the same way, it is important to identify the parameters that influence the most the building model and define their level of uncertainty. Even when the building model is created upon the "possible best estimates" (building characterization by setting the input data related to its use, operation, system, building envelope, etc.) disagreements between simulated and measured energy consumption may be encountered. Such discrepancies may be due to an incomplete knowledge, split information and data uncertainties about the building; this means that the building model may not reflect correctly the real behavior of the building intended to be simulated. Nevertheless, uncertainties are hence overlooked in calibration studies and uncertainty/sensitivity analyses are usually not included in the process of calibration.

To this regard, considering that calibration is a highly under-determined problem, it is of high relevance to account for uncertainties in the model during CS. Procedural techniques, such as uncertainty and sensitivity analyses should be integrated as necessary "components" of the calibration process of a building model. Heo [67] identifies four main categories of uncertainty sources in the physical domain of building models, as listed in Table 7.

The first category "Scenario uncertainty" concerns the external environment (e.g. outdoor weather conditions) and the building use. Uncertainty in the collection of real weather data, to be used in the simulation, may be encountered, due to incomplete and fragmented data. The second category refers to uncertainties in the building model definition, especially with regard to the building envelope thermo-physical properties, the definition of the building internal gains (people, appliances, lightings, etc), the HVAC definition and its operational and control settings. The third category refers to uncertainties in the building model as physical representation of the real phenomena and thus to the assumptions and simplifications in the model. The last category refers to observation errors in the measured data, which can affect the accuracy of the results. Many methods for carrying out uncertainty analysis (UA) and sensitivity analysis (SA) can be listed. Excluding all methods, which deal with the third category of uncertainties previously mentioned, two main categories can be observed [68]: local and global approaches. The first category includes both screening methods and local methods. They are both considered One At a Time (OAT) method as one parameter (input data) is varied at time while all the others are maintained constant indeed. Uncertainty in one parameters is thus calculated for studying how the variation affect the model output. Interactions between different model inputs are therefore overlooked. Global sensitivity methods are, on the other hands, based on varying more parameters simultaneously. They study thus the influence of uncertain input on the whole space. Further information can be found in **Paper V**.

Table 7 – Main source of uncertainty in building energy models. Adapted from [60] and [67].

CATEGORY	FACTORS
Scenario uncertainty	- Outdoor weather conditions - Building usage / occupancy schedule
Building physical / operational uncertainty	- Building envelope properties - Internal gains - HVAC systems - Operation and control settings
Model inadequacy	- Modeling assumptions - Simplification in the model algorithm - Ignored phenomena in the algorithm
Observation error	- Metered data accuracy

Based on the categories previously defined and according to additional criteria, such as the calibration level pursued, the model complexity and the application of SA/UA, a review of the most recent and relevant experiences of calibration in the building simulation domain is provided in Table 8.

4.3 Focus on Paper IV: Trial and error calibration of a multi-family monitored building for the evaluation of thermostatic radiator valves

Hereinafter the calibration of a multi-family buildings is presented. The case study has been calibrated for evaluating the application of thermostatic radiator valves (TRVs) on the whole building energy consumption and energy profiles, as a low investment energy efficiency measure. In particular, as the building is served by the district heating network, the study aimed at evaluating a reduction on the delivered heating rate at the building district heating sub-station level. For this reason, the building was simulated with and without TRVs and was calibrated based on the building measured energy consumption. The application of the TRVs was thus simulated on the calibrated building model. A trial and error approach was applied for calibrating the model based on the available data from monitoring.
The case study hereby presented is a multi-family residential building located in Turin. It is an existing heritage protected building of the beginning of the XX century. The data about the building geometry and construction features was collected and retrieved from the buildings energy certificate and technical drawings. In order to characterize correctly the building model further data were obtained from in situ inspections. In particular, the retrofit of the attic area was following to the issue of the building energy certificate and without an inspection it would have not been noted. The building was also defined as RB of residential buildings built at the beginning of the XX century. The building description is hence reported in Chapter 2.

As the aim of the study was to evaluate the effect of each single TRV, each room with a radiator, and consequently with a TRV, was defined as a thermal zone. For reducing the modeling and computational time, when possible, rooms with the same function (e.g. daytime area and nighttime area) were merged in a unique thermal zone. An average number of 5 conditioned thermal zones was defined for each apartment. Despite that, considering that the dwelling was a multi-family building, the building model proved to be quite detailed and complex, with an overall number of 60 thermal zones. Moreover, for higher accuracy in the simulations the buildings surrounding the case study were also modeled.

Measured data of the energy supplied to building were available at the district heating sub-station of the case study and they were used for calibrating the building model. Data were available only for half heating season from January to April 2012. The data, available in a quite short time step (6 min.), were harmonized in order to fill in the possible gap in the measurements. The measured data included the total water flow rate (m^3/h), the delivered heating rate (W), the primary loop inlet temperature (°C), the primary loop outlet temperature (°C) and the outdoor dry-bulb temperature (°C).

Standard boundary conditions were set in order to create a first model. The case study was first simulated for sizing the heating rate of each radiator. Only the total building heating rate was noted from monitoring data; the single radiator portion was not noted. Due to that, on-spot-investigations on typical apartments allowed the radiator typology and dimensions to be clarified. The simplified procedure of Italian Standard [69] that regards the allocation of heating and domestic hot water consumptions in multi-family buildings with central heating systems, was also used to support the correct sizing of the

Table 8 – Review of the calibration applications

Author	Title	Year	Journal / Conference
Palomo del Barrio, E.; Guyon, G.	Application of parameters space analysis tools for empirical model validation	2004	Energy and Buildings, 36, 23-33.
Liu, S.; Henze G.P.;	Calibration of building models for supervisory control of commercial building.	2005	9th International IBPSA Conference 2005, Montréal, Canada.
Pan Y.; Huang Z.; Wu G.	Calibrated building energy simulation and its application in a high-rise commercial building in Shanghai	2007	Energy and Buildings, 39, 651-657
Reddy T.A.; Maor I.; Panjapornpon C.	Calibrating Detailed Building Energy Simulation Programs with Measured Data – Part II: Application to Three Case Study Office Buildings (RP-1051)	2007	HVAC & Research, 13, 221-241.
Hassan, M.A.; Shebl, S.S.; Ibrahim, E.A.; Aglan, H.A.;	Modeling and validation of the thermal performance of an affordable, energy efficient, healthy dwelling unit.	2011	Journal of Building Simulation 4, 255–262
Liu, G.; Liu M.	A rapid calibration procedure and case study for simplified simulation models of commonly used HVAC systems	2011	Building and Environment 46, 409-420
Raftery, P.; Keane,M.; Costa, A.	Calibrating whole building energy models: Detailed case study using hourly measured data	2011	Energy and Buildings 2011, 43, 3666–3679
Bertagnolio, S.; Randaxhe, F.; Lemort, V.	Evidence-based calibration of a building energy simulation model: Application to an office building in Belgium,	2012	12th International Conference for Enhanced Building Operations, Manchester, UK
Heo, Y.; Choudhary, R.; Augenbroe G.A.	Calibration of building energy models for retrofit analysis under uncertainty.	2012	Energy and Buildings 47, 550–560
Fontanella,G.; Basciotti, D.; Dubisch, F.; Judex, F.; Preisler, A.; Hettfleisch, C.; Vukovic, V.; Selke, T.	Calibration and validation of a solar thermal system model in Modelica	2012	Journal of Building Simulation 5, 293–300
Maile, T.; Bazjanac, T.; Fischer, M.	A method to compare simulated and measured data to assess building energy performance	2012	Building and Environment 56, 241-251
Parker, J.; Cropper, P; Shao, L.	A calibrated whole building simulation approach to assessing retrofit options for birmingham airport	2012	IBPSA- England, 1st Building Simulation and Optimization Conference, Loughborough, UK
Kim, Y.; Yoon, S.; Park, C.	Stochastic comparison between simplified energy calculation and dynamic simulation	2013	Energy and Buildings 64, 332–342
Manfren, M.; Aste, N.; Moshksar, R.	Calibration and uncertainty analysis for computer models – A meta-model based approach for integrated building energy simulation.	2013	Applied Energy 103, 627–641.
O'Neill, Z.; Eisenhower, B.	Leveraging the analysis of parametric uncertainty for building energy model calibration	2013	Journal of Building Simulation 5, 365-377
Taheri, M.; Tahmasebi, F.; Mahdavi, A.	A case study of optimization-aided thermal building performance simulation calibration	2013	13th Conference of International Building Performance Simulation Association, Chambéry, France
Mihai, A.; Zmeureanu, R.	Calibration of an energy model of a new research center building	2014	13th Conference of International Building Performance Simulation Association, Chambéry, France
Mustafaraj, G.; Marini, D.; Costa, A.; Keane, M.	Model calibration for building energy efficiency simulation	2014	Applied Energy 130, 72–85.
Penna, P.; Gasparella, A.; Cappelletti, F.; Tahmasebi, F.; Mahdavi A.	Optimization-based calibration of a school building based on short-term monitoring data	2014	10th European Conference on Product & Process Modelling ECPPM 2014

Calibration Characterization							
Model type		Calibration level	Calibration Method		SA/UA	Monitoring period	Simulation tool or Standard
-	whole building model	-	-	Optimization	SA	-	CLIM2000
Detailed	whole building model	-	Automated	Optimization	-	-	EnergyPlus, GenOpt
Detailed	whole building model	Level 3	Manual	Iterative	-	-	DOE-2
Detailed	whole building model	Level 4	Mathematical	-	Montecarlo	N.A.	DOE-2
Detailed	whole building model	Level 4-5	Manual	Iterative	-	Short-term	Visual DOE-4
-	whole building model	Level 4	Graphical	Calibration Signature	NA	Short-term	-
Detailed	whole building model	Level 4	Manual	Iterative	-	Long-term	EnergyPlus
Normative (quasi-steady)	whole building model	Level 1 to 4	-	evidence-based	Morris Method	Short-term	ISO 13790
Normative (quasi-steady)	whole building model	-	Mathematical	Bayesian	Morris Method	-	ISO 13790
Detailed	Solar System	Level 4	-	Optimization	-	Short-term	Modelica (Dymola), GenOpt
Detailed	whole building model	N.A.	Manual	Iterative	-	Long-term	Not specified
Detailed	whole building model	Level 2	Manual (Raftery et al.)	Iterative	-	Long-term	IES
Simplified and detailed	whole building model	-	Mathematical	Bayesian	SA - Morris Method	-	ISO 13790, EnergyPlus
Simplified and detailed	whole building model	Level 4	Mathematical	Bayesian, Metamodelling	with Bayesian calibration	Short-term	-
meta-model	whole building model	Levels 4-5	Automated	Optimization	quasi-Montecarlo approach	Long-term	EnergyPlus, DesignBuilder
Dynamic	whole building model	Level 4	Automated	Optimization	-	Short-term	EnergyPlus, GenOpt
Dynamic	whole building model	Level 4	Manual	evidence-based	-	Short-term	eQuest
Dynamic	whole building model	Level 3-4	Manual	Iterative (based on Bertagnolio and Raftery methods)	SA	Short-term	DesignBuilder, EnergyPlus
Detailed	whole building model	Level 3-4	Automated	Optimization	-	Short-term	TRNSYS, GenOpt

radiators. In particular, the procedure allows to estimate the nominal thermal power of each radiator unit, depending on the typology and dimensions of the terminal units.

Then, the building model was calibrated before the TRVs installation by means of a trial and error approach. Based on the data availability a calibration level 4 was carried out within the study hereby presented.

With regard to the weather data, for the purpose of calibration, real data were used for simulating the building model rather than a Typical Meteorological Year (TMY), which is generally employed for simulation in standard conditions. To this regard, an ad hoc real weather file of Turin was created as representative of the heating season 2011-2012 in order to simulate the building model in the real climate conditions. The weather file was defined as a single year composed of 8760 hourly records of various climatic parameters (e.g. dry-bulb and wet-bulb temperature, dew point, wind direction and speed, etc), as well as for TMY. In particular, for the definition of the real weather file, three different data source were used:

- the database of National Climatic Data Center (NCDC) of the NOAA (National Oceanic and Atmospheric Administration) for most of the necessary weather file data;
- the local weather station of the building for providing hourly data of the outdoor dry-bulb temperatures monitored;
- the activities carried out by TEBE group on the roof the Department of Energy, at Politecnico di Torino, for providing data about the solar radiation during the considered period.

Since no monitored data about the real occupants' habits were available, the heating thermostat was defined on an expected users' behavior, based on experience. In the ground floor, given the commercial usage (e.g. professional studios, janitor's quarter), the temperature set point is lower (approx. 20.5°C) than in upper floors (21.5÷22°C), whereas in intermediate storeys it is set at 21°C. Moreover, in order to match the measured heating consumption with the simulated ones, some model input data were varied. The main adjustments to the input parameters were made on the infiltration flow rate and on the thermal conductance of opaque components. The building envelope thermal conductance was also changed due to the building old construction age. As no measured data for the building envelope characterization were available, the building envelope main components were first defined depending on the building construction age, based on data from national manuals [41] and standards [70]. In particular the U-values of the building envelope components were altered manually considering the envelope decay from its construction, without any retrofit intervention, until the current analysis. For instance the U-value of exterior walls was altered from a "standard value" of 1.4 W/m^{2}K from manuals, to a 1.9 W/m^{2}K as set manually in the calibrated model. To this regard, with reference to the windows decay, the infiltration rate was also altered.

The calibration process regarded only the monitored period from January to April. From measurements, the heating energy consumption amounted approximately to 59 kWh/m^2 while from calibrated simulations they were 52 kWh/m^2. Once the model was considered calibrated, a complete simulation (for the whole heating season) was run to assess the total building heating energy consumption, which amounted approximately to 115 kWh/m^2.

Then, in order to simulate the use of the TRVs by the occupants, different temperature set points were defined. In literature the use of a similar approach to simulate the effect of TRVs in residential buildings through different temperature set point was also adopted [71]. The models were thus tested under nine different conditions summarized into three scenarios. Scenario 1 (VS1) assumed the TRVs were kept open and constant in all rooms and flats with an imposed temperature set point of 20.5°C, 21°C and 21.5°C respectively for Scenario 1A,1B,1C, selected as considered the most frequent used by the occupants. Scenario 2 was based on different temperature set points depending on the storey (ground floors, intermediate floors and upper floors), with an increasing gradient difference of 0.5°C. For instance, the thermostat of Scenario 2A applied a 19.5°C set point to ground floor, 20°C set point to middle floor and 20.5°C to the top storey. Scenario 3 distinguished the temperature set point for three zones (living area, sleeping rooms and entry for the intermediate storey). The ground floor and the upper floor temperature were indeed kept constant, maintaining thus the same temperature set point as in Scenario 2.

Figure 14 outlines the main results obtained with the application of the TRV on the building model through different heating temperature set point profiles. The greater energy saving achieved is recorded in Scenario 3A, which brought to a reduction of 21% on the building heating energy consumptions. The lower reduction is encountered within Scenario 3C, that achieved a 14% reduction on the energy consumptions indeed.

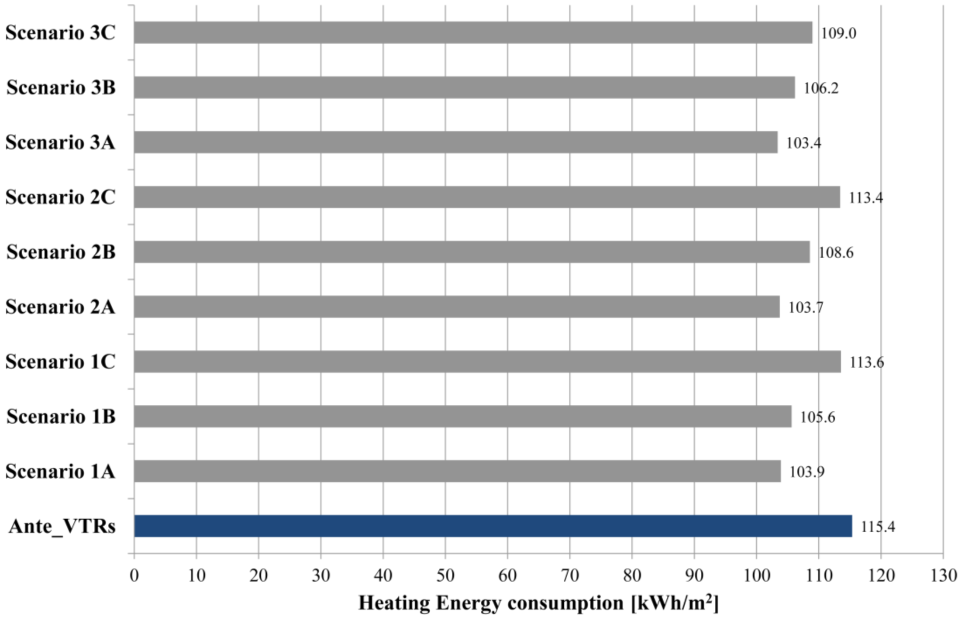


Figure 14 – Heating energy consumption of the simulated scenario and the calibrated model.

The lack of a greater number of monitored data made possible to only simulate the use of TRVs simulated on the basis of theoretical assumptions (due to the fact that the indoor temperature distribution was unknown). However the calibration methodology, even if it could be refined, gave back reliable results, also consistent with the general consideration regarding this type of heating control devices [72][73].

A similar range of energy savings, from a minimum of 5% to a maximum of 20%, was observed within the application of this same methodology to another multi-family building already equipped with TRVs also located in Turin (confidential information). Historical energy consumptions of the years previous the TRVs installation were noted in addition to the measurements coming from the district heating building sub-station, as reported in Table 9. Real historical annual gas consumptions from the bills were normalized to the standard Heating Degree Days and aggregated into a mean value before the installation of the TRVs, and in a mean value after the installation of the TRVs. The percentage reduction between the values after and before TRVs was between 10% and 15% and confirmed the results trend of the simulations conducted.

Table 9 – Historical energy consumption from a similar case study.

Heating season	TRVs installation	Real Energy consumption [kWh/m³]	Energy consumption normalized for HDD [kWh/m³]	Mean value [kWh/m³]	Reduction [%]
2007/2008	No	34.30	40.59	39.86	-
2008/2009	No	35.56	41.29		
2009/2010	No	34.57	37.70		
2010/2011	Yes	28.73	33.48	33.92	- 14.9
2011/2012	Yes	29.16	34.35		

Within the same study, other buildings were calibrated based on a similar trial and error approach. Further details can be found in paper D.

4.4 Focus on Paper VI: Optimization-based calibration of a monitored test building

After the first trial and error calibration, a more refined approach to calibration was studied within this Ph.D. thesis. In particular, an innovative four-step procedure for the calibration of building models was defined. The methodology, outlined in Figure 15, was tested on a case study, as depicted in **Paper VI**. Considering the techniques currently most used for calibration applications, the main objective was to calibrate detailed dynamic building energy models.

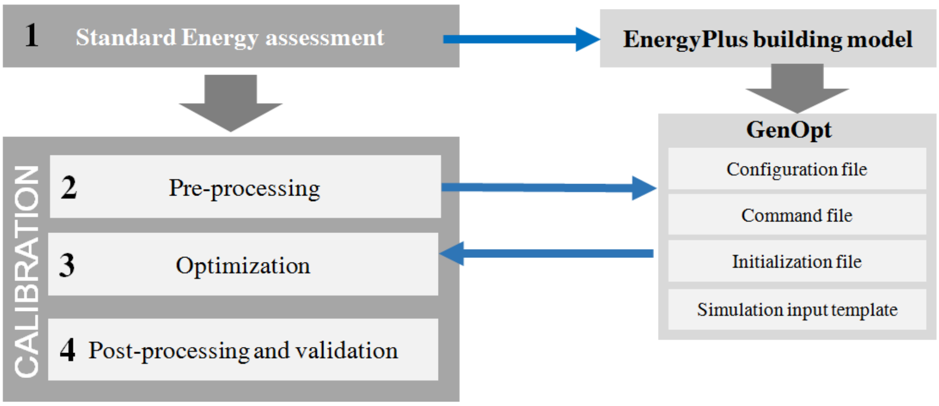


Figure 15 - Four-step methodology for calibration.

In addition, the inclusion of uncertainty and sensitivity analyses was closely considered by studying different possible approaches for implementing them within the calibration process. In particular, the application of the Morris method for carrying out a screening analysis was initially investigated. However, this solution was right away dropped due to an “unmanageable” time for running the simulations of the building model. It was estimated that, using a quite detailed building model, which simulation time was approximately 1:30 minutes, accounting at least 200 runs could have taken around 300 hours to complete the screening analysis. If considering to apply a Monte Carlo analysis for running an uncertainty analysis, on the same case study, it could have taken more than 1500 hours.

Usually, most of sensitivity and uncertainty analyses are carried out using simplified and normative energy models based on the Standard ISO 13790:2008 (complied in Matlab, Excel or other simplified simulation program) or other simple steady-state energy balance approach. In literature, few applications of these analyses on detailed dynamic building energy models can be found due to the high simulation time and the difficulty of coupling building simulation programs with tools running sensitivity and uncertainty analysis. For this reason since many studies were carried out about this topic, it was decided to accept the parameters most influencing on building models found in literature. Based on a detailed literature review, a set of parameters, referred as the most influencing the building energy consumption was defined. Based on the uncertainty categories and considering the uncertainties in the equations building models are built on are not investigated within this study, they were gathered into four categories (site, building envelope, operation, building system).

Once defined the set of parameters, an optimization-based approach was chosen for their tuning. The methodology builds on an optimization-based calibration of building energy models based on monitored data, similarly to Tahmasebi et al. [74]. The process of optimization was hence devoted to finding the parameters optimal values for a better matching of the simulated energy consumption with the building measured energy consumption, while in [74] the optimization process was set on the indoor air temperature. The calibration process was carried out by coupling the generic optimization program GenOpt with the dynamic building simulation software EnergyPlus. The stopping criteria of the optimization process was to find a convergence between measured and simulation data. The coupling of these two programs was chosen for the possibility of varying more than one parameters at the time (solution carried out by the optimization program). The possibility of running a parametric analysis, within EnergyPlus, was hence dropped due to the need of a manual variation of the parameters for each simulation run.

The case study is a test building monitored and located in the Environment Campus of the Université de Liege in Arlon. The building was chosen first for the availability of monitored data and secondly, considering the small and manageable dimensions (total gross floor area of 162 m^2), for the affordable time estimation both for modelling and simulation. Being a test building, it is built around a climatic room, surrounded by a buffer area. On each side of the climatic room two main zones can be identified: a two storeys office area on the north-east side of the building, including a small service area on the ground floor, and a technical equipment on the south-east side. The climatic room upper border faces the unconditioned attic. The building has an all wooden structure and envelope. Windows are equipped with exterior wooden blinds that were shut for the duration of the monitoring period.

The availability of data from short-term monitoring, allowed to perform a Calibration level 4, as defined previously in Table 5. In Step 1 the energy assessment of the building is carried out by means of a dynamic energy simulation model. The model defined at this stage is “uncalibrated” and based on the design data and standard boundary conditions. The building energy model was created within the EnergyPlus simulation program (version 7.0). Given the small dimensions, the modeling was quite detailed and a thermal zone was defined for each room (seven thermal zones in total). Four zones were modeled as conditioned ones (climatic room, office, buffer and upper-floor office), while the remaining three were not conditioned (technical room, attic, toilet). The building envelope components were characterized according to the as-built technical documentation.

For higher accuracy in the simulations the building surrounding urban context was also modeled. As the building is only used for experimental activities and test, the occupancy rate was set to zero; the power installed for the two computers in the office was set to 230 W, based on a literature review, and that of the attic server was fixed to 120 W based on measurements. Air flow rate for natural ventilation and infiltration was set to 0.43 ACH in some zones on the basis of a blower door test measurement and to 0.5 ACH in the remaining zones. The office areas, the climatic room and the buffer zone were conditioned by means of electric resistances with a constant heating set point of 20°C.

From Step 2 to Step 4, the process of calibration, distinguished into three sub-stages (Pre-processing, Optimization and Post-processing and Validation), was performed. Step 2 "Pre-processing" represents the very first stage of calibration. It concerns the collection of data to be used for calibration; metered meteorological data from the university campus weather station were processed for creating the real weather file for running the simulations; others data from monitoring (e.g. indoor ambient temperature, relative humidity, heating energy consumption) were also retrieved from ambient sensors located in the rooms of the case study and further used for optimization.

Due to the large computational time related to the use of a dynamic energy simulation model, sensitivity and uncertainty analyses were not conducted, but based on a detailed literature review, a set of parameters, referred as the most influencing the building energy consumption, was defined. Each influencing parameter was constrained in a range of a lower and an upper bound, representing the relative uncertainty domain. The selected parameters were gathered into four categories (site, building envelope, operation, building system), as reported in Table 10.

Table 10 – Parameters to be altered during the optimization-based calibration.

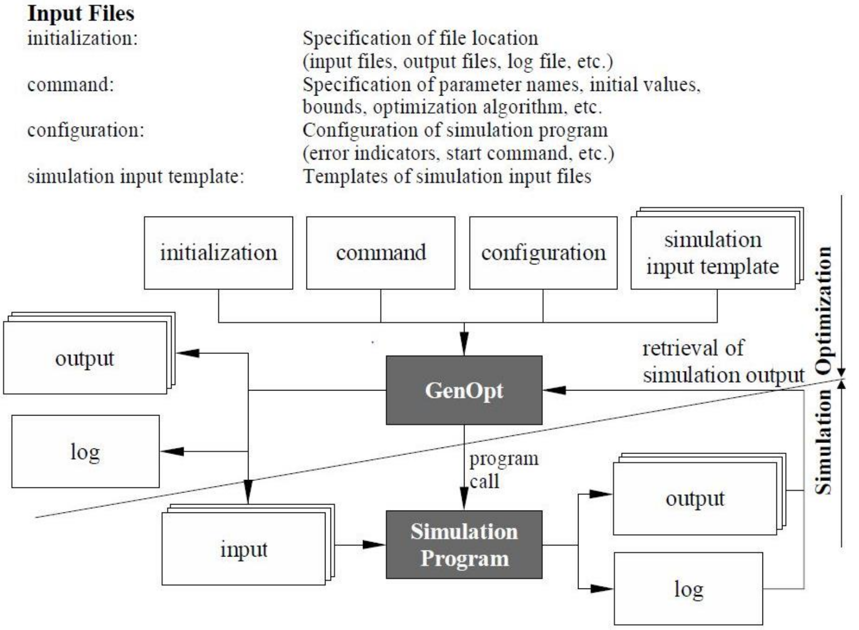
PARAMETERS CATEGORIES			
SITE	**BUILDING ENVELOPE**	**INTERNAL GAINS**	**VENTILATION**
Ground temperature [°C]	Material: Conductivity [W/ mK]	Equipment: Power [W]	Infiltration [ACH]
	Material: Density [kg/ m^3]	Equipment: Radiative fraction [-]	
	Material: Specific Heat [J/kg K]		
	Material: Thickness [m]		

With regard to the equipment internal gains defined in the energy model of the case study, the installed power in the attic room was set to a constant value of 120 W based on on-spot measurements. Moreover, the power of the two computers in the office room was set to 140 W as initial value, with a lower bound of 80 W and an upper bound of 230 W, based on a literature review on computers power.

Then, four different files were created to be used in stage 3, as reported in Figure 15 and Figure *16*. These files, used for coupling GenOpt with EnergyPlus and run the optimization, are listed as follows:

- an initialization file was created for specifying the files location;
- a configuration file set the configuration of the simulation program used (e.g. EnergyPlus);
- a simulation input template file of the energy model was created as a copy of the simulation energy model where the numerical values of each parameter to be altered during optimization, are replaced by its variable name;

- a command file was created for specifying all the parameters to be altered in the energy model, their variation constraints and the algorithm selected to perform the optimization.



Input Files

initialization:	Specification of file location (input files, output files, log file, etc.)
command:	Specification of parameter names, initial values, bounds, optimization algorithm, etc.
configuration:	Configuration of simulation program (error indicators, start command, etc.)
simulation input template:	Templates of simulation input files

Figure 16 - Interface between GenOpt and the simulation program that calculates the objective function. Retrieved from [75].

In particular within the initialization file, an error-minimizing objective function aimed at reducing the difference between measured and simulated data, was defined.

$$\mathrm{Function} = \mathrm{minimize}[(\mathrm{Abs}_{\mathrm{climatic\ room}}\,(\mathrm{S}-\mathrm{M})) + (\mathrm{Abs}_{\mathrm{buffer}}(\mathrm{S}-\mathrm{M})) + (\mathrm{Abs}_{\mathrm{office}}(\mathrm{S}-\mathrm{M})) + \ (\mathrm{Abs}_{\mathrm{office\ 1st\ floor}}\,(\mathrm{S}-\mathrm{M}))]$$

In stage 3 the optimization process was performed. It stopped when the minimum difference was found, that means that the simulated heating energy consumption of the case study matched closely the monitored data. A hybrid generalized pattern search algorithm with particle swarm optimization was used as generally recommended algorithm for problems where the cost function cannot be simply and explicitly stated, but can be approximated numerically by a thermal building simulation program [75]. Different optimization runs were performed to find the “best estimates” for calibration, varying within each run, different parameters in the energy model (e.g. internal gains, building envelope features, etc). First, a series of runs was performed varying time dependent parameters (equipment, infiltration and ground temperature). Then, building envelope related parameters were also included in the optimization process.

During stage 4, the optimization output data were post-processed in order to validate the calibrated building model based on its accuracy. To this regard, the Mean Bias Error (MBE), the Root Mean Square Error (RMSE) and the Coefficient of Variation of the RMSE (Cv (RMSE)) were calculated based on the building heating energy consumption and verified in compliance with ASHRAE guideline 14 limits [63], respectively ±10% and 30% on monthly basis, for a model to be considered calibrated. Data for a short term monitoring period, for approximately one month, from the 8th of February to the 5th of March, were used during the calibration process. The building model was simulated before calibration, to evaluate how far the model was from the real building operation. The simulation results of the “uncalibrated” energy model are reported in Table 11. At the whole building level, simulation results are not so far from the measured data and the calibration indices are also verified for hourly calibration. On the other hand, looking at the results for each single zone, major disagreements are observed and the indices are not verified. However, considering the building small extent, a thermal zone calibration should be performed rather than one at the whole building level.

Table 11 - Measured and simulated energy consumption of the case study (before calibration).

	ENERGY CONSUMPTIONS		**CALIBRATION INDICES [%]**	
	Simulated [kWh]	**Measured [kWh]**	**MBE ***	**Cv(RMSE)***
Climatic Room	92.9	20.6	352	8696
Office	62.1	77.5	- 20	490
Buffer	348.5	394.2	- 11	286
Office (1st floor)	208.8	224.9	- 7	177
Whole building	712.3	717.2	- 0.7	17

* ASHRAE Guideline 14 Threshold limit: MBE= ± 10; Cv(RMSE) = +30

As anticipated, different calibration runs were performed. Overall eleven calibration runs, distinguished into two main sets, were conducted. Although one calibration run should be considered sufficient to tune the building model, the process of calibration is a highly undetermined problem that brings to a non-unique solution [59]. For this reason it was decided to perform multiple calibration runs. For each run, GenOpt reached the minimum of the objective function approximately after 1500-1600 EnergyPlus simulations, as pictured in Figure 17.

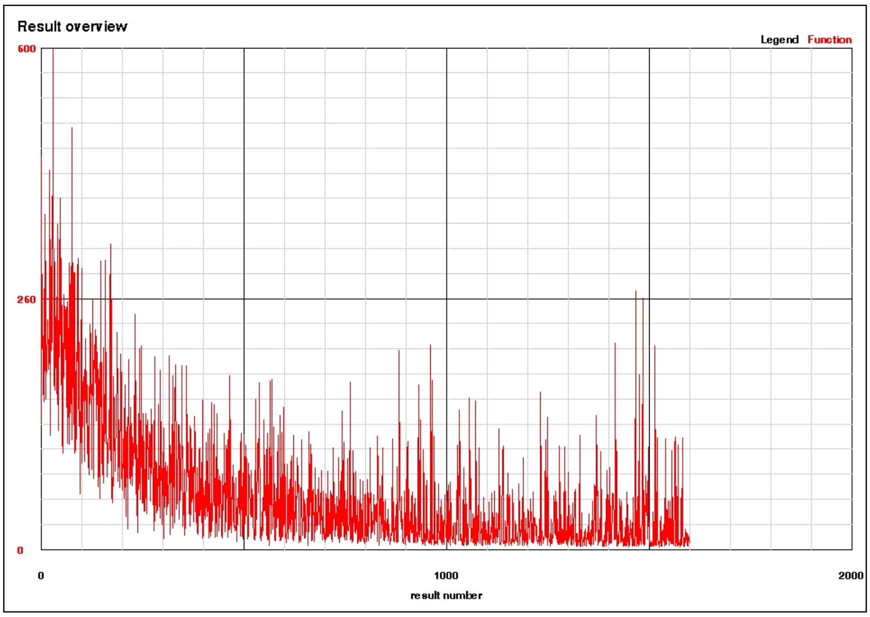


Figure 17 – Screenshot of the optimization process in GenOpt.

In the first set of runs (Calibration run 1 to 6) only time dependent parameters were altered and subjected to optimization. Then, in the second set of runs (Calibration run 7 to 11), materials related parameters were included in the optimization process. For each material selected (in total 8) the values of thickness, density, conductivity and specific heat were altered. With regard to the variation of the parameters during optimization, in general the most stable parameters are those related to the building envelope. Light deviations are hence observed during the optimization process, from the starting value to the simulated and optimal values. The variation of the density of the "OSB panel 12mm" is reported in Figure 18. On the other hand, larger variations are observed in the parameters related to the internal gains and the ventilation rate.

For instance, in Figure 19, the initial value associated to the computers installed power in the office was set to 140 W and during optimization, its value varied from 80W to 240 W.

For each calibration run the statistical indices were calculated and verified in each conditioned thermal zone, based on the heating building energy consumption The MBE and the Cv(RMSE) variation is reported in Figure 20 and in Figure 21, respectively. In the first set of runs, the MBE is always consistent with the ±10% threshold limit recommended by the ASHRAE guidelines for hourly calibration, while Cv(RMSE) is dramatically out of the threshold limit.

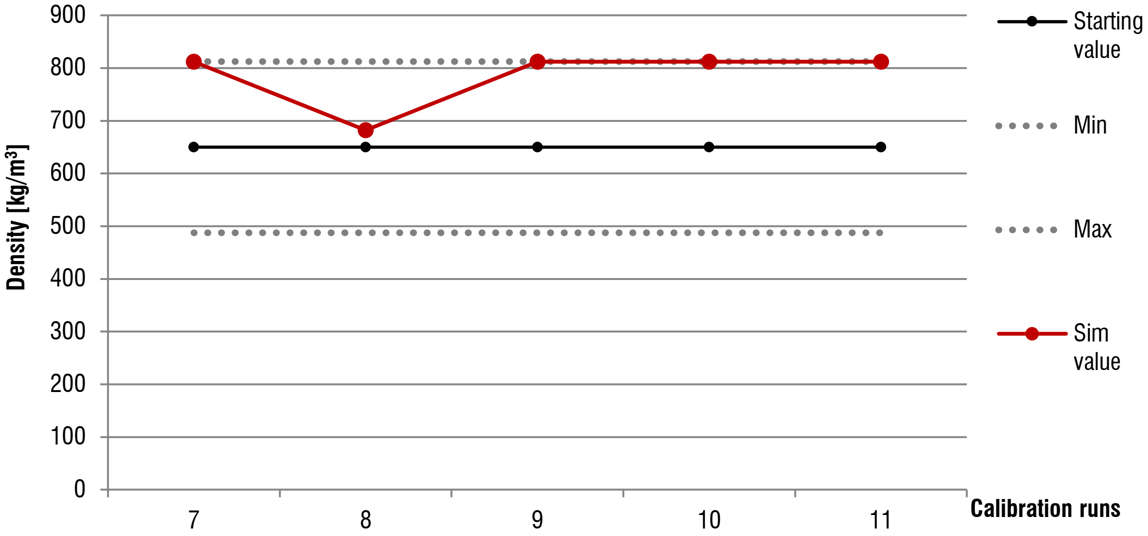


Figure 18 – Variation of OSB panel 12mm density during optimization.

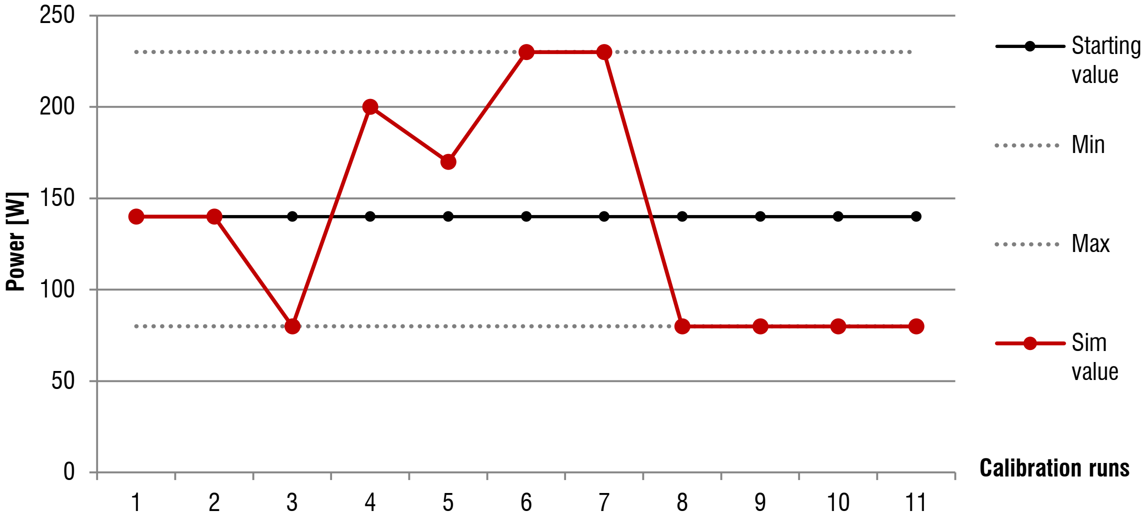


Figure 19 – Variation of the installed power related to computed in the Office room.

To this regard, considering both statistical indices is important to observe that, noted that Cv(RMSE) doesn't fall within the allowed limits, MBE may be verified only due to compensations errors. On the other hand, in the second set of runs, the

Cv(RMSE) significantly improved, especially in the last three runs (calibration runs 9 to 11) with the inclusion of non-time dependent variables, such as material proprieties, that allow considering the decaying of the building envelope.

Similar considerations can be made with regard to the MBE. In general, looking the indices trends in Figure 20 and in Figure 21, soften variations are observed for both the office zones. Except for the first runs, where higher values are recorded, after calibration run 4 there aren't strong variations in the indices trends for the buffer zones. On the contrary the strongest disagreements are met for the climatic room, especially for the Cv(RMSE), which trends record high peek in the first runs of both set of calibration runs. In particular, Table 12 reports the MBE and Cv(RMSE) values before calibration and in the calibration runs 5 (1^{st} stage) and 11 (second stage).

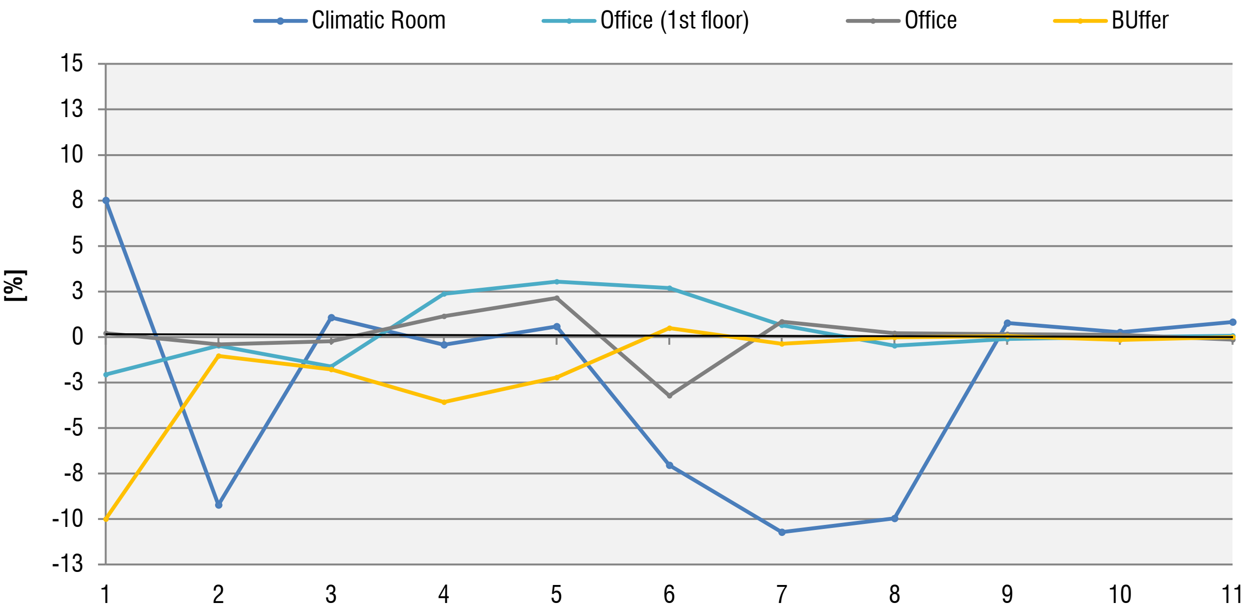


Figure 20 – MBE variation during calibration runs.

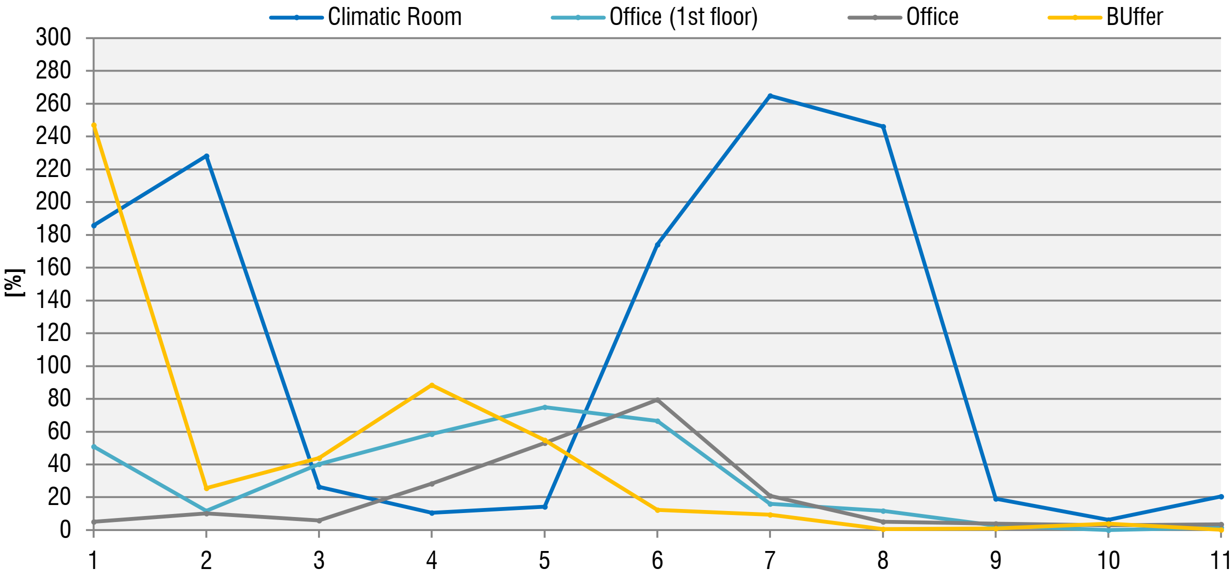


Figure 21 – Cv(RMSE) variation during calibration runs.

Finally, in

Table 13 the parameters subjected to the optimization process are listed. For each parameter the initial value (uncalibrated model), the defined constraints (minimum and maximum value of the parameter) and the final optimal (calibrated) value are reported. The reported values belong to the Calibration run 11, that corresponds to the calibrated model with the "best estimates". As can be observed, the parameters related to material properties were subjected to a 25% variation range, while for the values of material thickness, the variation was limited to 10%.

Table 12 - Validation results: values of MBE and Cv(RMSE) during different calibration runs

	MBE			**Cv(RMSE)**		
	Uncalibrated model	**Run 5**	**Run 11**	**Uncalibrated model**	**Run 5**	**Run 11**
Climatic Room	352	0.58	0.17	8696	14.34	20.40
Office	-20	1.66	-0.11	490	53.01	3.51
Office (1st floor)	-7	6.82	0.14	177	74.94	1.54
Buffer	-11	-8.75	-0.01	286	54.85	0.19

Table 13 – Setting of influencing parameters variation in the Calibration run 11.

INPUT: influencing parameters					
	Starting value	Min	Max	Variation range	Sim_value
SITE					
Ground temperature [°C]					
(February) Core slab area	6.96	8.650	16.060	30%	8.65
(March) Core slab area	8.5			30%	
(February) Perimeter slab area	5.77	9.040	16.780	30%	9.04
(March) Perimeter slab area	7.38			30%	
BUILDING ENVELOPE					
Material: Conductivity [W/ mK]					
Extruded Polystyrene	0.03	0.023	0.038	25%	0.0255
Mortar Slab	1.2	0.900	1.500	25%	0.9
OSB Panel 12mm	0.13	0.098	0.163	25%	0.1652
Osb Panel 18mm	0.13	0.098	0.163	25%	0.0975
Reinforced concrete	2.2	1.650	2.750	25%	2.75
Rockwool 89mm	0.04	0.030	0.050	25%	0.05
Rockwool 140mm	0.04	0.030	0.050	25%	0.05
Rockwool 150mm	0.04	0.030	0.050	25%	0.05
Material: Density [kg/ m^3]					
Extruded Polystyrene	35	26.25	43.75	25%	43.75
Mortar Slab	2000	1500	2500	25%	2400
OSB Panel 12mm	650	488	813	25%	812.5
Osb Panel 18mm	650	488	813	25%	650
Reinforced concrete	2400	1800	3000	25%	1920
Rockwool 89mm	100	75	125	25%	120

Rockwool 140mm	100	75	125	25%	125
Rockwool 150mm	100	75	125	25%	85
Material: Specific Heat [J/kg K]					
Extruded Polystyrene	1180	885	1475	25%	1062
Mortar Slab	840	630	1050	25%	630
OSB Panel 12mm	1880	1410	2350	25%	2162
Osb Panel 18mm	1880	1410	2350	25%	1410
Reinforced concrete	840	630	1050	25%	756
Rockwool 89mm	920	690	1150	25%	874
Rockwool 140mm	920	690	1150	25%	1150
Rockwool 150mm	920	690	1150	25%	1150
Material: Thickness [m]					
Extruded Polystyrene	0.08	0.072	0.088	10%	0.088
Mortar Slab	0.1	0.09	0.11	10%	0.009
OSB Panel 12mm	0.018	0.0162	0.0198	10%	0.011
Osb Panel 18mm	0.012	0.0108	0.0132	10%	0.019
Reinforced concrete	0.14	0.126	0.154	10%	0.14
Rockwool 89mm	0.15	0.135	0.165	10%	0.080
Rockwool 140mm	0.14	0.126	0.154	10%	0.134
Rockwool 150mm	0.089	0.0801	0.0979	10%	0.135
GAINS					
Equipment: Power [W]					
Technical room	100	75	125	25%	75
Office	140	80	230	based on literature review	80
Attic	120	120	120.00	In situ measurement	120
Equipment: Radiative fraction [-]					
Technical room	0.5	0.375	0.625	25%	0.35
Office	0.5	0.375	0.625	25%	0.65
Attic	0.5	0.375	0.625	25%	0.75
VENTILATION					
Infiltration [ACH]					
Technical room	0.5	0.125	1	-	0.91
Buffer Zone	0.43	0.11	0.75	75%	0.75
Climatic Room	0.43	0.215	0.75	75%	0.11
Office	0.43	0.1	1	75%	0.28
Meeting Room_top	0.43	0.1	1	75%	0.46
Attic	0.5	0.1	1	75%	0.19

4.5 Critical discussion

The application of calibration is of growing importance due to recent interest in the mismatch between the measured building energy consumption and the building energy consumption predicted by building simulation program. In particular the use of calibration is commonly encountered in post-construction activities, such as those related to the building commissioning, the estimation of energy savings from the application of energy retrofit interventions on existing monitored building and also failures detection and diagnostic. To this regard, the development and increased employment of monitoring technologies pushed the discovering of actual disagreements between the expected buildings energy performance and that measured during the buildings real operation. Moreover, given the widespread use of buildings energy and environment monitoring systems, it is relevant that calibration starts to become area of expertise also for professionals.

As far as we acknowledged, calibration is mostly dependent on the users' experience and assumptions. Given this, the user's role is thus of high relevance during the process. User's skills and knowledge are essential for performing calibration, having a direct impact on the building model accuracy and the calibration running time.

Experienced users may be able to detect more easily the causes of the disagreement between simulated and measured energy consumption but uncertainties are usually encountered in the data collection and in the building model definition. Therefore, uncertainties should be accounted as a major issue and integrated in the calibration of building models. As depicted previously, an analysis of uncertainties in the building model should be performed in order to select the most influencing parameters and rank them based on their impact on the building energy consumption. The selected parameters need to be tuned during the calibration process in order to match the building measured consumption with the simulated building energy consumption.

Within the modeling process the lack of data is a major issue often faced, especially during calibration. In particular, during the definition of a building model to be further calibrated, the quantity and quality of data plays an important role. The collection of data determines thus the level of calibration to be performed; for instance if measured data about the building operation are available, calibration level 4 or 5 can be performed, based on short-term and long-term monitoring respectively. On the other hand, calibration level from 1 to 3 are assessed if measured data are not applicable.

Undoubtedly, the choice of which calibration methodology should be used can play an important role in the process. Automated methods can guide users' in the calibration, improving on traditional trial and errors methods. However, they do not guarantee a successful calibration process, as they can mislead users. Moreover, the lack of a harmonized and officially recognized procedures still leaves the selection of the technique to the users, based on their preferences and skills. Some methods are emerging more than others, like for instance automated methods, which are slowly of growing interest and application. They are usually integrated with sensitivity and uncertainty analyses and allow fine-tuning the models, improving their accuracy. Choosing the methodology to use also depends on the type of building model to be employed: simplified normative models or detailed dynamic building models. Often simplified models are preferred to more detailed ones for lower computational time and to a smaller quantity of data. In particular, for complex dynamic building models, a high number of parameters and a better data quality are necessary, requiring thus larger computational times, both for the modeling process and the calibration/simulation process. Moreover, some asserted that the use of simplified models for calibration can provide similar and fine results as those achievable with the use of more detailed models [76] .

As depicted in this chapter, several academic applications of the calibration can be found in the literature. Nevertheless, today the challenge is to spread the use the calibration among professionals as an effective and assisting tool for the building design in post-construction phases. The performance gap between the expected and real building energy performance clearly justifies the need of its application in the design professionals' community. Although, concrete steps need to be made to provide designers with the right expertise to carry out a calibration of a building model. With regard to this, following U.S. experience, calibration should also be advised as the requested approach when dealing with deep renovation at the whole building level. The M&V protocol suggested thus a calibration-based approach (Option D of the protocol) for assessing the achievable energy savings in the retrofitting ox existing buildings. In order to promote the use of calibration it is hence necessary to enhance it by including into national regulations and standard. Once required for code compliance, calibration knowledge and expertise will spread in the professionals' community.

Furthermore, to this regard, EU has recently demonstrated a strong commitment in energy monitoring research projects which target the optimization of the energy performance of real/monitored building. These activities based on measured data, requires the calibration of the monitored building models. Once the building energy model is calibrated, further studies aimed at testing different design solution and optimize the building energy performance can be performed by means of building simulation on the calibrated building model. In addition, several research projects are actually based on the monitoring of new "high performing" buildings and of pilots buildings of the building stock to investigate the causes of the mismatch between the building real consumption and the expected one. Undoubtedly, occupants' have a major impact on the real building operation and therefore the use of monitoring devices can help in the understanding the occupants' behavior but also help finding possible failures in the building operation. To this regard, calibration can help completing these kind of analyses and can also be used as a tool for forecasting the building real energy consumption.

5.

Cost Optimal Analysis [COA]

This Chapter covers the assessment of energy retrofit interventions on both building stocks and single buildings by means of the cost-optimal methodology defined by the European Directive 2010/31/EU. This methodology was selected for the aim of this Ph.D. thesis as it represents the EU, but also national from 2015, normative reference for the definition of minimum requirements of the building energy performance. Moreover, the methodology allows considering simultaneously different energy retrofit measures. Therefore, in order to attain useful outcomes for professionals at national levels, the cost optimal analysis was selected for the analysis of different energy retrofit and energy efficiency measures.

First, a description of the methodology, as presented in the regulation, is provided. Second, some Cost Optimal Analysis (COA) experiences, both at national and European level, are depicted with a view of characterizing the state of the art in the COA applications.

Third, the results of the application of the methodology to both the two different scales of buildings are presented. The COA can thus be applied to buildings representative of wide portion of the building stock (reference buildings), for defining energy efficiency measures to be largely considered and employed in long-range energy retrofit strategies. To this regard, the COA was in particular applied to three of the reference buildings presented previously in Chapter 2: the existing multi-family building #01b, the single-family house for new constructions #01c and the existing medium office building #02. On the other hand, COA can also be used for the evaluation of specific energy retrofit interventions on single buildings. On this purpose, the application of thermostatic radiator valves, as low investment energy efficiency measure, on the calibrated multi-family building model presented in Chapter 3, was also assessed by means of the COA. The energy renovation measures were selected based on their economical and energy optimum. They were assessed at the energy level by means of the EnergyPlus software and economically, based on the global cost calculation method. Finally, a critical review of the COA applications is provided.

5.1 The Cost-Optimal Analysis: methodology and objectives

As anticipated in Chapter 1, the Directive 2010/31/EU on the energy performance of buildings (EPBD recast) stipulates that "MS must ensure that minimum energy performance requirements are set with a view of achieving at least cost-optimal levels for buildings, building units and building elements". A comparative methodology framework has been defined, within the Regulation, to be used by MS for calculating cost-optimal levels of minimum energy performance requirements and for comparing them with the minimum energy performance requirements, which they have adopted. The EC has to be notified with regular reports on the results of these comparisons, in order to assess the national MS progress towards cost-optimal levels achievements.

In particular, the methodology specifies how to compare energy efficiency measures, measures incorporating renewable energy sources and packages of measures, in relation to their energy performance and to the cost attributed to their implementation and how to apply these to selected RBs with the aim of identifying cost-optimal levels of minimum energy performance requirements.

The term "*cost-optimal level*" points out the energy performance level which leads to the lowest cost during the estimated economic lifecycle [1]. The lowest cost is determined taking into account energy-related investment costs, maintenance and operating costs (including energy costs and savings, the category of building concerned, earnings from energy produced), where applicable, and disposal costs, where applicable. The estimated economic lifecycle, defined by each MS, refers to the remaining estimated economic lifecycle of a building where energy performance requirements are set for the building as a whole, or to the estimated economic lifecycle of a building element where energy performance requirements are set for building elements.

The cost-optimal methodology defines for MS the following procedure to assess cost-optimal levels for RBs, as reported in Figure 22:

1. Definition of RBs.
2. Selection of energy efficiency measures or variants to be assessed for the RBs.
3. Energy performance assessment;
4. Global cost calculation;
5. Determination of cost optimal levels.

Step 1, clearly described in Chapter 2, concerns the RBs creation and selection.

With regard to step 2, energy efficiency measures should be assessed, at each MS level for the selected RBs, for individual buildings as a whole and/or for individual or combination of building elements. The measures defined should cover high-efficiency alternative system solutions (decentralized supply, cogeneration, district heating and cooling and heat pumps, as well as systems based on RES) that are technically, functionally and economically feasible.

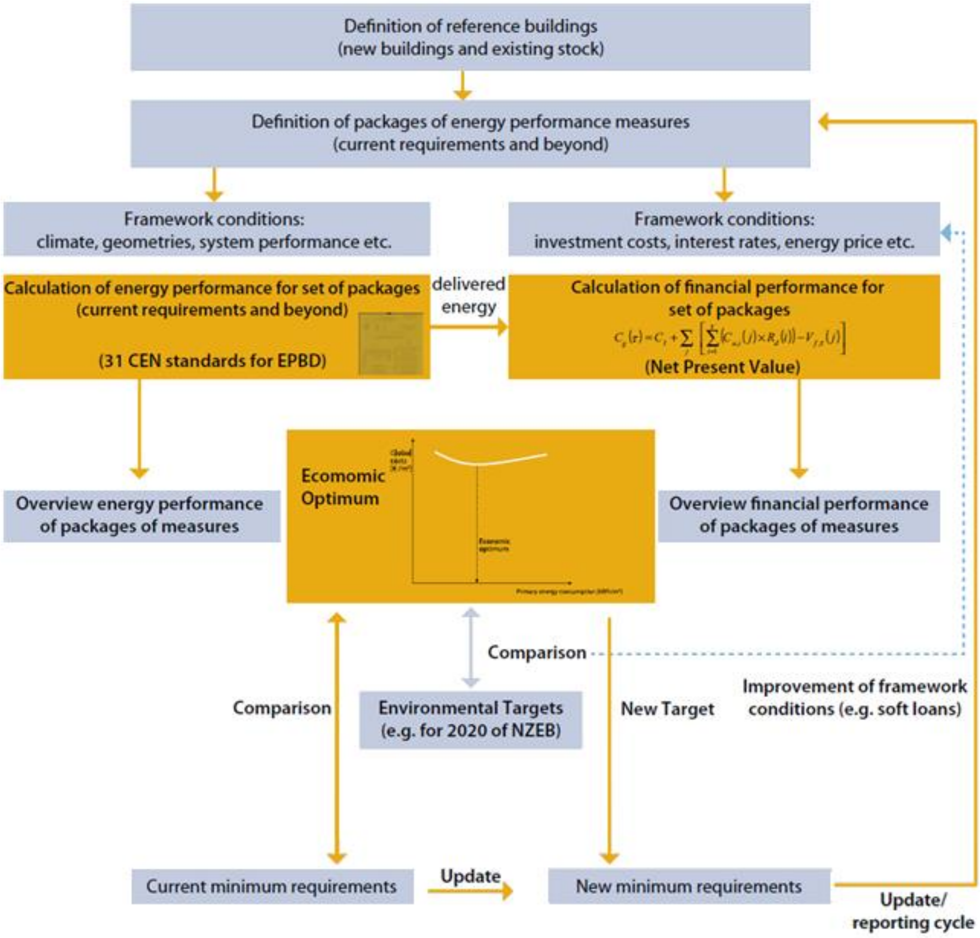


Figure 22 - Main steps of the Comparative methodology framework. Retrieved from [77] .

The EC requires that the number of measures/variants calculated and applied to each RB is equal or superior to 10 packages/variants, plus the case of the RB. The measures should be assembled into different packages and calculated either for new buildings and for completed renovated buildings. Firstly, in order to define the current ambition level, the packages need to comply with minimum performance requirements in force. The ambition level will be visualized, on the cost curve, with the position of the cost optimum. Secondly, the measures need also to go beyond current minimum requirements, and to focus on higher ambition levels towards nearly zero-energy buildings levels. The measures should also consider all measures with a possible impact on the primary or final energy use of a building. Innovative solutions, based also on other MS experiences, are encouraged to enlarge the combination of measured considered within the calculations. Notwithstanding that the more packages, the more accurate the calculated economic optimum will be, it is important to ensure calculations to be manageable and proportionate, with special regard to the number of packages.

Step 3 concerns the calculation of the building energy performance. The energy assessment involves firstly the calculation of the building final energy needs for all uses, secondly the energy delivered and thirdly the primary energy use, as depicted in Figure 23. The EPBD does not identify the calculation method to be used for the energy assessment, but specify that calculations have to be performed according to national methodologies harmonized with the European Standards, especially those developed for supporting the regulation implementation. For this reason, an ad hoc CEN technical report TR 15615

(Umbrella Document) provides an overview of the 31 CEN standards developed to be applied in the framework of the EPBD. Moreover, for the purpose of cost-optimal calculations, it is suggested to perform calculations based on a dynamic method. With respect to the energy needs for heating and cooling, the energy balance of the building and its systems should be assessed according to standard EN ISO 13790.

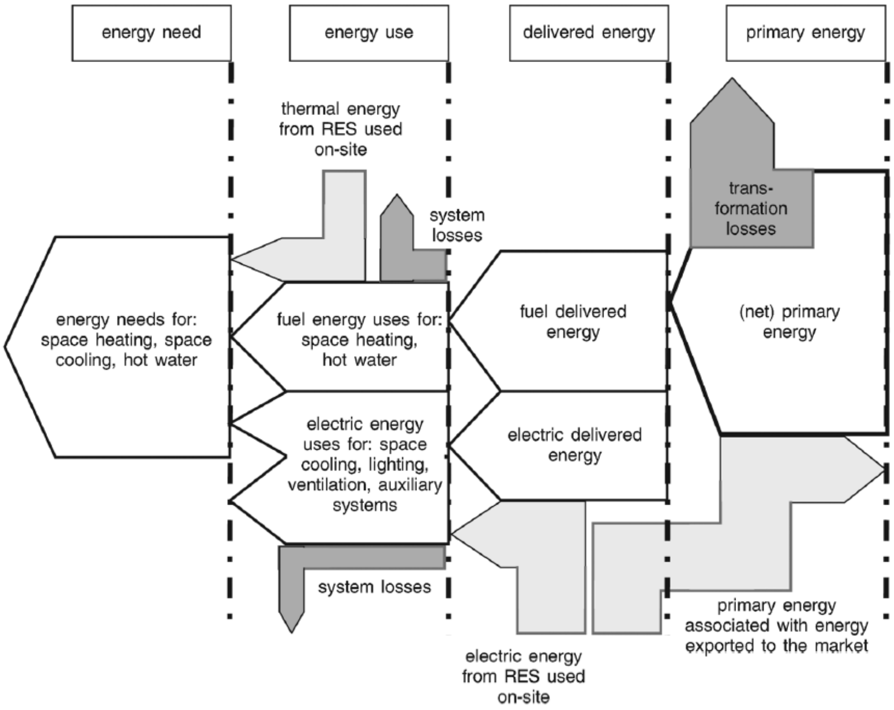


Figure 23 – Illustration scheme of energy assessment calculations [78].

Within step 4, as prescribed within the Regulation [1], the economic assessment is performed, based on the net present values calculation, by using the global cost calculation method. The net present value is a standard method for the financial assessment of long-term projects. EPBD recast aims at analyzing the whole lifecycle during the process of cost optimal levels definition. The costs related to the achievement of the prescribed energy performance requirements, should include all energy-related lifecycle costs and not only the usually considered investment cost. In order to reach this goal, the global cost calculation is suggested as calculation methodology for the economic assessment of the energy renovation measures. Under the recommended CEN umbrella, EN 15459 (Energy performance of buildings. Economic evaluation procedure for energy systems in buildings) is the standard to be used for carrying out the financial calculations. The global cost is assessed as a sum, during the calculation period, of the initial investment, of annual costs for every year and of the final value as well as of disposal costs if appropriate, all with reference to the starting year. The global cost is directly linked to the duration of the calculation period. The EN 15459 does not prescribe the use of a specific calculation period for the whole building, that should be selected by MS indeed. The estimated building lifecycle can either be longer or shorter than the calculation period. In general the calculation period rather corresponds to the refurbishment cycle of a building, which is the period of time after which a building undergoes major refurbishment and that is almost never below 20 years [78]. Moreover the calculation period might be set at 30 years, as this timeframe may cover the lifecycle of most of the measures assessed. Longer calculation periods are not recommended, as beyond a 30-year timeframe, assumptions on interest rates and forecasts for energy prices, to be used within the calculation, are scarcely reliable [77]. As previously depicted, the calculation period is defined for the whole building. However, considering that the lifetime of single building components could be shorter or longer than it, residual values should be included in the calculations, for those components with longer lifetime than the calculation period. On the other hand, components with shorter lifetime, are replaced during the selected calculation period. It important to note that the global cost, as intended for cost-optimal calculations, takes into account only energy-related costs. Therefore the concept of global cost here presented is not in compliance with a full life cycle assessment, where the environmental impacts are also considered. Further details on the calculation of the global cost can be found in **Paper II**. The various elements composing the global cost is clearly pictured in Figure 24, where a selection of the energy efficiency packaged applied to the reference buildings of the single-family house studied in details in **Paper II**, is depicted.

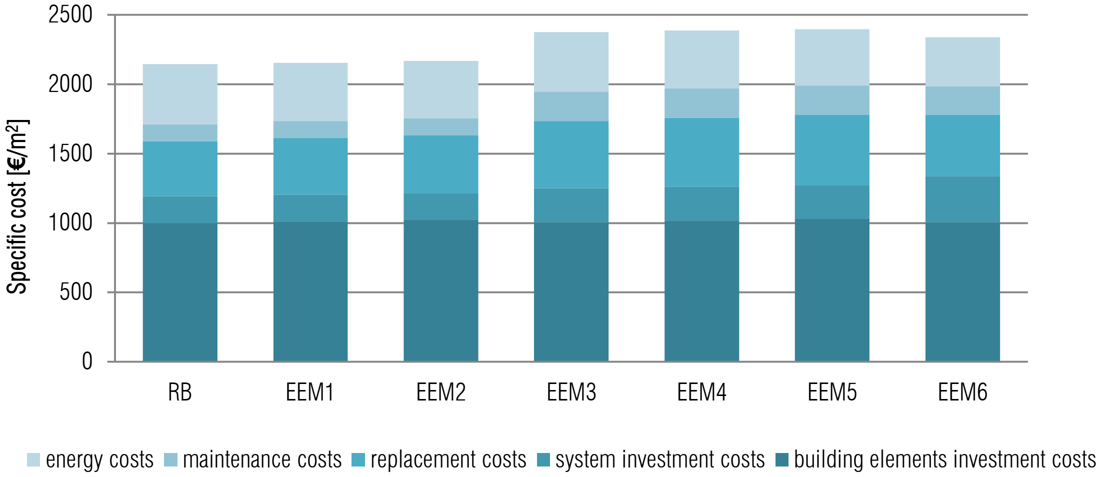


*Figure 24 – Cost calculations of different packages. Extract from **Paper II**.*

For a complete financial assessment, the following financial information should be collected for each package applied to the RB:

- energy related investments;
- periodic costs for replacement;
- corresponding costs for maintenance, operation and added costs;
- energy costs for energy carriers.

The values of such information become different when calculations are performed when considering individuals (private costs) or the society. According to the regulation two main perspectives should thus be considered during cost-optimality calculations:

- the macroeconomic perspective (societal level);
- the microeconomic perspective (private/end-users or financial level).

Both perspectives are important for building regulations and policy making and there need to be calculated separately for the assessed reference buildings.

Table 14 provides a list of the main assumptions that characterize each perspective.

Table 14 – Assumptions for private and societal perspectives. Adapted from[79].

	FINANCIAL PERSPECTIVE	MACROECONOMIC PERSPECTIVE
Interest rate	Market interest rate (adjusted for inflation)	Societal Interest Rate
Subsidies and incentives	Included	Excluded
Taxes	Included	Excluded
Cost of emissions	Excluded	Included

The main differences concerns parameters such as interest rates, subsidies, VAT and environmental costs. In fact, macroeconomic calculations exclude taxes (e.g. VAT) and subsidies, and include the cost of greenhouse gas emissions, defined as the monetary value of environmental damage caused by CO_2 emissions related to the energy consumption in a building. GHG emissions costs are considered as sum of the annual greenhouse gas emissions multiplied by the expected prices per ton CO^2 equivalent of GHG emission allowances issued in every year (e.g. minimum 20 Euro per ton of CO_2 equivalent lower bound at least until 2025, 35 Euro until 2030 and 50 Euro beyond 2030).

Calculations at financial level consider price as paid by the end consumer. In general, subsidies and incentives are usually referred to the private perspective of building owners and individual investors. Therefore, the inclusion of available support schemes (along with taxes and all available subsidies) would usually be required to reflect the real financial situation. For instance direct subsidies can be directly subtracted from the investment cost. However, given that such schemes often change quickly it is also possible for a Member State to calculate without subsidies for a private investor point of view. Moreover, in MS where not VAT-based subsidies and support measures are present, for simplifying the calculation, it is admissible to fully exclude VAT from all cost categories of the global cost calculation. Once both calculations are performed, it is up to the Member States to decide which of the calculations is to be used as the national cost optimal benchmark.

Further differences, unlikely difficult to assess, can be noted in the economic calculation for each perspective: for instance the increase of the building value, when energy renovation projects are carried out, or on the other hand the impact of energy retrofit on the work sector, with the creation of new jobs.

However it is important to note that the cost optimal methodology is addressed to national authorities (and not to investors) for developing generally applicable regulations at national level. Solving barriers at the financial level, such as for instance the renovation split incentives that concern owners and tenants, is not the aim pursued within the cost optimal methodology. On the other hand, COA can be useful, for MS as a calculation exercise, to get informed about the existing gap of the cost optimum between the societal level and the financial level, and to give hits for the necessary funding and financial support to make renovation investment economically attractive to investors.

Finally, based on the calculations of primary energy use (step 3) and global costs (step 4) associated with the different measures/packages (step 2) on the RBs reference buildings (step 1), a cost curve can be drawn describing the building primary energy use (x axis) and the global cost (y axis). However, depending on the variety of packages considered, it is usually unlikely to form an exact curve, but rather a “cloud” of data points from which an average curve can be derived. The lowest part of the curve represents the economic optimum for a combination of packages. Actually, the cost-optimum is rarely found as a single package but rather as a set of more or less equally valid or cost-optimal solutions. The COA should serve for each MS, to the definition of minimum performance requirements for sustainable buildings, which correspond to the cost optimal points (the area of the cost curve) that delivers the best energy and environmental performance at the lowest cost, which could be better than current requirements at less or at the same overall cost.

These requirements could prove to be more effective and efficient than current national requirements, at less or equal cost. The area of the curve to the right of the economic optimum represents solutions that underperform in both aspects (environmental and financial), as picture in Figure 25.

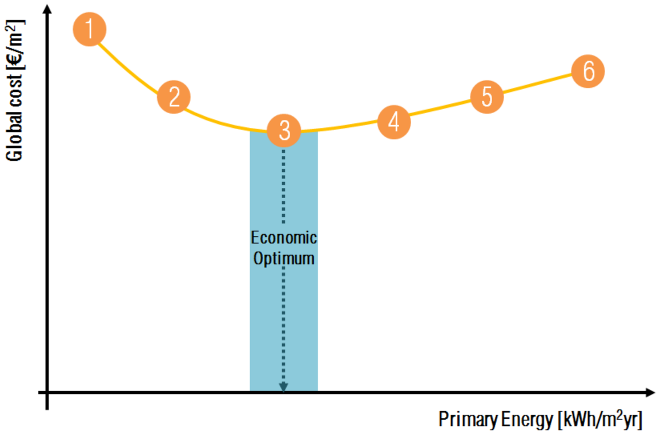


Figure 25 – Economic optimum and cost curve of different packages Adapted from [79].

Additionally, in the application of the cost optimal methodology it is important to carefully take into account the long-term decarbonisation goals of the EU and for this reason to make clear connections with energy savings requirements and Co_2 emissions requirements in the building design, towards nZEBs. Three potential existing gaps need to be addressed and bridged as follow and reported in Figure 26:

- Financial gap. The actual cost difference between cost-optimal and nZEB levels;
- Energy performance gap. The difference between primary energy need at cost-optimal and nZEB levels;
- Environmental gap, The difference between associated CO2 emissions to primary energy need of cost-optimal and nZEB levels, the latter aiming to nearly zero-carbon emissions (or <3kg CO2/m2/yr) in order to be consistent with the 2050 decarbonisation goals of the EU.

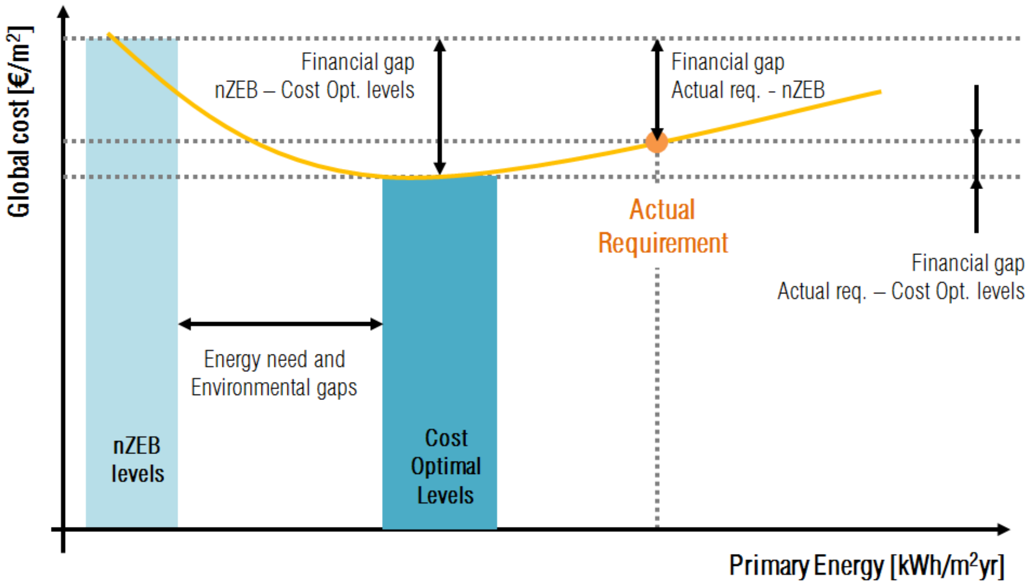


Figure 26 – Energy, environmental and financial gaps in cost optimal calculations.

5.2 Experiencing COA in EU

Since its introduction within the EPBD recast, several applications of COA, with a view of achieving nZEB levels, can be reported as conducted by either at academic research bodies and EU and national bodies. Different approaches pursuing the definition of cost optimal levels can be noted; distinguishing from a dynamic simulation-based approach to simplified models and from deterministic models to optimization-based models.

BPIE carried out two exemplar studies on the COA; the first one, in 2010 presented an exhaustive description of the methodology to provide support to the process of the COA implementation within MS and targeting at policy makers and other market actors [77]; the latter study, published in 2013, aimed at providing an analysis and guidance on how to properly implement the cost-optimality methodology by MS [80]. In particular, it focused on the calculation methodology and on the impact of financial factors (e.g. discount rates, costs, energy prices) at national levels. To this regard, both the macroeconomic and microeconomic perspectives are hence presented. All findings are based on three country reports (Austria, Germany and Poland) on new residential RBs (single-family and multi-family house). The study demonstrates how existing national nZEB definitions can be tested for cost-optimality and explores additional implications of the EU decarbonisation and resource efficiency goals. Different lessons were learnt from each application of the COA by the three countries involved. In general, a sensible gap was identified between each country actual requirements and the cost optimal levels of energy performance reached within the calculations. Moreover, regardless of the perspective considered (macroeconomic and private perspective) similar cost-optimal levels were observed. Looking at the results of each country, sensible differences can be noted. With special regard to the Austrian study, the cost-optimal analysis was carried out for a multi-family reference building. From the financial perspective, and if the actual heating source (e.g. district heating) remains unchanged, the difference between actual and cost-optimal energy performance is 10.5% to 14.5%, according to different assumptions on input factors. Whereas, if different heating systems are employed, the gap between actual and cost-optimal energy performance increases to 15.4-21.6%. If different assumptions are made (e.g. lowering discount rate from 3% to 1%, increasing energy prices, etc.), among the same packages of measures, more ambitious cost-optimal levels are reached.

The cost-optimal calculation for Germany were applied on an exemplary single-family building (semi-detached house) and one multi-family building, selected as new reference buildings for the aim of the study. From calculations it was observed that, from a financial perspective, the calculated cost-optimal primary energy values do not change for both the selected reference buildings as they are very similar (respectively 53 kWh/(m^2a) for the multi-family reference building and 54 kWh/m^2a for the single-family building). The cost of the greenhouse gas emissions do not alter the cost optimal levels due to too low carbon prices, as assumed from the Regulation[81]. From calculations, it could be observed that lower cost-optimal primary energy values could be gained with lower discount rates and higher energy price development, increasing thus the gap with between cost optimal and current energy performance requirements.

Concerning Poland, the cost-optimal calculation were carry out on three new reference buildings: a single family house, a multi-family house and an office building. The building simulations were undertaken within TRNSYS. A higher gap between current energy performance requirements and cost optimal levels was recorded. Despite the highly different primary energy demand, depending on the varied climate locations, the influence of the location on cost–optimality was not observed.

Another report produced by the European Council for an Energy Efficient Economy and the Ecofys staff, provides, consistently with the first one from BPIE, additional insights for contributing to the ongoing discussion in Europe around the cost-optimal methodology [79]. In particular, within the report, a comprehensive description of the comparative methodology framework for assessment of the cost optimal levels is provided.

Similarly, at EU level, a Working Group (WG) in Concerted Action 2 (CA2 EPBD) called "Cost-optimum procedures" was created in December 2010 in order to support the EC in its work of establishing the framework methodology on cost optimal energy performance requirements.

Kurnitski et al. presented a systematic and robust scientific procedure to determine cost optimal and nZEB energy performance levels of an Estonian residential reference building [82] and of an office building [83]. The energy assessment for the two RBs was carried out by means of the dynamic building simulation software IDA-ICE. In both studies different levels of insulation and different building systems were investigated, emphasizing that the cost optimal energy performance is still quite far from nearly zero energy performance level.

With regard to the single-family house, the cost optimal energy performance level (110 kW h/m^2 a) was quite far from the minimum requirement (180 kW h/m^2 a). Furthermore the distance from cost optimal to nearly zero energy performance level was about 239 €/m^2 extra construction cost, i.e. about 20%. For the office RB different fenestration design solutions were analysed together with alternative measures for achieving nZEB levels. From a cost perspective point of view, the use of large fenestration areas with a triple glazing was preferable to small areas and to window with four panes, which were 41% more expensive than a window with three panes. It was observed that for the cold Estonian climate, high level of thermal solutions are necessary (e.g. triple glazed argon filled windows, 200 mm thick insulation) to reach cost optimal and energy efficient solutions during a 20 years calculation. Moreover, for achieving nZEB levels, photovoltaic systems were required for the covering the electricity consumption.

Different optimization-based approaches can be found in the literature. A three -stage methodology was studied for exploring several combination of of energy saving measures and energy-supply systems including renewable energy sources in order to find cost optimal and nZEB solutions for a single family house in Finland [84]. In the first stage, an efficient multi-objective genetic algorithm find cost-effective energy-efficient EEMs combinations which influence the thermal performance of the house. The second stage assesses the primary-energy consumption and the life-cycle cost of the optimal combinations, including the building systems. The third stage improves the financial and/or environmental viabilities of the optimal EEMs, including both the building envelope, HVAC solutions and the solar thermal and photovoltaic systems. The energy assessment of the reference building was performed by means of IDA ICE [30] and IDA ESBO, respectively for the building and systems. The calculations proved that reaching nZEB levels can be economically feasible with 70 kWh/m^{2}a. However, incentives and financial instrument are required to improve the economic feasibility of solutions targeting nZEBs levels.

Ballarini et al [85] studied a new procedure for optimizing the definition of cost optimal levels and applied it to an Italian residential reference building. Based on a sequential search technique, the procedure considers a number of discrete options and simultaneously take into account different technological solutions. The energy performance assessments was performed by means of a simplified building model, set in compliance with the national standard UNI/TS 11300. The results demonstrated that regardless of the starting point, the optimization procedure brought to a unique solution, which corresponds to the optimal and minimum global cost and energy performance. With regard to the studied technological measures, the optimal package was composed both by measures fulfilling the requirements of the in force legislation and by measures against the regulations. In particular, the measures on the building envelope, were set in compliance with the minimum requirements fixed by the in force legislation. On the other hand, the measures acting on the building system and concerning the use of renewable energy source system do not always fulfill with them. A more exhaustive description of the procedure studied by Ballarini et al. and applied to different residential reference buildings, can be found in the cost optimal activities report founded by ENEA (Italian National Agency for the New Technologies, Energies and Sustainable Economic Development) [86]. Within this report a specific section, which the author of this Ph.D. thesis work at, is devoted to the development of dynamic building energy models for the assessment of cost optimal level of energy performance.

Moreover, Ascione et al [87] proposed a new methodology for the evaluation of the cost-optimality to be used for the optimization of the energy retrofit interventions in existing buildings and applied to a residential case study located in Naples, Italy. The methodology was based on a multi-objective optimization of buildings energy performance and indoor thermal comfort by means of coupling MatLab with EnergyPlus. In particular, the multi-objective optimization problem was solved by means of the Pareto front that is implemented in MatLab. The EEMs were analysed by applying both the utopia point criterion and the comfort criterion for the decision-making. Based on calculation, the cost optimal EEMs package is characterized by a basic external insulation of the roof and on external walls, mechanical ventilation, a condensing heating boiler and a water-cooled chiller.

Ferrara et al.[88] used an optimization-based approach based on the coupling of TRNSYS and GenOpt, for selecting cost optimal solutions for a reference building of a single-family house in the French H1 climate zone. The global cost function was defined as objective function for the optimization within the GenOpt software. The particle swarm optimization algorithm was used to minimize the objective function and find the cost-optimal building configuration within the current regulatory framework. From the calculations, it was observed that the current regulatory limits allow designing a cost-optimal building. The cost optimal solution for the building envelope was that of a lightwood envelope. Which allowed to reach good energy performances and limited costs. On the other hand, among energy systems, pellet boilers were observed as the cost optimal solution from the cost point and high-performing all-in systems allowed to reach better energy performances with a low cost.

Ganiç et al [89] implemented the cost optimal methodology in Turkey and investigated the validity of the procedure under national market conditions. A preliminary study, on a reference office building, was carried out to define the frame of the national cost optimal methodology, based on the EPBD recast, in Turkey. The energy assessment of the case study was performed by means of the EnergyPlus dynamic simulation software, on two different Turkish locations: Ankara for a temperate-dry climate and Antalya for a hot humid climate. Overall 18 retrofit scenario, mostly targeting the building envelope, the lighting system and the cooling system, were defined and investigated based on the existing national standards and common applications in Turkey. The EEMs were assessed in two stages: first as single retrofit measures and second, gathered into different packages, defined as a combination of different measures. A sensitivity analysis on the use of different calculation period (30 years, 20 years, 10 years and 5 years) was also included within this study. Different cost optimal solutions are achieved for the two considered locations.

Barthelms et al.[90] investigated the impact of energy and economic assumptions in the preliminary design of a building project by means of cost optimal analysis. Different building envelope and system configurations were simulated by means of the dynamic simulation software EnergyPlus on a new representative single-family house. Especially, four different design configurations were assessed for both the building envelope and the HVAC system, in order to create 16 different design scenarios, evaluated based on their energy and economic performances within the calculations. Within the study sensitivity analyses were also performed with regard to the escalation of the energy prices, the variation of the discount rate and the calculation period. Among the studied scenarios, five achieved nZEB levels and one reached a positive-energy standards. All these scenarios were characterized by radiant panels with a water heat pump, natural or mechanical ventilation and a photovoltaic system. Consistently with Kurnitski et al. [83], this study demonstrated that the contribution of renewable sources for reaching the nZEB target is fundamental requirement.

5.3 Focus on Paper II and III: COA application on RBs

The COA methodology, as previously described, was applied to representative building models of the building stock, by means of some of the RBs presented in Chapter 2, in order to define cost optimal renovation solutions. The methodology was applied to different building typologies, such as residential and non-residential buildings, considering both existing buildings and new constructions, customized to the Italian contest.

In particular, the COA was applied to three reference buildings:

- two residential reference buildings, the multi-family existing building (RB#01b) and the new single-family RB for new construction (RB#01c);
- the existing office reference building (RB#02).

Hereafter the main results of the COA application on the selected RBs, which complete cost optimal analysis is described in **Paper II**, **Paper III and Paper J**, are presented. Several Energy Efficiency Measures (EEMs), gathered into different packages, were tested on the RBs aiming to find the cost optimum solution with a view of achieving nearly zero solutions. For all RBs, in order to reduce the building energy needs, a first set of EEMs was defined for improving the building envelope performance. Secondly, a new set of EEMs was created aiming at improving the system building efficiency, with the inclusion of on-site energy production from RES. Since the RBs were simulated in Turin, the minimum energy requirements of the in force legislation of Piedmont region was taken as a reference. Moreover, in the global cost calculation, replacement and maintenance costs were defined in compliance with Standard EN 15459.

RB#01b– Existing multi-family building

The RB is a multi-family building located in Turin. It is a Real RB, which full description and cost optimal levels assessment are provided in Chapter 2 and in **Paper J**, respectively.

In total 37 packages of EEMs, distinguished in two sets, were simulated and applied to the RB. As depicted in Table 15, within the first set of EEMs, 10 packages of EEMs, aimed at retrofitting the building envelope, were defined and distinguished in "homogenous" and "not homogenous". Homogeneous EEMs packages (EEM 1 to EEM3) concerned the retrofitting of all building envelope components, while not homogenous ones (EEM 4 to EEM10) regarded only selected components. In particular EEM1 and EEM2 were defined in compliance with the minimum and optional (higher than minimum) requirements of the in force legislation respectively. On the other hand, in EEM3 lower U-values were set for the characterization of the building envelope components. The not homogenous packages are thus defined as a mix of EEMs defined in the first three homogenous packages.

The second set of EEMs, from EEM 10 to 37, consisted in the definition of nine different packages applied to the RB and also to EEM1 and EEM3. Since the possible combinations related to the application of the nine packages to the EEMs previously defined, are quite numerous, only EEM1 and EEM3 were considered for the implementation of the second set of EEMs. Table 16 provides a description of each package, listing the associated EEMs.

Table 15 –EEMs concerning the building envelope retrofit applied to the Multi-family RB (RB#01b)

EEM DESCRIPTION and ID		U-value [W/m²K]
RB	Exterior wall	1.15
	Windows	4.9
	Slab	1.65
	Ground slab	1.30
EEM1	Exterior wall	0.33
	Windows	2.00
	Slab	0.30

	Ground slab	0.30
EEM2	Exterior wall	0.25
	Windows	1.70
	Slab	0.23
	Ground slab	0.23
EEM3	Exterior wall	0.18
	Windows	1.70
	Slab	0.16
	Ground slab	0.16
EEM4	Exterior wall	0.33
	Windows	2.00
	Slab	1.65
	Ground slab	1.30
EEM5	Exterior wall	0.33
	Windows	4.90
	Slab	0.30
	Ground slab	0.30
EEM6	Exterior wall	1.15
	Windows	2.00
	Slab	1.65
	Ground slab	1.30
EEM7	Exterior wall	0.25
	Windows	4.9
	Slab	1.65
	Ground slab	1.30
EEM8	Exterior wall	0.25
	Windows	4.9
	Slab	0.23
	Ground slab	0.23
EEM9	Exterior wall	0.18
	Windows	1.70
	Slab	1.65
	Ground slab	1.30
EEM10	Exterior wall	0.18
	Windows	4.90
	Slab	1.65
	Ground slab	1.30

Table 16 –EEMs concerning the system retrofit as applied to the Multi-family RB (RB#01c).

EEMS DESCRIPTION		1st STAGE EEM CONSIDERED	ID
Package 1	Condensing heating boiler;	RB	EEM11
	Thermostatic radiator valves;	EEM1	EEM12
	Thermal insulation of the distribution system.	EEM3	EEM13
Package 2	Condensing heating boiler;	RB	EEM14
	Radiant panels;	EEM1	EEM15
	Thermal insulation of the distribution system.	EEM3	EEM16
Package 3	Photovoltaic system	RB	EEM17
		EEM1	EEM18
		EEM3	EEM19
Package 4	Condensing heating boiler; Thermostatic radiator valves; Thermal insulation of the distribution system; Photovoltaic system	RB	EEM20
		EEM1	EEM21
		EEM3	EEM22

Package 5	Condensing heating boiler; Radiant panels; Thermal insulation of the distribution system; Photovoltaic system.	RB	EEM23
		EEM1	EEM24
		EEM3	EEM25
Package 6	Condensing heating boiler; Thermostatic radiator valves; Thermal insulation of the distribution system; Mechanical ventilation.	RB	EEM26
		EEM1	EEM27
		EEM3	EEM28
Package 7	Condensing heating boiler; Radiant panels; Thermal insulation of the distribution system; Photovoltaic system; Mechanical ventilation.	RB	EEM29
		EEM1	EEM30
		EEM3	EEM31
Package 8	Condensing heating boiler; Thermostatic radiator valves; Thermal insulation of the distribution system; Photovoltaic system; Mechanical ventilation.	RB	EEM32
		EEM1	EEM33
		EEM3	EEM34
Package 9	Condensing heating boiler; Radiant panels; Thermal insulation of the distribution system; Photovoltaic system; Mechanical ventilation.	RB	EEM35
		EEM1	EEM36
		EEM3	EEM37

In general this second set of EEMs concerned the improvement of the efficiency of the boiler (replacement with a condensing heating boiler), of the heating distribution system (thermal insulation of the network) and the installation of thermostatic radiator valves, the replacement of radiators with radiant panels and a photovoltaic system and a mechanical ventilation system.

Table 17 lists the main financial assumptions, together with other input data necessary for finding the cost optimal solution. Since calculations refer to an existing building, the calculation period was set to 30 years as suggested by the Guidelines [78]. The real interest rate was set to 2.28%, adjusted to inflation as in compliance with [78] but excluding VAT, as the private perspective was assessed within this calculation. Investment costs were set fulfilling the 2010 Price list of the Piedmont Region and further actualized to 2011 with a harmonized index of 2.9%.

Table 17 – Assumptions and input data for cost-optimal calculations of the Multi-family RB (RB#01c).

COST-OPTIMAL CALCULATION INPUT DATA AND ASSUMPTIONS	
Reference Building	Existing multi-family building – RB#01b
Energy efficiency Measures/Variants	37 of packages of energy efficiency measures investigated: - Ten measures for improving the building envelope efficiency; - Twenty-seven measures for improving the building system;
Energy performance assessment method	Dynamic hourly building simulation based on EN ISO 13790 EnergyPlus dynamic building simulation program
Economic assessment method	Global cost calculation – net present value method (UNI EN 15459) Financial perspective (private investor)

Calculation period	30 yrs
Cost categories	- Investment cost - Residual value - Replacement cost - Maintenance cost - Energy cost
Building components Lifetime	Set in compliance with Standard EN 15459
Market Interest Rate	4.50 %
Real interest Rate	2.28%
Energy price	0.72 €/m^3 for natural gas 0.17 €/kWh for electricity 0.233 €/kWh for 20 years as incentive for the electricity consumed on site: 0.003 €/kWh as feed-in tariff.

As depicted in Figure 27, the simulated EEMs allowed saving from 37 up to 193 kWh/m^{2}y in absolute terms, and between 13 and 78%, in percentage terms. The minimum energy consumption is observed with EEM37.

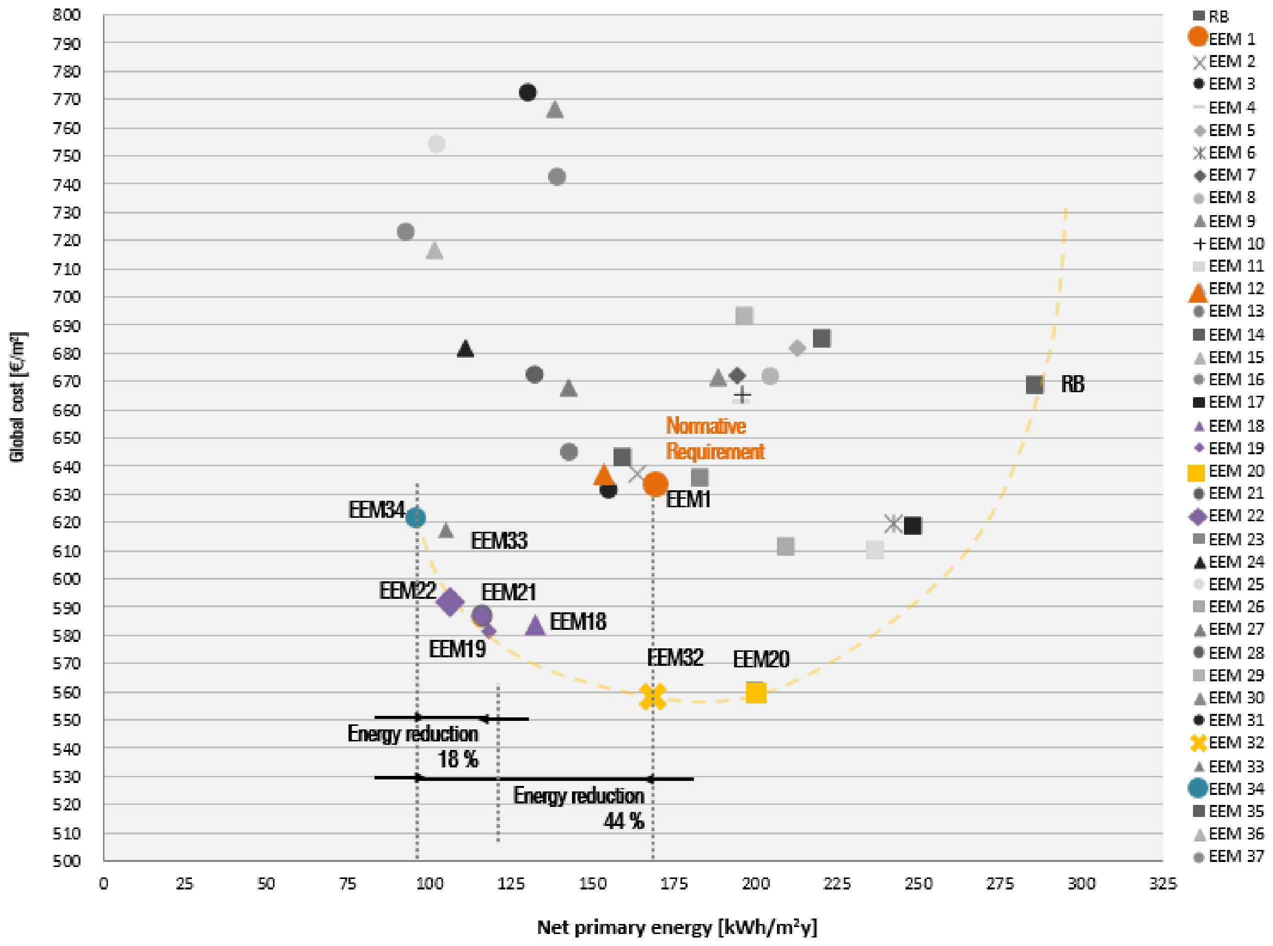


Figure 27 – Global cost calculations of the Multi-family RB (RB#01b).

It corresponds to the highest level of thermal insulation investigated within this analysis (EEM3), the thermal insulation of the system distribution, the replacement of the heating boiler and radiators with a condensing boiler and radiant panels respectively, the installation of a mechanical ventilation system and the energy production from a photovoltaic system on the roof (25kW$_p$). Nevertheless EEM37 does not represent the cost optimal value due to a too high global cost (723 €/m^2), which investment costs are deeply higher than the energy savings achievable with the retrofit interventions considered. In particular, the building envelope investment cost constitutes approximately 60% of the investment cost of EEM37. An energy consumption close to that of EEM37 can be observed in EEM34 with a net primary energy consumption of 96 kWh/m^{2}y. In this EEM the global cost is much lower, amounting to 622 €/m^2, with a reduction of the 14% of the global cost value of EEM37.

The cost optimal solution is reached with EEM32, which corresponds to the application of the package 8 to the RB. Nevertheless, this solution is not compliant with in force regulations for the building envelope energy performance minimum requirements. To this regard EEM18, 19, 21 and 22 are identified as regulation compliant for the building envelope characterization. EEM18 and 19 correspond to the application of photovoltaic system to EEM1 and EEM3, whereas EEM21 and 22 correspond to the application of package 4 to EEM1 and 3. Their energy consumption and global cost values are quite close: they thus range from 106 up to 132 kWh/m^2 for the net primary energy and from 582 to 592€/m^2 for the global cost.

The minimum normative energy requirements are represented by EEM1 and 12. EEM1 concerns the energy retrofit of the building envelope fulfilling to the minimum requirements of the regulation in force. EEM12 corresponds to the application of package 1 to EEM1. Neither EEMs1 and 12 include the onsite energy production from renewable sources. Both the cost optimal solutions (EEM18, 19, 21 and 22) and the low energy solution (EEM34) require lower global costs than the minimum requirements. No financial gap can be thus be observed for this analysis. This means the EEMs necessary for reaching the minimum normative energy requirements (at the building envelope level), requires larger investment cost and smaller energy savings than those that can be achieved with the cost optimal and low energy solutions.
On the other hand, an energy performance gap of 74 kWh/m^2 is recorded between EEM34 and the normative requirements (EEM1). A smaller energy performance gap, 36 kWh/m^2, is observed between the cost optimal (normative compliant) solutions EEM18 and EEM34.

RB#01c – New single-family house

Single-family houses represent the most common building typology in Italy and EU, covering 52% and 64% of the residential building stock respectively[7]. Given this, in order to obtain results to be widely replicated on the building stock, RB#01c was selected. The RB was defined as representative of new construction single-family houses in compliance with the current regional and national minimum requirements of building energy performance. The RB description can be found in the summary table presented previously in Chapter 2. The cost optimal levels assessment is carried out in detail in **Paper III**.

Several measures were defined and applied to the RB, as depicted in Table 18:

- three solutions for the building insulation:
- four shading systems;
- three alternatives primary systems;

- three solar systems.

Since the possible combinations are quite numerous, only a limited number of EEMs was selected and evaluated by means of dynamic simulation for limiting the computational time. EEMs with external shading options, such as SO 3/4, were used only with high levels of envelope insulation (EI2/3) because of the higher demand for space cooling energy; technical systems with gas boilers, such as BTS0/1, were associated only with medium/low levels of thermal insulation EI0/1, while buildings with better insulation (EI2/3) were entirely based on heat pumps systems (BTS2/3). Overall 40 EEMs packages were simulated. EEMs from 1 to 29 were selected to assess the influence of insulation, shading options and building systems on the global cost. EEMs from 30 to 40 were defined to evaluate PV systems, combined with different heating and cooling system. EEMs 38/39/40, are equal to 19/24/28 (characterized by a low energy demand) but the entire roof was covered with PV panels (PV6,3) in order to achieve a Net Zero Energy balance. For additional information about the EEMs definitions, further details can be found in **Paper III**.

Table 18 – List of EEMs applied to the Single-family RB (RB#01c).

	Envelope insulation				Shading options					Building Technical Systems				RES Systems				
														Solar Collectors		PV System		
ID	0	1	2	3	0	1	2	3	4	0	1	2	3	DHW 80%	Heat	1.6	3.2	6.3
RB	■				■					■				■	■	■		
EEM1	■					■				■				■	■	■		
EEM2	■						■			■				■	■	■		
EEM3	■				■						■			■		■		
EEM4	■					■					■			■		■		
EEM5	■						■				■			■		■		
EEM6	■				■							■		■		■		
EEM7	■					■						■		■		■		
EEM8	■						■					■		■		■		
EEM9		■			■					■				■	■	■		
EEM10		■				■				■				■	■	■		
EEM11		■					■			■				■	■	■		
EEM12		■			■						■			■		■		
EEM13		■				■					■			■		■		
EEM14		■					■				■			■		■		
EEM15		■			■							■		■		■		
EEM16		■				■						■		■		■		
EEM17		■					■					■		■		■		
EEM18			■		■							■		■		■		
EEM19			■					■				■		■		■		
EEM20			■						■			■		■		■		
EEM21			■		■								■	■		■		
EEM22			■					■					■	■		■		
EEM23			■						■				■	■		■		
EEM24				■	■							■		■		■		
EEM25				■				■				■		■		■		
EEM26				■					■			■		■		■		
EEM27				■	■								■	■		■		
EEM28				■				■					■	■		■		
EEM29				■					■				■	■		■		
EEM30	■				■					■				■	■		■	
EEM31	■				■						■			■			■	

EEM32			■		■							■		■			■	
EEM33			■		■								■	■			■	
EEM34	■				■					■				■	■			■
EEM35	■				■						■			■				■
EEM36			■		■							■		■				■
EEM37			■		■								■	■				■
EEM38 ZEB1			■					■				■		■				■
EEM39 ZEB2				■	■							■		■				■
EEM40 ZEB3				■				■					■	■				■

In order to perform the economic assessments, several assumptions were made as provided in Table 19, together with other input data necessary for finding the cost optimal solution.

Table 19 – Assumptions and input data for cost-optimal calculations of the Single-family RB (RB#01c).

COST-OPTIMAL CALCULATION INPUT DATA AND ASSUMPTIONS	
Reference Building	New Single-family House – RB#01c
Energy efficiency Measures/Variants	40 of packages of energy efficiency measures investigated: - Three different insulation levels; - Four shading solutions; - Three different systems solutions; - Three different solar system variants;
Energy performance assessment method	Dynamic hourly building simulation based on EN ISO 13790 EnergyPlus dynamic building simulation program
Economic assessment method	Global cost calculation – net present value method (UNI EN 15459) Financial perspective (private investor)
Calculation period	50 yrs (whole building lifecycle)
Cost categories	- Investment cost - Residual value - Replacement cost - Maintenance cost - Energy cost
Building components Lifetime	Set in compliance with Standard EN 15459
Inflation	2.15 %/a
Market rate	2.67 %/a
Energy price	0.899 €/m£ for natural gas 0.190 €/kWh for electricity 0.039 €/kWh for feed-in tariff for PV electricity

As calculations are performed for a new construction, the calculation period was set to 50 years, that corresponds to the whole building lifecycle. Based on an average of the Euro area trend in the last 10 years, the inflation rate and the market rate were set to 2.15%, and to 2.67% respectively. Investment costs were set fulfilling the 2013 Price list of the Piedmont Region, after VAT. Maintenance costs were defined in compliance with Standard EN 15459, as specific percentage of the investment costs. The replacement period was also set based on the Standard EN 15459 (e.g. windows lifespan was set to 25 yrs). The real interest rate was adjusted to inflation as the financial perspective was assessed.

Looking at the calculation results in Figure 28, the cost optimal solution is reached in EEM9 and 10, with a level of thermal insulation higher than minimum requirements, combined with internal or between-glass shading systems, condensing gas boiler with water terminals integrated by solar collectors, direct expansion cooling and a small amount of photovoltaic panels.

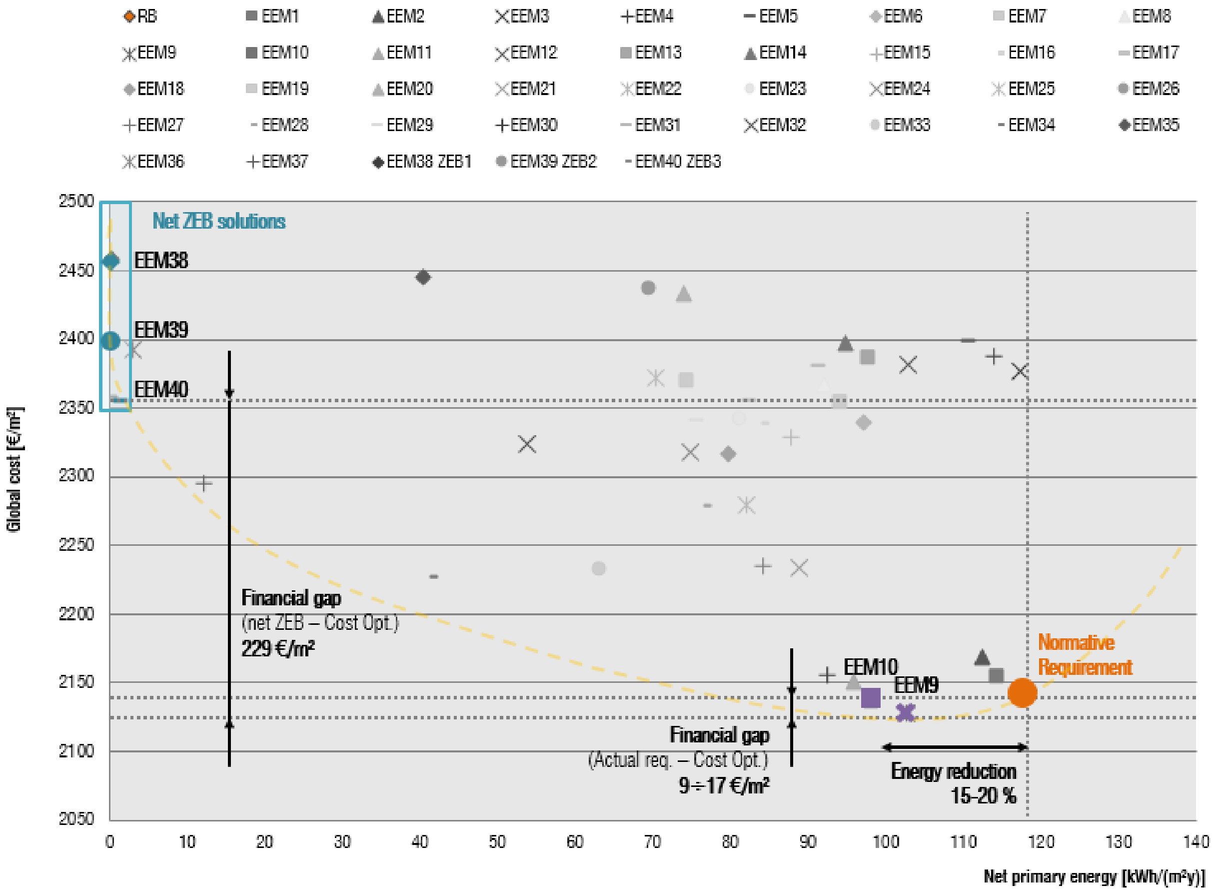


Figure 28 – Global cost calculations for RB#01c

A small financial gap, accounting to a 9÷17 €/m^2, is met between the cost optimal solutions and the RB (normative requirements). Cost optimal solutions are thus quite close to actual minimum requirements in terms of global costs. On the other hand, relevant energy savings, from 15 to 20% can be reached in the building primary energy consumption indeed.

Net ZEB solutions allow energy savings from 2 to 118 kW h/m^{2}y (net primary energy) in absolute terms, and from 2 to 100% in percentage terms. In order to reach net zero balance solutions, high levels of thermal insulation, heat pump with mechanical ventilation and heat recovery, and the maximum level of PV installed are required.

Sensible differences, in terms of global cost, can be found in the three solutions studied, ranging from EEM40 with 2357 €/m^2 to EEM38 with 2457 €/m^2. The financial gap between the actual minimum requirements and the net ZEB solution is hence quite large, accounting for a 10% increase on the global cost.

The difference, in terms of cost, is due to higher maintenance and replacement costs than in the RB case, as reported in Figure 29. On the contrary, as the RB is a new construction, the difference in the investment cost regards only the building systems, while costs are similar for the building envelope components.

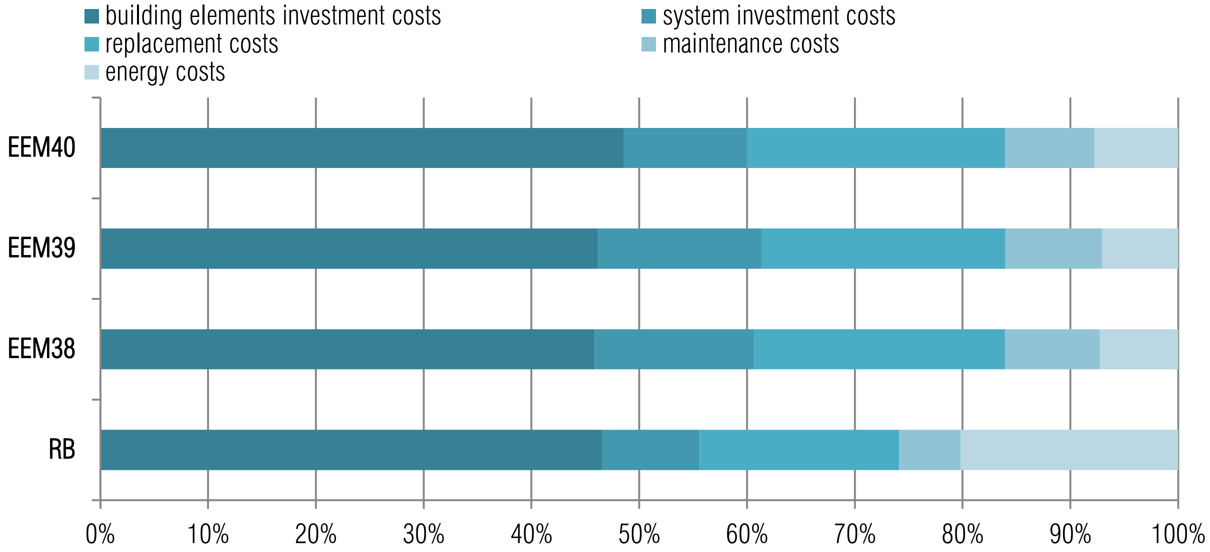


Figure 29 – Cost break down analysis for the RB case (minimum requirements) and the net ZEB solutions.

RB#02 – Existing office building

The RB was defined in compliance with the current regional minimum requirements of building energy performance. The RB description can be found in the summary table presented previously in Chapter 2. The cost optimal levels assessment is carried out in detail in **Paper II**.

In total 24 packages were studied and applied to the RB. The EEMs packages were distinguished in two different set of EEMs. Similarly to RB#01b, the first set, from EEM1 to 12, was composed by EEMs distinguished in “homogenous” and “not homogenous” measures aimed at the improvement of the building envelope performance. The U-value of the building envelope components set within this set of EEMs are reported in Table 20.

Table 20 – EEM1 to 12 applied to the Office RB (RB#02).

EEM DESCRIPTION and ID		U-value [W/m²K]	EEM DESCRIPTION and ID		U-value [W/m²K]
RB	Walls	0.75	EEM7	Walls	0.75
	Windows	3.19		Windows	1.5
	Roof	0.81		Roof	0.81
	Ground slab	1.45		Ground slab	1.45
EEM1	Walls	0.33	EEM8	Walls	0.75
	Windows	2		Windows	3.19
	Roof	0.29		Roof	0.22
	Ground slab	0.30		Ground slab	0.26
EEM2	Walls	0.24	EEM9	Walls	0.24
	Windows	1.5		Windows	1.5

	Roof	0.22		Roof	0.81
	Ground slab	0.26		Ground slab	1.45
EEM3	Walls	0.14	EEM10	Walls	0.75
	Windows	1.2		Windows	1.2
	Roof	0.15		Roof	0.81
	Ground slab	0.16		Ground slab	1.45
EEM4	Walls	0.75	EEM11	Walls	0.75
	Windows	2		Windows	3.19
	Roof	0.81		Roof	0.15
	Ground slab	1.45		Ground slab	0.16
EEM5	Walls	0.75	EEM12	Walls	0.14
	Windows	3.19		Windows	1.2
	Roof	0.29		Roof	0.81
	Ground slab	0.30		Ground slab	1.45
EEM6	Walls	0.33			
	Windows	2			
	Roof	0.81			
	Ground slab	1.45			

The second set of EEMs, from EEM 13 to 24, consisted in the introduction of an artificial lighting control (ALC) and in the different solution of PV panels installation on the plane roof (the entire roof with PV panels, one half of the roof with PV panels, covering of one fourth of the roof with PV panels). Since the possible combinations are quite numerous, as reported in Table 21, only some EEMs, from the first set, were considered for the implementation of the second set of EEMs, based on a first stage cost optimal calculations. EEMs 3, 8 and the RB were thus selected and used for the definition of seven additional EEM packages. For additional information about the EEMs definitions, further details can be found in **Paper II**.

Table 21 – EEM13 to 24 applied to the Office RB (RB#02).

EEMS DESCRIPTION		**1st STAGE EEM CONSIDERED**	**ID**
Package 1	ALC	RB	EEM13
		EEM3	EEM14
		EEM8	EEM15
Package 2	PV: 100% roof	RB	EEM16
Package 3	PV: 50% roof	RB	EEM17
Package 4	PV: 25% roof	RB	EEM18
Package 5	ALC PV: 100% roof	RB	EEM19
		EEM3	EEM20
Package 6	ALC PV: 50% roof	RB	EEM21
		EEM3	EEM22
Package 7	ALC PV: 25% roof	RB	EEM23
		EEM3	EEM24

Similarly to the other studied RBs, Table 22 lists the main financial assumptions, together with other input data necessary for finding the cost optimal solution. Since calculations refer to an existing building, the calculation period was set to 30 years as suggested by the Guidelines [78]. The real interest rate was set to 4%, excluding inflation, in compliance with [78], as with this calculation the macroeconomic perspective was assessed. Investment costs were set fulfilling the 2012 Price list of the Piedmont Region. With regard to the replacement and maintenance costs, they were defined in compliance with Standard EN 15459.

Table 22 – Assumptions and input data for cost-optimal calculations for the office reference building (RB#02).

COST-OPTIMAL CALCULATION INPUT DATA AND ASSUMPTIONS	
Reference Building	Existing medium office building – RB#02
Energy efficiency Measures/Variants	24 of packages of energy efficiency measures investigated: - Twelve different insulation levels; - Twelve EEMs with artificial lighting control and RES based on PV systems;
Energy performance assessment method	Dynamic hourly building simulation based on EN ISO 13790 Simulation program :EnergyPlus
Economic assessment method	Global cost calculation – net present value method (UNI EN 15459) Macroeconomic perspective (societal)
Calculation period	30 yrs
Cost categories	- Investment cost - Residual value - Replacement cost - Maintenance cost - Energy cost
Building components Lifetime	Set in compliance with Standard EN 15459
Real Interest Rate	4 %/a
Energy price	0.083 €/m^3 for natural gas 0.16 €/kWh for electricity 0.089 €/kWh (11 kWp) or 0.075 €/kWh (21 and 38 kWp) for 20 years as incentive for the electricity consumed on site: feed-in tariff: 0.171 €/kWh (11 kWp), 0.157 €/kWh (21 and 38 kWp) taken for 20 years; 0.03 €/kWh from 21st to the 30th year.

Looking at the calculation results in Figure 30, the simulated EEMs allow energy savings from 6 to 97 kWh/m^2y in absolute terms, and between 4 and 58%, in percentage terms. Global cost values higher than RB tend to be the ones of the envelope EEMs, because the investment costs for the different efficiency measures cannot be repaid by the economic savings associated with energy savings obtained. Global costs lower than the cost of the RB tend to be associated with systems EEMs. The cost optimal solution is reached in EEM13, with the minimum level of thermal insulation required by law, combined with a condensing boiler and a chiller with fan coil units, and a system for the artificial lighting control. System from the energy production from RES are not included within this EEM. EEM13 corresponds to 499 €/m^2 as global cost and to 143 kWh/m^2 as primary energy consumption, bringing approximately to a 8% and 14% reduction on the global cost and energy consumption respectively.

Minimum energy consumption are reached with EEM20, EEM22 and EEM24. The minimum value of consumption is achieved with the EEM20, which corresponds to a high level of thermal insulation, (EEM3), combined with the artificial lighting control and the covering of the entire roof with PV panels (power: 38 kW_p), which covers approximately 65% of the building energy demand. Overall a 58% energy saving, with reference to the minimum energy requirements (RB), is obtained with EEM20.

With regard to the financial gap, relevant differences in the overall global cost are detected between low energy solutions (identified with EEM20,22 and 24) and the cost optimal solution. Large financial gaps, respectively of 153 and 120 kWh/m^2 are observed, between the low energy solution EEM20 and the cost optimal solution EEM13, and between EEM20 and the minimum requirement (EEM1). This EEM requires thus high disposal of financial capitals given the higher investment cost related to the energy retrofit interventions.

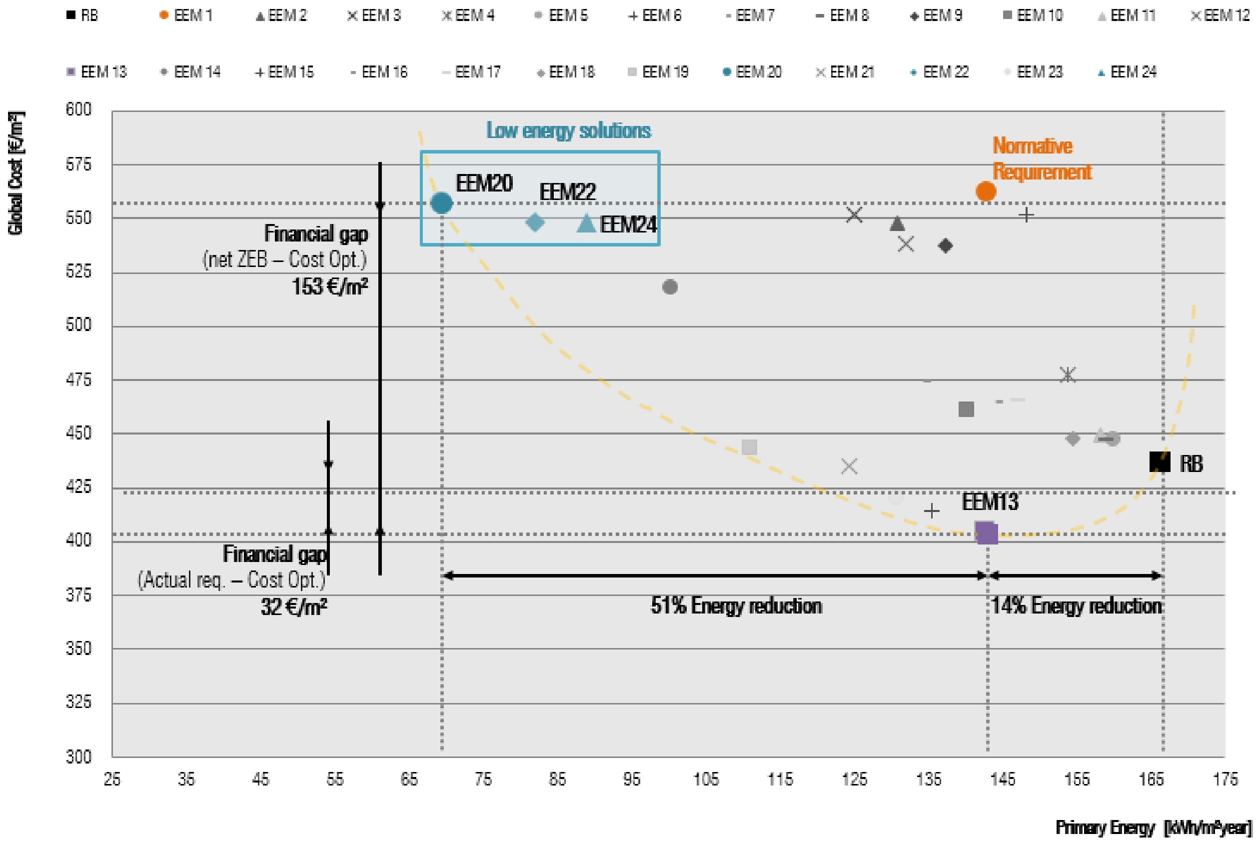


Figure 30 – Global cost calculations for the office reference building (RB#02).

5.4 Focus on Paper IV: COA application on single buildings

The COA methodology can also be used for the economic assessment of building-specific energy retrofit measures on single buildings. To this regard it was applied to the calibrated building model of the multi-family building described previously in Chapter 3. In particular, the building was calibrated based on data from monitoring and COA was applied for the economic evaluation of radiator thermostatic valves as low investment energy efficiency measure, as reported in **Paper IV**. This building was also defined as reference building in Chapter 2 (RB#01a), as it can be considered representative of historical residential buildings in the North of Italy. The selected case study, an existing multifamily building located in Turin (North Italy), was thus built at the beginning of XIX century and belongs to the category of heritage protected buildings. The RB description can be found in the summary table presented previously in Chapter 2.

The range of energy efficiency measures that can be applied to heritage protected buildings, is quite small. Radiator thermostatic valves were selected for the aim of this study as, due to building construction age and to its belonging to the cultural heritage patrimony, they represented one of the most eligible EEMs for reducing the energy consumptions with the lower impact on the building structure. Other kinds of EEMs, which may obtain higher energy savings, such as those concerning the building envelope could not be taken into consideration for their impact on the building façade, subjected to protection and thus to architectural restraints for its cultural heritage. Therefore it is important to point out energy retrofit actions to be widely applied to the whole building stock and to be cost optimal. To this regard, thermostatic radiator valves represent a quite common refurbishment measure, which is to be reinforced by law by 2016 in the city of Turin, and that can bring an average energy saving from 10% to 50% if considered together with the increase of the envelope thermal insulation.

This case study represents a real existing RB but also a single building model, calibrated based on the measured total heating energy rate delivered at the building district heating sub-station for about two months operation during the winter season. The case study was simulated with and without TRVs. The application of TRVs was proved to bring back significant energy savings, around 10% in compliance with results found in literature. Different simulations (referred as Scenario) were performed for evaluating the effect of the thermostatic valves on the building energy consumptions. To this regard, for simulating the use of the TRVs by the occupants' opening of the TRVs, different temperature set points, and thus different thermostats were defined based on the occupants' habits with the TRVs setting.

Unlike the other COA applications presented previously presented, only one measure, corresponding to the radiator thermostatic valve application, was studied by means of the cost optimal methodology. Table 23 lists the main calculation assumptions. The annual maintenance cost of the TRVs package was set to 1.5% in compliance with the Appendix A of EN 15459. Overall the total investment cost (Table 24) can be considered affordable, accounts for approximately 7.3 €/m^2, as depicted in Table 25. Due to a reduction on the running cost, also a lower global cost is achieved. Looking at the "Scenario 3" a mean energy savings of 9.11 kWh/m^2 was achieved. It means that in less than 7 years the overall investment cost

(15'484 €) can be overcome. Considering the building is served by the district heating network, approximately 2'300 € per year may be saved. If not served by the district heating grid, higher savings, around 14'000 €, may be reached.

Table 23 – Assumptions and input data for cost-optimal calculations

COST-OPTIMAL CALCULATION INPUT DATA AND ASSUMPTIONS	
Reference Building	Existing Multi-family House – RB#01a
Energy efficiency Measure	Implementation of radiator thermostatic valves
Energy performance assessment method	Dynamic hourly building simulation based on EN ISO 13790 Simulation program :EnergyPlus
Economic assessment method	Global cost calculation – net present value method (UNI EN 15459) Financial perspective (private investor)
Calculation period	30 yrs
Cost categories	- Investment cost - Residual value - Replacement cost - Maintenance cost - Energy cost
Building components Lifetime	Set in compliance with Standard EN 15459; 20 yrs for the thermostatic valves replacements
Real interest rate	2.28 %/a
Energy price	0.12 €/m£ for the district heating tariff

Table 24 – Investment cost for the thermostatic valves installation.

EEM PACKAGE	**TOTAL COST [€]**
TRVs package per radiator	
Valve with lockshield (supply included)	2,345.00
Radiator control (supply included)	1,953.00
Radiator radio heating counter (supply included)	2,520.00
Assembly (Removing of old valves and installation of new TRVs)	435.00
Energy measures at the building level	
System pump with variable flow rate	6,400.00
System scrubbing for removing contaminants	1,830.00
	15,484.00

In a view of retrofitting the existing building stock, among a wide range of EEMs, from the building envelope interventions to the improvement of the building systems, TRVs can thus be considered low investment cost measures that can be easily applied to large portions of the existing dwellings, including the historical buildings.

Table 25 – Global cost calculation for the thermostatic valves installation.

	ENERGY CONSUMPTIONS	INVESTMENT COST	REPLACEMENT COST	RUNNING COST	FINAL VALUE	GLOBAL COST
	kWh/m^{2}a	€/m^2	€/m^2	€/m^2	€/m^2	€/m^2
RB	115	0.00	0.71	303.03	-0.45	303.29
Scenario 1A	103	7.32	2.19	277.17	-0.93	285.76
Scenario 1B	105	7.32	2.19	281.69	-0.93	290.27
Scenario 1C	113	7.32	2.19	302.55	-0.93	311.13
Scenario 2A	103	7.32	2.19	276.72	-0.93	285.30
Scenario 2B	108	7.32	2.19	289.42	-0.93	298.00
Scenario 2C	113	7.32	2.19	302.17	-0.93	310.76
Scenario 3A	103	7.32	2.19	275.81	-0.93	284.39
Scenario 3B	105	7.32	2.19	283.15	-0.93	291.73
Scenario 3C	108	7.32	2.19	290.52	-0.93	299.10

5.5 Critical discussion

Since its introduction, cost-optimality has become a well-established procedure at EU level per evaluating the energy performance of buildings, both at economical and energy level. As previously mentioned Member States are required to implement it for establishing national minimum requirements for the energy performance of buildings and building elements. The methodology is well defined within the EPBD recast [81] and its accompanying guidelines [78]. Nevertheless, as its application is far from being easy and straightforward, assessing the cost-optimal analysis constitutes a big challenge.
Several assumptions that impact on the calculations, need to be made to perform a COA. Except for a few suggestions included in the guidelines accompanying the EBPD directive (e.g. setting the discount rate to 3% in the macroeconomic perspective), the perspective adopted and the assumptions in the calculations are left to the users.

An important and very influential phase for the cost-optimal methodology is thus the selection of input factors, which establishment and definition should be closely regarded. Without a proper guidance, there is thus a risk that the cost-optimal methodology could lead to a misalignment between the defined cost-optimal levels and the long-term goals, leaving a significant energy saving potential unexploited. It is thus necessary to focus on the implication of choosing different values for key factors (e.g. discount rates, simulation variants/packages, costs, energy prices) at national levels.

To this regard, sensitivity analyses, as also stated in the Directive guidelines [78], should be performed to assess uncertainties in the calculation assumptions, such as the variation of energy prices as well as the interest rate. Sensitivity analyses allow to show that the change of one input factor (discount rate, energy price development) has a certain influence on the results and this influence became significant if two input factors are changed simultaneously.

Another important factor is the reference building selection. When dealing with cost optimal analysis with possible impact on a wide-range building stock, representativeness in a narrow sense cannot be achieved. On one hand, this deals with the concept of representative as applied to a reference building. In this sense, the RB cannot be considered realistic of the whole building stock but also of a portion of it. To this regard, it is important to not overestimate the impact of the precise definition of reference buildings on cost optimal analysis. For instance similar results were obtained for single and multi-family house within cost optimal studies [80]. On the other hand, it is also advisable to select more than one reference building per building category. In order to get a more comprehensive and representative picture on cost optimal analyses, different RB may be necessary for describing different building forms, sizes, etc. within the same building typology.

Cost-optimality can be considered from different points of views, which can drive towards different results. Therefore, it is fundamental to establish the objective of the cost-optimal analysis in order to customize calculation in term of input data and of expected outcomes. As depicted within this Chapter and prescribed in the EPBD [81], the methodology was created for being addressed to national authorities and not to investors. Therefore cost optimal levels, in order to provide generally applicable results at national level, should not be applied to single buildings for calculations, but rather to reference buildings. The consideration of the investors' perspective is not suggested as each investor will have its own perspective and it will be different from the perspective of another investor. Therefore, a multitude of cost optimal levels will need to be defined in order to match each one with the relative investor's perspective and it will thus bring to the establishment of different minimum energy requirements.

Within this Ph.D. thesis, the cost optimal analysis is applied to different case studies based on different purpose. First, following the EPBD recast, the COA is used with reference buildings to draw renovation scenario at national level. Concerning this particular application with reference buildings, both the macroeconomic and microeconomic perspective, as prescribed by the regulation, were assessed. Second, the COA was employed for providing an economic assessment of the renovation interventions on single buildings. In this case, the cost-optimal analysis is customized for a real specific context, and applied to a calibrated building energy model.

Uncertainties in economic calculations are faced in both cases (single building and reference buildings), in particular with regard to assumptions related to future development (e.g. inflation rate, energy price, etc.). Therefore, as previously stated, sensitivity analyses should be performed and integrated in the cost optimal methodology.

With regard to the results presented within this Ph.D. thesis, large and sensible differences are observed in the calculations performed given the different building typology, perspectives and the construction age considered.

Looking at the full cost optimal analysis applied to the reference buildings case studies, generally large financial gaps between the minimum energy requirements and the net ZEB (single family house) or low energy solution (office building) are met. Nevertheless, a smaller financial gap is encountered, for the new single-family house reference buildings, between the cost optimal solution and the minimum energy requirements. The cost optimal solution is thus not far from the actual requirements as the case of a reference buildings for new construction is investigated. At the same time, for the existing office reference building, due to higher investment costs, a larger financial gap is faced.

For the existing reference buildings, the cost optimal analysis investigated deep renovations at the whole building level. This application demonstrated that even when the retrofit measures are cost effective, they revealed to be too expensive as demonstrated by the financial gap between the cost optimal solution and the more energy performing solutions (net ZEB and low energy). That gap shows that, regardless of the perspective considered (societal or single investor), efforts need to be made at national level to support renovation interventions. In particular, it is important to fill up the lack of funds which are necessary to secure finance but, on the contrary, have been tighten up by the current financial crisis. The upfront capital required for covering the investment cost overcomes the financial instruments currently available. As stated previously in Chapter 1, financial barriers represent the first and greater obstruction to a wide renovation of the building stock. In addition to the already widespread grants, subsidies and tax incentives, more effective financial instruments have to be promoted and enhanced by EU and especially by MS at national level. Concrete actions need to be taken to unlock private investors and attract them into financing deep renovations on the existing building stock.

However, contextually to the creation of more supportive financial instruments, it is equally important to fill the lack of confidence towards the financial benefits that can be achieved from deep renovations of the existing building stock and that characterize the financial institution but especially investors. This lack of confidence, spread out also because of the financial crisis, is especially due to the lack of clarity and information about the actual effectiveness of deep renovations.

The COA, if correctly implemented by researchers, can serve as an instrument for sharing important outcomes about the cost-effective energy saving solutions. On one hand, researchers can receive new suggestions from the professional community about which EEMs include in cost optimal studies, considering new and feasible technology solutions. On the other hand, the outcomes of these studies may be used by professionals for concretely implementing cost and energy effective solutions in new construction or renovation projects.

Moreover with the Italian legislative decree 90/2013 to enter into force from July 2015, cost optimal analysis are necessary in order to optimize the cost/benefits ratio of energy efficiency measures towards the definition of nZEB. To this regard, a recognized and comprehensive definition of nZEB at national level is necessary for the definition of the energy performance requirements to refer to when dealing with COA analyses.

6.

Conclusion

The research conducted within the present Ph.D. thesis led to the definition of a methodology for the energy retrofit of the existing building stock. In fact, due to the high energy consumption, low energy performance and old construction age of existing buildings, larger energy savings can be achieved with the retrofitting of the existing building stock rather than with the construction of small portion of new energy efficiency buildings. The annual rate of new constructions, around 1% in Europe, hinders thus the potential of energy savings that can be achieved with the application of the new energy performance requirements from current standard and regulations. Retrofitting existing buildings represents the most realistic and concrete option for the reduction of the building energy demand indeed. Therefore, the research addressed the existing building stock with a systematic methodology.

This works attempted to make a contribution to the professional community by providing some guidelines for the definition of energy retrofit scenario, which can be scaled based on the aim and the objective of the study. Two different scales of buildings were studied: the one of the building stock and the one of single building. In the first case, when defining renovations for large sample of buildings, such as portions of the existing building stock (e.g. at national level), reference buildings were used as representative models of the building stock. On the other hand, when a smaller renovation scale is considered, single buildings became the objective of the study and were analysed by means of models of existing building calibrated based on monitoring data.

Outcomes of different scales were also attained from the application of the methodology. The outcomes correspond thus to the different scale of retrofit solutions achieved: on one hand by using representative models, a series of energy retrofit interventions were defined for being further applied to and replicated in similar buildings, which constitute a portion of the building stock; on the other hand, single customized renovation measures were studied for specific buildings. The flexible "scale" characterizes the methodology proposed, which can thus be adapted based on the aim pursued.

From the results and the discussion reported in this thesis, some recommendations are made in general with regard to the methodology and, in detail with regard to the different cross topics.

Overall it is important to report that the methodology presented within this research didn't aim to provide an exhaustive solution for the definition of retrofitting scenario for the existing building stock. It wasn't conceived to accomplish this purpose.The methodology should be rather regarded as guidelines for being used by professionals (e.g. architects, engineers, etc.). Different systematic steps were identified within the methodology with a view of an integrated design approach. The methodology was defined fulfilling the requirements of the legislation in force, at Italian and European level, and was intended to push the application of building simulation towards the community of professionals.

To this regard, the selection of dynamic building simulation as tool for carrying out the energy assessment of energy retrofit scenarios was justified by the high level of detail achievable during simulations. Moreover, building simulation application is growing due to the international endorsement received by many standards and bodies as reference tool for the building energy assessment, such as the LEED protocol. In addition, within EU, the EBPD recast strongly recommends the use of dynamic building simulation for the calculation of cost optimal levels of energy performance. Furthermore, the design of sustainable architecture has been recently requiring integrated design approaches based on a more extensive role of building simulation in particular during early phases of the design process. The simulation-based design is thus becoming the standard approach during the design of high performing buildings. Of course, many criticalities can be faced in the used of building simulation programs, but the growing application of building simulation is paving the way to the development of new programs with user-friendly interface and the designers' experience in the building simulation domain is growing as well.

With regard to the scale of representative models, reference buildings can serve as an instrument to draw and estimate the impact of widespread and representative renovation scenarios on the existing building stock. Reference buildings can be thus exploited as a basis for analysing energy saving potentialities by retrofitting the national building stock in fast analysis as well as in detailed ones. Moreover, they are often worldwide employed for carrying out benchmark calculation analysis.
To this regard, their application is explicitly requested for applying measures improving the building energy performance at European level by the EPBD recast for the purpose of the cost-optimal methodology. With reference to Italy, the legislative decree 90/2013, in force starting from the 1st July 2015, will require the use of reference buildings as baseline buildings for the implementation of the EBPD recast. RBs will be used for establishing minimum requirements of energy performance for new buildings and existing building subjected to major renovations. Similarly to the approach of the ASHRAE Standard 90.1, the normative check of the minimum requirements will thus be based on the comparison of the new building (or the retrofitted existing building) energy performance with that of the reference (baseline) building. Beyond code compliance applications, such as in the Standard 90.1 and the legislative decree 90/2013, baseline buildings are also used within performance paths as in the USGBC LEED program. Reference buildings application and relevance is thus destined to increase at national and international level in the next years.

With regard to the second scale of buildings studied, different remarks are made. As opposed to reference buildings, which can be used in the early phases of the design process, calibrated models are requested for addressing the performance gap between the real building energy consumption and the simulated energy performance. Calibrated building models are thus employed in post-construction phases (e.g. building commissioning, estimation of energy savings from energy retrofit interventions on existing monitored building, failures detection and diagnostic studies, etc.) and their application is thus of growing importance.

As stated in this research, many issues have to be faced during the calibration process. To this regard, it is relevant not to underestimate the role of users that with their assumptions can have a large impact on the calibration of the building model. Moreover, a systemic procedure should be employed, with the integration of sensitivity and uncertainty analyses. As observed during the presented calibrations, data quality and quantity strongly impact on the outcomes of the calibration. Therefore, it is important to verify if the information available is necessary for carrying out a calibration study and which level of calibration can be performed.

Calibration studies of simplified energy models prevails over those of dynamic building energy models. Some studies states that the use of simplified models does not compromise the model accuracy, nervertheless, this research chose to pave the way of more detailed building models. Undoubtedly, the building model definition is more complex but towards the diffusion of an integrated building design approach, calibrated dynamic building models can be employed to complete wih additional information BIM models. The use of BIM (Building Information Modeling) is of growing importance in the design process. Calibration can be the missing piece of whole building, represented by the BIM as a puzzle composed of different pieces. As the BIM is an intelligent model-based process that guides professional to plan, design, construct, and manage buildings and infrastructure, the integration of the calibration is fair to the point.

Furthermore, to date, the application of monitoring and management technologies is increasing for checking the building energy performance and when necessary, for reducing and optimizing it. Calibrated building models can help designers in the definition of renovation solutions and can especially forecast the building energy consumption and performance based on data from monitoring.

Concerning the economic assessment of the energy retrofit, the cost-optimal methodology, as defined by the European Directive 2010/31/EU, was selected for the aim of this research in order to attain useful outcomes for professionals at national levels. In particular, the application of the cost-optimal analysis was addressed to national authorities, as suggested by EU regulation but also to single investors. Therefore, it was applied to reference buildings, considering both the macroeconomic and microeconomic perspective, for obtaining representative results and to single buildings, for customized studies.

The cost-optimal methodology represents hence the normative reference at European and Italian levels for the definition of minimum requirements of the building energy performance. Since its introduction cost-optimality has become a well-established procedure but its application is far from being easy and straightforward. The complexity of the methodology is due to the several assumptions that accompany calculations and which establishment and definition should be closely regarded. Therefore sensitivity analyses should be performed to assess uncertainties in the calculation assumptions.

Beyond the reported remarks on the methodology, come critical observations need to be made.

Despite the different positions held in the literature about their effectiveness and utility, given the limited statistical knowledge about the building stock, it is fair to assert that the definition of Reference Buildings has a more arbitrary nature. This can be regarded as a source of deviation and inconsistency in the representativeness and accuracy of the outcomes when using RBs. In fact, RBs cannot provide an accurate and realistic description of the building stock as a whole. It is important to bear into mind that RBs can provide a fair picture of a rather small sample of existing buildings indeed. Therefore, the term representative should not be intended in absolute terms.

Moreover, representativeness-in a narrow sense-cannot be achieved if only one reference building is selected per building category. When carrying out studies with a wide spread impact on the building stock, such as cost optimal analyses, an accurate selection of reference buildings is a prerequisite to reach realistic results. To this regard, due to the limitations of the research carried out, the reference buildings defined within this thesis are not an exhaustive results but can rather be seen only as a piece of the puzzle. In order to represent the reality as faithfully as possible, furthers studies will be necessary for defining additional reference buildings.

Moreover and with regard to the reference buildings, the energy retrofit measures studied were not intended to be representative and replicated to the same building typology in the existing building stock. They cannot be considered exhaustive as many potential retrofit solutions could be defined. Therefore, as for reference buildings, representativeness-in a narrow sense cannot be applied to the outcomes of this research.

The use of dynamic building models limited the number of energy retrofit solutions to be studied. Indeed, the modelling and computational time related to the assessment of several measures in building simulation programs, can be extremely high and, consequently affect the outcomes delivery.

On the other hand, it also important to made a selection of “feasible and realistic” energy retrofit measures, omitting those that do not fulfil with the requirements of feasibility from both the economic and technical perspective.

However, further efforts are needed to enlarge the set of energy retrofit solutions to consider. Parametric analyses applied to building simulation programs may help overcoming this issue.

Recently the mismatch between building simulated and real energy consumption is of growing importance. So far bridging the gap between the predicted (at design stage) and measured energy consumption of real building is of high interest as also demonstrated by the program EeB7–2015 (Energy-Efficient Buildings), *“New tools and methodologies to reduce the gap between predicted and actual energy performances at the level of buildings and blocks of buildings*”, within the H2020 call for funding research activities.

Notwithstanding, further steps need to be taken to reduce this gap. Beyond monitoring the building real operation, the next step aims to forecast the building energy consumption to predict failures in the future building operation and optimize the building energy performance. Many monitoring technologies allow the collection of large amount of data about the building and its use, but do not provide further analysis on the gathered data. In order to cope with this objective calibrated energy models, created within building simulation programs, can be used as tools for predicting the building real operation and also for forecasting other parameters (e.g. weather). The comparison between the “predicted” and the actual energy performance allows to verify the proper building energy operation or to detect possible anomalies or failures in the system operation.

To this regard, calibration of building models can represent a clear answer. The use of calibration as standard methodology for the definition of renovation scenario on monitored buildings should also be promoted between professionals and not only in academic domain.

Looking at the full cost optimal analysis applied to the reference buildings, generally large financial gaps between the minimum energy requirements and the net ZEB or low energy solutions were met. Even when the retrofit measures demonstrated to be cost effective, they were still too expensive. Financial barriers represent thus the first and greater obstruction to a wide renovation of the building stock. Therefore, efforts need to be made at national level to support renovation interventions.

7.

References

[1] European Commission, «Directive 2010/31/EU of the European Parliament and the Council on the energy performance of buildings (recast),» *Official Journal of the European Union,* n. L153, p. 40–43, 2010.

[2] European Commission, Febraury 2015. [Online]. Available: http://ec.europa.eu/energy/en/topics/energy-efficiency/buildings.

[3] B. Lapillonne, K. Pollier e C. Sebi, «Energy Efficiency Trends in the EU. Lessons from the ODYSSEE MURE project,» ODYSSEE MURE project supported by Intelligent Energy Europe, 2013.

[4] BPIE, A guide to developing strategies for building energy renovation, Brussels: Building Performance Institute Europe (BPIE), 2013a.

[5] ISTAT, «Edifici e abitazioni,» ISTAT, Roma, 2014.

[6] M. Economidou e P. Bertoldi, «JRC Science and Policy Reports. Financing building energy renovations. Current experiences & ways forward.,» Publications Office of the European Union, Luxembourg, 2014.

[7] BPIE, Europe's buildings under the microscope, Brussels: Building Performance Institute Europe (BPIE), 2011.

[8] European Commission, «Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings,» *Official Journal of the European Communities,* n. L1, pp. 65-77, 2002.

[9] European Commission, «Directive 2012/27/EU of the European Parliament and the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC,» *Official Journal of European Union,* n. L 315, pp. 1-56, 2012.

[10] European Commission, «Commission staff working document accompanying the document. Report from the commission to the European Parliament and the Council. Financial support for energy efficiency in buildings. COM(2013) 225 final,» European Commission, Brussels, 2013.

[11] S. Shnapp, R. Sitjà e J. Laustsen, «What is a deep renovation definition?,» Global Buildings Performance Network., Paris, 2013.

[12] BPIE, Europe's buildings under the microscope, Brussels: Building Performance Institute Europe (BPIE), 2011.

[13] ISTAT, «L'abitazione delle famiglie residenti in Italia: Anno 2008. Statistiche in breve: famiglia e società.,» ISTAT, Roma, 2010.

[14] Eurostat, «Energy, transport and environment indicators. 2014 Edition,» Publications Office of the European Union, Luxembourg , 2014.

[15] M. Nocera, «Le detrazioni fiscali del 55% per la riqaulificaizione energetica del patrimonio edilizio esistente -2012,» Agenzia Nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile, Roma, 2014.

[16] The Economist Intelligence Unit, «Investing in energy efficiency in Europe's buildings. A view from the construction and the real estate sector.,» commissioned by the Global Buildings Performance Network (GBPN) in collaboration with its EU hub, The

Buildings Performance Institute Europe (BPIE) and in partnership with the World Business Council for Sustainable Development (WBCSD)., 2013.

[17] European Commission, «Energy-Efficient Buildings- Multi-annual roadmap for the contractual PPP under Horizon 2020,» European Union, Brussels, 2013.

[18] FIEC, «2014-11-12 - FIEC Position - FIEC reaction on energy efficiency,» FIEC - European Construction Industry Federation, Brussels, 2014.

[19] Tackling Fuel Poverty in Europe. Recommendations Guide for Policy Makers, European Fuel Poverty and Energy Efficiency project (EPEE) Intelligent Energy Europe, 2009.

[20] L. Mark, D. Urge-Vorsatz, K. Blok, L. Geng, D. Harvey, S. Lang, G. Levermore, A. Mongameli Mehlwana, S. Mirasgedis, A. Novikova, J. Rilling e H. Yoshino, «Residential and commercial buildings,» in *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge and New York, Cambridge University Press, 2007.

[21] DECC, «Annual Report on Fuel Poverty Statistics 2013,» Department of Energy & Climate Change (DECC), London, 2013.

[22] FIEC, «FIEC – BFW position paper:Financing Solutions for Energy Savings in Housing. A view from the construction industry,» European Construction Industry Federation (FIEC), Brussels, 2011.

[23] IEA, «Energy Efficiency Governance Handbook. Paris:.,» International Energy Agency (IEA), Paris, 2010 .

[24] European Commission, «Communication from the commission to the european parliament, the council, the european economic and social committee and the committee of the regions. A roadmap for moving to a competitive low carbon economy in 2050,» European Commission, Brussels, 2011.

[25] European Commission, "Europe 2020 - A strategy for smart, sustainable and inclusive growth," COM (2010) 2020 final, European Council conclusions, Brussels, 2010.

[26] European Commission, «Regulation (EU) No 1291/2013 of the European Parliament and of the Council of the 11 December 2013 establishing Horizon 2020 - the Framework Programme for Research and Innovation (2014-2020) and repealing Decision No 1982/2006/EC,» *Official Journal of the European Union,* n. 347, pp. 104-173, 2013.

[27] European Commission, «Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC,» *Official Journal of the European Union,* n. L 140, pp. 16-62, 2009.

[28] V. Bürger, «Overview and assessment of new and innovative integrated policy sets that aim at the nZEB standard.,» ENTRANZE Project. , 2013.

[29] K. Field, M. Deru e D. Studer, «Using DOE Commercial Reference Buildings for Simulation Studies. NREL/CP-550-48588,» NREL, 2010.

[30] NREL, PNNL e LBNL, «U.S. Department of Energy Commercial Reference Building Models of the National Building Stock. Tehcnical Report NREL/TP-5500-46861,» NREL, Golden, 2011.

[31] U.S. Department of Energy, «Commercial Reference Buildings,» [Online]. Available: http://energy.gov/eere/buildings/commercial-reference-buildings. [Consultato il giorno 15 March 2015].

[32] T. P. Team, «Typology Approach for Building Stock Energy Assessment. Main Results of the TABULA project. Final Project Report,» Institut Wohnen und Umwelt GmbH, Darmstadt, 2012.

[33] «Inclusion of new buildings in residential building typologies. Step towards nZEBs Exemplified for Different European Contries. EPISCOPE Synthesis Report No.1.,» Institut Wohnen und Umwelt, Dramstadt, 2014.

[34] M. Spiekman e N. Kalamees, «Reference buildings for EP calculation studies. Report of ASIEPI. WP2,» 2009.

[35] D. P. Team, «DATAMINE Collecting Data from Energy Certification to Monitor Performance Indicators for New and Existing buildings. Final Report.,» Institut Wohnen und Umwelt GmbH, Darmstadt, 2009.

[36] B. T. Atanasiu B, A. Hermelink, S. Schimschar, J. Grözinger, M. Offermann, K. Engelund Thomsen, J. Rose e S. Aggerholm, «Principles for Nearly Zero Energy Buildings. Paving the way foreffective implementation of policy requirements.,» Building Performance Institute Europe, Brussels, 2011.

[37] M. Citterio, «Analisi statistica sul parco edilizio non residenziale e sviluppo di modelli di calcolo semplificati.Report RSE/2009/161,» ENEA, Cresme Ricerche Spa e Ministero dello Sviluppo Economico, 2009.

[38] G. Dall'O, A. Galante e G. Pasetti, «A methodology for evaluating the potential energy savings of retrofitting residential building stocks,» *Sustainable cities and society,* vol. 4, n. 1, pp. 12-21, 2012.

[39] G. V. Fracastoro e M. Serraino, «A methodology for assessing the energy performance if large scale building stock and possible applications,» *Energy and Buildings,* vol. 43, n. 4, pp. 844-852, 2011.

[40] UNI, UNI 10339:1995. Impianti aeraulici a fini di benessere. Generalità, classificazione e requisiti. Regole per la richiesta d'offerta, l'offerta, l'ordine e la fornitura., Roma: Ente Italiano di Normazione (UNI), 1995.

[41] I. Ballarini, S. Corgnati, V. Corrado e T. Novella, «Building Typology Brochure - Italy (Fascicolo sulla Tipologia Italiana). Italian TABULA Report,» 2011.

[42] M. Citterio, Analisi Statistica sul parco edilizio non residenziale e sviluppo di modelli di calcolo semplificati. Report RSE/2009/161, Roma: ENE, Cresme Ricerche Spa, Ministero dello Sviluppo economico, 2009.

[43] CEN, EN 15232:2012. Energy performance of buildings - Impact of Buildings Automation, Control and Building Management., Brussels: European Committee for Standardization (CEN), 2012.

[44] C. F. Reinhart, «Lightswitch-2002: a model for manual and automated control of electric lighting and blinds.,» *Solar Energy,* vol. 1, n. 77, pp. 15-28, 200a.

[45] S. Corgnati, E. Fabrizio, F. Ariaudo e L. Rollino, «Edificio tipo, indici di benchmark di consumo per tipologie di edificio, ad uso scolastico (medie superiori e istituti tecnichi),» ENEA, Dipartimento di Energia, Politecnico di Torino, 2010.

[46] L. Pagliano, M. Pietrobon e P. Zangheri, «Indici di banchmark di consumo per tipologie di edifici ad uso scolastico.,» ENEA. Dipartimento di Energia, Politecnico di Milano, 2010.

[47] C. Carano e M. Venco, «La climatizzazione dei supermercati e degli ipermercati: soluzioni efficaci da un sistema dedicato basato su unità packaged,» in *Convegno Aicarr*, Milano, 2004.

[48] L. Cecchinato, M. Corradi e S. Minetto, «Verso un supermercato in classe A,» *Aicarr Journal,* n. 3, pp. 50-59, 2010.

[49] M. Vaudetti, Edilizia per il commercio: punti vendita, ceoncept store, grandi magazzani, centri commerciali, temporary store, Torino: UTET, 2007.

[50] S. Venco, «La climatizzazione e la frigoconservazione nella cosidetta zona "freschi" degli ipermercati e dei supermercati: gli aspetti critici e le opportunità di risparmio energetico,» in *Converno Aicarr, Impianti, edifici, città: integrazione e nuove visioni di progetto e di gestione*, Milano, 2004.

[51] AIA, «An Architect's Guide to Integrating Energy Modeling in the Design Process,» The American Institute of Architects (AIA), 2012.

[52] J. L. Hensen e R. Lamberts, Building performance simulation for design and operation, Routledge, Taylor & Francis Group, ISBN: 978-0-415-47414-6., 2011.

[53] J. A. Clarke, Energy Simulation in Building Design, Oxford: Butterworth-Heinemann, Second Edition ISBN: 0750650826, 2001.

[54] «Building Information Modeling and Green Design, Environmental Building News Volume 16, Number 5,,» May 2007. [Online]. Available: https://www2.buildinggreen.com/article/building-information-modeling-and-green-design. [Consultato il giorno 28 April 2015].

[55] M. Filippi e E. Fabrizio, Introduzione alla simulaizone termoenergetica dinamica degli edifici, Milano: Editoriale Delfino Srl, 2012.

[56] J. Hensen e M. Trcka, «Overview of HVAC system simulation,» *Automantion in construction,* pp. 19 (2), 93-99, 2010.

[57] S. Robinson, «Conceptual modelling for simulation Part I: Definition and Requirements,» *Journal of the Operation Research Society,* pp. 59 (3), 278-290, 2008.

[58] T. Reddy, I. Maor e C. Panjapornpon, «Calibrating Detailed Building Energy Simulation Programs with Measured Data – Part I: General Methodology (RP-1051),» *HVAC&Research,* pp. 13, 221-241, 2007.

[59] W. Carroll e R. Hitchcock, «Tuning simulate building description to match actual utility data: Methods and implementation.,» *ASHRAE Transactions ,* vol. 99, pp. 982-34.

[60] S. Bertagnolio, «Evidence-based model calibration for efficient building energy services.,» Ph.D. Thesis, University of Liège, Liège, June 2012.

[61] D. Claridge, « Building simulation for practical operational optmization,» in *Building performance simulation for design and operation, 1st ed.*, Routledge, UK, Spon Press, 2011.

[62] IPMVP, «International Performance Measurement & Verification Protocol: Concepts and Option for Determining Energy Savings in New Construction, Volume III.,» IPMVP New Construction Subcommittee. , 2003.

[63] ASHRAE, «ASHRAE Guideline 14-2002: Measurement of Energy Demand and Savings,» American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, USA, 2002.

[64] FEMP, «M&V Guidelines: Measurements and Verification for Federal Energy Projects, Version 3.0,» Federal Energy Management Program (FEMP), 2003.

[65] J. Clarke, P. Strachan e C. Pernot, «An approach to the calibration of building energy simulation models,» *ASHRAE Transaction* , vol. 99, pp. 917-927, 1993.

[66] T. Reddy, «Literature review on calibration of building energy simulation programs: Uses, problems, procedures, uncertainty and tools,» *ASHRAE Transactions,* vol. 112, pp. 226-240, 2006.

[67] Y. Heo, «Bayesian calibration of building energy models for energy retrofit decision-making under uncertainty. Ph.D. Thesis.,» Georgia Institute of Technology, December 2011.

[68] F. Campolongo, i. A. Saltell e J. Cariboni, « From screening to quantitative analysis. A unified approach.,» *Computer Physics Communications,* vol. 182, pp. 978-988, 2011.

[69] UNI, «UNI 10200 Standard. Centralized heating systems - Heating costs,» Italian National Body for Standard (UNI), Milan, 2005.

[70] UNI, «UNI/TS 11300-1 Standard. Energy performance of buildings - Part 1: Evaluation of energy need for space heating and cooling.,» Italian National Body for Standard, Milan, 2011.

[71] V. Fabi, R. Vinther Andersen e S. Corgnati, « Influence of occupant's heating set point preferences on indoor environmental quality and heating demand in residential buildings,» *HVAC&R Research,* vol. 19 , n. 5, pp. 635-645, 2013.

[72] B. Xu, L. Fu e H. Di, «Dynamic simulation of space heating systems with radiators controller by TRVs in buildings,» *Energy and Buildings,* n. 40, pp. 1755-1764, 2008.

[73] F. Tahersima, J. Stoustrup e J. Rasmussen, «Stability Performance Dilemma in Hydronic Radiators with TRV,» in *2011 IEEE International Conference on Control Applications (CCA)*, Denver, CO, US, 2011.

[74] F. Tahmasebi e A. Mahdavi, «A two-staged simulation model calibration approach to virtual sensors for building performance data,» in *Proceeding of 13th Conference of International Building Performance Simulation Association*, Chambery, 2013.

[75] M. Wetter, «Design Optimization with GenOpt,» *Building Energy Simulation User News,* vol. 21, n. 19-28, September/October 2000.

[76] Y. Heo, R. Choudhary e G. Augenbroe, «Calibration of building energy models for retrofit analysis under uncertainty,» *Energy and Buildings,* vol. 47, pp. 550-560, 2012.

[77] BPIE, «Cost Optimality. Discussing methodology and challenges within the recast Energy Performance of Buildings Directive,» Building Performance Institure Europe, Brussels, 2010.

[78] European Commission, «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 on the energy performance of buildings,» *Official Journal of the European Union,* n. C 115, pp. 1-28, 2012.

[79] T. Boermans, K. Bettgenhauser, A. Hermerlink e S. Schimschar, «Cost-optimal building performance requirements. Calculation methodology for reporting on national energy performance requirements on the basis of cost-optimality within the framework of the EPBD,» European Council for and Energy Efficiency Economic (Eceee), Stockholm, 2011.

[80] BPIE, «Implementing the cost-optimal methodology in EU countries. Lessons learned from three case studies,» Building Performance Institute Europe (BPIE), Brussels, 2013.

[81] European Commission, «Directive 2010/31/EU of the European Parliament and the Council on the energy performance of buildings (recast),» *Official Journal of the European Union,* n. L153, pp. 13-53, 2010.

[82] J. Kurnitski, A. Saari, T. Kalamees, M. Vuolle, J. Niemela e T. Tark, «Cost optimal and nearly zero (nZEB) energy performance calculations for residential buildings with REHVA definition for nZEB national implementation,» *Energy and Buildings,* vol. 43, pp. 3279-3288, 2011.

[83] E. Pikas, M. Thalfeldt e J. Kurnitski, «Cost optimal and nearly zero energy building solutions for office buildings,» *Energy and Buildings,* vol. 74, p. 30–42, 2014.

[84] A. M. Hamdy, A. Hasan e K. Siren, «Multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010,» *Energy and Buildings,* vol. 56, p. 189–203, 2013.

[85] I. Ballarini, V. Corrado e S. Paduos, «Assessment of cost-optimal energy performance requirements for the Italian residential building stock,» *Energy Procedia,* vol. 45, pp. 443-452, 2014 .

[86] V. Corrado, I. Ballarini e S. Paduos, «Sviluppo della metodologia comparativa cost-optimal secondo Direttiva 2010/31/UE. Report RdS/2013/144,» ENEA, Roma, 2013.

[87] F. Ascione, N. Bianco, C. De Stasio, M. G. Mauro e G. P. Vanoli, «A new methodology for cost-optimal analysis by means of the multi-objective optimization of building energy performance,» *Energy and Buildings,* vol. 88, pp. 78-90, 2015.

[88] M. Ferrara, E. Fabrizio, M. Filippi e J. Virgone, «A simulation-based optimization method for cost-optimal analysis of nearly Zero Energy Buildings,» *Energy and Buildings,* vol. 84, pp. 442-457, 2014.

[89] N. Ganiç e Y. A. Z. , « Adaptation of the cost optimal level calculation method of Directive 2010/31/EU considering the influence of Turkish national factors,» *Applied Energy 143 ,* vol. 143, pp. 94-107., 2014.

[90] V. M. Barthelmes, C. Cristina Becchio, M. C. Bottero e S. P. Corgnati, «The Influence of Energy Targets and Economic Concerns in Design Strategies for a Residential Nearly-Zero Energy Building,» *Buildings ,* vol. 4, pp. 937-962, 2014.

[91] Eurostat, «Smarter, greener, more inclusive? Indicators to support the Europe 2020 strategy,» Publications Office of the European Union, Luxembourg, 2013.

[92] BPIE, Alleviating fuel poverty in the Eu, Brussels: Building Performance Institute Europe (BPIE), 2013b.

[93] NEAP, «Italian Energy Efficiency Action Plan,» Italian National Energy Efficiency Action Plan. http://ec.europa.eu/energy/node/84, 2014.

[94] D. o. E. U.S. DOE, «Building Energy Software Tools Directory,» 04 03 2015. [Online]. Available: http://apps1.eere.energy.gov/buildings/tools_directory/.

[95] L. Stefanutti, Impianti di climatizzazione: tipologie applicative, Milano: Tecniche Nuove, 2007.

[96] A. Capazzoli, P. Mazzei, F. Minichiello e F. Palma, «Impianti di climatizzazione con deumidificazione chimica per i supermercati,» in *Covegno Aicarr: Impianti, edifici, città: integrazione e nuove visioni di progetto e di gestione*, Milano, 2004.

[97] «D.M. del 18 Dicembre 1975, Norme tecniche aggiornate relative all'edilizia scolastica, ivi compresi gli indici minimi di funzionalità didattica, edilizia ed urbanistica da osservarsi nella esecuzione di opere di edilizia scolastica,» *Supplemento Ordinario della Gazzetta Ufficiale,* n. 29, 2 Febbraio 1976.

[98] E. Fabrizio, D. Guglielmino e V. Monetti, «Italian benchmark building models: the office building,» in *Driving better design through simulation*, Melbourne, IBPSA Australia & AIRAH, 2011, pp. 1981-1988.

[99] C. Becchio, P. Cantamessa, E. Fabrizio, P. Florio, V. Monetti e M. Filippi, «Dynamic simulation of BACS (Building Automation and Control Systems) for the energy retrofitting of a secondary school,» in *Proceedings of BS2013: 13th Conference of the International Building Performance Simulation Association*, Chambery, IBPSA, 2013, pp. 2060-2068.

[100] C. Becchio, E. Fabrizio e V. Monetti, «Livelli di prestazione energetica ottimali per edifici a energia quasi zero: il caso di un edificio multifamiliare,» in *67° Congresso Nazionale ATI*, Trieste, 2012.

[101] D. E. Claridge, N. Bensouda, S. U. Lee, G. Wei, K. Heinemeier and M. Liu, "Manual of procedures for calibrating simulation of building systems," Lawrence Berkley National Laboratory, 2003 October.

[102] EC, «Directive 2010/31/EU of the European Parliament and the Council on the energy performance of buildings (recast),» Official Journal of the European Communities, L153, 40–43, Brussels, 2010.

[103] European Commission, «Commission staff working document accompanying the document. Report from the commission to the European Parliament and the Council. Financial support for energy efficiency in buildings. COM(2013) 225 final,» European Commission, Brussels, 2013.

[104] European Commission, "Europe 2020 - A strategy for smart, sustainable and inclusive growth," COM (2010) 2020 final, European Council conclusions, Brussels, 2010.