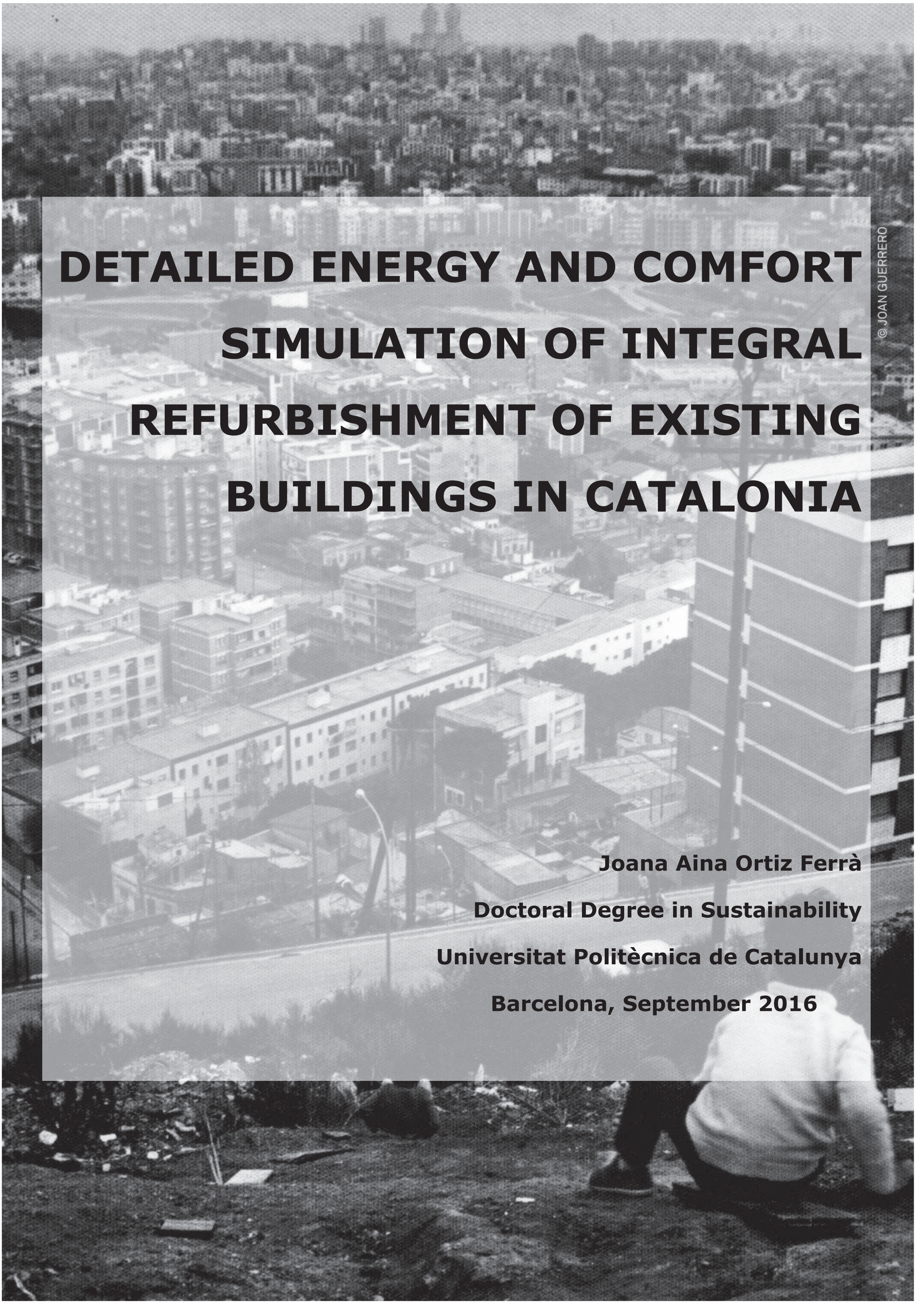

DETAILED ENERGY AND COMFORT SIMULATION OF INTEGRAL REFURBISHMENT OF EXISTING BUILDINGS IN CATALONIA

Joana Aina Ortiz Ferrà

Doctoral Degree in Sustainability

Universitat Politècnica de Catalunya

Barcelona, September 2016

UNIVERSITAT POLITÈCNICA
DE CATALUNYA
BARCELONATECH

Institut de Recerca en Energia de Catalunya
Catalonia Institute for Energy Research

PhD Thesis

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Abstract

The energy renovation of buildings is an essential action to achieve the European target of 20/20/20. However, the dynamics of the energy renovation are very slow and the development of urgent policy actions beyond the national energy efficiency action plans is needed. In that context, the main objective of the thesis is to develop a cost-effective analysis for the energy renovation of the main residential building typologies of Catalonia, considering three main criteria: thermal comfort, primary energy use and global costs. The main building typologies of Catalonia are analysed, comparing the current situation with the effect of different energy efficiency measures. Four building typologies are studied, each of them in different climates and locations, in order to evaluate the differences and the particularities of every one.

The building model definition is an important task where all the methods and hypotheses to estimate the energy consumption are defined. In that sense, the objective of the building model definition is to go further to the previous studies, trying to improve the detail and the results of the simulation. The emphasis of the PhD is on the following aspects: the building characterization, including information from surveys and monitoring campaigns; the user behaviour and its interaction with the building, using stochastic occupancy profiles; the improvement of the implementation of passive strategies, as natural ventilation and the use of solar protections; and the thermal comfort of the users, as a criteria to choose the appropriate measures.

A validation process of the building model is done to obtain reliable results. A pilot site is used to develop the validation of the model. A monitoring campaign has been done to characterize the pilot site and to implement the simulation model. The pilot site is a dwelling representative of one of the typologies analysed under the PhD. The validation of the model confirms that the hypotheses and methods included in the model are appropriate for the residential building simulation.

Finally, the simulation process is defined in two-step evaluation: passive and active evaluation. The objective of the passive evaluation is to reduce, as much as possible, the thermal discomfort with the minimum initial investment cost of passive measures. This first step provides information to make a first selection of the appropriate passive measures in each building. In the second step where the passive and active measures are implemented in the building, the active evaluation wants to obtain the cost-effective measures, minimizing the primary energy use and the global costs. For concluding, the PhD provides technical and economic information to help to take decisions for the energy renovation of residential buildings in Catalonia.

Resum

La rehabilitació energètica dels edificis és una acció essencial per assolir els objectius Europeus 20/20/20. Malauradament, les dinàmiques de renovació energètica són molt lentes i requereixen de accions polítiques urgents emmarcades sota els plans d'acció nacional per l'eficiència energètica. En aquest context, el principal objectiu de la tesi es desenvolupar un anàlisis cost-efectiu per la renovació energètica dels principals edificis residencials de Catalunya, considerant tres criteris principals: confort tèrmic, energia primària i costos globals. Les principals tipologies d'edificis de Catalunya s'analitzen comparant la seva situació actual amb l'efecte de les diferents mesures d'eficiència energètica. S'han estudiat quatre tipologies d'edifici, cada una d'elles en diferents climes i localitzacions, per tal d'avaluar les diferencies i les particularitats de cada una d'elles.

La definició dels models d'edifici és una tasca important on s'han de definir tots els mètodes i hipòtesis per estimar el consum energètic. En aquest sentit, l'objectiu de la definició del model d'edifici és anar mes enllà dels estudis previs, intentant millorar el detall i els resultats de la simulació. L'enfoc de la tesis es centra en els següents aspectes: la caracterització de l'edifici, incloent informació obtinguda d'enquestes i campanyes de monitorització; el comportament de l'usuari i la seva interacció amb l'edifici, fent servir perfils d'ocupació estocàstics; la millora en la implementació de estratègies passives, com ara la ventilació natural o les proteccions solars; i el confort tèrmic dels usuaris com a criteri per elegir els mesures adequades.

S'ha realitzat la validació del model d'edifici per tal d'obtenir resultats fiables. S'ha utilitzat un habitatge pilot per realitzar la validació del model. S'ha realitzat una campanya de monitorització per tal de caracteritzar el pilot i poder implementar el model. L'habitatge pilot és un habitatge representatiu de una de les tipologies analitzades al PhD. La validació del model confirma que les hipòtesis i mètodes implementats al model son els adequats per la simulació d'edificis residencials.

Per concloure, el procés de simulació s'ha definit en dos etapes d'avaluació: avaluació passiva i activa. L'objectiu de l'avaluació passiva és reduir lo màxim possible el desconfort tèrmic amb el mínim cost d'inversió inicial en mesures passives. Aquesta etapa proporciona informació per realitzar una primera selecció de les mesures passives adequades per cada edifici. A la segona etapa, on les mesures passives i actives s'implementen a l'edifici, l'avaluació passiva proporciona les mesures cost-efectives, minimitzant l'energia primària i els costos globals. Finalment, la tesi proporciona informació tècnica i econòmica per ajudar la presa de decisions per la renovació energètica dels edificis residencials de Catalunya.

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Primer de tot vull donar les gràcies als meus directors de tesi. A la Dr. Inmaculada Rodríguez per accedir a dirigir-me la tesi sense conèixer-nos abans. Gràcies per fer-me un forat a la teva agenda i pels teus consells. Tot i tenir molt aspectes definits de la tesi abans d'anar-te a veure, ha estat molt enriquidor incorporar el teu punt de vista, ajudant a que la tesi quedi mes completa. D'igual manera, agraeixo al Dr. Jaume Salom la confiança que ha dipositat en mi, donant-me l'oportunitat de formar part del seu equip i alhora poder fer el doctorat. Ja són cinc, els anys que porto treballant al grup d'Energia Tèrmica i Edificació; han estat molt intensos i profitosos. Sento que l'aprenentatge ha anat molt mes enllà del doctorat. Gràcies pel teu temps i dedicació, i per transmetre'm la teva passió per la recerca. Encantada d'haver-te tingut com a director de tesi.

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Contents

List of Figures

List of Tables

Nomenclature

AC	Air Conditioning
ACH	Agencia Catalana de l'Habitatge
BC	Base Case
BM	Biomass
BPIE	Building Performance Institute Europe
BSC	Building Stock Characterization
BT	Building Typology
CIBSE	Chartered Institution of Building Services Engineers (CIBSE)
CO	Cost optimal
CTE	Código Técnico de la Edificación
DHW	Domestic Hot Water
DR	Deep Renovation
ELA	Effective Leakage Area
ELE	Electricity
EPBD	Energy Building Performance Directive
EPS	Expanded Polystyrene insulation
ERB	Energy Renovation of Buildings
ERF	Estudi Ramon Folch
EU	European Union
HVAC	Heating, Ventilation and Air Conditioning
IDAE	Instituto para la Diversificación y Ahorro de la Energía
IPMVP	International Performance Measurement and Verification Protocol
MED	Mediterranean
MEDBEES	Mediterranean Building Energy Efficiency Strategy
MIP	Macro Investment Project
NG	Natural Gas
nVENT	Dwelling without natural ventilation

nZEB	nearly Zero Energy Building
PA	Pilot Activity
PS	Pilot Site
PV	Photovoltaic
RW	Mineral wool insulation
SD	Standard dwelling
TUD	Time Use Data
TUS	Time Use Survey
UD	Under roof dwelling
VAT	Value-Added Tax
VENT	Dwelling with natural ventilation
XPS	Extruded Polystyrene insulation

Variables

η	Efficiency of the boiler
ALD	ASHRAE Likelihood of Dissatisfied
C_i	Initial investment cost
C_p	Total replacement cost
CV(RMSE)	Coefficient of Variation of the Root Mean Square Error
$E_{APP,BC}$	Energy consumption of appliances of the base case
E_{ELE}	Final energy consumption of electricity
$E_{LIG,BC}$	Energy consumption of lighting of the base case
E_{NG}	Final energy consumption of natural gas
$E_{R,label-i}$	Energy label scale
$E_{T,label-i}$	Total energy labelling scale
EER	Energy Efficiency Ration of the cooling system
I	Irradiance
LDP	Long-Term Percentage of Dissatisfied
n	Sample size
n_{50}	Air change rates at 50Pa
NMBE	Normalized Mean Bias Error
OH	Overheating
P	Markov Chain Probability
PMV	Predicted Mean Vote
PPD	Percentage of People Dissatisfied
R^2	Coefficient of Determination
R	Market interest rate
R_E	Energy evolution rate
R_D	Discount rate
R_R	Real interest rate

R_S	Total Solar Radiation
RI	Inflation rate
RX_E	Energy cost evolution
t	time interval
T	Calculation period
T_c	Courtyard temperature
T_{op}	Operative temperature
$T_{op,in}$	Operative temperature of the building
$T_{op,comf\text{-}ASHRAE}$	Comfortable Operative temperature according to ASHRAE adaptive comfort model
T_{out}	Outdoor temperature
$T_{out,m}$	Mean monthly outdoor air temperature
$T_{sol\text{-}air}$	Soil-air Temperature
Q_C	Cooling demand
Q_{DHW}	Domestic hot water demand
Q_H	Total heating demand
Q_h	Heating demand
$Q_{l,em}$	Heating losses related to the emission system
$Q_{l,ctr}$	Heating losses related to the control system
y_t	Simulation results for a certain period of time t
Y_t	Monitoring data for a certain period of t
$\overline{Y}$	Arithmetic mean of monitoring data
V_f	Final value

Chapter I Introduction

I.1 Motivation and objectives

Within the European regulatory framework and the agreement signed by Member States, the nations and regions have an essential role in decision-making to reach the 20/20/20 targets, applying the Energy Performance of Building Directive (EPBD, recast) [1] and the Energy Efficiency Directive [2]. The global impacts of building energy refurbishment policies depend on the specific energy improvements of the measures and the rate at which these are implemented in practice. There are very little data on the refurbishment rates in the EU countries. The publication by the Buildings Performance Institute Europe (BPIE) [3] assumes an average of 1% refurbishment rate over the European countries. However, the study remarks that the refurbishment rates largely vary among countries and regions. In Catalonia, the energy renovation rate is around 0.2% dwellings per year [4], which represents a low fraction of the building stock. These energy refurbishment rates are an order of magnitude lower than the 3% target for EU public buildings [2]. The very slow natural refurbishment rate in the Mediterranean area demonstrates the need for urgent policy actions beyond the national energy efficiency action plans.

The energy efficiency action plan must be designed to increase the energy refurbishment dynamics, but at the same time, guaranteeing the maximum impact of each intervention. The promotion of the energy renovation of buildings is needed, being sure that the measures are cost-effective in a long term as well as they improve the comfort of the users. In consequence, the impact of the energy refurbishment of buildings should be evaluated in three fields (Figure I.1), which also are sided with the EPBD [1]: environmental, economic and social perspective.

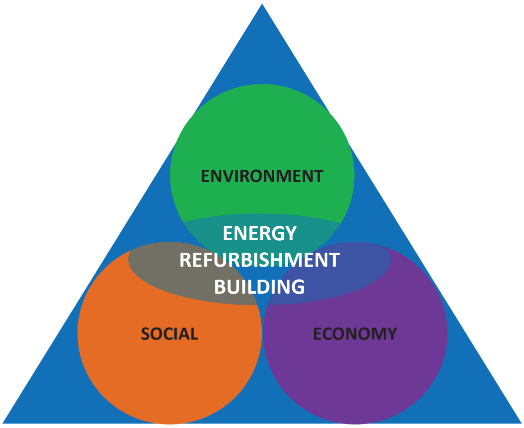

Figure I.1 Impacts of the energy refurbishment of residential buildings

The environmental benefits are related directly to the 20/20/20 objectives, and consist in the reduction of the energy consumption and the CO_2 emissions. Regarding the economic impacts, the energy efficiency action plan requires cost-optimal solutions in order to reduce as much as possible the private investment, especially considering the current economic and social situation. In that sense, the EPBD suggests a procedure for the economic evaluation based on the global cost calculation [5]. The last effect of the energy refurbishment is the social impact. The energy renovation of the building must represent an improvement of the quality of the life of the users, increasing the thermal comfort, consequently a benefit on the health of the people (especially in the people with low purchasing power). The last BPIE publication [6] provides an overview of the regulatory framework related to the indoor air quality, thermal comfort and daylight conditions. The report concludes that national regulations and the current building codes should be complemented with appropriate requirements and recommendations to secure proper indoor air quality, thermal comfort and daylight. These conclusions reflect the need to introduce the environmental comfort as a variable of design of the new and refurbished buildings.

I.1.1 General objectives

The aim of the thesis is to evaluate and to provide the cost-optimal measures for the energy renovation of residential buildings of Catalonia, considering three main criteria: thermal comfort, primary energy use and global costs. The main objectives are:

- **Objective 1:** The PhD thesis wants to evaluate which energy efficiency measures are appropriate for the refurbishment of the residential buildings in Catalonia. The residential building stock of Catalonia can be classified in different building typologies, each of them with their particularities. For that reason, it is interesting to analyse which measures are suitable in every building typology, climate and environment, considering their costs and primary energy savings. In this regard, dynamic building simulations of the dwellings are used to estimate the energy consumption of the building. The objective of the PhD is to reduce the uncertainties and improve the estimation of the primary energy use. To this end, detailed building model with realistic characterization of the building and its interaction with the user are needed. The PhD proposal wants to answer: *Are all the measures appropriate in all the typologies and climates? How can it relate the actual state of the building with the simulation model? How can it be introduced realistic user behaviour in the simulation?*
- **Objective 2:** The Mediterranean climate is a temperate climate and is characterized by warm/hot summers and mid/cool winters. In that sense, Mediterranean climate does not have severe weather conditions over the year. It can be an advantage relative to the energy consumption, because the heating loads are not high in comparison with the central-north of Europe. The thesis evaluates how the comfort of the occupants can be improved only by the

implementation of passive strategies (as natural ventilation, solar protections, improvement of the envelope) in the different buildings, climates and locations. The PhD seeks to answer the following questions: *Which are the thermal comfort differences between typologies and climates? What are the differences between warm season and cold season thermal comfort? Is it possible to avoid active cooling systems in some locations and for some typologies with appropriate passive solutions?*

- **Objective 3:** The approach of the thesis is to analyse the refurbishment from the point of view of the final user: *How much would the refurbishment of my home cost? Which would the amount of my bills be after the renovation? Which are the most effective measures in each building typology and climate?* For that reason, the perspective of the economic evaluation is microeconomic, including the Value-Added Tax (VAT) on the costs. In addition, the energy consumption included in the study considers all the uses: heating, cooling, domestic hot water, lighting and appliances. The objective is to have a direct relation between the results of the study and the total energy expenditures of the households. In that sense, one of the results with especial interest is to analyse the energy savings achieved with the cost-optimal measures. This information related to the energy expenditures of the households could help to develop future building regulations and policies, especially for the existing buildings.

I.1.2 Specific objectives

The specific objectives of the thesis are described following:

- **Specific objective 1.1:** To develop stochastic models to reproduce the occupancy behaviour in the building and its interaction with the systems. Using these models, the variability of the occupants is reproduced.
- **Specific objective 1.2:** To relate the physical and behavioural parameters of the building with the results of surveys, monitoring campaigns and experimental data, in order to define the simulation model with realistic information.
- **Specific objective 1.3:** To validate the method and hypotheses implemented in the building model. The validation of the model provides the reliability of the method implemented in the building simulation model, making possible to extrapolate it to other building typologies.
- **Specific objective 1.4:** To define a complete method to implement the whole process in a single simulation, with the objective to integrate the three main criteria in the building simulation. Dynamic building simulation programmes are tools that make possible to customize the building simulation and to include the calculations and interactions with a wide range of possibilities.

- **Specific objective 1.5:** The building simulation model has to be designed to be used in a co-simulation process, in order to run all the combination of measures automatically. It means, the building simulation model has to integrate all the energy efficiency measures and while being chosen automatically during the co-simulation process.
- **Specific objective 2.1:** The thermal comfort evaluation of the building is needed in order to guarantee comfortable combination of measures. The thermal parameters used for the evaluation should describe the thermal comfort over the year, but also they have to reflect the punctual problematic situations, as for example the overheating during the warm season.
- **Specific objective 2.2:** To introduce passive strategies for cooling based on Mediterranean behaviours. To improve the integration of these strategies into the building model.
- **Specific objective 3.1:** To use an economic method which compares in a neutral way the different energy efficiency measures. The method has to include all the costs generated over a long term, considering the investment costs, replacement costs, maintenance costs, and energy costs.

I.2 Framework of this thesis: MARIE project

The thesis is developed in the framework of the MARIE project as part of the contribution of the Catalan Institute for Energy Research (IREC), who was a partner of the project. A brief description of the project is explained in order to provide a context of the thesis.

The MARIE project[1] (Agreement Nº 1S-MED10-002) was a strategic project, whose objective was to develop the Mediterranean Building Energy Efficiency Strategy (MEDBEES) in order to intensify, motivate and facilitate the progress toward the 20/20/20 European objectives. The project was led by Department of Territory and Sustainability from Catalonia and the consortium was made up of 23 partners from 9 Mediterranean countries (Figure I.2).

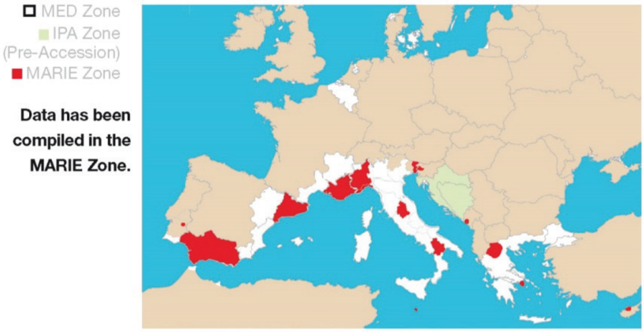

Figure I.2 Mediterranean regions involved in the MARIE project (Source: MARIE project)

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[1] MARIE Project website: www.marie-medstrategic.eu

The process to build the MEDBEES (Figure I.3) started with the diagnosis of the Mediterranean regions involved in the project, determining the main barriers and outlining a first scheme of the most promising strategic lines.

This first proposal was evaluated in the study Potential Impact Evaluation [4, 7], which was carried out by IREC with the collaboration of the partners of the project. The study shows that the MARIE scenario achieves larger energy use reductions in all the analysed regions, both for the residential and the tertiary sectors. The good evaluation results of the first draft of the MEDBEES validate it as a sound strategy for energy refurbishment in the MED space. The benefits of the MEDBEES arrive slowly, but steadily increase with time. The MARIE scenario shows better results in the long run due to the longer cycles associated to the MARIE measures (e.g., market transformation towards easier integral refurbishment).

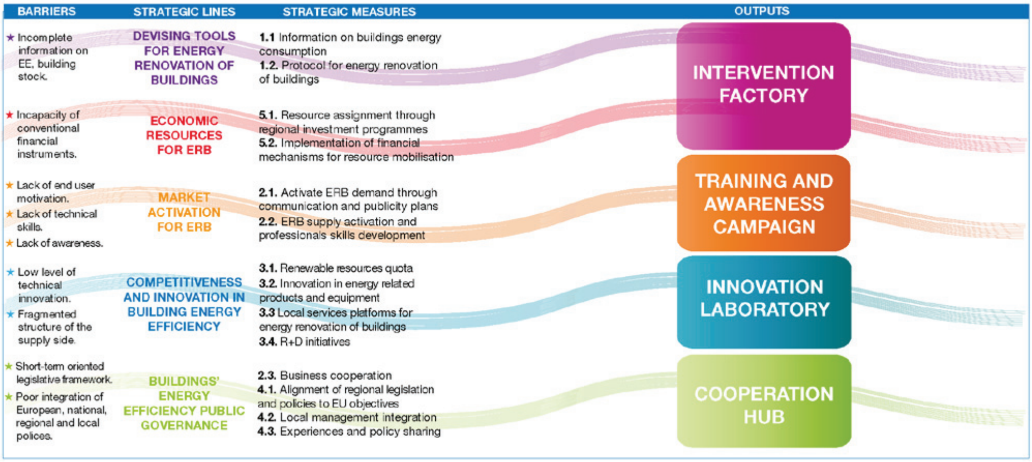

Figure I.3 Process to build the MEDBEES (Source: MARIE project)

After the validation of the strategy, the MARIE project defined in detail every strategic measure with the development of several pilot activities. The pilot activities have contributed to improve the strategy definition and their interactions, helping to identify the straightness and also the weakness of the measures.

Figure I.4 represents how the strategic measures are integrated in a cycle process. The key point of the MEDBEE Strategy is to create and to implement an Intervention Factory to produce Macro Investment Projects (MIP) for the Energy Renovation of Building (ERB). This Intervention Factory was conceived as a continuous and efficient process of ERB MIP generation. To implement the Intervention Factory, different mechanisms are needed (Figure I.4): a suitable information system; policies and regulation aligned with ERB; specific protocols for ERB projects; appropriate funding mechanisms; and a monitoring and evaluation system. The process is conceived as an open cycle, activated by new solutions, experiences and best practices in management, communication, training and technical innovation.

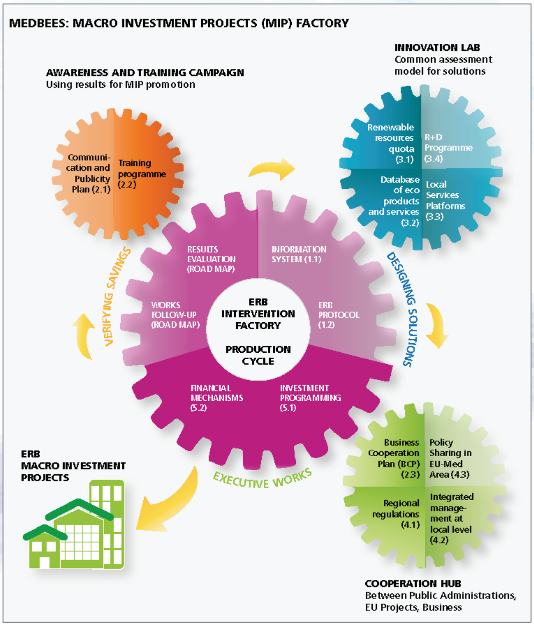

Figure I.4 MEDBEES interaction process (Source: MARIE project)

I.2.1 Energy renovation of residential buildings of Catalonia

One of the pilot activities (PA) developed during the MARIE project was the PA2.2: Regional Investment Plan for the Energy Renovation of Buildings. The goal of this PA was to increase the demand for energy efficient renovation of buildings of the Mediterranean territory, creating a methodology to develop regional investment plans for energy renovation of existing buildings by means of integrating all agents involved, in order to assure that the proposed plan is feasible, considering also the special case of districts with low-income residents. Figure I.5 shows how the project is divided in two parts: Building Stock Characterization and "Cost-optimal evaluation of energy efficiency measures for the energy renovation of residential buildings in Catalonia" (OptiHab study). The Building Stock Characterization has been developed by Agencia Catalana de l'Habitatge (ACH) and Estudi Ramon Folch (ERF) with the collaboration of IREC. The OptiHab study has been conducted by IREC working together with SummLab[2] and inLab[3]. The whole study provides the technical and economic information to design a Regional Investment programme for the Energy Renovation of Residential Buildings in Catalonia.

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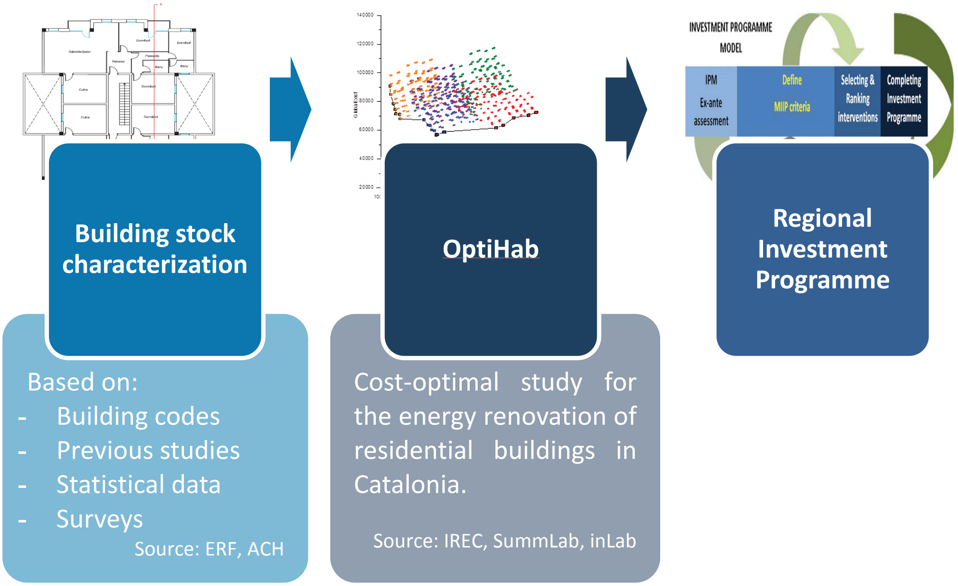
[2] SummLab - Sustainability Measurement and Modeling Lab. Research group of Universitat Politecnica de Catalunya – BarcelonaTech

[3] inLab – Research grup of Universitat Politecnica de Catalunya – BarcelonaTech



Building stock characterization

Based on:
- Building codes
- Previous studies
- Statistical data
- Surveys

Source: ERF, ACH

OptiHab

Cost-optimal study for the energy renovation of residential buildings in Catalonia.

Source: IREC, SummLab, inLab

Regional Investment Programme

Figure I.5 Energy renovation of residential building of Catalonia

I.2.2 Interactions with the PhD

The PhD thesis takes part of the PA2.2: Energy renovation of a residential building of Catalonia of the MARIE project, where the collaboration of several partners was needed. For that reason, it is important to differentiate the work that defines the PhD.

Figure I.6 represents the interactions between the partners involved in the PA and the PhD thesis. ERF and ACH defined the building stock characterization and the energy efficiency measures defined through three main activities:

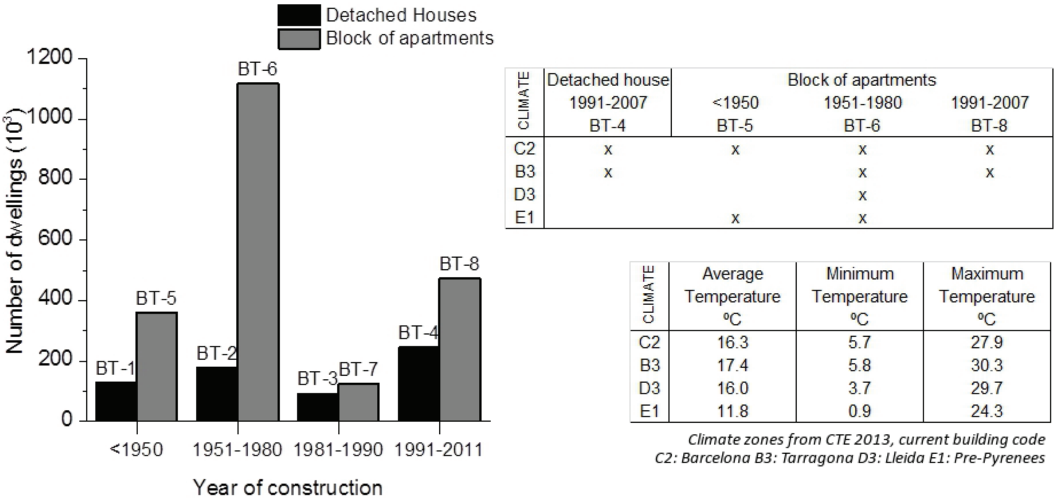
- Previous analysis: collection of information from previous studies and methodologies related to the building stock characterization. Pre-selection of the building typologies and definition of the information needed.
- Typology definition and validation: Survey campaign to collect the missed information and to highlight aspects related to ownership of systems and appliances, and information about the user behaviour (hereafter the BSC surveys). Verification of the pre-selection typologies. Final typology definition.
- Energy efficiency measures: definition of energy efficiency measures for every building typology. The measures are defined by technical and economic information.

Objective: cost-optimal evaluation for the energy renovation of residential buildings of Catalonia, considering three main criteria: thermal comfort, primary energy use and global costs.

- Detailed building model
- Comfort evaluation
- Economic evaluation

Figure I.6 Context of the PhD. Collaboration in the framework of the MARIE project

As a results of the ERF and ACH activities, the residential building stock was classified in 8 typologies (4 are detached houses and 4 are block of apartments), which are consistent with previous studies [8]. Thereafter, the most representative building typologies were chosen by ERF and ACH, in order to carry out the OptiHab study. The Figure I.7 shows the distribution of the residential building stock in Catalonia and the selected building typologies with their corresponding climates. The climate classification follows the Spanish building code (“Código Técnico de la Edificación CTE”, [9]). The letter represents the winter severity (E is the coolest), and the number is the summer severity (3 is the hottest).



CLIMATE	Detached house 1991-2007 BT-4	Block of apartments <1950 BT-5	 1951-1980 BT-6	 1991-2007 BT-8
C2	x	x	x	x
B3	x		x	x
D3			x	
E1		x	x	

CLIMATE	Average Temperature ºC	Minimum Temperature ºC	Maximum Temperature ºC
C2	16.3	5.7	27.9
B3	17.4	5.8	30.3
D3	16.0	3.7	29.7
E1	11.8	0.9	24.3

Climate zones from CTE 2013, current building code
C2: Barcelona B3: Tarragona D3: Lleida E1: Pre-Pyrenees

Figure I.7 Distribution of the residential building stock in Catalonia based on the ERF and ACH classification. Selection of the building typologies (BT) and their climate for the OptiHab study

Once the building typologies are selected, the OptiHab study was carried out. The distribution of tasks between IREC, Summlab and inLab is shown in the Figure I.6 and is described following:

- PhD thesis (IREC): definition and implementation of the method to develop the cost-optimal study. Development of the detailed building model, including comfort, economic and energy evaluation. Validation of the building simulation model. Results evaluation and conclusion.
- SummLab: they have participated in the method definition providing their expert knowledge in the building characterization and the energy refurbishment of residential buildings. They collaborate with inLab in the development of the co-simulation architecture.
- inLab: they have developed the co-simulation and have provided the computational resources to run the whole simulations.

I.3 Thesis outline

The building simulation models are used to estimate the current situation of the households and the effect of the energy efficiency measures, in terms of thermal comfort, energy savings and global costs. The definition and the design of the building model is a crucial task to obtain feasible results. In Chapter II all the methods and hypothesis implemented in building simulation are described. In that sense, the building model definition tries to go further in aspects where the previous studies applied simplifications in order to improve the results of the simulation.

Chapter III shows the validation of the building simulation model to check the reliability of the method and the hypotheses included in the model. For that purpose, a pilot site has been studied in order to be compared with the results of the building simulation model. In this sense, the Chapter III introduces the pilot site and the validation process.

Once the building simulation model is validated, it is possible to extrapolate the method to other building typologies. Chapter IV presents an overview of the strategies followed in previous studies to analyse the building typologies and the impact of different energy efficiency measures, from the point of view of the thermal comfort, energy savings and economic impacts. The literature review provides the context to introduce the two-step evaluation process, which is the method proposed to analyse and to select the appropriate refurbishment measures for residential buildings.

Chapter V presents the results of the two-step evaluation process, first making a detailed analysis of the results of one building typology, followed by an overview of the results of all the typologies. In addition, Chapter V includes an example of the application of the results showing the usefulness of the method.

Finally, Chapter VI sums up the main conclusion and the outcomes of the thesis. The tasks done during the PhD have been designed to achieve the objectives of the PhD thesis, which must be answered at the end. In the concluding Chapter a justification and argumentation of the success and/or failure of the expected objectives are included. In addition, the contribution of the PhD in the field of research is described, highlighting the findings of the research and providing an outlook for further research topics.

I.4 Publications and contributions

The contents of the thesis have been partially published in the following papers:

I.4.1 Journal publications

I.4.1.1 Previously published providing background for this Thesis

E. Cubí, **J. Ortiz**, J. Salom, Potential impact evaluation: an ex ante evaluation of the Mediterranean buildings energy efficiency strategy, International Journal of Sustainable Energy, (2013) 1-17.

I.4.1.2 Published as part of this research work

J. Ortiz, A. Fonseca, J. Salom, N. Garrido, P. Fonseca. Cost-effective analysis for selecting energy efficiency measures for refurbishment of residential buildings in Catalonia, Energy and Buildings, 128 (2016) 442-457.

J. Ortiz, A. Fonseca, V. Russo, J. Salom, N. Garrido, P. Fonseca. Comfort and economic criteria for selecting the optimal passive measures for the energy renovation of residential buildings in Catalonia, Energy and Buildings, 110 (2016) 195-210.

J. Ortiz, F. Guarino, J. Salom, C. Corchero, M. Cellura, Stochastic model for electrical loads in Mediterranean residential buildings: Validation and applications, Energy and Buildings, 80 (2014) 23-36.

P. Fonseca i Casas, A. Fonseca i Casas, N. Garrido-Soriano, **J. Ortiz**, J. Casanovas, J. Salom. Optimal Buildings' Energy Consumption Calculus through a Distributed Experiment Execution, Mathematical Problems in Engineering, (2015) 12.

I.4.1.1 Under review

A. Fonseca, **J. Ortiz**, N. Garrido, P. Fonseca, J. Salom. Application of a co-simulation model to find the best comfort, energy and cost scenarios for building refurbishment. 2016.

I.4.2 Congress contribution

I.4.2.1 Proceedings as part of this research work

J. Ortiz, A. Fonseca, J. Salom, N. Garrido, V. Russo, P. Fonseca. Optimization of energy renovation of residential sector in Catalonia based on comfort, energy and costs, in BS2015: 14th International Conference of the International Building Performance Simulation Association (IBPSA), Hyderabad, India. 2015.

J. Ortiz, V. Russo, J. Salom. Impact of natural ventilation in energy consumption and thermal comfort of residential buildings in Catalonia, in: 36th AIVC Conference: Effective ventilation in high performance buildings, Madrid, Spain, 2015.

P. Fonseca, A. Fonseca, N. Garrido, **J. Ortiz**, J. Casanovas, J. Salom. Distributed experiment for the calculus of optimal values for energy consumption in buildings, in: INASE Conferences, Barcelona, Spain, 2015.

J. Salom, **J. Ortiz**, V. Russo, Method to develop cost-effective studies of energy efficiency measures for Mediterranean residential existing buildings with multi-criteria optimization, in: World Sustainable Building 2014, Barcelona, Spain 2014.

I.4.2.2 Other related conferences contributions

J.Ortiz, J. Salom, Republic_Zeb: Rehabilitación de edificios públicos en base a criterios nZEB y niveles coste-óptimos, in: III Congreso Edificios Energía Casi Nula, Madrid, Spain, June 2016.

J. Ortiz, J. Tarrés, M.L. González, J. Salom. Rehabilitación energética de edificios públicos en base a niveles coste-óptimos y nZEB, in: CONTART: La Convención de la Edificación, Granada, Spain, April 2016. ***Best Paper Award***.

I. Sartori, **J. Ortiz**, J. Salom, U.I. Dar. Estimation of load and generation peaks in residential neighbourhoods with BIPV: bottom-up simulations vs. Velander, in: World Sustainable Building 2014, Barcelona, Spain, 2014.

J. Ortiz, J. Salom, C. Corchero, F. Guarino, The uncertainty of the energy demand in existing Mediterranean urban blocks, in: SB13 Graz. Sustainable Building Conference, Graz, Austria, 2013. ***Best Paper Award***.

I.5 References

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[9] CTE, Código Técnico de la Edificación, 2013

Chapter II Definition of the simulation model

Chapter II describes how the building model has been implemented, giving detail about the methods, hypotheses and approaches implemented to obtain a realistic model. The information described has been published as results of this work in the following papers [1-4].

II.1 State of the art

The detailed modelling of a household's energy consumption is a complex task that involves different issues and requires different skills. In detail, the main energy consumption sources in a household are: space heating/cooling, domestic hot water, appliances and lighting. A major issue in modelling is to estimate the uncertainties implicit in the building model. There are many unknown and uncertain parameters that affect directly the results, especially when the model reproduces existing buildings. The uncertainties can be related to the quality of building works, real properties of materials and their performance degradation, the real performance of heating and cooling systems, quantification of air infiltrations, subjectivity in comfort condition, and an important group of uncertainties related to the user behaviour (appliances, lighting, setpoints...).

In the following sections a review of the state of the art is done. The review is focused on the occupancy behaviour and appliances consumption. The objective is to summarize the techniques and approaches that have been applied the last decade in those fields, to evaluate the strength and the weakness and try to improve them in the PhD thesis.

II.1.1 Occupancy in the building simulation models

Several simulations and practical studies have confirmed the significant influence of human behaviour on building energy consumption. The occupancy has different effects in the buildings which have to be included in the building models: a) a main goal of a building is to provide a good environmental comfort (thermal, visual and air quality). b) Occupancy is an important heat source and a modifier of the air quality in buildings; c) Occupants interact with the system of the building such as heating, ventilation, air conditioning, lighting, solar protections… The development of models to describe the occupancy behaviour has been an objective in the last decade. This objective follows the need to include better patterns of the occupancy in the building simulation in order to improve the energy results and reduce the gap between the simulation and the reality. The models for occupant presence aim to predict the probability for the active presence of occupants during the day in a building. Most of these models are based on survey data or occupancy data logs which are used as input for calibrating and developing stochastic models or deterministic methods to infer significant occupancy profiles.

The approach presented by Richardson [5] generates statistical occupancy patterns in UK households, with a 10 minute resolution and taking into account differences between weekdays and weekends. The model also indicates the number of occupants that are active within a house at a given time, which is important for example in order to model the sharing of energy use (shared use of appliances etc.). The model is based upon the UK 2000 Time Use Survey (TUS) data set. The TUS describes in detail the everyday life time of households members. The model uses a Markov-Chain technique to generate further data with statistical characteristics that matches the original. The data from the model can be used as input to any domestic energy model that uses occupancy time-series as a base variable, or any other application that requires detailed occupancy data. Widen et al. [6] presents a stochastic bottom-up model based on domestic occupancy patterns and data on daylight availability. A three state non-homogeneous Markov chain is used for the generation of occupancy patterns and a conversion model transforms occupancy patterns into lighting demand, with respect to the daylight level. Markov chain transition probabilities are determined from a detailed set of Time Use Data (TUD) in Swedish households and the parameters in the occupancy-to-lighting conversion model are adjusted to make the resulting load curves fit recent measurements on the aggregate population level. The performance of the model is analysed by comparison of simulated demand to measured lighting demand.

The model presented by Lu et al. [7] is based on Hidden Markov approach applied to historical schedules as well as actual data collected by several sensors (e.g. PIR sensors). The model estimates whether the household is occupied or unoccupied, and in the former case also whether the occupants are sleeping or active. The model is trained over a set of past actual past occupancy schedules and sensor data traces and is used to set heating systems, setpoint switches on or off according to occupancy. Krumm et al. [8] presented a scheduled based model in which occupancy is detected using a GPS device carried by the residents. The household is assumed to be occupied when the device indicates the resident is less than 100 meters away from it. Using the GPS the algorithm computes the probability of a household to be unoccupied during any time slot of a day of the week, with time slots of 30 minutes each. Mamidi et al. [9] uses a wide set of sensors such as video cameras, sound, ambient light, temperature, humidity, carbon dioxide, door/window state, ground truth occupancy counts from a counter app that is deployed on iPads installed next to the doorways. The objective is the estimation of two problems: 1) estimation of whether or not there are any occupants in a room, and 2) estimation of the exact number of occupants in a room. Solving these problems, it is possible to modify HVAC operation so that it is turned off when there are no occupants. The second problem is much harder, given the goal of estimating an exact number of occupants. Two general methods are compared: Simple heuristic method (regression), like linear regression, logistic regression, multi-layer perceptron, and support vector machines.

Aert et al. [10] developed a deterministic methodology that obtains occupancy profiles based on the 2005 Belgian time-use survey that contains detailed activity data of 6400 individuals from 3474 households. Using hierarchical clustering, the authors identified seven profiles that include highly differentiated yet the general behaviour that is relevant to building simulations, considering three possible states: (1) at home and awake, (2) sleeping or (3) absent. The approach provides a number of discrete user occupancy profiles that can be easily implemented in building simulation tools, keeping in mind the limitations regarding the predictability and the lack of interactions between users and building. The main contributions of these profiles are the identification of characteristic behaviour for subgroups of the population and connections between these subgroups and a number of socioeconomic variables. López-Rodríguez et al. [11] developed a study where the occupancy patterns in Spanish properties were determined using the 2009–2010 TUS, conducted by the National Statistical Institute of Spain. The survey identifies three peaks in active occupancy, which coincide with morning, noon and evening. This information has been used to input into a stochastic model which generates active occupancy profiles of dwellings, with the aim to simulate domestic electricity consumption.

Concluding the literature review of the occupancy modelling, most of the authors based their models on Markov approaches, however the base data can be different. Most of them develop the models with TUD and few of them with monitoring information. The potentiality of the models based on TUD is the easy replicability in other countries. The TUS are a harmonised European survey[4] that makes possible comparing the results between countries. One of the contributions of this thesis is to implement a stochastic profile of the occupancy based on TUS from Spain.

II.1.2 Appliances consumption

For modelling the consumption of appliances, a difficult aspect is the quantification of purely stochastic variables, namely the simulation of electrical consumption profiles for appliances and plug loads. In practice, electricity consumption caused by appliances has been often based on fixed profiles derived from statistical data. Although this kind of approach has some strong points (e.g., simple calculations, perfect for first stage analysis), it is not useful when a detailed characterization of the household consumption is needed, as for example in models for studies on nearly zero energy buildings, design of renewable energy systems or the energy interactions of a “prosumer” (producer and consumer) building [12]. For that reason, the development of models to estimate an electric load profile has gained growing interest by the scientific community in the last decade. The model presented by Paatero [13] generates domestic electricity load profiles at the individual household level. The model is a bottom-up approach, where the consumption is composed by individual appliances or appliance groups. The input

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[4] Harmonised European Time Use Survey website: www.h2.scb.se/tus/tus/

data of the model were mainly collected from public reports and statistics, and complemented with two hourly domestic consumption data sets from Finland (mainly data of appliances and lighting). The analysis of the results shows that the model correlates well with real data of different studies and generates realistic profiles of domestic electricity consumption.

Widén et al. [14] developed a deterministic model to obtain daily electricity and hot-water demand profiles, using TUS from Sweden. Simple conversion scheme was used to translate each activity in energy uses. Five different modelling schemes were used to describe the energy demand connected to the activity: power demand not defined by activity (e.g. refrigerator); power demand constant during the activity (e.g. TV); power demand constant after the activity (e.g. dish-washing); power demand constant during the activity with time constraint (e.g. bath); activities with time-dependent power demand (e.g. lighting). The model has been applied to two sets of TUS from Sweden (1996 and 2006), and the results are compared with different sets of measurement data (2006 and 2007). The aggregated results of both simulations show correspondence with the measurement surveys, in general better for electricity than for hot-water. Thereafter a high-resolution stochastic model for electricity demand has been developed by Widen and Wäckelgard [15]. The model generates activity sequences of individual household members and domestic electricity demand based on these patterns. The model is based on non-homogeneous Markov-chain, whose transition probabilities are obtained from TUD from Sweden (1996). Non-homogeneous model means that the probabilities of transitions vary over the day. A detailed validation against measurement data is done. The validation shows at individual household as well as aggregate level, that the model is highly realistic in terms of end-use composition, annual and diurnal variations, diversity between households, time-scale fluctuations and load coincidence.

Richardson et al. [16] described and validated a high resolution model of domestic electricity use. It is based upon a combination of the pattern active occupants (when people are at home and awake) and daily activity profiles for each different appliance. The resolution of the model is one-minute and distinguishes between weekday and weekend. The model is configured to simulate households with 1-5 occupants and to include up to 33 different appliances. The model is based on UK 2000 TUS and some national statistics. The TUS has been used: I) to define the active occupants by stochastic occupancy model [5]; II) to obtain the daily activity profile, considering the number of active occupants for different activities, at each time. The model has been validated with one year measurement data of 22 dwellings of the UK, showing similar statistical characteristics. An occupant behaviour model has been developed by Yamaguchi et al. [17] for estimating high-resolution electricity demand profiles for residential buildings. The occupant behaviour is based on statistical treated data of TUS in Japan: average on going minutes (AOM), standard deviation of AOM (SDOM), and percentage of respondents who adopt the behaviour (PB) at specific times of a day. Five priorities are defined and undertaken routinely: sleeping, commuting to and from work/school, eating and bathing. The second part of the model makes a conversion from behaviour to electricity, linking each one to the use of home appliances and equipment, the use of water heating and the location of the occupant.

The work presented by Baetens and Saelens [18] is based on the non-physical modelling of probabilistic occupant behaviour in buildings with an impact on the thermal and the electrical loads. The model is implemented in Modelica and can be divided in two parts: occupancy model (embedded discrete time Markov chains) and appliances use (semi-Markov processes). The model behaviour, which influences the internal heat gains and the power demand, is integrated in a building simulation. In a similar way, Neu et al. [19] integrate a Markov Chain Monte Carlo approach in EnergyPlus platform to simulate multi-zone single-storey detached building. The model is based on TUD in Ireland to obtain disaggregated residential appliances uses profiles, as Widen et al. [14] did. The model generates occupancy profiles at a fifteen-minute time resolution, electrical appliance load and lighting load profiles. They relate these profiles with the building models, including the associated heat gains of each element (occupancy, appliances and lighting).

Recently, "Instituto para la Diversificación y Ahorro de la Energía" (IDAE) has carried out the SECH-SPAHOUSEC project [20]. This project characterizes the energy consumption of the residential sector in Spain, including detailed information about the equipment stock and the main energy uses. The information is aggregated by regions (Atlantic, Continental and Mediterranean) and by building type (detached houses and apartment buildings). The data collection done by SECH-SPAHOUSEC has been performed by three complementary methods: telephone surveys, in-person surveys and electrical measurements of individual equipment in 600 dwellings. The main information obtained from surveys is related to the occupancy, the equipment stock and the annual energy consumption (based on estimations and bills). The electricity measurements give information about the use and the hourly consumption profile of each equipment and the hourly aggregate profile of the electricity consumption for each dwelling. In addition, the energy label of the characterised equipment is known and a detailed knowledge of the energy efficiency level of the equipment stock is possible.

Guarino et al. [21] developed a simplified and semi-detailed stochastic models of electrical consumption based on the data collected in SECH-SPAHOUSEC. The model includes data by region (Mediterranean, Continental and Atlantic) and type of building (detached house and multi-dwelling building). The simplified model is based on daily average profile of each equipment and the stochasticity is included in the stock of appliances for each dwelling. The semi-detailed model is based more on stochastic process than the simplified. In that case, the stock of appliances of each dwelling is also different, and in addition, the use of each one is variable and does not follow average profiles. The use of each equipment is defined by a set of 24-h probabilities to be on for every equipment. To choose which is the stock of equipment of each dwelling, and which appliances is to be switched on, a set of random number is generated during the simulation (at the beginning of the stock of equipment, and at each time step for their use). The model presented by Ortiz et al. [1, 22] is an improvement of the semi-detailed model of [21]. The model is based on the same method: first, a random selection of the equipment stock of each dwelling is done; then, at each time step the model defines stochastically which equipment is *on* or *off*. The difference between both models comes from the increased detail of the available SECH_SPAHOUSEC data. This fact has given the possibility to include aspects as detailed stand-by consumptions, multi-equipment considerations and accurate input data (probabilities of use, energy consumption…). Figure II.1 shows an example of two energy consumption profiles obtained from the stochastic model. In addition, the stochastic model was validated with measurement data obtained from the European project REMODECE[5].

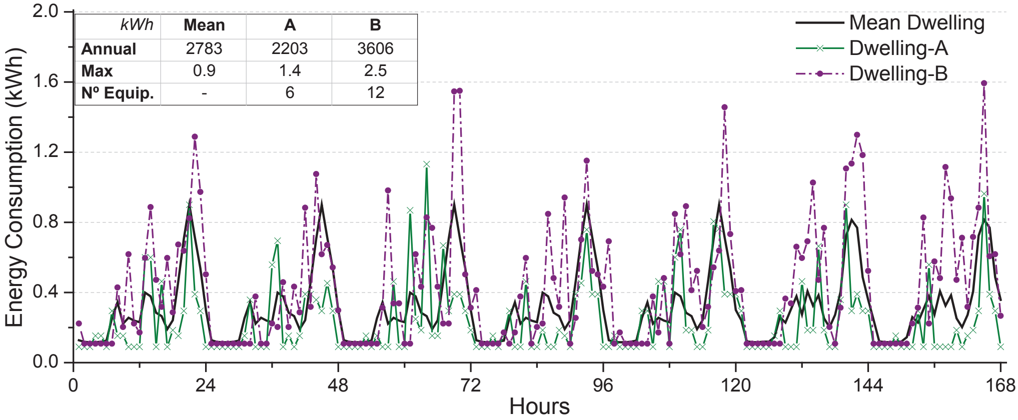

Figure II.1 Hourly electric consumption for a winter week. Example output of the model: two random dwellings and a mean dwelling [1, 22]

The works developed by Ortiz et al. [1, 22] were done under the PhD framework and is included in the building simulation model. The equipment stock of each building typology is defined according to the results of the surveys done in the building characterization. Then, the electric model is run with the corresponding appliances in order to obtain the energy consumption of each building typology. The electrical model adjusts the consumption to the characteristics of the households obtaining realistic results.

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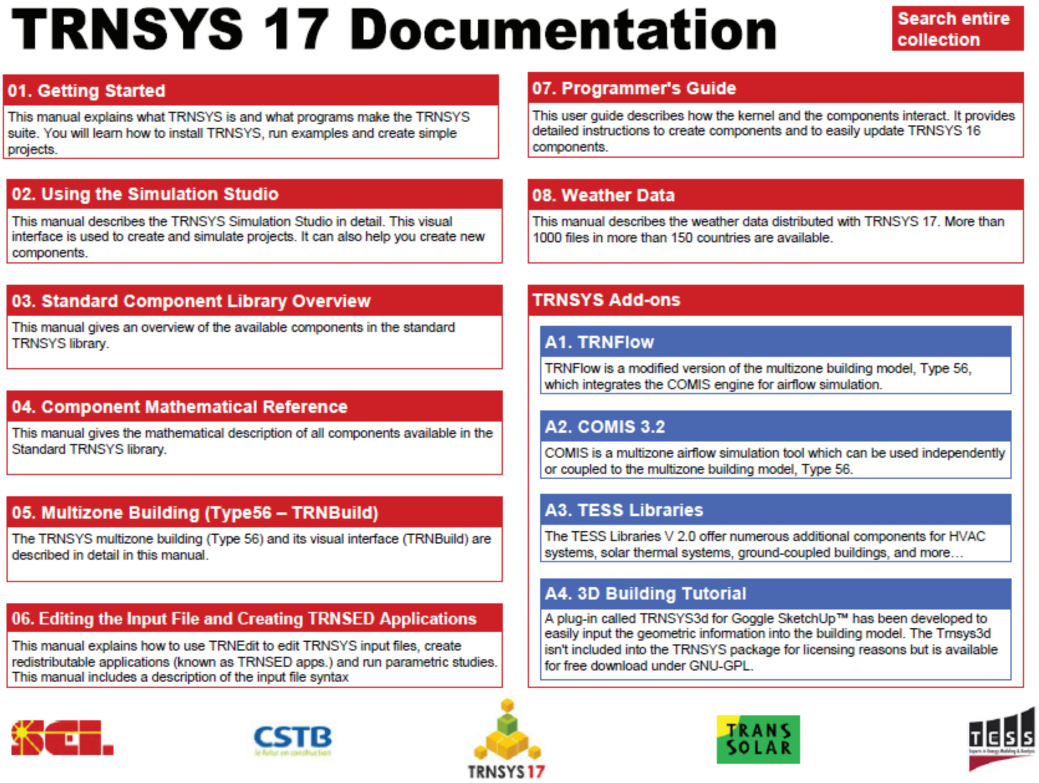
[5] REMODECE Project website: remodece.isr.uc.pt

II.2 Building simulation tool

The building model has been implemented in TRNSYS (Transient System Simulation Tool) [23]. TRNSYS is flexible software used to simulate the behaviour of transient systems. This flexibility makes possible to simulate thermal and electrical systems and it is used for many application (building simulation, couple multizone thermal and airflow modelling, solar thermal process, high temperature solar applications, geothermal heat pump systems, power plants…) TRNSYS is made up of two parts. The first is an engine (called the kernel) that reads and processes the input file, iteratively solves the system, determines convergence, and plots system variables. The kernel also provides utilities that (among other things) determine thermophysical properties, invert matrices, perform linear regressions, and interpolate external data files. The second part of TRNSYS is an extensive library of components, everyone models the performance of one part of the system. The standard library includes approximately 150 models ranging from pumps to multizone buildings, wind turbines to electrolyzers, weather data processors to economics routines, and basic Heating, Ventilation and Air Conditioning (HVAC) equipment to cutting edge emerging technologies. These components, called “types”, can be developed by the users with the objective to extend the capabilities of the environment.

The TRNSYS engine, the standard component library and most of the publicly available non-standard component libraries are written in Fortran and are compiled into a dynamic link library for the Windows operating system. TRNSYS is commercial software with open source code for the entire kernel and all standard components. In addition, TRNSYS has a complete documentation to understand the methods and calculation implemented in the kernel and in the standard component library, as Figure II.2 details.

TRNSYS has been chosen as a tool for the building simulation due to its high flexibility and the possibility to create new components. There are several specific objectives of the thesis that require this flexibility for a better implementation (co-simulation process and new components, as comfort index calculation and economic evaluation).



TRNSYS 17 Documentation

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01. Getting Started
This manual explains what TRNSYS is and what programs make the TRNSYS suite. You will learn how to install TRNSYS, run examples and create simple projects.

02. Using the Simulation Studio
This manual describes the TRNSYS Simulation Studio in detail. This visual interface is used to create and simulate projects. It can also help you create new components.

03. Standard Component Library Overview
This manual gives an overview of the available components in the standard TRNSYS library.

04. Component Mathematical Reference
This manual gives the mathematical description of all components available in the Standard TRNSYS library.

05. Multizone Building (Type56 – TRNBuild)
The TRNSYS multizone building (Type 56) and its visual interface (TRNBuild) are described in detail in this manual.

06. Editing the Input File and Creating TRNSED Applications
This manual explains how to use TRNEdit to edit TRNSYS input files, create redistributable applications (known as TRNSED apps.) and run parametric studies. This manual includes a description of the input file syntax

07. Programmer's Guide
This user guide describes how the kernel and the components interact. It provides detailed instructions to create components and to easily update TRNSYS 16 components.

08. Weather Data
This manual describes the weather data distributed with TRNSYS 17. More than 1000 files in more than 150 countries are available.

TRNSYS Add-ons

A1. TRNFlow
TRNFlow is a modified version of the multizone building model, Type 56, which integrates the COMIS engine for airflow simulation.

A2. COMIS 3.2
COMIS is a multizone airflow simulation tool which can be used independently or coupled to the multizone building model, Type 56.

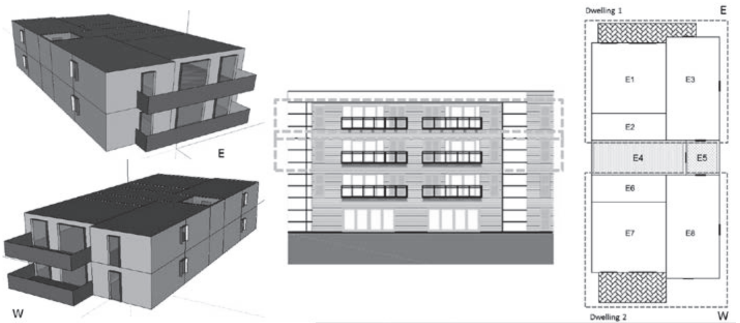
A3. TESS Libraries
The TESS Libraries V 2.0 offer numerous additional components for HVAC systems, solar thermal systems, ground-coupled buildings, and more…

A4. 3D Building Tutorial
A plug-in called TRNSYS3d for Goggle SketchUp™ has been developed to easily input the geometric information into the building model. The Trnsys3d isn't included into the TRNSYS package for licensing reasons but is available for free download under GNU-GPL.

Figure II.2 TRNSYS 17 Documentation [23]

II.3 Building features

The building geometry (Figure II.3) is introduced in the simulation by a multizone 3D model, using the plugin TRNSYS3D for Google SketchUp [24]. Only two floors are included in the simulation, in order to simulate the building with more detail: the standard floor and the under roof floor. There are two dwellings per floor and each one is divided following two zonification criteria: night and day use, and orientation. The building model includes the external environment and their corresponding shadings.



I	Area (m^2)	Day Zone	Night Zone	Corridor	Courtyard
Dwelling 1	103.1	E1,E2	E3	E4	E5
Dwelling 2	103.4	E6,E7	E8		

Figure II.3 Building typology BT-8 block of apartments 1990–2007

The envelope materials are defined depending on the year of construction and according to the previous building characterization. The cold bridges are considered in façade, roof, windows and columns, using linear thermal transmittance from CE^{3}X Handbook [25]. Annex II OptiHab described the characteristics of every building typology.

II.3.1 Infiltration

To finish the building characterization, a detailed model of infiltration is included in the building simulation model. The infiltration or air leakage is the unintentional introduction of outside air into a building, typically through cracks in the building envelope and through the border of doors and windows. Four different methods have been analysed in order to select the model of infiltration:

- K1, K2, K3 approach [26]: this method calculates the instantaneous air change rate, depending on outdoor temperature, indoor temperature, wind speed, and K1, K2, K3 coefficients. These coefficients have different values for tight, medium and loose construction. The method can be implemented in TRNSYS, using Type 571 (Thornton, 1998).
- LBL infiltration model [27]: this method calculates the instantaneous air change rate, depending on the Effective Leakage Area (ELA) and the superposition of wind and stack effects. The ELA depends on leakage coefficient and it can be calculated from experimental data of blower door test. The wind and stack effects depend on the outdoor temperature, indoor temperature, wind speed, the height of the building and its environment. The method can be implemented in TRNSYS using Type 960 [28].
- Sherman Grimsrud approach [29]: this method is based on the LBL infiltration model too, with the difference that two coefficients are used to consider the superposition of the wind and stack effects. The method can be implemented in TRNSYS using Type 932 [30].

- EN15242 method [31]: the direct method for exfiltration and infiltration calculates the instantaneous air change rate as a superposition of wind and stack effects. The result depends on outdoor temperature, indoor temperature, the height of the building, wind speed, and a coefficient that considers the pressure difference between windward and leeward sides. In addition, the method takes into consideration the building conditions, using the results of the blower door test (air changes per hour at 50 Pa, n_{50}) to calculate both the wind and stack air change rate. The method has been implemented in TRNSYS using equations.

In order to choose the infiltration method, the results of these four methods have been compared with the reference values of the PassivHaus design, which is based on the European Standard EN13790 [32]. It permits to calculate a constant annual air renovation rate, as a superposition of wind and stack effect. It depends on the n_{50} parameter and two tabulated exposure coefficients: the number of façades exposed to wind and the environmental exposure.

Figure II.4 compares the four methods with the reference of PassivHaus considering three values of n_{50} (5, 7 and 10), obtained as typical values from experimental data in existing buildings. Analysing the results of the different methods, it is possible to observe that the K1, K2, K3 approach is not able to distinguish the building features with a high detail, in comparison with the other methods, due to the qualitative definition of the construction (tight, medium and loose). It means that this approach is not able to distinguish different levels of loose construction, and the same coefficients have been used in the three cases, with no changes in the result. If the analysis is focused on both ELA methods (LBL infiltration model and Sherman Grimsrud approach), the average air change rates have a direct relationship with the different n_{50} values; however, the air change rates obtained are the lowest of all methods. If both methods are compared with the PassivHaus reference, the air change rate is 0.1-0.3 h^{-1} lower, being this difference higher as the value of n_{50} increases. Finally, the EN15242 is analysed: the air change rate is also lower than the reference value, with a difference between 0.05-0.1 h^{-1}. In this case, the difference is lower in comparison with the other methods, and the relationship with the n_{50} and the air change rate is similar to the PassivHaus reference.

After the analysis, the selected method is the EN15242, due to two main reasons: the method relates the air leakage of the household with experimental data (blower door test), and the results of the method are consistent with the reference of PassivHaus Design and EN13790.

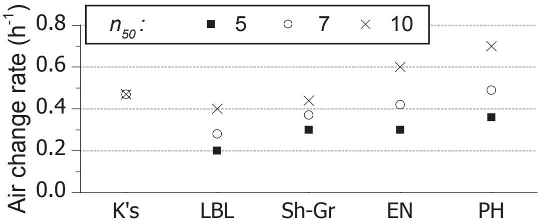


Figure II.4 Comparison of the methods of air leakage's modelling (K's: K1, K2, K3; LBL: LBL infiltration; Sh-Gr: Sherman Grimsrud; EN: EN15242; PH: PassivHaus)

The EN15242 method has been implemented in the building model to estimate the air change rate due to the air leakage of the building. The method considers the indoor conditions, the weather and the building conditions. In that sense, the method improves the estimation of the air infiltration flow and adjust it to: a) the location of the buildings; b) the variation over the year and c) the real conditions of the building. The model of infiltration includes two effects: stack and wind effect. The indoor and outdoor temperatures and the height of the dwelling are needed for the stack effect calculation. Relative to the wind effect, the wind velocity is used. In both cases, the tightness of the construction has to be characterized by n_{50} parameter and it has been obtained from experimental data [33, 34] (n_{50}=7.5 h^{-1} for current building and n_{50}=5 h^{-1} for the renovated building). In the building model, the infiltration is related mainly to the window perimeter. For that reason, although actually the infiltration is present all the time, in the building model the effect of the infiltration is active only when the natural ventilation (window opening) is not used.

II.4 Occupancy as a driver

In the simulation, the occupancy has been defined as the main driver of the use of the building (heating and cooling systems, natural ventilation, solar protections, and lighting). For that reason, one of the main objectives is to use realistic profiles of the occupants. This profile has to reproduce the variability of the real occupants and, at the same time, their behaviour has to be representative of the average occupant.

The occupancy characterization starts with the definition of the family type: how many people are in every household and their ages. This information has been obtained from the BSC surveys done in the building characterization study [35]. The family type for every building typology is described in the Annex II OptiHab. The stochastic profile of each user is created from the TUD survey of Spain [36]. The TUD survey gives information about what the people are doing at every moment of the day. Then, this information has been used to develop a stochastic model. The model generates occupancy profiles characterized for being different between occupants, days and seasons. The stochastic model is based on the Markov chain theory [37]. The main characteristic of the Markov process is that the stochastic process has the past-forgetting property, *only the most recent conditioning matters*. It means that the current situation depends only on the previous time step or period, or what is the same, what happens next depends only on the current state. Then, the information from the TUD has been used to develop the transition matrix that defines the Markov chain. For that, the TUD has been classified according to the family type. Three family types have been defined, as Table II.1 shows. The activities registered in the TUD survey have been classified in three states: outside home, passive at home and active at home. When a person is active at home means that it is doing an activity that implies energy consumption. The activities included in the active state are detailed in Table II.2.

Table II.1 Family description used in the occupancy model

Family	>25 years	<25 years
Type 1	1 or 2	no
Type 2	1 or 2	Up to 3
Type 3	Up to 5	no

Table II.2 Activities included in the state "active at home", based on the TUD activities

State	Activities	Description
Active at home	Housekeeping	Food preparation Dishwashing Cleaning dwelling Laundry Ironing
	Social activities	Receiving visitors Celebrations
	Computer activities	Computing programming Information by computing Communication by computing Other or unspecified computing Computer games
	Media activities	Watching TV, video or DVD Listening to radio or recordings

Once the information is classified, the transition matrices are calculated following the scheme represented in Figure II.5. A, B and C represent the three states (outside home, passive at home and active at home, respectively), and P is the probability to move from a certain state to another. For every time step (1 hour), there are 9 probabilities, one for every possibility, and their sum is 1.

Figure II.6 describe how the stochastic model has been developed. Before starting the simulation, the selection of the family type, number of occupants and the initialization of the state of each occupant are done. The initial state for all the occupants is A. After the configuration of the simulation, the loop over time starts. For each time step and occupant, a random number is generated, using the default function of FORTRAN. The random number (RN) has a value between 0 and 1. Then, this RN is compared with the matrix transition. If the previous state at *t-1* was A, then the RN is compared with $P_{A\rightarrow A}$. If the RN is lower than $P_{A\rightarrow A}$, the occupant continues in the same state; however, if the RN is equal or higher than $P_{A\rightarrow A}$, the RN must be compared with the next probability $P_{A\rightarrow B}$. The process is repeated in order to find the new state of the occupant. This step is done for every occupant and time step, in order to obtain the annual occupancy profile of the household.

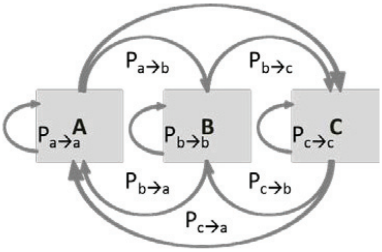


Figure II.5 Transition matrix of the Markov chain

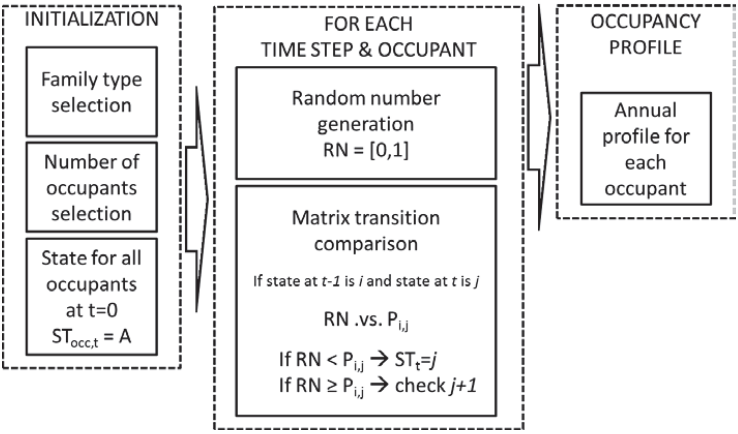


Figure II.6 Structure of the stochastic model

For every building typology has been simulated 500 households with its corresponding typology characterization (type of family) in order to choose a representative profile. A representative profile is the one whose annual characteristics are equal to the average profiles.

Table II.3 shows which information is used in the different systems of the building simulation: the occupancy, the number of occupants, or the state of each occupant.

Table II.3 Use of the occupancy profile in the building simulation

	Profile information
Internal gains	Nº of occupants and state
Natural ventilation	Occupancy
Solar protection	Occupancy
Artificial lighting	Occupancy, nº of occupants and state
Heating and cooling system	Occupancy

II.4.1 Natural ventilation

The natural ventilation is considered as the main strategy to reduce the temperature during the warm season, following vernacular strategies of the traditional Mediterranean architecture. The strategy is based on the following assumption: the users use the natural ventilation for cooling the household. In the case that the natural ventilation is not enough and overheating occurs, then, the windows are closed and the cooling system is switched on. This assumption is consistent with the results obtained in the BSC surveys of the building characterization study in [35, 38] which shows that the cooling system is used occasionally. The implementation of the natural ventilation can be divided in two parts: calculation of renovation rates and control of the natural ventilation. The method for modelling the renovation rate due to natural ventilation depends on the building features and the type of ventilation. This can be: single sided ventilation, cross ventilation or stack effect due to courtyards. The references used to model each natural ventilation phenomenon are described in the paragraphs below.

1. Single sided ventilation, using Gids and Phaff approach [39]: this method calculates the air change rate in function of the opening dimensions, wind speed, indoor and outdoor temperature depending on wind and buoyancy effect.

2. Cross ventilation, using British Standard [40]: this method calculates the air change rate considering the thermal buoyancy effect and the wind effect, depending on the wind speed and the difference of indoor and outdoor temperature, in each moment. The method takes also into consideration the opening area, the height of the building and pressure coefficients.

3. Courtyard effect: in this case, the stack effect due to courtyard effect has been implemented in a simplified way, due to the complexity of the calculation. The courtyards are designed to extract the air from the households, due to the difference of temperatures between the outdoor and the courtyard. For that reason, the rule used to define the courtyard effect is mainly related to the outdoor temperature (T_{out}) and the courtyard temperature (T_c), because depending on

that difference, the direction of the air flow changes (from household to outside, or from outside to household). If the $T_c > T_{out}$, the air flow goes from household to outside and the effect is the desirable. On the contrary, if the $T_c \leq T_{out}$, the air flow is opposite and does not comply with the design. Usually, the courtyard ventilation is a complementary phenomenon from the main ventilation strategy: single sided or cross ventilation. For that reason, the air change rate is related to the main ventilation method of the household, and the temperature comparison defines if the courtyard ventilation is active or not. If the courtyard ventilation is active, then the rooms (zones) of the households that are influenced by the courtyard are ventilated.

The control of the natural ventilation depends on the following parameters: occupancy, operative temperature of the zone, courtyard temperature and outdoor temperature. Table II.4 describes the control rules of the natural ventilation applied in the simulation model.

Table II.4 Control strategy of the natural ventilation

General rules of control	**Condition**	**Natural ventilation**
First condition:		
Occupancy	>0	YES
	0	NO
If the occupancy is >0		
Operative temperature (T_{op})	$T_{op} \leq 24ºC$	OFF
	$24ºC > T_{op} \geq 28ºC$	ON
	$T_{op} > 28ºC$	$f(T_{out})$
If the natural ventilation is OFF because $T_{op} > 28ºC$		
Outdoor temperature (T_{out})	$T_{out} \geq T_{op}$	OFF
	$T_{out} < T_{op}$	ON
If there is a courtyard in the household and the natural ventilation is ON		
Courtyard temperature (T_c)	$T_c > T_{out}$	Courtyard effect ON
	$T_c \leq T_{out}$	Courtyard effect OFF

In general terms and if there is occupancy in the household, the natural ventilation is active when the operative temperature is between 24ºC and 28ºC. The Figure II.7 shows that this range of temperature is comfortable for ASHRAE adaptive comfort model [41], especially, when the outdoor temperature is higher than 20ºC (warm season). If the operative temperature is higher than 28ºC, the natural ventilation is off (the windows are closed). The windows will remain closed until the outdoor temperature will be lower than the operative temperature, usually at night.

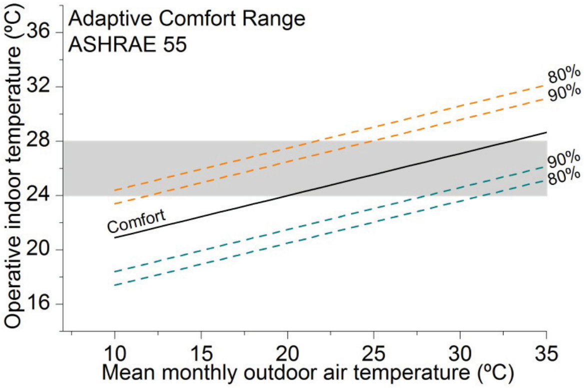


Figure II.7 Adaptive comfort ranges following the ASHRAE 55 comfort model

The building model has been configured with the option to simulate the building with natural ventilation and without natural ventilation. The objective of this configuration is to be able to distinguish the buildings that have the possibility to do natural ventilation or not due to its surrounding (the possibility of ventilation is not the same in a spacious village than in a compact city, due to noise, air quality or security).

II.4.2 Solar protections

The solar protection is the strategy used to prevent the increase of the temperature during the warm season. The use of the solar protections has been introduced as a complementary strategy of the natural ventilation. The BSC surveys done in the building characterization study [35] reflect that 90% of households have external shadings (blinds) and the 84% of the families use them during the warm period. Accordingly, the use of the solar protections has been implemented in the simulation in the base case. The idea is that when the operative temperature is lower than the comfort criteria, the solar radiation is used to heat the household. However, when the operative temperature is higher, it is needed to protect the household of the solar radiation to prevent the overheating. Two control strategies have been defined and they are described in Table II.5: typical use and optimal use of the solar protection. For the typical use, the occupants use the solar protections (blinds) when they are at home and the environmental conditions require it. On the contrary, in the optimal use configuration, the occupants have a preventive attitude using the solar protection: if the day is hot, the users will put the solar protection (blinds and awnings) before leaving the household, as vernacular strategy [42].

Table II.5 Control strategy of the solar protection.

General rules of control	**Condition**	**Typical use of solar protection**	**Optimal use of solar protection**
Occupancy	>0	YES	YES
	0	NO	YES
If the occupancy > 0			
Operative temperature (T_{op}) & Total solar radiation (R_S)	$T_{op} \geq 25$ºC $R \geq 140$ W/m^2	YES	YES
	$T_{op} < 25$ºC $R < 140$ W/m^2	NO	NO
If the occupancy < 0			
Operative temperature (T_{op}) & Total solar radiation (R_S)	$T_{op} \geq 25$ºC $R \geq 140$ W/m^2	NO	YES
	$T_{op} < 25$ºC $R < 140$ W/m^2	NO	NO

II.4.3 Daylighting and artificial lighting

In order to define the use of the artificial lighting, the daylighting availability has been calculated to know when it is needed to switch on/off the lights. The artificial lighting is controlled by occupancy and daylighting. Table II.6 describes the control strategy for the artificial lighting. As a difference of the other controls implemented in the model, this control takes into consideration the state of the occupants. In addition, the control has different rules depending on the hour of the day: night (from 24h to 7h) and day (from 7h to 24h).

The conversion of radiation to irradiance over the window is based on a simplified method proposed by French building regulation [43]. The method has been implemented in TRNSYS. This is a simplified method that is useful for this model because details of daylight distribution and visual comfort are not needed. There are no specific actuations to improve the daylighting use.

Table II.6 Control strategy of the artificial lighting

General rules of control	**Condition**	**Use of artificial lighting**
Occupancy = 0		NO
If the occupancy > 0		
Hour of the day & Irradiance (I)	Day (7-24h) I<150lux	YES
	Day (7-24h) I>200lux	NO
	Night (24-7h)	Only when active occupancy

The characteristics of the lighting system considered in all building typologies are described in Table II.7 and in the Annex II OptiHab. The selection of the type of light bulb has been done in coherence with the results of the BSC survey: 63% of the households have installed efficient lamps in the main rooms. In addition, the table shows the characteristics of the LED lamps, which are considered as a measure of improvement.

Table II.7 Characteristics of the lighting system

Lighting system	**Power installed**	**Luminous efficiency**
Fluorescent compact lamp	2 W/m^2	60%
LED lamp	1.5 W/m^2	80%

II.5 Heating, domestic hot water and cooling systems

The definition of the active systems and their use is based on the BSC surveys results of the MARIE project [35]. Around 60% of the households have a natural gas boiler to cover the heating and domestic hot water (DHW) demand, using water radiators as emitters. For the cooling system, around 50% of the households have an air conditioning split (AC) in one or two zones of the household. The only exception is for the building located in the Pre-Pyrenees climate, which does not have cooling system. The characteristics of the systems considered in each building typology are described in the Annex II OptiHab.

The energy systems have been defined using a simplified method based on the efficiency of the different parts of the system: generation, emission and control. The efficiency of generation is calculated using [44], which proposes a set of equations to correct the performance of the equipment depending on the partial load, and the indoor and outdoor temperature.

Regarding the efficiency of the emitters and the control of the heating system, the methodology implemented follows the European standard EN15316 [45]. The method takes in consideration different factors that affect the efficiency of the system: intermittent operation, radiative effect, stratification effect due to heating system and type of external walls, losses through external elements, type of control and hydraulic equilibrium. Table II.8 shows the values used for the base case and for the system after improving the performance of the installation through a programmable thermostat and thermostatic radiator valves.

Table II.8 Parameter to estimate the efficiency of the emitters and the control system [45]

Parameter	**Base case**	**EE measure**
Factor for intermittent operation	0.97	0.97
Factor due to the radiative effect	1.00	1.00
Efficiency due to stratification (temperature)	0.93	0.93
Efficiency due to stratification (type of wall)	0.95	0.95
Efficiency due to loses through external walls	1.00	1.00
Efficiency due to temperature control in the room	0.88	0.97
Factor for hydraulic equilibrium	1.03	1.00

Eq. II.1, Eq. II.2 and Eq. II.3 represent how the heating, DHW and cooling system has been implemented in the building model. The heating and the cooling demand are obtained directly from the dynamic simulation and the DHW is introduced in the simulation as an input data, obtained from the following reference daily profile [46].

Eq. II.1
$$E_{NG} = \frac{Q_H + Q_{DHW}}{\eta}$$

Eq. II.2
$$Q_H = Q_h + Q_{l,em} + Q_{l,ctr}$$

Eq. II.3
$$E_{ELE} = \frac{Q_C}{EER}$$

Where E_{NG} represents the final energy consumption of natural gas and E_{ELE} the final energy consumption of electricity in kWh. Q_C is the cooling demand, Q_{DHW} is the domestic hot water demand and Q_H is the total heating demand, including the losses related to the emission ($Q_{l,em}$) and the control system ($Q_{l,ctr}$), in kWh. Q_h represents the heating demand of the dwelling. η is the efficiency of the boiler and *EER* is the energy efficiency ratio of the cooling system.

In addition, the BSC surveys provide information about the use of the systems. Figure II.8 shows that the use of the heating and cooling system follows different patterns. With regard to the heating system use: 20% of the households use the heating system for the whole cold season; 28% use the system only when is very cold; 27% use the system when there is occupancy for the day-time, switching off for night; 17% use the heating system depending on the situation, without following any schedule; and the 8% use the heating system when there is occupancy. The setpoint of the heating system is between 21-23ºC (44%) and lower or equal than 20ºC (42%). The information about the use of the systems has been translated into the building model, as Table II.9 describes. The heating system is used when there is occupancy in the dwelling with two setpoints, depending on the hour of the day (20ºC and 15ºC, day and night respectively).

During the warm period, the cooling system is used basically when the temperature is hot (57%) and the setpoint of the cooling system varies between 24-25ºC (42%). These results are consistent with the hypothesis that the main strategy to reduce the temperature in summer is the natural ventilation, and the cooling system is used only when the weather conditions are extremes. Then, the use of the cooling system has been implemented in the model following the same rationale, prioritizing the natural ventilation.

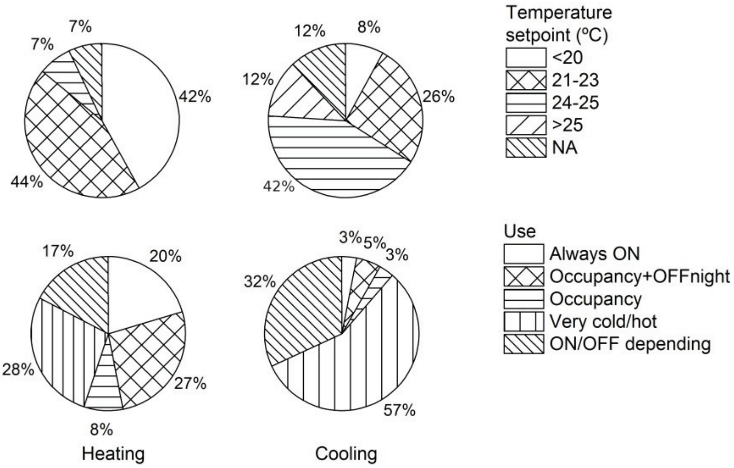


Figure II.8 Use of the heating and cooling system obtained from the BSC surveys

Concerning the setpoint from both systems, the temperature to have comfort conditions has been calculated, assuming a comfort Category II for new and renovated buildings (Predicted Mean Vote=±0.5). For the calculation it has been considered: the mean radiant temperature equal to the air temperature, indoor air relative humidity of 50%, air velocity of 0.1m/s, metabolic rate of 1.2met, clothing insulation of 1clo and 0.5clo, for cold and warm periods respectively, and an external work of zero met. The objective of that is to ensure that the setpoint used in the simulation is coherent with Fanger comfort model [47] (comfort model used in buildings with mechanical heating and cooling systems). The comfort range temperatures obtained are 19.2ºC - 23.7ºC and 23.0ºC - 26.2ºC for cold and warm periods. In conclusion, the temperatures used in the building simulation are inside the comfort range, according to the Category II of the Fanger model.

Table II.9 Use of the heating and cooling system implemented in the building model

System	Use	Setpoint
Heating	Occupancy	20ºC during day 15ºC during night
Cooling	Very hot	24.5ºC

II.6 Appliances consumption

The stock of equipment for each building typology has been obtained from the BSC surveys and is detailed in the Annex II OptiHab. The appliances follows the characteristics of the average household of a multifamily building in the Mediterranean region, which are obtained from the SECH-SPAHOUSEC project [20] and described in [1]. Table II.10 described the energy label of each appliance and their annual energy consumption.

Table II.10 Characteristics of the appliances of the average household in Mediterranean region, Spain

Appliance	Energy label	Annual energy consumption	Appliance	Energy label	Annual energy consumption
Washing machine	A	304 kWh/yr	Electric kitchen	-	436 kWh/yr
Drier	A	249 kWh/yr	Electric oven	-	163 kWh/yr
Dishwasher	A	246 kWh/yr	Microwave	-	61 kWh/yr
Refrigerator	B	674 kWh/yr	PC	-	291 kWh/yr
Television	C	211 kWh/yr			

The energy consumption profile of the appliances has been obtained through the stochastic model [1, 22]. The model uses a stochastic approach to simulate more than one household at the same time. The main output of the model is energy consumption of the household, in terms of aggregated and single energy use consumption. The idea behind the model is having a high-resolution tool, dependent on easily modifiable parameters. The model permits a simple and effective customization by the user, keeping it robust. The parameters of the model are also related with energy standards of appliances, making possible an analysis of their effect at neighbourhood level. The modelling environment chosen for the implementation of the model is TRNSYS, in order to complement the simulation of thermal loads in buildings. The description about the model and its validation are presented in [1].

Finally, one of the measures that have been considered in the study is the implementation of an awareness campaign in order to change the behaviour of the users and to reduce their energy consumption. The campaign consists in a training session about how they can save energy at home, and an installation of smart metering in each dwelling to provide information of their consumption. The smart metering visualizes the electric consumption in real-time as well as via web-server. This measure provides a reduction of 13% of the lighting and appliances consumption according to the results obtained from the local project “Smart Metering” in Sabadell [48]. The project developed an awareness campaign installing smart meters in 100 households, obtaining positive results after six months of actuation.

II.7 Renewable energy systems

The base case of the building typology does not have installed renewable energy systems. However, the building model has implemented two renewable energy systems in the simulation, in order to be considered as energy efficiency measures.

Solar thermal is one of the renewable energy systems considered in the study to cover partially the DHW demand, following the current regulation in Spain. In this case, the heat produced by the system has been calculated through the software Transol [49, 50], generating different profiles depending on the surface of the system and the climate. The solar thermal system is designed for the whole building and includes a centralized storage tank.

The other renewable energy is a photovoltaic (PV) system. In this case, the system has been implemented in the building model through a group of TRNSYS's components. The PV system has been designed at building level to cover the lighting consumption of the common areas of the building. The simulation model does not include this consumption because the simulation is done at household level. Then, in order to take into consideration the savings produced by the system, the proportional amount of PV generation will be considered as a saving of the electric consumption of every dwelling.

II.8 Energy efficiency measures

A brief description of the measure is introduced in the following section. Table II.11 includes the description of the measure and their additional benefits. The characteristics of the energy performance and their associated costs are detailed for every building typology in the Annex II OptiHab. The measures and their corresponding costs were defined in the framework of the MARIE project [35]. The investment costs include the material, their installation and the taxes (21% VAT). All the measures have been simulated both individually and combined.

Table II.11 Summary of the energy efficiency measures

Measure	**Code**	**Description**	**Additional benefits**
Façade insulation	F11-F15	External – EPS 4-12 cm	Reduce the thermal bridge.
	F16-F20	External – XPS 4-12 cm	
	F21-F23	Air chamber – rock wool 3-10 cm	
	F24-F26	Air chamber – EPS + graphite 3-10 cm	
	F27-F28	Air chamber – cellulose 5-10 cm	
	F29-F31	Internal – EPS 4-8 cm	
	F32-F34	Internal – rock wool 4-8 cm	
Roof insulation	R11-R13	Inverted – XPS 8-12 cm	-
	R14-R16	Internal – rock wool 4-8 cm	
	R17-R19	Internal – EPS 4-8 cm	
Window change	W11	4/16/4 Aluminium with thermal break	Reduce air infiltration (n50=5h^{-1})
	W12	4/16/4 PVC	
Solar protection	S11	Awning	Optimal use of the solar shadings
Heating and DHW system	H11	Condensing boiler + Improve the installation performance	Programmable thermostat Thermostatic radiator valve Tap aerators Water volume saving
	H12	Biomass boiler + Improve the installation performance	
	H13	Heat pump Air-water + Improve the installation performance	
Cooling system	C11	Efficient air conditioning system (Split)	-
	C12	No cooling system	The natural ventilation guarantee the comfort conditions
Lighting	L11	LED	-
Awareness	A11	Awareness campaign	Reduction of 13% of electric consumption
Solar thermal	T11	Solar thermal system + storage tank	-
PV system	P11	Photovoltaic system	-

II.9 Output of the building models

Figure II.9 shows the results of the simulation visualizing how the occupancy is linked to the use of the building: heating and cooling system, natural ventilation, artificial lighting and solar protection. In the left column there are the results of a winter week and in the right column a summer week. The first row of graphs represents the state of the occupancy during the week: outside home, passive at home and active at home. In the second row there are the temperature profiles including the outside temperature, indoor temperature and operative temperature. The third row shows the behaviour of the infiltration and the natural ventilation represented by the air renovation and its relation to the wind velocity. The fourth row of graphs represents the use of the solar protection together with the solar radiation over the windows. In the last row, the availability of daylighting and the use of artificial lighting are shown.

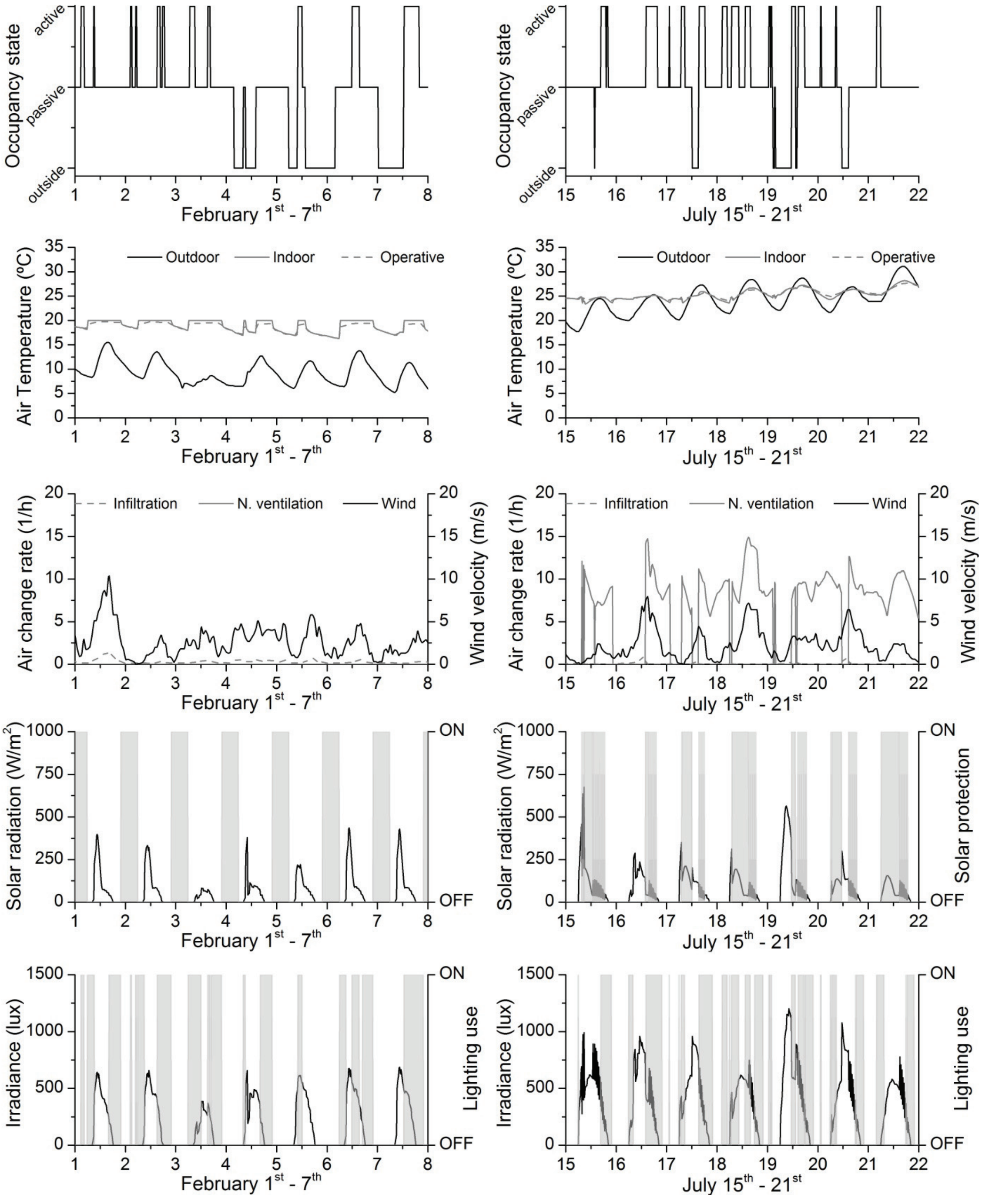


Figure II.9 Results of the simulation for a winter (left) and summer (right) week. BT-8 building typology (multifamily building built between 1991-2007)

Analysing the winter week of the Figure II.9, it is possible to see how the temperature of 4th February is below the setpoint (20ºC) because there are no occupants in the building and the heating system is off. As soon as the household is occupied, the heating system is switch on, increasing the temperature up to the setpoint. The solar protections (blinds) are used only at night as a thermal protection. As to the air renovation, the only phenomenon present during the winter week is the infiltration because the natural ventilation is not used.

For the summer week, the use of the natural ventilation and the solar protection has an important role in the building. The natural ventilation is active when there are occupants and the operative temperature is higher than 24ºC, as it is represented during the 17th July: at night the temperature is lower than 24ºC and the natural ventilation is not used; in the morning the temperature is increasing and the natural ventilation is active; at midday, there are no occupants in the household and the natural ventilation is off. In reference to the use of the solar protection, it is also possible to observe that their use depends on the operative temperature, the occupancy and the solar radiation.

Finally, the use of the lighting is the result of several factors: the availability of daylighting, the occupancy, and the state of the occupants. Some of these factors are not related with the season variability, for that reason there are not big differences between winter and summer despite the difference of daylighting hours.

The annual results for every building typology without any energy efficiency measure are detailed in Table II.12 and Table II.13. Table II.12 describes the energy demand for each building typology and climate, breaking down the energy demand by uses: heating, cooling, DHW, lighting and appliances. The results are expressed in energy demand per dwelling (kWh/dw) and per square meter (kWh/m^2).

The first analysis is focused on the results of a building typology changing the climate and the natural ventilation use (VENT and nVENT, with natural ventilation and without natural ventilation respectively). The main differences between climates are reflected in the heating and cooling demand. The nomenclature of the climates represents: letters (A-E) are the winter season and numbers (1-4) are the summer season. The highest values are the coolest (E) or hottest climates (4). For example E1 is the coolest climate in winter and in summer; B3 is the warmest climate in winter and in summer; D3 is an extreme climate with a cold winter and hot summer. Then, the heating and cooling demand of each climate follows the climate definition. The heating demand of the D3 climate is higher that the C2 climate; although, the cooling demand of the C2 is lower than the D3. On the other hand, the difference between the simulation of VENT and nVENT is reflected in the cooling demand. The building typologies that cannot use the natural ventilation as a cooling strategy increase the cooling demand considerable: more than a half in most of the building typologies and climates. The differences of domestic hot water and lightning demand due to the climate are reduced.

Table II.12 Energy demand for each building typology and climate

	Clima Natural ventilation	C2 VENT	C2 nVENT	B3 VENT	B3 nVENT	D3 VENT	D3 nVENT	E1 VENT	E1 nVENT
BT-4 (Semi-detached house, 1991-2007. Dwelling surface: 175.3 m^2)									
Heating	(kWh$_t$/dw·yr)	12 777	12 777	10 482	10 482	-	-	-	-
	(kWh$_t$/m^2·yr)	73	73	60	60	-	-	-	-
Cooling	(kWh$_t$/dw·yr)	92	417	373	806	-	-	-	-
	(kWh$_t$/m^2·yr)	1	2	2	5	-	-	-	-
DHW	(kWh$_t$/dw·yr)	1 965	1 965	1 881	1 881	-	-	-	-
	(kWh$_t$/m^2·yr)	11	11	11	11	-	-	-	-
Lighting	(kWh$_e$/dw·yr)	540	540	542	542	-	-	-	-
	(kWh$_e$/m^2·yr)	3	3	3	3	-	-	-	-
Appliances	(kWh$_e$/dw·yr)	4 306	4 306	4 306	4 306	-	-	-	-
	(kWh$_e$/m^2·yr)	25	25	25	25	-	-	-	-
BT-5 (Block of apartments between buildings, up to 1950. Dwelling surface: 60.5 m^2)									
Heating	(kWh$_t$/dw·yr)	3 044	3 040	-	-	-	-	4 794	-
	(kWh$_t$/m^2·yr)	50	50	-	-	-	-	79	-
Cooling	(kWh$_t$/dw·yr)	49	254	-	-	-	-	-	-
	(kWh$_t$/m^2·yr)	1	4	-	-	-	-	-	-
DHW	(kWh$_t$/dw·yr)	982	982	-	-	-	-	1 149	-
	(kWh$_t$/m^2·yr)	16	16	-	-	-	-	19	-
Lighting	(kWh$_e$/dw·yr)	219	219	-	-	-	-	217	-
	(kWh$_e$/m^2·yr)	4	4	-	-	-	-	4	-
Appliances	(kWh$_e$/dw·yr)	1 831	1 831	-	-	-	-	1 831	-
	(kWh$_e$/m^2·yr)	30	30	-	-	-	-	30	-
BT-6 (Block of apartments between buildings, 1951-1980. Dwelling surface: 78.8 m^2)									
Heating	(kWh$_t$/dw·yr)	4 797	4 797	3 939	3 937	7 797	7 796	7 738	-
	(kWh$_t$/m^2·yr)	61	61	50	50	99	99	98	-
Cooling	(kWh$_t$/dw·yr)	86	312	276	566	253	432	-	-
	(kWh$_t$/m^2·yr)	1	4	3	7	3	5	-	-
DHW	(kWh$_t$/dw·yr)	1 473	1 473	1 411	1 411	1 625	1 625	1 724	-
	(kWh$_t$/m^2·yr)	19	19	18	18	21	21	22	-
Lighting	(kWh$_e$/dw·yr)	224	224	220	220	222	222	224	-
	(kWh$_e$/m^2·yr)	3	3	3	3	3	3	3	-
Appliances	(kWh$_e$/dw·yr)	1 832	1 832	1 832	1 832	1 832	1 832	1 832	-
	(kWh$_e$/m^2·yr)	23	23	23	23	23	23	23	-
BT-8 (Isolated block of apartments, 1991-2007. Dwelling surface: 103.2 m^2)									
Heating	(kWh$_t$/dw·yr)	5 506	5 507	4 420	4 420	-	-	-	-
	(kWh$_t$/m^2·yr)	53	53	43	43	-	-	-	-
Cooling	(kWh$_t$/dw·yr)	114	748	415	1 214	-	-	-	-
	(kWh$_t$/m^2·yr)	1	7	4	12	-	-	-	-
DHW	(kWh$_t$/dw·yr)	1 473	1 473	1 411	1 411	-	-	-	-
	(kWh$_t$/m^2·yr)	14	14	14	14	-	-	-	-
Lighting	(kWh$_e$/dw·yr)	292	293	289	289	-	-	-	-
	(kWh$_e$/m^2·yr)	3	3	3	3	-	-	-	-
Appliances	(kWh$_e$/dw·yr)	3 472	3 472	3 472	3 472	-	-	-	-
	(kWh$_e$/m^2·yr)	34	34	34	34	-	-	-	-

The comparison between building typologies is done below. Starting the analysis with the heating demand, the results reflect that for the same period of construction, which implies the same level of energy performance, the semi-detached house (BT-4) has a higher heating demand than the block of apartments (BT-8), 73 and 53 kWh/m^2·yr respectively. Comparing the cooling demand, the BT-4 presents better results due to have a more effective strategy of natural ventilation and solar protection. The semi-detached house has natural cross ventilation and external solar protections (awnings); however the BT-8 has single-sided ventilation and blinds as a solar protection. Analysing the block of apartments and the different construction periods it is possible to observe how the heating demand is reduced as the thermal regulation improves. There is an exception with the oldest building typology (BT-5). This typology has a low heat demand, being lower than the BT-8. The main reason is that the building typology is protected, having only one and small external façade and one external window (see Annex II OptiHab), and the inertia of the materials is higher than the other building typologies (solid bricks instead of hollow bricks). This building typology is typical from the old town of the cities and is characterized to be located in narrow streets and to have different floor configurations from one building to another.

Finally, the DHW, lighting and appliances demand are related to the occupancy and the size of the building. The BT-4 is the highest dwelling and is occupied by four people, for that reason the demands are higher. On the contrary, the BT-5 is occupied by two people and the demands are lower.

To finalize the comparison, Table II.13 shows the final energy consumption and the non-renewable primary energy consumption for each building typology and climate. The main differences that can be reflected in these results are related to the final energy used by each system. Basically, the heating and DHW demand are covered by natural gas boiler, and the cooling, lighting and most of the appliances by electricity. However, the stove of the kitchen can use natural gas or electricity. The building typology BT-5 and BT-6 use natural gas stoves, and the BT-4 and BT-8 electrical stoves. In addition, the building typologies with natural ventilation and without natural ventilation have high differences in the electric consumption due to the increase of the cooling demand.

Table II.13 Final energy consumption and non-renewable primary energy consumption for each building typology and climate

	Clima	C2	C2	B3	B3	D3	D3	E1	E1
	Natural ventilation	VENT	nVENT	VENT	nVENT	VENT	nVENT	VENT	nVENT
BT-4 (Semi-detached house, 1991-2007. Dwelling surface: 175.3 m^2)									
Electricity	(kWh/dw·yr)	4 943	7 536	5 215	7 770	-	-	-	-
	(kWh/m^2·yr)	28	43	30	44	-	-	-	-
Natural gas	(kWh/dw·yr)	21 539	21 539	18 078	18 077	-	-	-	-
	(kWh/m^2·yr)	123	123	103	103	-	-	-	-
Primary energy	(kWh/dw·yr)	35 226	41 615	32 194	38 488	-	-	-	-
	(kWh/m^2·yr)	201	237	184	220	-	-	-	-
BT-5 (Block of apartments between buildings, up to 1950. Dwelling surface: 60.5 m^2)									
Electricity	(kWh/dw·yr)	2 099	3 389	-	-	-	-	2 049	-
	(kWh/m^2·yr)	35	56	-	-	-	-	34	-
Natural gas	(kWh/dw·yr)	6 499	6 494	-	-	-	-	9 327	-
	(kWh/m^2·yr)	107	107	-	-	-	-	154	-
Primary energy	(kWh/dw·yr)	12 125	15 299	-	-	-	-	15 029	-
	(kWh/m^2·yr)	200	253	-	-	-	-	248	-
BT-6 (Block of apartments between buildings, 1951-1980. Dwelling surface: 78.8 m^2)									
Electricity	(kWh/dw·yr)	2 137	4 758	2 310	4 907	2 293	4 627	2 056	-
	(kWh/m^2·yr)	27	60	29	62	29	59	26	-
Natural gas	(kWh/dw·yr)	9 204	9 203	7 853	7 851	13 814	13 812	13 875	-
	(kWh/m^2·yr)	117	117	100	100	175	175	176	-
Primary energy	(kWh/dw·yr)	15 114	21 571	14 094	20 490	20 431	26 180	19 912	-
	(kWh/m^2·yr)	192	274	179	260	259	332	253	-
BT-8 (Isolated block of apartments, 1991-2007. Dwelling surface: 103.2 m^2)									
Electricity	(kWh/dw·yr)	3 874	6 639	4 148	6 918	-	-	-	-
	(kWh/m^2·yr)	38	64	40	67	-	-	-	-
Natural gas	(kWh/dw·yr)	10 239	10 239	8 556	8 556	-	-	-	-
	(kWh/m^2·yr)	99	99	83	83	-	-	-	-
Primary energy	(kWh/dw·yr)	20 501	27 315	19 375	26 200	-	-	-	-
	(kWh/m^2·yr)	199	265	188	254	-	-	-	-

II.10 References

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Chapter III Validation of the energy simulation model

III.1 Introduction

The development of a building simulation model that is able to reproduce and fit with the actual buildings is a challenge. If the building model has the capacity to predict the building performance in terms of energy and temperature, it will be possible to use it to design a retrofit intervention with a higher reliability in the prediction of the building performance. For that reason, it is interesting to validate the methods and hypotheses implemented in the building models. However, it is important that the parameters and characteristics of the building model are realistic.

There are two main references used for the validation process: ASHRAE Guideline 14-2002 [1] and International Performance Measurement and Verification Protocol (IPMVP) [2]. Both methodologies are based on the need to develop a protocol or standardized procedure to quantify the savings obtained after a building intervention. The methods provide guidance on minimum acceptable levels of accuracy to determine savings, using measurements and/or simulation models. Details about the parameters and criteria for the validation process are described in the section III.2. Most of the works reviewed implement these methodologies as criteria to consider that a building simulation is calibrated.

Historically, the calibration has been a process where the user knowledge has played an essential role and has not followed a standardized guideline. Reddy et al. [3] made a review of tools, techniques, approaches and procedures used for calibration process, in order to define a systematic calibration methodology. The method consists of five parts: 1) identifying the building energy simulation programme more appropriate for the case study; 2) defining a set of influence parameters, their values and range of variation; 3) coarse search wherein the influence parameters are combined using Monte Carlo simulation to obtain promising combinations; 4) performing a guided research to refine the results; 5) using a small number of plausible calibrated models to determine the prediction uncertainty. Thereafter, several studies were carried out implementing the main steps of the method proposed by [3], and proposing specific technics and approaches for each step. Raftery et al. [4] calibrated a detailed EnergyPlus model of a new office building implementing an evidence-based methodology for calibrating it. Heo et al. [5] quantified the uncertainty in the retrofit decision-making process by applying Bayesian calibration to an office building model. Roberti et al. [6] presented a semi-automatic calibration method of a historic building retrofit. Cipriano et al. [7] proposed a multi-stage guided search approach for the calibration of building energy simulation models. It is important to highlight that most of the works underline the risk of working with a calibrated model whose parameters or outputs do not correspond to reality. Then, there are many techniques that can be used in the calibration process; however, all of them still need the expert criteria to interpret properly the results.

One of the main steps of the validation process is to identify the most influential parameters. There are some works that analysed which are the ones with more impact in residential buildings. Ioannou and Itard [8] developed a sensitivity analysis to evaluate the influence of building parameters and occupancy in the energy performance and comfort of residential buildings. They made the analysis considering different scenarios: single-zone and multi-zone building model; Class-A and Class-F dwellings; and three different heating systems. First, they evaluated the effect of technical parameters, as orientation, U-values and g-values, and thereafter, they added behavioural parameters (setpoint, ventilation and infiltration and number of occupants) to compare and to decide which are the most influential parameters. The results showed that when the behavioural parameters are included in the analysis, they become predominant in the sensitivity analysis, having a greater influence over the energy consumption and the comfort parameters, especially the setpoint and the ventilation rates. They recommend that since the thermostat and ventilation have a very high impact but at the same time cannot be determined precisely, energy consumption should be shown as bandwidth. Guerra and Itard [9] studied the influence of the occupancy behaviour in the energy consumption of residential buildings. For that, they carried out statistical analysis on energy use and self-reported behaviour data from a household survey in the Netherlands. They found some consumption patterns depending on the type of heating system. Households with a programmable thermostat were associated with higher temperature settings and more hours of heating system use, in comparison with manual thermostats. Silva and Ghisi [10] went further and tried to quantify the uncertainty associated to the user behaviour and physical parameters in residential building simulations. They simulated a household using probability density functions for the physical and user behaviour parameters. Their results show that for heating energy consumption up to 19.5% and 36.5% of uncertainty was related to physical and user behaviour parameters, respectively. However, for cooling energy consumption up to 43.5% and 38.0% of uncertainty was related to physical and user behaviour parameters. All these uncertainties were determined with 95% confidence. Recently, Huebner et al. [11] developed a study to analyse the contribution of building characteristics, socio-economic parameters, and behaviours and attitudes to the energy consumption of a household. They used 924 English households data collected in 2011/12 to develop regression models. These models showed that building variables on their own explained about 39% of the variability in energy consumption, socio-demographic variables 24%, heating behaviour 14% and, attitudes and behaviours only 5%. In addition, they developed a combined model including all variables, and the model explained only 44% of all variability. It means that more than half of the energy consumption variability cannot be explained with the parameters analysed.

Despite the efforts to improve calibration methods, it has been shown that uncertainties associated to behavioural patterns are usually important. In that sense, the validation wants to explore the impact of this uncertainty in the results of the model, as for example occupancy and use of the heating system.

III.2 Validation method

The method implemented to validate the model is based on the following steps:

1. Selection and characterization of the pilot site. A data collection to characterize the pilot site is needed in order to adapt the building model to the real case. For that reason, several surveys (hereafter the PS surveys) and monitoring campaigns have been carried out in the pilot site. The main parameters collected during the campaigns are: the building and equipment features, the occupancy and behaviour of the users, indoor environmental data (temperature, humidity and CO_2 concentration), weather data (temperature, humidity, solar radiation, wind velocity and direction) and energy consumption (electricity and natural gas bills).
2. Simulation of the pilot site. All the information collected in the previous step is analysed and is adapted to be implemented in the building model. The information is: building geometry, constructive materials, occupancy and behaviour profiles, energy systems and appliances stock.
3. Validation of the model. A comparison between the monitoring data and the results of the building simulation has been developed. The results of the validation should provide the reliability of the method implemented in the building simulation model, making possible to extrapolate the method to other building typologies.

The indicators used for the validation are based on the ASHRAE Guideline 14-2002 [1] and IPMVP protocol [2]. The three indicators are the Normalized Mean Bias Error (NMBE), the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) and Coefficient of Determination (R^2), which are detailed in the Eq. III.1, Eq. III.2 and Eq. III.3, respectively. In the equations, Y_t represents the monitoring data for a certain period of t; $\overline{Y}$ is the arithmetic mean of monitoring data; y_t is the simulation results for a certain period of time t; n is the total number of data points or periods in the baseline period.

The NMBE indicates how well the energy consumption is predicted by the model as compared to the measured data, normalized by the mean value of the measured data. Positive values indicate that the model overpredicts actual values; negative values indicate that the model underpredicts actual values. However, negative and positive differences between the predictions and the measurements are balanced out and the NMBE is reduced.

Eq. III.1

$$NMBE = \frac{\sum (y_t - Y_t)}{n} \cdot \frac{1}{\overline{Y}} \cdot 100$$

The CV(RMSE) is the normalized RMSE by the mean value of the monitoring data. RMSE represents the sample standard deviation of the differences between predicted values and observed values (simulation and monitoring data). The RMSE aggregates the magnitudes of the error and it is a good measure of accuracy. This value represents the overall uncertainty in the prediction of whole-building energy use.

Eq. III.2

$$CV(RMSE) = \sqrt{\frac{\sum (Y_t - y_t)^2}{n}} \cdot \frac{1}{\overline{Y}} \cdot 100$$

The coefficient of determination is a statistic parameter that gives information about the goodness of fit of a model. The R^2 is a statistical measure of how well the linear regression approximates the real data, measuring the agreement between observed and modelled values. R^2 has values between 0 and 1, being 1 the perfect regression between observed and modelled.

Eq. III.3

$$R^2 = \frac{\sum (y_t - \overline{Y})^2}{\sum (Y_t - \overline{Y})^2}$$

Table III.1 describes the criteria of acceptance for each statistical parameter. The ASHRAE guideline defines two different thresholds depending on the data resolution (hourly or monthly). The R^2 criterion is only defined by the IPMVP protocol.

Table III.1 Statistical validation following ASHRAE [1] and IPMVP [2] guidelines

Statistics	**NMBE**	**CV(RMSE)**	**R^2**
ASHRAE Hourly data	± 10%	<30%	Not defined
ASHRAE Monthly data	± 5%	<15%	Not defined
IPMVP Monthly data	± 7%	<15%	>0.75

III.3 Pilot site description

The pilot site is located in Terrassa (Barcelona, Spain) in a residential urban area. The weather data used for the simulation are from a weather station located in the city centre of Terrassa (official weather station nº 189C, “Agencia Estatal de Meteorología”). The data used for the validation are from 2013, 2014 and 2015. Figure III.1 summarized the monthly air temperature (left) and relative humidity (right) in Terrassa for every year. Comparing the weather conditions of the three years, it is possible to observe how the 2013 and 2015 winters are colder than the

2014 winter. However, the summer of 2015 was hotter than the other years. It is possible to say that 2014 was a temperate year, with soft winter and summer, and 2015 was an extreme year with cooler winter and hotter summer.

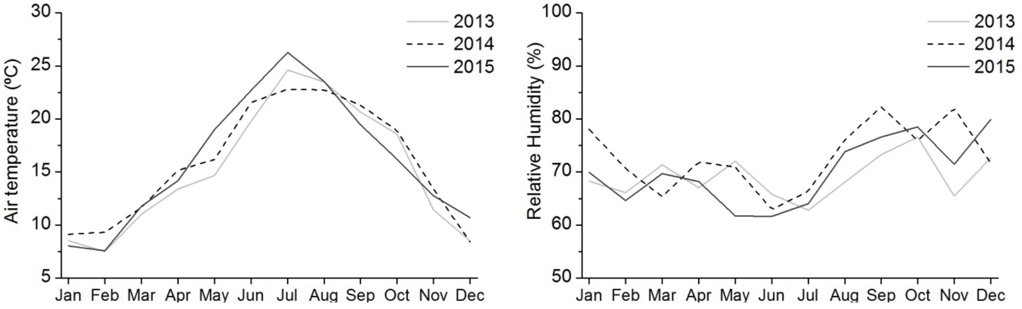

Figure III.1 Weather conditions in Terrassa for 2013, 2014 and 2015: air temperature (left) and relative humidity (right). Official weather station nº 189C, "Agencia Estatal de Meteorología"

The dwelling used as a pilot site corresponds to a BT-8 building typology (multifamily building built between 1991-2007). The dwelling is on the first floor of the building with two external façades oriented to north and west, as Figure III.2 shows. There is no information about the construction features of the building then, the building typology characteristics are used in the model (Annex II OptiHab). There are blinds in all openings and awing in the western façade.

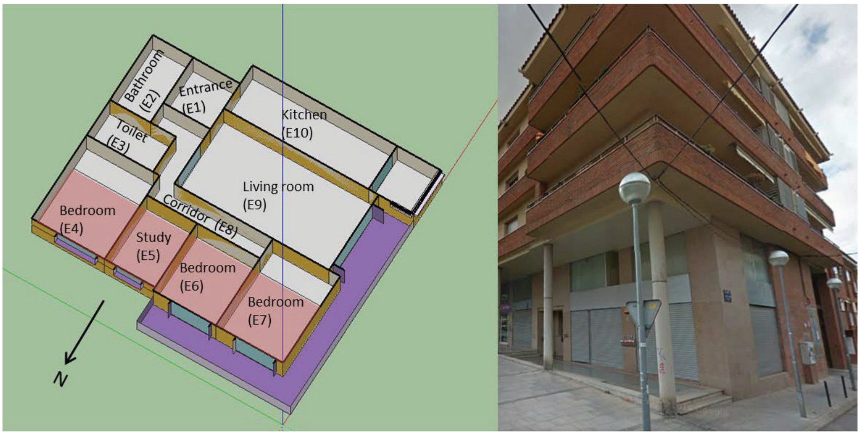

Figure III.2 Drawing and picture of the pilot site

The dwelling is occupied by a family with two adults and two children. The occupancy profile has been adapted according to the habits of the family. This occupancy profile includes a typical winter week and a typical summer week (according to the school periods), as well as the holiday periods of each year (summer and Christmas holidays).

Concerning the equipment of the household, there is an individual heating system to cover the heating and DHW demand. The system consists of a conventional natural gas boiler (η=0.85) with water radiators and a temperature controller located in the living room. The setpoint is 20ºC during the winter period. The heating system is turned on when there is occupancy in the household until 22h at night, according to the PS survey. The household does not have cooling system, using the natural ventilation and the solar protections as the main strategy in summer. The solar protections are used throughout the day, and the natural ventilation is used basically at night, according to the PS survey results.

The lighting systems of the household are energy efficient lamps, assuming that all the lamps are FCL. The appliance stock is detailed in Table III.2 and their electric consumption has been obtained using the stochastic model described in [12].

Table III.2 Characteristics of the appliances of the pilot site dwelling

Appliance	**Annual energy consumption**	**Appliance**	**Annual energy consumption**
Washing machine	481 kWh/yr	Natural gas kitchen	545 kWh/yr
Drier	708 kWh/yr	Electric oven	163 kWh/yr
Refrigerator	324 kWh/yr	Microwave	38 kWh/yr
Television	243 kWh/yr	PC	247 kWh/yr

The energy consumption of the pilot site has been obtained through the bimonthly bills of electricity and natural gas. Figure III.3 shows the energy consumption: electricity (left) and natural gas (right). The monthly aggrupation has been adapted according to the billing periods. The electric consumption is similar in every period, with the exception of the summer and Christmas whose consumption is smaller due to the holiday periods, being the household empty. For the natural gas consumption, there is a clear increase of consumption in winter due to the heating use. In addition, there is also an important difference between the 2014 and the other years because of the soft weather conditions.

In addition, several monitoring campaigns have been done to obtain indoor environmental data of the household. The information collected is air temperature, humidity and CO_2 concentration. The different periods are detailed in Table III.3, as well as the zones monitored.

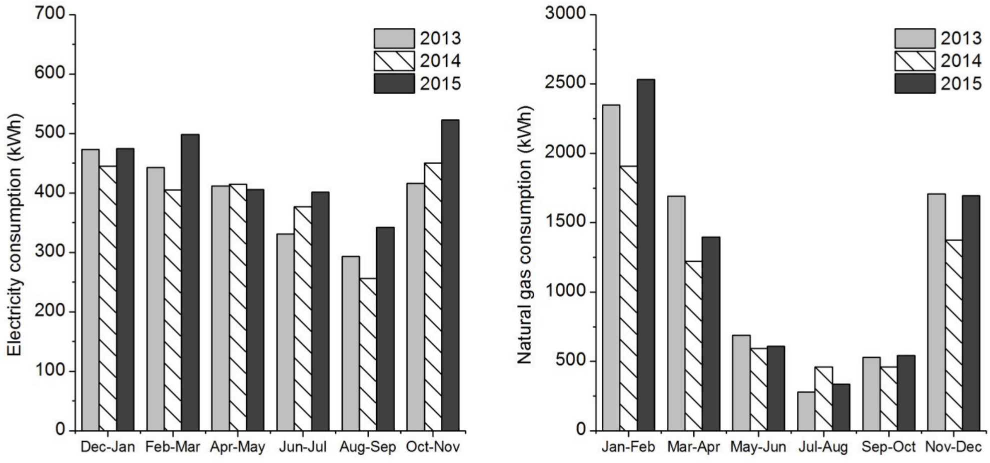

Figure III.3 Energy consumption by the pilot site for 2013, 2014 and 2015: electricity (left) and natural gas (right)

Table III.3 Monitoring campaign description

Period	Days	Living room (E9)	Bedroom (E4)
Winter 2015	11	X	X
Summer 2015	13	X	X

III.4 Validation of the building simulation

The validation has been based on an iterative process, in order to implement realistic modifications and to understand the reasons of the main differences between the model results and the actual data. The building model has been adapted to the pilot site characteristics according to the data collected. Once the building model has been adapted, the results of the simulation have been analysed in order to find the reasons of the differences between the model and the monitoring data.

The first finding is related with the heating system and the variation of the temperatures over the household. The heating system implemented in the building model is the ideal system available in TRNBuild. The ideal heating system, with a limited heat power in each zone, provides the setpoint temperature just after turning on the heating system and this temperature is constant and uniform in the whole household. However, the monitoring data shows that this situation does not fit with the reality, because there are important differences in the temperature of the north, west and internal zones. Analysing the monitoring data, it is possible to conclude that the north zones are on average 2ºC cooler than the west and internal zones. For those reasons, the setpoint has been adapted according to Table III.4, reducing the setpoint temperature 2ºC in the north zones (which are the night zones of the dwelling).

Table III.4 Heating setpoint configuration of the building model

Zones	**Orientation**	**Setpoint**
E9, E10	West	20ºC
E1, E2, E3, E8	Internal	20ºC
E4, E5, E6, E7	North	18ºC

Figure III.4 shows the results for the winter season of the simulation in comparison with the monitoring data of the winter campaign of 2015. The figures reflect five main features:

- The difference between the living room temperature and the room is around 2ºC according to the monitoring data.
- The occupancy schedule and the use of the heating system are very variable and introduce a high level of uncertainty to the building model.
- The setpoint is not constant and changes from one day to another.
- The inertia of the building model is underestimated, and the temperature falls down instantaneously after turning off the heating system, fact that is not observed in the monitoring data.
- There is a relation between the monitored temperature and the use of the heating system, with the CO_2 concentration: when there is nobody in the room, the CO_2 concentration decays until the outdoor levels (around 400-500 ppm) due to the infiltration.

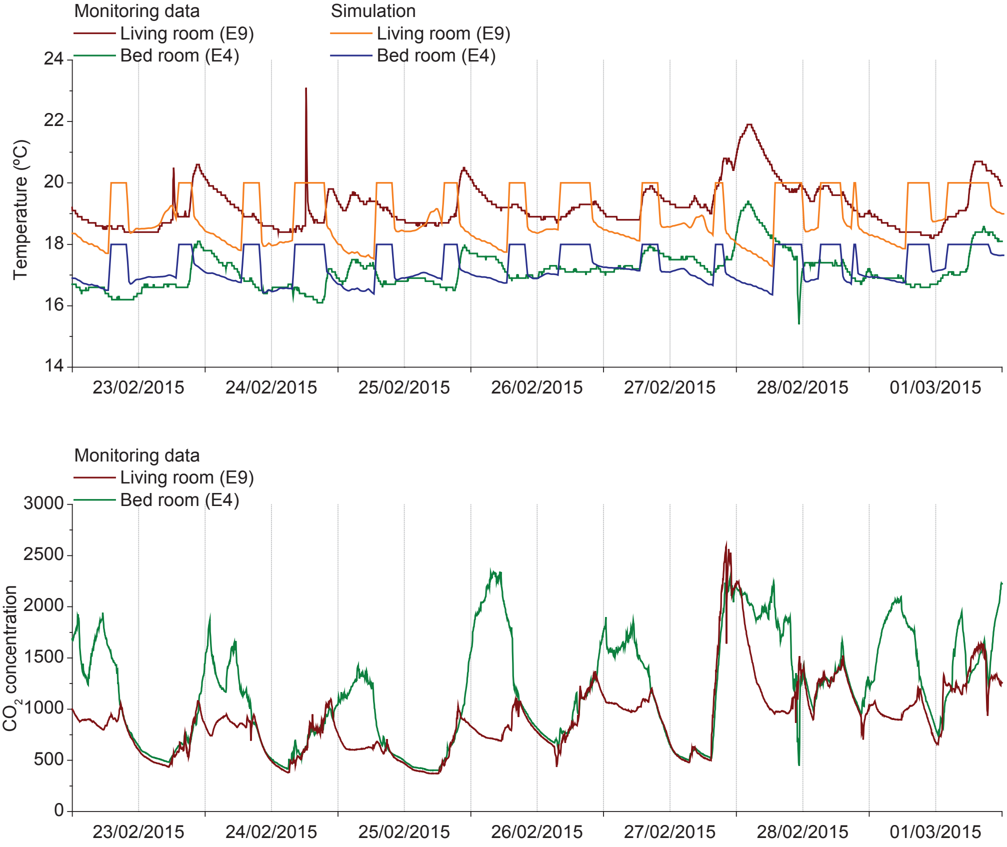

Figure III.4 Winter 2015 comparison. Air temperature comparison (top) and CO_2 concentration monitored (bottom)

Figure III.5 presents the results of the simulation for a summer week in 2015. The results are presented in terms of air temperature of the bedroom and the living room, as well as monitored data of CO_2 concentration. In general, the simulation of the building underestimates the air temperature, especially for the day time. At night, the trend and the levels of air temperature are more similar to the monitored data. In addition, the monitored data shows different patterns between the living room and the bedroom. As one possible reason it could be related to the operability of the windows and its implementation in the model. As the CO_2 concentration shows, the household is ventilated most of the time, achieving maximum levels lower than the winter week, when there was not natural ventilation. However, the natural ventilation of the model depends on the occupancy and the relation between the comfort temperature, the indoor temperature and the outdoor temperature. This control forces that the natural ventilation is mainly used at night. Nevertheless, the monitored data could be interpreted as the household is ventilated as soon it is occupied (low level of CO_2 concentration), as the thermal sensation of the users is improved with the natural ventilation.

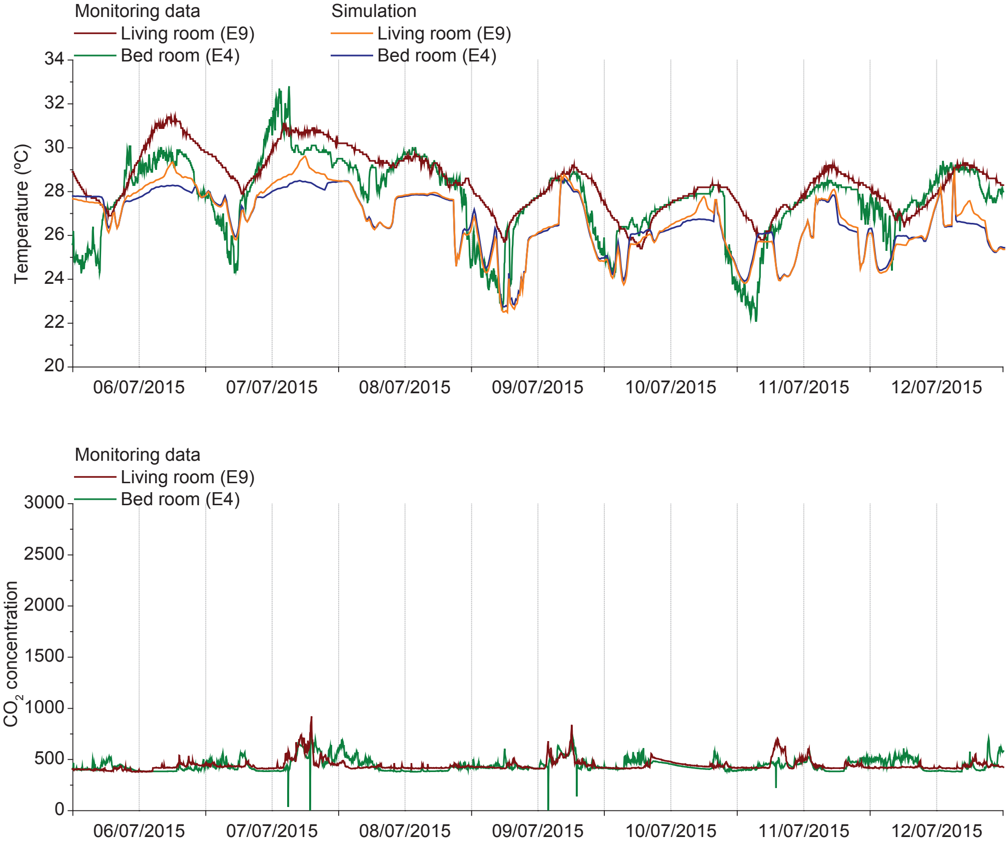

Figure III.5 Summer 2015 comparison. Air temperature comparison (top) and CO_2 concentration monitored (bottom)

Figure III.6 focuses the analysis on the energy consumption, comparing the bimonthly bills of natural gas (top) and electricity (bottom) with the results of the simulation. The figures are complemented with the statistic indicators, summarized in Table III.5. The graphs of the natural gas consumption reflect a general underestimation for the winter period (Jan-Feb and Nov-Dec) and a lower overestimation for the rest of the months. Comparing the results of the three years, the 2015 shows a better fit with the bimonthly bills in comparison with the 2013 and 2014. This behaviour is observed also in the statistics, having the best values for the 2015 (except for the NMBE). In general terms, it is possible to say that the simulation underestimates the natural gas consumption. Regarding the ability of the model to fit with the real consumption, the model achieves the level proposed by the validation protocols only for the 2015. However, the overall performance is quite close to the threshold (CV(RMSE)=16%). Finally, the coefficient of determination (R^2) is greater than 0.9 for all the cases, reaching values of 0.99 for the 2015.

In relation to the electricity consumption, the simulation results provide similar consumptions for all the months, with the exception of the holiday period in summer. The electricity bills show some variability between months and the model is not able to reproduce it. However, the differences between model and bills are relatively small, being around 100 kWh for each period. This situation is more evident for the 2013 and 2015. The statistic indicators show a good performance of the electricity estimation. In general, the electrical consumption is underestimated, especially for the 2015; nevertheless, the overall NMBE achieves the threshold of 7%. According to the CV(RMSE), the indicator presents good values for all the years, being lower than 15%. Nevertheless, the R^2 does not reach the IPMVP criteria (<0.75). R^2 reflects how well the linear regression reproduces the relationship between the monitored data and the model results. Then, if the monitoring data increases or decreases, the model must reproduce the same trend in order to obtain a good correlation. However, the comparison between the simulation and the bills shows opposite trends in some periods (i.e. Dec-Jan and Feb-Mar of 2015), and this fact could explain the lower values of R^2 (Figure III.6).

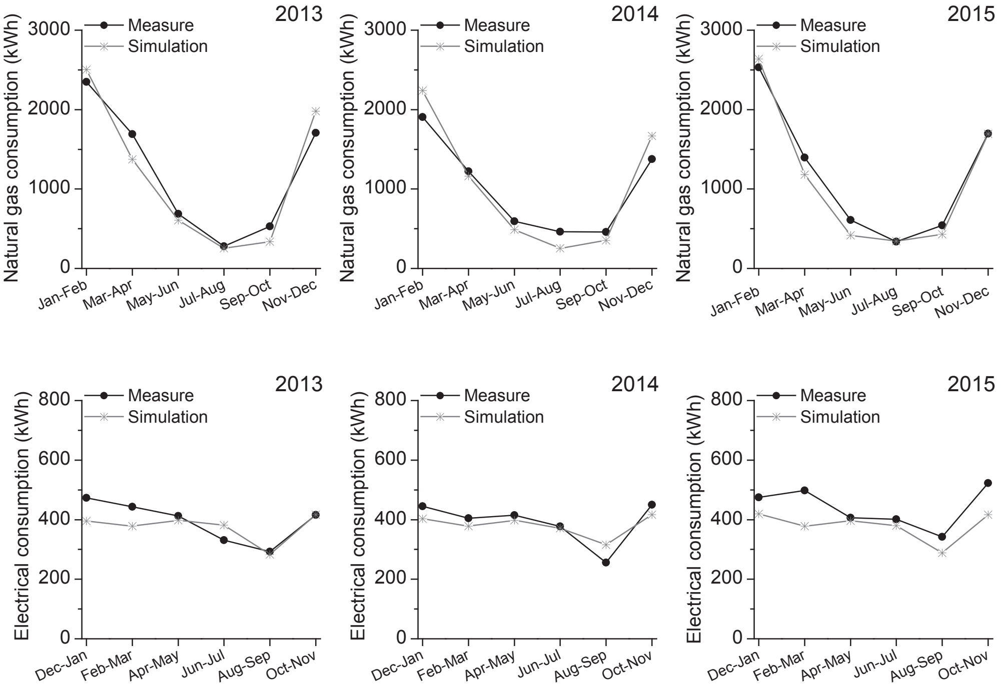

Figure III.6 Energy consumption comparison: bimonthly bills of natural gas (top) and electricity (bottom) with the results of the simulation

Table III.5 Statistic indicators for comparing the annual consumption of natural gas and electricity with the results of the simulation

Energy consumption		**Natural gas**				**Electricity**			
		2013	**2014**	**2015**	**2013-2015**	**2013**	**2014**	**2015**	**2013-2015**
Annual (monitored)	kWh	7,247	6,014	7,111	6,791	2,368	2,348	2,645	2,454
Annual (simulation)	kWh	7,049	6,164	6,703	6,638	2,253	2,282	2,277	2,271
NMBE [±7%]	%	-3	3	-6	-2	-5	-3	-14	-7
CV(RMSE) [<15%]	%	17	21	11	16	12	9	17	13
R^2 [>75]	-	0.95	0.94	0.99	0.98	0.54	0.97	0.59	0.59

The results show that the model is able to reproduce the real behaviour of the model. However, there are some discrepancies in the results and the statistic parameters do not meet all the criteria established by the ASHRAE and IPMVP protocols. It is important to remark that the data used for the validation have some uncertainties associated to the billing period and the estimation of some registers by the utility. In the case of electricity consumption, one of the main reasons for the differences between the monitoring data and the results of the model is related to the stochasticity of the user behaviour and the use of the appliances, as it has been introduced in the previous chapter (section II.1.1 and II.1.2). Thereafter, in this context the results obtained for the electricity consumption are considered acceptable and the validation process is satisfactory, as NMBE and CV(RMSE) are within the expected thresholds (-7% and 13%, respectively).

In the case of the natural gas consumption, a sensitivity analysis has been done to validate the hypotheses of some parameters and to analyse the changes in the results of the model.

III.4.1 Sensitivity analysis

The sensitivity analysis has been focused on the infiltration level, the occupancy profile and the use of the heating system. Table III.6 describes the value used in the different tests and are explained below:

- The infiltration rate, characterized by the n_{50} parameter, has been defined according to a typical value of existing buildings. This value n_{50}=7.5 represents a low level of air tightness. However, after the visual inspection and the PS surveys done in the pilot site, all the windows of the household have draught excluder installed so the air tightness of the household could be better. The first test implies an improvement of the n_{50} parameter (n_{50}=5). The infiltration has a high influence in the air temperature and consequently in the heating consumption. The expected impacts are a reduction of the natural gas consumption in the winter period.

- The occupancy profile is an important input of the simulation. The occupancy is the driver of all the systems of the building, and especially the heating system. In addition, the occupancy represents a contribution of internal gains to the household. In the simulation, the household is occupied by the users during 65% of the year. Thereafter, two additional occupancy profiles have been generated in order to reduce up to 60% the occupancy and to increase up to 70% of occupancy. The modification of the occupancy has been done homogeneously in every month, reducing or increasing some hours of occupancy per day. The idea is to quantify how the occupancy variation could affect the natural gas consumption.
- The use of the heating system is modified through the occupancy profile; however, the heating system is also dependent of the setpoint values. The Figure III.4 demonstrates that the setpoint of the heating system is not the same for every day and it is subject to the user modifications. For that reason, it is difficult to predict which setpoint is the appropriate for the whole year. In addition, the thermostat used in the simulation is ideal and it does not have a dead band temperature defined. The ideal thermostat provides a constant temperature over the time and it does not present fluctuations. This hypothesis has an effect in the temperature of the rooms and in the energy consumption. However, the energy consumption has been corrected by the implementation of the performance of the control system, following the EN 15316 [13]. In that sense, the test wants to quantify the impact of different setpoints (19ºC and 21ºC) in terms of natural gas consumption.

Figure III.7 shows the results of the different tests, in terms of natural gas consumption (left) and coefficient of determination, R^2, (right). The simulation with higher natural gas consumption is the V18, with the highest setpoint (21ºC), the highest occupancy (70%) and the highest infiltration (n_{50}=7.5). On the contrary, the simulation with the lowest natural gas consumption is the V1, which corresponds to the simulation with the lowest setpoint (19ºC), the lowest occupancy (60%) and the lowest level of infiltration (n_{50}=5). From a general point of view, there is a clear differentiation between the setpoint variations. However, not always the same configuration provides the best results. In 2013, the monitoring data is between the setpoint of 19ºC and 20ºC, being closer to the 20ºC. In 2014, the setpoint of 20ºC is the best one and the monitoring data is just in the middle of the different options of occupancy and infiltration; and in 2015, the best setpoint is 21ºC, being the lower occupancy (60%) and the best infiltration (n_{50}=5) the most appropriate in this case. The last comparison includes the three years of data and provides results quite similar than the 2013.

Table III.6 Configuration of the simulations done for the iterative process of validation

Code	Simulation	Infiltration	Occupancy	Setpoint*
□	V1	5	60%	19ºC
□	V2	7.5	60%	19ºC
○	V3	5	65%	19ºC
○	V4	7.5	65%	19ºC
△	V5	5	70%	19ºC
△	V6	7.5	70%	19ºC
▣	V7	5	60%	20ºC
▣	V8	7.5	60%	20ºC
◉	V9	5	65%	20ºC
◉	V10 (BC)	7.5	65%	20ºC
◬	V11	5	70%	20ºC
◬	V12	7.5	70%	20ºC
■	V13	5	60%	21ºC
■	V14	7.5	60%	21ºC
●	V15	5	65%	21ºC
●	V16	7.5	65%	21ºC
▲	V17	5	70%	21ºC
▲	V18	7.5	70%	21ºC

*2ºC below in the north zones (E4, E5, E6 and E7)

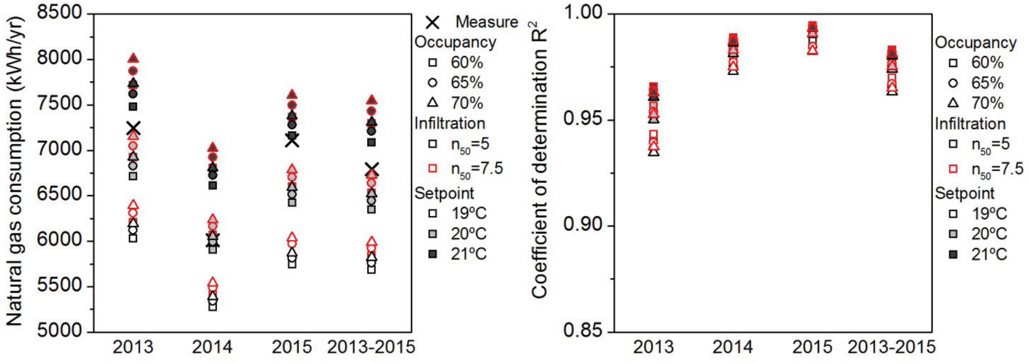

Figure III.7 Comparison of the simulation results done for the iterative process of validation

The coefficient of determination has a small variation between the simulations, except for the 2013 where the R^2 varies from 0.93 to 0.97. The best values of R^2 are in 2015, followed by the 2014 and 2013. Considering the three years, R^2 is between 0.97 and 0.98. Concluding, all the simulation fit the threshold established by the IMPVP, presenting values of R^2 higher than 0.9 in all the cases.

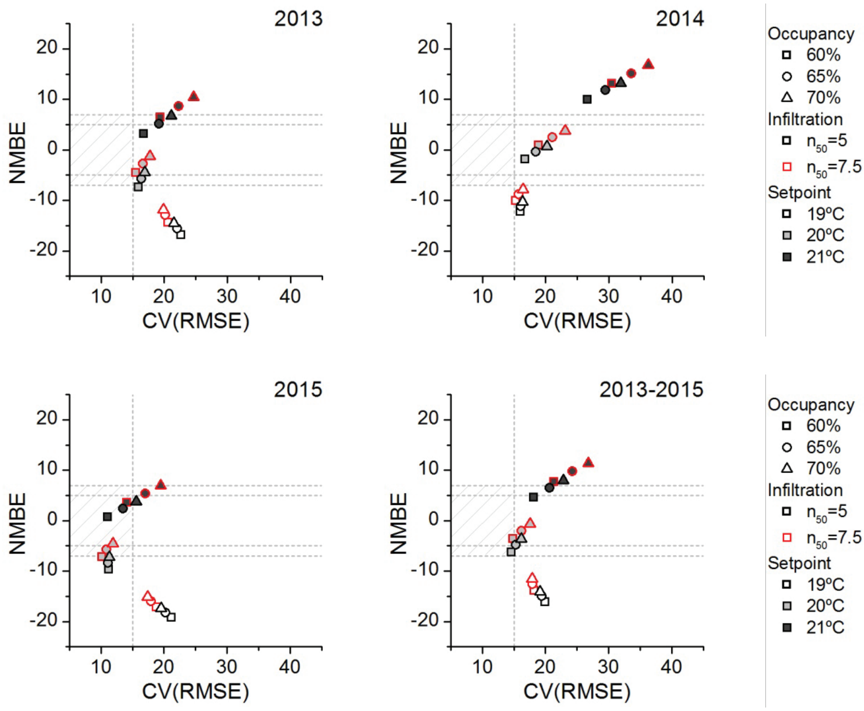

Figure III.8 Comparison of the simulation results: NMBE and CV(RMSE)

Figure III.8 gives information about the performance of each simulation in terms of NMBE and CV(RMSE). The hatched area of the figure represents the compliance of both criteria. In general, the behaviour of each simulation is different from one year to another; however, a common pattern is observed in the figures. In all the years, the variability of the statistical parameters is much lower in the simulations with a setpoint of 19ºC than in the simulations with 21ºC. In addition, the results of the simulations with 19ºC improve following this order: from lower occupancy to higher, and for better n_{50} to worse. It means, the simulation V1 (60% and n_{50}=5) is worse than V6 (70% and n_{50}=7.5). However, this trend changes slightly in the simulation with 20ºC, being completely opposite in the simulations with 21ºC. The increase of the setpoint makes the indicators of the simulations with higher occupancy and n_{50}=7.5 be worse than simulations with lower occupancy and n_{50}=5 (for example, simulation V13, 60% and n_{50}=5, is better than V18, 70% and n_{50}=7.5). In addition, the variability in the simulation with the setpoint of 19ºC and 20ºC is much lower than the variability observed in the simulation with 21ºC of setpoint. This behaviour indicates that there are some parameters of the simulation that are dependent of the setpoint and have a higher impact when the setpoint increases.

Analysing year by year, it is possible to observe:

- In 2013 all the simulations with 20ºC provide the best results. In those cases, the NMBE achieves the threshold established by the IPMVP protocol; however, there is only one combination that fits both criteria, the simulation V8 (CV(RMSE)=15% and NMBE=-4%). In addition, there are some simulations with 21ºC that meet the NMBE criterion, despite of the CV(RMSE) is higher than 15%.
- In 2014 the simulations with 20ºC meet the NMBE criterion. The simulations with the setpoint of 19ºC trend to underestimate the natural gas consumption, and on the contrary, the setpoint of 20ºC and 21ºC tend to overestimate. In terms of CV(RMSE), the results vary from 15% to 36%, presenting a high range of variability from one simulation to another. The simulations with a setpoint of 19ºC have better CV(RMSE) values, being between 15% and 16%. Then, for this year, the best simulations in terms of NMBE are the ones with a setpoint of 19ºC (simulation V2 with CV(RMSE)=15% and NMBE=10%, 19ºC, n_{50}=7.5 and 60%), and the simulations with the best CV(RMSE) are the ones with 20ºC (simulation V9 with CV(RMSE)=19% and NMBE=0%, 20ºC, n_{50}=5 and 65%).
- In 2015 the best results are provided by the simulations with a setpoint of 20ºC and 21ºC; however, different trends are observed. The simulations with 19ºC have better values of CV(RMSE) and higher values of NMBE, presenting overestimation in all the cases. It is important to remark that in all the simulation with a setpoint of 20ºC, the CV(RMSE) meets the criterion defined by the calibration protocols (<15%), having values from 10% to 12%. In the simulations of 21ºC the NMBE has better results, overestimating the consumption; however the CV(RMSE) is worse than the simulations with 20ºC. For this year, the best simulations are V8 in terms of CV(RMSE) and V13 in terms of NMBE (CV(RMSE)=10% and NMBE=7%, CV(RMSE)=11% and NMBE=-1%, respectively). Both simulations have an occupancy of 60%, and in the simulation V8 the setpoint is 20ºC with an n_{50}=7.5, and for the simulation V13 the setpoint is 21ºC with an n_{50}=5. In this case, both simulations accomplish the criteria of validation, as well as these other simulations: V10, V11, V12, V14 and V15.
- Finally, evaluating the results of every year, it is possible to observe that the simulations with a setpoint of 20ºC provide better results than the other setpoints. In this case, the NMBE goes from -6% to -1%, being inside the range acceptance (NMBE±7%). The CV(RMSE) is between 15% and 18%. In that case, there are three simulations that meet both criteria: V7 (CV(RMSE)=15% and NMBE=-6%, 20ºC, n_{50}=5 and 60%), V8

(CV(RMSE)=15% and NMBE=-4%, 20ºC, n_{50}=7.5 and 60%) and V9 (CV(RMSE)=15% and NMBE=-5%, 20ºC, n_{50}=5 and 65%).

Concluding the validation process, the simulation V8 (20ºC, n_{50}=7.5 and 60%) is considered the best configuration of parameters for this particular pilot site. The average performance of the building model is detailed in Table III.7. Analysing the three years at the same time, it is possible to conclude that the building model fulfil the validation criteria for ASHRAE and IPMVP protocols, obtaining a R^2 of 0.98, NMBE=-4% and CV(RMSE)=15%.

Table III.7 Building model performance according to the calibration protocols

Year	**Sim.**	**Natural gas MONITORING**	**Natural gas SIMULATION**	**R^2**	**NMBE**	**CV(RMSE)**
2013	V8	7,247 kWh	6,923 kWh	0.96	-4%	15%
2014	V8	6,014 kWh	6,071 kWh	0.99	1%	19%
2015	V8	7,111 kWh	6,602 kWh	0.99	7%	10%
2013-2015	V8	6,791 kWh	6,532 kWh	0.98	-4%	15%

III.5 Conclusions of the validation

The validation process is concluded satisfactory, despite the uncertainties associated to the occupancy behaviour. The indicators related to the electricity consumption are CV(RMSE) of 14%, NMBE of -7% and a R^2 of 0.59. For the natural gas consumption, the CV(RMSE) is 15%, the NBME is -4% and R^2 is 0.98, obtained from the simulation V8. The main sources of variation between the building model results and the monitoring data are the following:

- The ideal heating system used in the simulation makes the temperature be homogenous in the whole household. To improve the simulation, the setpoint temperature of the north zones is 2ºC lower than the other zones, according to the monitoring data.
- The building model presents an underestimation of the inertia of the building. Further research is needed in order to improve the results of the model.
- The variability of the occupancy profile introduces a high uncertainty in the model. As well, the use of the heating system has a direct relationship with the behaviour of the users, in terms of turning on the heating system and setting up the thermostat. During the validation process, it has been demonstrated how a small variation in the occupancy profile causes important changes in the natural gas consumption and in the calibration statistics.
- Several configurations of occupancy and setpoint have been tested; however, the variability from one year to another and from one month to another makes difficult to define an appropriate input for the building model. However, it seems that 20ºC and 60% of occupancy are acceptable configurations for this particular household.

- As to the level of infiltration, both values of infiltration (5 and 7.5) have provided good simulation results, depending on the configuration of the other two variables (occupancy and setpoint). Nevertheless, the assumption of n_{50}=7.5 is the one used in the final version of the simulation.

Concluding, the building model, its hypothesis and methods are validated to be used in the estimation of the energy consumption of the building typologies, as well as to evaluate the impact of the energy efficiency measures in the cost-optimal analysis, considering comfort, energy and economic criteria. However, it is important to remark, that the building typologies represents an average household and the results must be adapted to the particularities of each household, such as it has been done with the building model of the pilot site.

III.6 References

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Chapter IV Cost-optimal evaluation based on thermal comfort, energy and economic criteria

IV.1 State of the art

One of the main objectives of the thesis is to define a method that analyses the residential building typologies from three points of view, thermal comfort, energy and costs, with the purpose to test different energy efficiency measures and obtain the most appropriate ones depending on the building typology, climate and environment. In that sense, the literature review has been focused in three main fields, building stock characterization, thermal comfort evaluation and cost-optimal analysis, in order to have a complete vision about how these issues have been addressed in the last years.

IV.1.1 Building stock characterization

In the last years, several studies have been done with the objective to characterize the building stock and to evaluate their potential energy savings. The main techniques to model residential energy uses can be grouped up into two main categories [1]: top-down and bottom-up. Top-down models underwent a major development during the energy crisis of the late 1970s. The major aim of such research effort was to understand better consumer behaviour with changing supply and pricing. Such models analyse the residential sector as a whole and their objective was to determine and to analyse trends of the sector. The strength of "top-down" models is that they do not need very detailed input data to work. They just need widely available energy aggregate data and rely on historic residential sector energy values. The heavy reliance on historical trends and data for these models is also a major drawback, since they are not able to handle discontinuities in the major trends.

The bottom-up approach goes beyond the limits of the top-down one, accounting in detail for individual houses and energy end-uses. After that, the results of the model may be extrapolated to represent a region or a nation, according to the level of detail of the inputs. Common input data to bottom-up models are dwelling properties, equipment and appliances, climate characteristics, occupancy schedules and use levels of equipment. This detail in characterization is the strength of these methods. It permits a very accurate modelling, but has the drawback of obtaining all the needed data. No historical data are required. However, in order to extrapolate the results for a whole region or country, data must be representative of the zone. The archetype or building typology is an engineering bottom-up approach and it is defined as a sample of building that is representative of actual buildings. As the building stock of a country consists of buildings with different characteristics, several building typologies are required in order to derive the thermal characteristics of the building stock. In the last decades, several studies have applied this method to estimate the energy consumption of an urban, regional or national building stock.

TABULA project [2] developed national building typologies representing the residential building stock of several European countries (Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Germany, Denmark, Spain, France, Great Britain, Greece, Hungary, Ireland, Italy, The Netherlands, Norway, Poland, Serbia, Sweden and Slovenia). The project made a classification of existing residential buildings according to age, size and further parameters, which includes a set of building examples to represent specific building types of the national stock. The typical energy consumption and the possible energy savings were given for the example buildings. The TABULA project represents one of the first initiatives to create a European database to collect information related to the existing building stock. Based on the work developed in the TABULA project, Dascalaki et al. [3] used the building typologies as a showcase for demonstrating the energy performance and the potential energy savings from typical and advanced energy conservation measures on the thermal envelope and the heat supply system. The study was focused on the residential building stock from Greece.

Mata et al. [4] describes a methodology for systematic description of the building stock of European countries based on archetype buildings. They analysed the building stock of four countries (France, Germany, Spain and UK) in order to estimate the energy consumption of the building sector using the model Energy, Carbon and Cost Assessment of Building Stocks [5]. The method assesses the effects of energy efficiency measures in building stocks. The model is based on a one-dimensional building energy balance (developed with Simulink), which gives hourly net energy demand. The model is implemented so that the results can be extrapolated to a building stock.

At Spanish level, Cuchí and Sweatman [6] evaluated the residential building stock of Spain identifying the hotspots for the energy renovation. The hotspots were defined following 4 criteria: building’s age, building’s height, home urban surroundings and single family units vs. multi-units apartment building. They obtained 10 hotspots which represent the 76% of the building stock of Spain. They proposed an ambitious action plan for the deep renovation of the building sector, including political, regulatory and financial actions. The Ministry of Development of Spain [7] analysed the current building code to determine if it is possible to achieve the minimum energy performance requirement with cost-optimal solutions. Six existing building typologies and ten reference new buildings were evaluated in the study, taking into account the existing building database and typical characteristics of buildings in Spain. Different orientations of buildings and six climatic zones have been also considered, summing a total amount of one hundred and twenty subcategories of buildings. Many individual measures have been defined for each subcategory of building and multiple combinations of them have been calculated in order to find the cost-optimal values. The method used for the economic calculation is based on the global costs [8], which takes into consideration the energy costs, investment costs, replacement costs and maintenance costs over a long period.

If the review is focused in Catalonia, Ivancic et al. [9] developed different tools to carry out the energy balance analysis, future scenarios evaluation, and cost benefit optimization of the city of Barcelona. The set of tools was very useful in the decision-making process for community planning purposes. An important amount of data was linked to the city database using a geographical information system. The same data were introduced into an energy and environmental balance simulator of the city to calculate the total and sectorial energy and emission balances for different situations, such as the base year, or for different scenarios. The balance simulator was calibrated for the base year, taking into account the real use data provided by the utilities. Garrido et al. [10, 11] extended the work made by [9] and made a detailed characterization of the residential building stock of Catalonia. They define 11 building typologies in accordance to historical events, building regulation codes and the location of the buildings (urban and rural environment). They obtained the energy consumption of the building typologies using Lider and Calener programmes. The objective was to estimate and calibrate the energy consumption of the residential sector in Catalonia, in order to compare the current situation with two additional scenarios, national regulation and regional regulation, evaluating the energy savings and the economic impacts. InnoCons project [12] analysed the most representative building typology of Catalonia, pre-defined in [11]. In that case, the objective was to evaluate deeper the retrofit options for this building typology. In that case, the building simulation was done with EnergyPlus. Manyes et al. [13] applied a similar method to develop a building characterization, with the difference that the scope of the study was a block of building level rather than a regional level. The scope of the study was to provide an estimation of the energy and economic savings entailed in a block scale intervention, rather in a building level. The study is focused in neighbourhood of Santa Coloma de Gramenet (Barcelona). A more accurate characterization of the systems and their use is introduced in the building simulation, including concepts like fraction of energy demand supplied and energy poverty.

Several studies have been developed to have a general view of the building stock and their energy consumption, especially if the review is focused on Catalan level. The reviewed studies try to improve the building characterization, increasing the representation of the typologies over the region, using more sophisticated models to simulate the buildings, and finally starting to include an actual use of the building. However, there are some aspects that can be improved, as, for example, the actual state of the buildings and the dwelling definition, the heating and cooling characterization, the occupancy and its interaction with the building.

IV.1.2 Thermal comfort evaluation

Environmental comfort is related to comfort and well-being of the body with the environment. The concept of environmental comfort depends on environmental physic parameters (environmental and architectural) and the characteristics of the person (socio-cultural and personal factors). A not appropriate environmental comfort can affect the human health in several ways. Bonnefoy [14] made a review of the most relevant health threats that can be found in dwellings: indoor air quality, home safety, noise, humidity and mould growth, indoor temperatures, lack of hygiene and sanitation equipment, missing daylight and crowding. In that sense, the environmental comfort is becoming an important parameter to design and improve the buildings. Recently, BPIE [15] has concluded that the indoor health and comfort requirements should be included in the building regulation of each country in order to guarantee an appropriate design for the people.

Four categories of environmental comfort can be distinguished: visual, thermal, acoustic and air quality. For each of them, different levels or categories of comfort are defined based on statistical data. The categories depend on the activity performed by the user, the environment and the requirement. The scope of the PhD thesis is to evaluate the thermal comfort of the users in the building with different energy efficiency measures. For that reason, the following review is focused on the thermal comfort models. The thermal comfort is the mind condition which expresses satisfaction with the thermal environment. Thermal sensations of people are primarily concerned with the thermal state of the body. This state depends on the physical activity undertaken and clothing, as well as environmental parameters: air temperature, mean radiant temperature, air velocity and humidity.

Fanger [16] developed a comfort model where the thermal comfort represents the thermal balance of the body and it happens when the internal heat of the body is equal to their loss to the environment. The parameters that take part of the heat exchange are environmental parameters (air temperature, humidity, air velocity…), human body parameters (heat generation, skin temperature and surface among others) and the clothing.

- Environmental: air temperature, humidity, air velocity, radiant temperature of the walls and openings.
- Human body: heat generation, skin temperature, skin humidity and skin surface.
- Clothing: thermal resistance, superficial temperature and emissivity.

The energy balance equation is obtained combining these parameters. The details of the equation are explained in [16]. If the internal heat of the body is different than the heat loss to the environment the user is in thermal imbalance. If the internal heat is greater than the losses, the person feels hot; and if the internal heat is lower than the losses, the person feels cold. The index to evaluate the thermal imbalance is the PMV (Predicted Mean Vote) and reflects the opinion of a large group of people on their thermal sensation, valued in a scale of seven levels (Table IV.1).

Table IV.1 Thermal sensation scale

Value	Sensation
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

The thermal environment is not evaluated equally for all the occupants. For that reason, the PPD (Percentage of People Dissatisfied) is defined in order to predict the number of people dissatisfied with the thermal environment. PPD is related with PMV following Eq. IV.1. The function is represented in Figure IV.1. Fanger model is applicable in buildings with mechanical heating and cooling systems.

Eq. IV.1

$$PPD = 100 - 95 \cdot e^{-(0.03353 \cdot PMV^4 + 0.2179 \cdot PMV^2)}$$

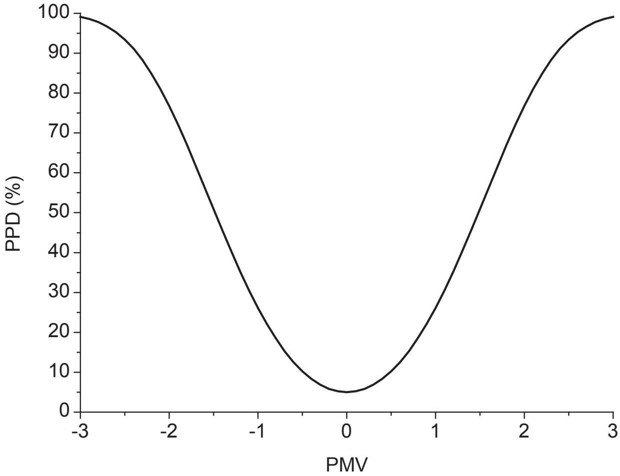


Figure IV.1 Percentage of People Dissatisfied (PPD) in function of Predicted Mean Vote (PMV)

An alternative and complementary comfort model is the adaptive model [17], which includes the psychological dimension of people. Thermal sensations, satisfaction, and acceptability are all influenced by the expectations about the indoor climate in a particular context. The adaptive comfort model is based on the assumption that the people adapt the environment depending on the weather conditions and their level of activity. In that sense, the adaptive comfort model is applicable in buildings without mechanical cooling systems.

The index to estimate the comfort level is the Operative Temperature (T_{op}), defined as a uniform temperature of a radiant black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment. In the ASHRAE adaptive comfort model, the operative temperature is defined following Eq. IV.2.

Eq. IV.2

$$T_{op} = 0.31 \cdot T_{out,m} + 17.8$$

where $T_{out,m}$ is the mean monthly outdoor air temperature.

Different categories are defined by both comfort models. The requirement of each category depends on the needs of the building. These categories are described in Table IV.2 and represented in Figure IV.2.

Table IV.2 Comfort categories comparison. Left: Fanger comfort model. Right: Adaptive comfort model

Fanger comfort model (ISO 7730)		
Cat.	Description	Operative temperature
I	High level	+/- 2 ºC
II	Normal level (new buildings and renovations)	+/- 3 ºC
III	Moderate level (existing buildings)	+/- 4 ºC

Adaptive comfort model (ASHRAE 55)		
Cat.	Description	Operative temperature
90%	High standard	+/- 2.5 ºC
80%	Typical applications	+/- 3.5 ºC

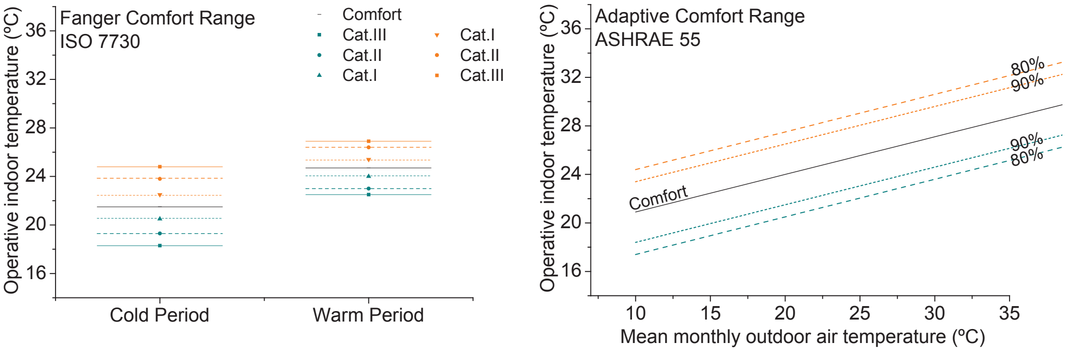


Figure IV.2 Comfort categories comparison. Left: Fanger comfort model (Assumptions for T_{op}: $T_a=T_{rm}$, Relative Humidity=50%, V_a=0.1m/s, Metabolic activity=1.2met, External work=0met, Clothing resistance cold period=1clo, Clothing resistance warm period=1clo). Right: Adaptive comfort model

The PMV, PPD and T_{op} are instantaneous comfort index: they represent the comfort conditions at a moment, but not for a long period. The long-term indices aim at assessing comfort qualities of a building over a span of time and considering all the building zones. They can be calculated from simulated or measured data. Carlucci and Pagliano [18] made a systematic review of 15 indices for the long-term evaluation of thermal comfort conditions in a building. The indices were classified depending on the type of index (percentage, cumulative, averaging and risk indices) and whether it is based on a comfort model or in a reference temperature. The authors analysed the strengths and weakness of the indices, concluding that there is not an index for the long-term evaluation of discomfort that completely fulfils all the desirable features:

- It has to be applicable for both free-running and mechanically cooled buildings
- It can be used with both the adaptive and the Fanger comfort models
- It has to reflect the nonlinear relationship between perception of discomfort and the theoretical comfort temperature
- In case of a multi-zone building, weights the zone indices with the number of occupants inside the zone
- It is applicable to evaluate different periods of the year (annual, summer, winter…)
- It is able to estimate possible discomfort due to the upper and lower exceedance from the theoretical comfort temperature.

For that reason, the author proposed a new comfort index, Long-term Percentage of Dissatisfied (LDP) [19], with the objective to cover all the desirable features. LDP is a symmetric index that is able to evaluate the overheating and the overcooling of the building. The index is normalized over the total number of people inside the household, over all the zones and over all time corresponding to the calculation period (annual, warm or cold season). An advantage of the calculation period is to detect the weaknesses and strengths of the building.

One of the main problems of the Mediterranean regions is the overheating hours, in some cases increasing after the refurbishment of the building. For that reason, it has been included in the review how this phenomenon can be estimated. In the literature, it is possible to find a wide range of overheating definitions. Psomas et al. [20] remarked that there is no rigorous or widely accepted definition of what constitutes overheating indoors for different type of buildings, climates or a group of people. Then, it seems that is a research topic that continuous under development and needs additional studies to create evidence about which is the appropriate criteria to define the overheating conditions. Focusing on some of the overheating indices, Chartered Institution of Buildings Services Engineers (CIBSE) [21], proposed an index to estimate the percentage of overheating for buildings with natural ventilation. The index compares the environmental conditions with a fixed threshold temperature to obtain an exceedance criterion. They defined two different criteria depending on the type of room which is analysed (day and night zones). Nicol et al [22] defined the NaOR overheating risk. NaOR assumes that thermal discomfort is related to the difference of the operative temperature and comfort temperature, based on the EN 15251 adaptive comfort model [23]. It is an asymmetric index, which aims at predicting overheating phenomena and cannot be applied in mechanically cooled buildings.

Finally, several studies used the comfort parameters to improve the design of the buildings. Carlucci and Pagliano [24] optimized the building with the objective to minimize the thermal discomfort of the users. They applied the LDP in a method to design a new net zero energy building, analysing a set of passive measures (insulation and windows performance). Their objective was to reduce the heating and cooling demand through the comfort improvement. Griego et al. [25] optimized the energy efficiency and the thermal comfort measures of the residential buildings in Salamanca, Mexico, using the PMV as a comfort parameter. Penna et al. [26] implemented a multi-objective optimization for the retrofit of existing buildings using, in this case, Weighted Discomfort Time, energy performance for heating and net present value as variables of optimization.

Concluding the literature review of the comfort indices, there are several options to estimate the thermal comfort of the users and there is no a unique criteria for that, especially when the objective is to evaluate the overheating. In addition, in the last years it has been introduced the comfort as a criterion to design and improve the building performance. In this context, the thesis is trying to test some of the index and methods proposed in the literature, as well as, improve some of them.

IV.1.3 Cost-optimal analysis

To promote the refurbishment of the residential building, which presents very low rates of energy renovation, the countries and region must define retrofit strategies implementing cost-effective solutions following the EPBD approach. In this context, several studies have implemented the cost-effective methodology to evaluate both, new and existing building, and define the cost-optimal measures. These studies cover different climates, types of buildings and energy efficiency strategies, and want to evaluate the effectivity of the method and the most appropriated strategies for each scenario.

Brandão et al. [27] developed the cost-optimal evaluation for a residential building of Portugal. They studied around 35,000 combinations of passive measures to evaluate which was the most suitable strategy for the envelope renovation. They used EnergyPlus for the primary energy calculation. The work concluded that the rehabilitation of the roof produces the greatest variation in terms of primary energy consumption and the combination of thermal envelope measures creates synergy effects that lead to better results than single measures. Stocker et al. [28] implemented the cost-optimal method for the renovation of school buildings in the Alps. The objective of the study was to reduce the heating energy consumption and they implemented measures to improve the envelope performance as well as, the efficiency of the heating system. Additionally, they developed a sensitivity analysis in order to evaluate the impact of some parameters used for the calculation. They concluded that the variation on the energy price, the measure cost and the interest rate are the most influential ones in the results. Similar results were obtained in ECOFYS study [29], where it was analysed the link and consistency between the nearly zero energy buildings definition and the cost-optimal levels of the minimum energy requirements. One of the aspects that they evaluated was the gap in the global cost calculation, mainly related to the variability of some parameters over the period calculation: technology costs, energy costs and primary energy factors for electricity or district heating. They performed some scenarios to quantify the impact of this variability into the cost-optimal analysis, obtaining significant changes in the optimum levels (from 25% to 50% of variability, depending on the scenario).

Aelenei et al. [30] implemented the methodology for the refurbishment of public buildings toward nearly Zero Energy Buildings (nZEB). The analysis was applied to a reference building of an existing office building in five different countries: Italy, Portugal, Romania, Spain and Greece. The evaluation tool used a new cost optimization procedure based on a sequential search optimization technique considering discrete options [31], which was implemented before in a cost-optimal study in residential buildings in Italy. The results were presented in terms of optimal "package of measures", primary energy consumption and global costs, as well as a cross-country comparison. The study presented by Hambdy et al. [32] introduced an efficient, transparent, and time-saving simulation-based optimization method. The method was applied to find the cost-optimal and nZEB energy performance levels for a study case of a single-family house in Finland. They proposed a multi-stage optimization: in the first stage they selected the optimal passive strategies in terms of heating demand and total investment costs; followed by the second stage where the active systems were evaluated from the primary energy consumption and Life Cycle Cost point of view; to finalize with the renewable energy design in order to improve the results obtained in the second stage. Moreover, they used two different optimization technics in the different stages of the study (genetic and deterministic algorithms). Asadi et al. [33] wanted to demonstrate the potentiality of the cost-effective evaluation to provide decision support. Therefore, an optimization methodology was developed based on combining TRNSYS, GenOpt and a multi-objective optimization algorithm in MatLab. The optimization approach was applied to a case study to evaluate all available combinations of alternative retrofit actions.

At Spanish level, the Spanish Ministry of Development [7] analysed the current building code to determine if it is possible to achieve the minimum energy performance requirement with cost-optimal solutions, obtaining that in most of the building typologies and climates, the current building regulation goes further than the cost-optimal measures. In addition, there are also several scientific studies developed in Spain [34-37]. They cover different regions, the north [34, 36] and the south [35], and all of them are focused on residential sector. However, not all the studies implement the cost-optimal method but, they proposed other variables of decision: [36] included the payback period as additional parameter for the economical evaluation; [35] used the construction costs and the CO_2 emissions to analysed the impact of different building legislations; and [34, 37] implemented the Life Cycle Cost and the Life Cycle Impact Assessment.

Then, it is clear that there is a wide range of possibilities to develop this type of studies, from the point of view of the criteria and parameters and, from the point of view of the tools. In that sense, Tadeu et al. [38] compared the cost-optimal evaluation with the return of investment. The results from the real options perspective enabled to conclude that the global cost is not enough for the investors and must be complemented with additional information (such as the value of operational flexibility and other strategic factors), and the return of investment must be evaluated in a long-term rather than in the short-term perspective. Other point of view of the same discussion is described by Becchio et al. [39]. They introduced the need to incorporate some additional benefits to the global cost calculation, in order to achieve more interesting results for all the actors involved, including investors and final users. They proposed a method to quantify qualitative benefits in monetary terms, as the increase of the real estate market value, the enhancement of the indoor comfort, the reduction of CO_2 emissions.

IV.2 Two step evaluation process

The thesis proposes a detailed process to analyse passive and active measures focusing on the thermal comfort, energy performance and economic parameters. The novel method aims to develop cost-optimal studies for the energy renovation of buildings as Salom et al. [40] was introduced. The analysis is done using dynamic building simulations, where the building and its interaction with the user is characterized in detail with TRNSYS [41]. The simulation evaluates the three main criteria for the base case, i.e. the existing building, and for the building with different combination of energy efficiency measures (passive and active measures).

All the method is done in the two-step evaluation process (Figure IV.3): passive and active evaluation. In the first one, which has been described in [42], the objective is to obtain the passive measures that provide a better thermal comfort without the use of mechanical systems and considering the required economic investment. In the second step, published on [43], the active measures are applied and the non-renewable primary energy consumption and the global costs have been compared to obtain the cost-optimal solution of each building typology.

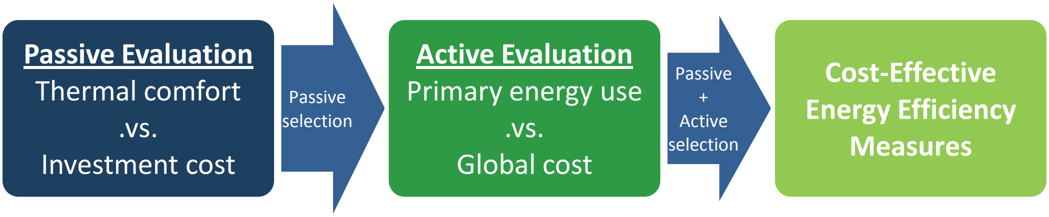


Figure IV.3 Two-step evaluation process of the energy efficiency measures

A co-simulation process is done to carry out each evaluation step, using SDLPS as a management tool and TRNSYS as a calculus engine for the energy simulation. SDLPS [44, 45] is a general purpose software infrastructure that makes possible to manage the main simulation process, running all the scenarios and collecting the results (Figure IV.4). The Brute-Force approach was used since the objective is to obtain a complete characterization of the problem [46, 47]. This approach consists on running the simulation with all the possible combinations i.e no optimization algorithm is used. Figure IV.5 represents the scheme of building simulation, where the software (solid lines), the methods (dashed lines) and the results (dotted lines) are remarked (details are explained in Chapter II).

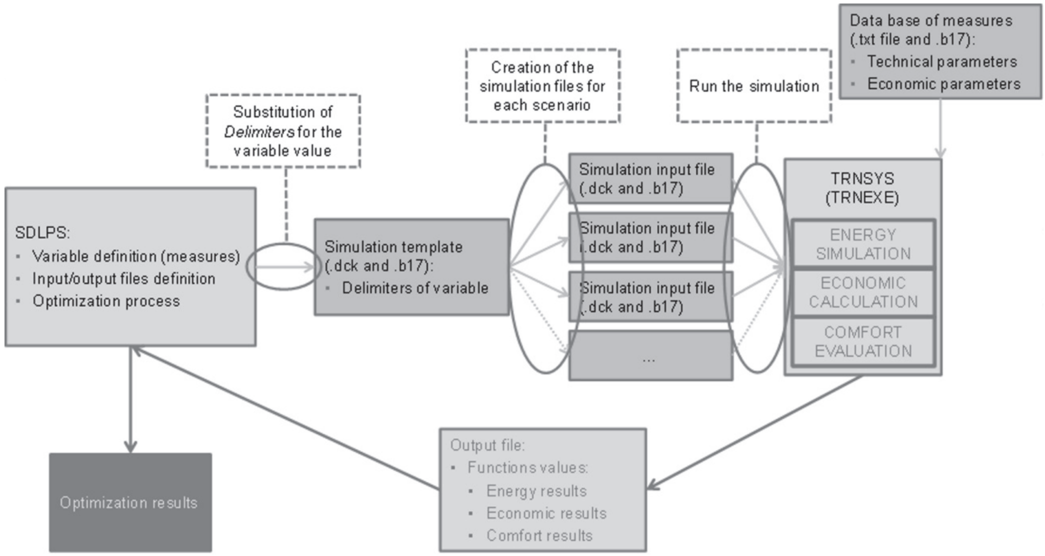


Figure IV.4 Architecture of the co-simulation process

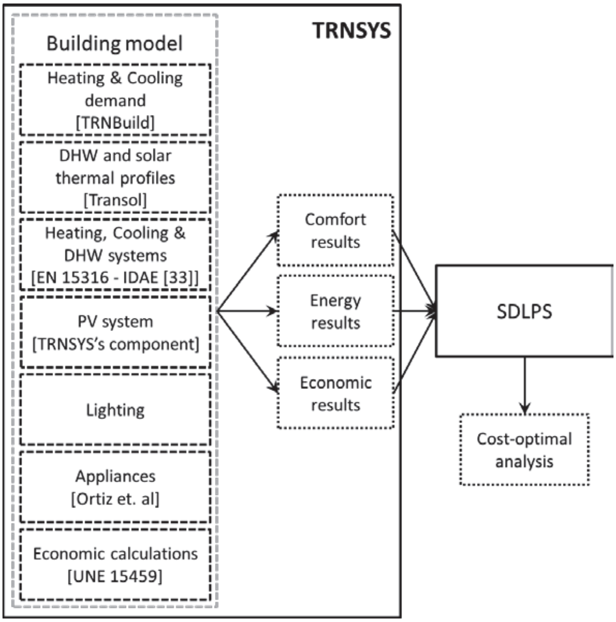


Figure IV.5 Software and methods implemented for the active measure evaluation to develop the cost-optimal analysis (solid line: software; dashed line: method; dotted line: results)

IV.2.1 Thermal comfort evaluation

The comfort evaluation is one of the main points of the method. The comfort model selected for the evaluation is ASHRAE adaptive model [17]. The ASHRAE adaptive model is used in the passive measure evaluation because in that case, the simulations are done in free running mode (without mechanical systems). The selection of the model is based on the analysis done by Carlucci in [18, 19].

The long-term index used in the study is the Long-term Percentage of Dissatisfied (LDP) developed by Carlucci [19], which has been introduced previously in the state of the art. The LDP is calculated following Eq. IV.3:

Eq. IV.3

$$LDP = \frac{\sum_{t=1}^{T} \sum_{z=1}^{Z} (p_{z,t} \cdot LD_{z,t} \cdot h_t)}{\sum_{t=1}^{T} \sum_{z=1}^{Z} (p_{z,t} \cdot h_t)}$$

where t is the counter of the time step of the calculation period, T is the calculation period, z is the counter for the zones of the household, Z is the total of zones of the household, $p_{z,t}$ is the zone occupation rate at certain time step, h_t is the duration of a calculation time step and $LD_{z,t}$ is the Likelihood of Dissatisfied inside a certain zone (z) at a certain time step (t). The LD depends on the comfort model and is a function of the short-term index. The LD used for Fanger model is the PPD and for the Adaptive model is the ASHRAE Likelihood of Dissatisfied (ALD) which was also developed by Carlucci [19] and follows the equations Eq. IV.4 and Eq. IV.5.

Eq. IV.4

$$ALD = \frac{e^{0.008 \cdot \Delta T_{op,ASH}^{2} + 0.406 \cdot \Delta T_{op,ASH} - 3.050}}{1 + e^{0.008 \cdot \Delta T_{op,ASH}^{2} + 0.406 \cdot \Delta T_{op,ASH} - 3.050}}$$

Eq. IV.5

$$\Delta T_{op,ASH} = \left| T_{op,in} - T_{op,comf-ASHRAE} \right|$$

Where $T_{op,in}$ is the operative temperature of the building and $T_{op,comf\text{-}ASHRAE}$ is the comfortable operative temperature following the ASHRAE adaptive comfort model (Eq. IV.2).

An advantage of the LDP is that it can be calculated for different periods (annual, warm and cold season), detecting the weakness of the building. This index describes the average comfort of the household over a period; however the extreme values are not represented with the LDP. Then, the index only reflects the problems of overheating or overcooling when this phenomenon is sufficiently representative of the period.

However, in order to avoid overheating problems, the hours of overheating (OH) have been included for complementing the LDP index in the comfort evaluation. There are several international initiatives (EBC Annex 69 Strategy and Practice of Adaptive Thermal Comfort in

Low Energy Buildings, and IEA EBC Annex 62 Ventilative Cooling) that are discussing about which are the appropriate indices to quantify the overheating and which variables has to be used. The criterion used in the evaluation says that the percentage of OH hours has to be lower than the 1% of the period calculation in order to have a comfortable building. This criteria is based on the design-overheating criteria proposed by CIBSE [21], however, some adaptation has been done in the calculation of the index. The overheating is considered when the operative temperature of the zone is above the upper comfort temperature of the ASHRAE model, as in Eq. IV.6 is represented.

Eq. IV.6

$$P_{OH} = \frac{\sum_{t=1}^{T} p_t \cdot OH_t}{\sum_{t=1}^{T} p_t \cdot h_t} \quad \begin{cases} OH_t = 1 \Rightarrow T_{op} > T_{upper,ASH} \\ OH_t = 0 \Rightarrow T_{op} \le T_{upper,ASH} \end{cases}$$

All the comfort calculations are included in the building simulation and therefore the comfort indices are outputs of the simulation. The assumption done for the air velocity to calculate the comfort index depends on whether there is natural ventilation or not, being 0.25m/s and 0.1m/s respectively [48].

IV.2.1.1 Climate analysis

As explained above, the LDP index is calculated for different periods of time: annual, warm and cold season. However, one of the uncertainties, as Carlucci analysed in [19], is how to define the calculation period. There are some definitions, such as meteorological definition or Spanish Building Regulation (Código Técnico de la Edificación, CTE [49]) definition, where the season periods are independent of the local climate. It does not seem reasonable that the winter period of the Pyrenees is the same than the one in Barcelona. An unsuitable definition of the calculation period could have consequences in the comfort index: if the calculation period increases, the comfort index tends to improve.

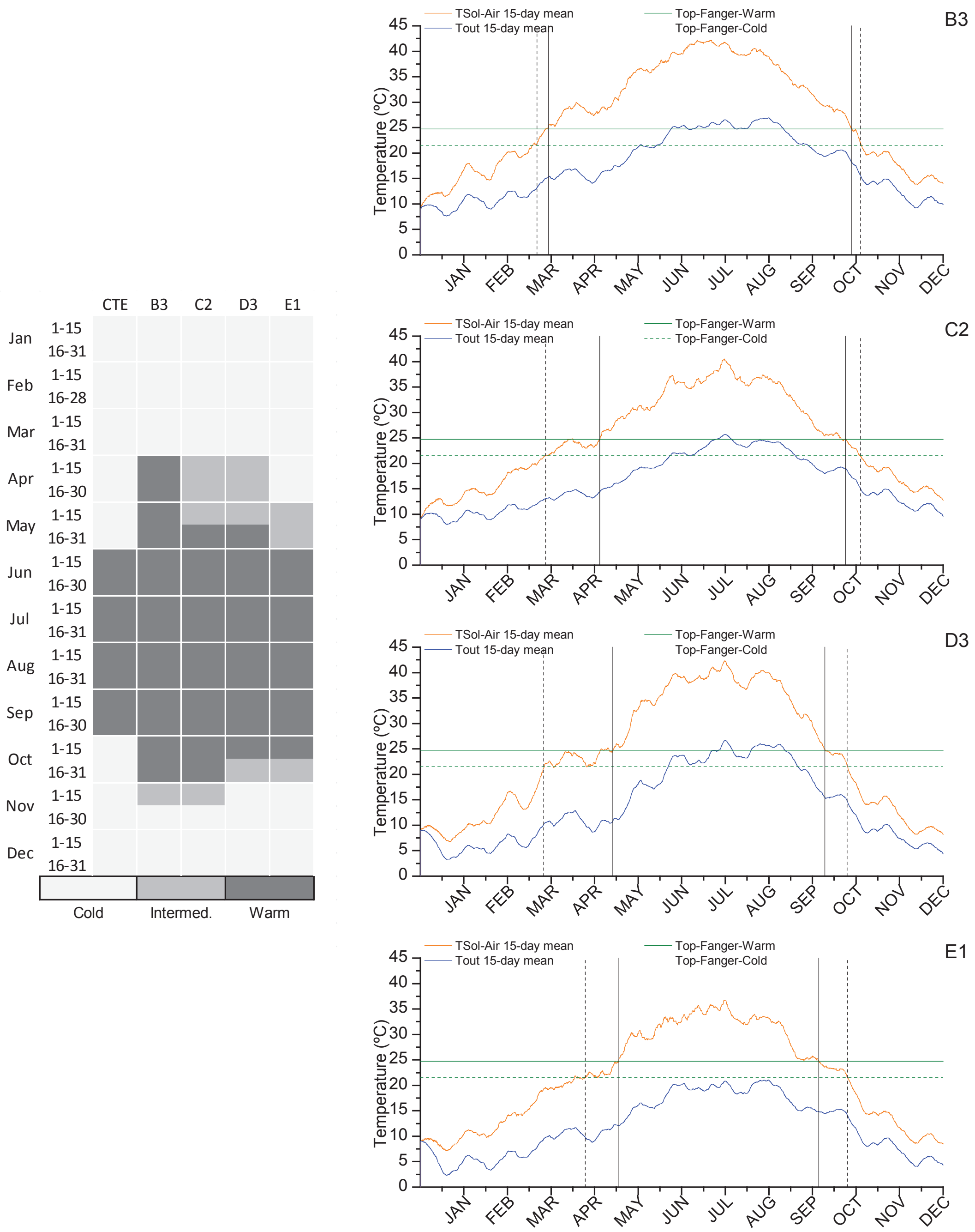
The method used for identifying the calculation period is proposed by Carlucci [19] and is based on the relationship between outdoor conditions and the indoor comfort target. The objective of this approach is to define the cold period (or warm period) when the outdoor conditions start to be lower (or higher) than the comfort target. The metric used to represent the outdoor condition is the sol-air temperature [31] (Eq. IV.7), which is a function of: dry-bulb air temperature, solar radiation incident at the building and the radiation exchange with the surrounding surfaces and the sky.

Eq. IV.7

$$T_{sol-air} = T_o + \frac{\alpha \cdot I}{h_o} - \frac{\Delta q_i}{h_o}$$

where T_o is the dry-bulb air temperature, α is the solar absorptivity, I is the global solar irradiance on the surface, h_o is the heat transfer coefficient for radiation and convection and Δq_i is the correction due to long wave infrared radiation transferred between building surface and the sky. The first term of the equation (3) represents the effect of the solar radiation and assuming that the wall has a light coloured surface α/h_o=0.026(m^2ºC)/W. The second term represents the convection and the radiation heat transfer and for vertical surfaces it could be assumed that is 0, as suggests [19, 50].

Following this approach and using the Fanger model as a comfort target, the season periods have been obtained for the climates analysed in the thesis. The climates are B3 (Tarragona), C2 (Barcelona), D3 (Lleida) and E1 (Pre-Pyrinees), following the climate classification of the CTE (in brackets there is the reference city/region for each climate in Catalonia). Figure IV.6 shows the results obtained for each climate. The graphs show the evolution of the outdoor temperature and the sol-air temperature over the year, represented by a 15-day average. The horizontal lines represent the comfortable temperature for the Fanger model (solid line for warm period and dot line for cold period). Then, when the sol-air temperature is higher than the cold comfort temperature, the cold season has finished (vertical dots line). The warm season starts when the sol-air temperature is higher than the warm comfort temperature (vertical solid line), and so on. The results of the calculation periods are represented on the left side of the Figure IV.6. In this scheme, there are three seasons: cold, warm and intermediate. The intermediate season represents the period of the year where the sol-air temperature is in the comfort range. In that sense and in order to simplify the comfort evaluation, only two seasons have been considered and the intermediate season has been included as a cold season.



		CTE	B3	C2	D3	E1
Jan	1-15	□	□	□	□	□
	16-31	□	□	□	□	□
Feb	1-15	□	□	□	□	□
	16-28	□	□	□	□	□
Mar	1-15	□	□	□	□	□
	16-31	□	□	□	□	□
Apr	1-15	□	■	▨	▨	□
	16-30	□	■	▨	▨	□
May	1-15	□	■	▨	▨	▨
	16-31	□	■	■	■	▨
Jun	1-15	■	■	■	■	■
	16-30	■	■	■	■	■
Jul	1-15	■	■	■	■	■
	16-31	■	■	■	■	■
Aug	1-15	■	■	■	■	■
	16-31	■	■	■	■	■
Sep	1-15	■	■	■	■	■
	16-30	■	■	■	■	■
Oct	1-15	□	■	■	■	■
	16-31	□	■	■	▨	▨
Nov	1-15	□	▨	▨	□	□
	16-30	□	□	□	□	□
Dec	1-15	□	□	□	□	□
	16-31	□	□	□	□	□

□ Cold ▨ Intermed. ■ Warm

Figure IV.6 Calculation period for the climates B3 (Tarragona), C2 (Barcelona), D3 (Lleida) and E1 (Pre-Pyrinees) based on the Fanger comfort model

IV.2.2 Cost-optimal analysis

The parameters that are selected to carry out the cost-optimal analysis are the non-renewable primary energy consumption (from this point forward, primary energy consumption) and the global costs. In order to approach the results from the point of view of the final user, the energy uses included in the primary energy are: heating, cooling, domestic hot water, lighting and appliance consumption. Including all the energy uses of the household it is possible to compare the results with the actual natural gas and electric bills of households.

The economic approach used to estimate the global cost is described in the European standard EN 15459 [8]. The global cost calculation method is the calculation of a present value of all the costs during a long period, taking into account the residual values of components with longer lifetimes. Figure IV.7 represents the costs that are included in the global cost indicator. Basically, the costs can be divided in three main groups: energy costs, investment costs and running costs. Each of these costs is calculated for the established period in the study, in this case 30 years.

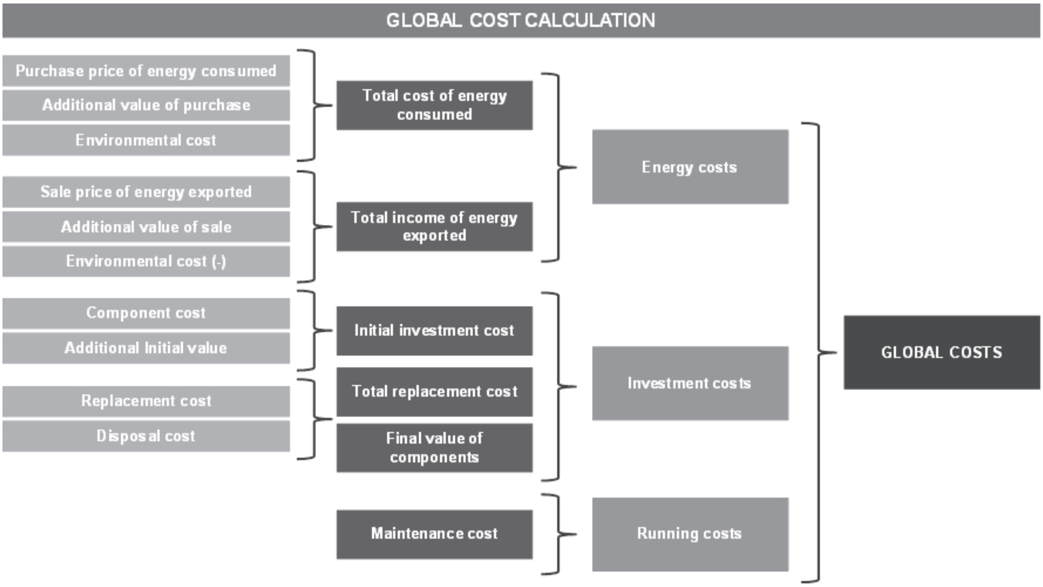


Figure IV.7 Global costs calculation scheme

The energy costs are composed of two terms: costs related to the consumed energy by the building (purchased energy) and the costs related to the produced energy in the building (sold energy). In both terms, the included costs can be: energy cost (€/kWh), additional values for purchase/sale (€/yr, as for example power fix term of the electrical contract), and environmental costs (€/CO_2emission). In this study, the environmental cost is not included because the perspective of the evaluation is microeconomic.

The investment cost of each retrofit option includes three terms: the initial investment cost, the replacement cost and the final value of the component. The total replacement cost and the final value of the component are related to the lifespan of the retrofit measures. Figure IV.8 describes the relationship between the initial investment cost (C_i), the total replacement cost (C_p), the final value (V_f) and the lifespan of the component. In the example, the calculation period (T) is 30 years and the lifespan of the component is 8 years. At initial conditions (Year=0), the initial investment cost is considered and every 8 years the component is replaced by a new one, being replaced several times over the calculation period. At the end of the period, the final value of the component is calculated, in order to take into account the cost of the remaining active service of the component (in the example, remains 2/8 years).

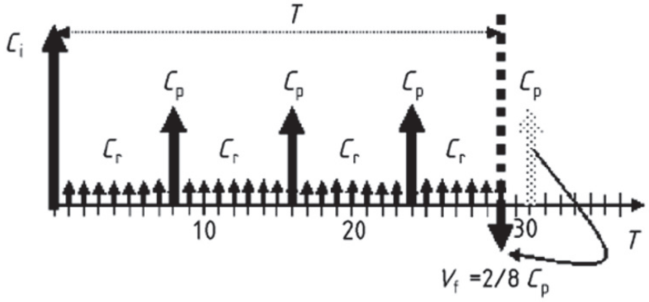


Figure IV.8 Representation of the investment cost calculation. C_i: initial investment cost; C_r: running costs; C_p: replacement costs; V_f: final value of the component; T: economic calculation period. Source: [8]

Finally, the running cost includes the annual cost for the maintenance of the building and their systems, which is considered every year of the calculation period.

Figure IV.9 represents the sequence of calculation that is implemented in TRNSYS to obtain the global costs. The first step is to obtain the information about the reference year: energy consumption, energy costs and environmental costs. In the reference year (year=0), the initial investment cost is considered. After the reference year, the energy costs, environmental costs and the component costs are included every year being modified according to their corresponding evolution rate. Finally, at the end of the period, the final value of the components is calculated.

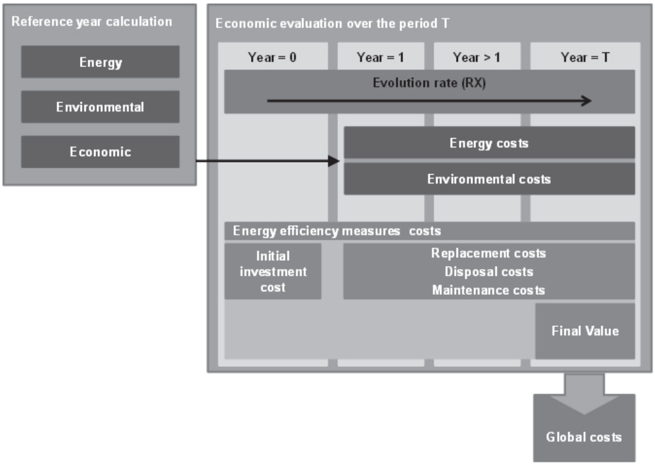


Figure IV.9 Global costs calculation procedure

Figure IV.9 shows that the costs are estimated according to an evolution rate. This figure represents how the cost of an element (energy, emissions, components…) will change over the years. However, not all the elements follow the same evolution rate. Table IV.3 describes the different evolutions rates used in the cost calculation:

- Discount rate: it is the rate used to compare the money value in different years. The discount rate is implemented in all the elements that follow the market evolution.
- Energy evolution rate: it is the rate used to compare the energy cost in different years. The energy evolution rate is implemented for each different energy source, applying in each case its corresponding value.

Table IV.3 Description of the evolution rates implemented in the global cost calculation

Economic term	**Evolution rate calculation**	**Equation**	
Replacement cost Disposal cost Maintenance cost Additional values for purchase/sale energy	Discount rate (R_D): Market interest rate (R) Inflation rate (RI) Real interest rate (R_R)	*Eq. IV.8* *Eq. IV.9*	$R_R = \frac{R-RI}{1+(RI/100)}[\%]$ $R_D = \frac{1}{1+(R_R/100)^t}[-]$
Energy cost	Energy evolution rate (R_E) Energy cost evolution (RX_E)	*Eq. IV.10*	$R_E = (1+RX_E/100)^{t-1}[-]$

t is the year of calculation

Three main groups of data are needed: economic, energy and environmental, and energy efficiency measures. Relative to the economic assumptions needed for the global cost calculation, there are basically two parameters: inflation rate and market interest rate. Table

IV.4 shows the values used in the present study, which are consistent with the values proposed in [8].

Table IV.4 Economic hypotheses

Parameter	**Hypothesis**
Inflation rate (RI)	2%
Market interest rate (R)	4.5%
Discount rate (R_D)	2.5%

The energy and environmental hypotheses depend on the energy system of each country. Table IV.5 shows the hypotheses and their corresponding sources. Finally, parameters needed for the energy efficiency measures evaluation are detailed in the Annex II OptiHab. In this case, the investment and the maintenance costs are obtained from [51] and the lifespan from [8]. The perspective of the evaluation is microeconomic (i.e. energy bills), for that reason the costs must include taxes.

Table IV.5 Energy and environmental hypothesis

Parameter	**Catalonia (2014)**	**Source**
Electricity		
Energy cost (€/kWh)	0.1315	[51]
Additional values for purchase (€/kW·yr)	40.58	[51]
Energy cost evolution, $RX_{E,ele}$ (%)	2.50	[51]
Conversion factor from final energy to primary energy (kWh_p/kWh_f)	2.464	[7]
Conversion factor from final energy to CO_2 emissions (g_{CO2}/kWh_f)	248	[7]
Natural gas		
Energy cost (€/kWh)	0.0527	[51]
Additional values for purchase (€/yr)	106.56	[51]
Energy cost evolution, $RX_{E,ng}$ (%)	2.00	[51]
Conversion factor from final energy to primary energy (kWh_p/kWh_f)	1.070	[7]
Conversion factor from final energy to CO_2 emissions (g_{CO2}/kWh_f)	201	[7]
Biomass		
Energy cost (€/kWh)	0.0368	[51]
Additional values for purchase (€/yr)	-	[51]
Energy cost evolution, $RX_{E,bm}$ (%)	2.00	[51]
Conversion factor from final energy to primary energy (kWh_p/kWh_f)	0.25	[7]
Conversion factor from final energy to CO_2 emissions (g_{CO2}/kWh_f)	-	[7]

*Prices not include the VAT

IV.2.3 Energy labelling

The results obtained from the building simulation are in terms of energy (energy demand, final energy and primary energy) and global costs. However, it is interesting to translate these results to the energy labelling, in order to have a high impact on the results implementation. This section explains how the results have been adapted.

In Spain, the energy label legislation [52] establishes that for residential buildings the primary energy consumption must include the energy consumption of: heating, cooling and domestic hot water. As it has been explained before, in this study, the energy consumption includes also the consumption of lighting and appliance. For that reason, an adaptation of the energy label scale is needed.

Basically the steps followed for this adaptation are represented in Eq. IV.11. First, the energy label scale ($E_{R,label-i}$) has been obtained for each climate following [53, 54]. Then, the energy consumption of lighting ($E_{LIG,BC}$) and appliances ($E_{APP,BC}$) of the base case have been added to the scale in order to take into consideration these energy uses in the labelling. After the adaptation, the energy labelling represents the total energy consumption of a dwelling (Table IV.6): total energy labelling scale ($E_{T,label-i}$).

Eq. IV.11

$$E_{T,label-i} = E_{R,label-i} + (E_{LIG,BC} + E_{APP,BC})$$

Table IV.6 Total energy labelling scale for each building typology and climate

kWh/m_2·yr		Primary energy consumption		Total energy labelling scale ($E_{T,label-i}$)					
		$E_{LIG,BC}$	$E_{APP,BC}$	A-B	B-C	C-D	D-E	E-F	F-G
C2	**BT-4**	7.6	60.5	106	130	164	215	315	364
	BT-5	8.9	74.6	109	125	148	183	269	300
	BT-6	7.0	57.3	90	106	129	164	250	281
	BT-8	7.0	82.9	115	131	155	189	276	307
B3	**BT-4**	7.6	60.5	96	122	158	213	282	317
	BT-6	6.9	57.3	82	99	123	159	234	256
	BT-8	6.9	82.9	108	125	148	184	259	281
D3	**BT-6**	6.9	57.3	97	119	149	194	302	349
E1	**BT-5**	8.8	74.6	112	137	173	228	413	471
	BT-6	7.0	57.3	131	156	193	247	432	490

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Chapter V Analysis of the results

The following chapter describes the results obtained in the cost-optimal evaluation based on three criteria: thermal comfort, energy savings and economic analysis. The method of the evaluation process has been described previously in Chapter IV, the building simulation model and its hypotheses are detailed in Chapter II and the building typologies characteristics are found in Annex II OptiHab. The results are divided in four sections: passive measure evaluation, active measure evaluation, general results and applications.

A detailed analysis of the results is done in the passive measure evaluation and active measure evaluation. In both sections, the analysis is focused on the building typology BT-8 located in C2 (Barcelona) and B3 (Tarragona) climate. The results presented in both section are published in [1, 2] , respectively. Thereafter, an overview of all the typologies and all climates is done. To visualize the results it is designed a factsheet for each building typology and climate in order to summarize the main results. Finally, the results of the study have been used as a tool to define a subsidy plan for the energy renovation of buildings based on cost-effective measures [3]. In that case, the results used are those from the building typology BT-6 in the C2 (Barcelona) climate.

V.1 Passive measure evaluation

The results of the passive analysis are described in the following section. The objective of the passive measure evaluation is to obtain the measures or combination of measures that provide the best thermal comfort with the lowest initial investment cost. For the evaluation, it has been has been simulated the building without the use of the heating and cooling system (free running mode) and the comfort model used is the ASHRAE adaptive model. The purpose is to explore to what extend the passive measures are able to reduce the discomfort conditions without the use of the mechanical systems. Despite that the climates B3 and C2 are temperate, the heating demand is more important than the cooling demand. In that sense, one of the objectives of the passive measure evaluation is to identify in which cases the cooling system could be avoided: the summer discomfort and the hours of overheating are in the comfort ranges only with passive measures.

A general view of the results is done in the sections V.1.1 and V.1.2, and particular situations are evaluated in the following ones: the impact of the natural ventilation (V.1.3), the effect of measures (V.1.4), and the difference between climates (V.1.5).

V.1.1 Main results: thermal comfort vs. investment costs

To develop the passive measure evaluation, the building simulation has been run for the base case, to know the current situation, and for the different package of passive measures. The parameters evaluated are: LDP annual, LDP cold season, LDP warm season, OH hours and the initial investment cost. The climate of Barcelona and the simulations with natural ventilation are selected for the general analysis of the results.

All the graphs of the Figure V.1 represent the results of the mean dwelling: each dot represents one simulation. The results of the mean dwelling are calculated as the weighted average between the results of the standard dwelling and the results of the under roof dwelling. In the graphs, the results are analysed using the different comfort parameters. The colours of the dots represent the measures of the Pareto frontier, depending on the corresponding criteria (annual discomfort, warm season, cold season and hours of overheating).

The annual discomfort (top-left of the Figure V.1) of the starting point is around the 33%. It means that, the occupants are in discomfort conditions during the 33% of the year. As the cost of the energy efficiency measures is increasing, the discomfort tends to decrease, reaching values near the comfort zone: 24% (the threshold of a comfortable building is 20%). However, the discomfort levels are quite different if the season indices are analysed (bottom of the figure). For the cold season, the current building has around 55% of discomfort, reaching a 40% with the best combination of measures. Nevertheless, the warm season discomfort index reflects comfortable conditions for all the simulations (LDP<9%). With this discomfort values during the cold season, it can be concluded that the heating demand can be reduced; however, the heating system is already needed to provide comfort condition to the users.

For a more detailed evaluation of the comfort during the warm season, it must be included the hours of overheating in the analysis (bottom-right graph). For Barcelona’s climate, the threshold of a household without overheating problems is 41 hours (1% of the warm season). The current building presents slight problems of overheating (45 hours). In that case, the effect of the different measures does not follow a linear behaviour and whether the overheating is reduced or increased depends on the measures. There is a set of measures that reduce the hours of overheating below 1%. In those cases, the household has a comfortable condition during the warm season without the use of mechanical systems.

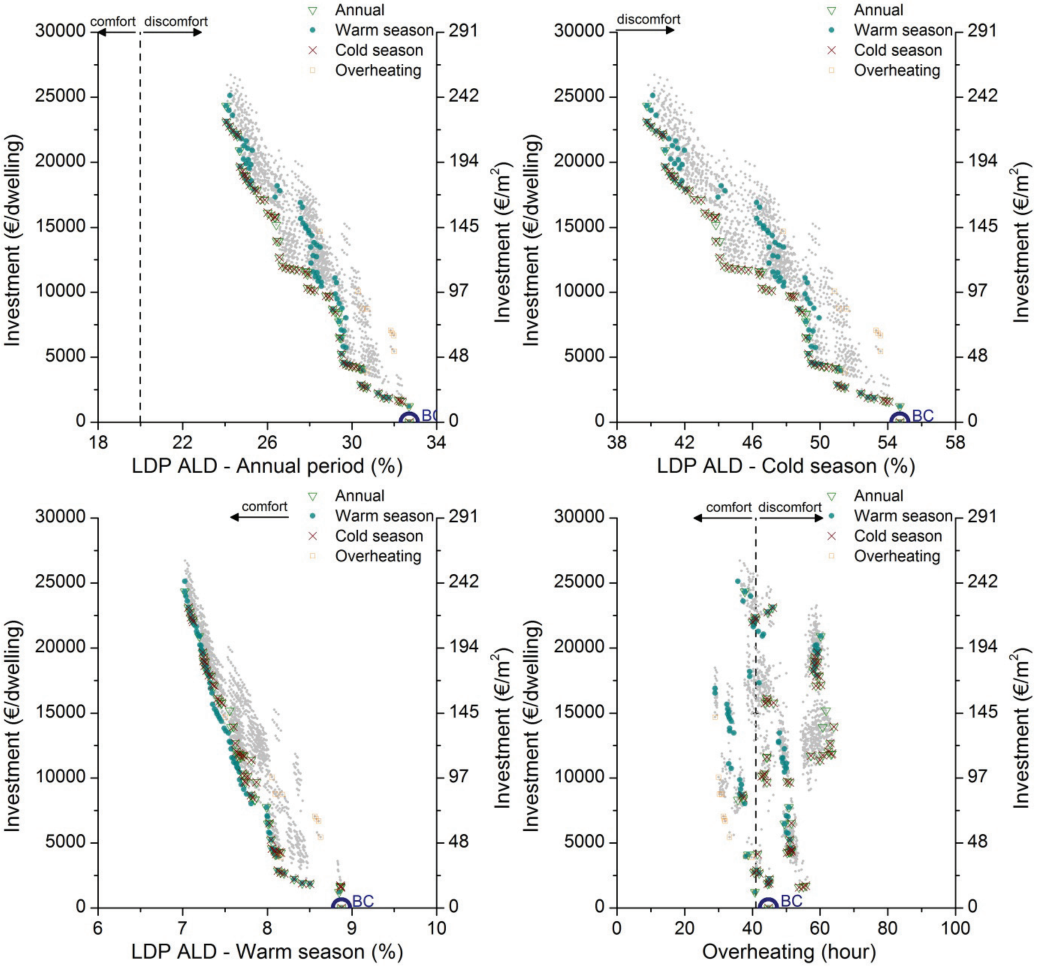


Figure V.1 Economic and comfort parameters of the simulation for Barcelona (C2) with natural ventilation. Top-left: annual discomfort. Top-right: hours of overheating. Bottom-left: cold season discomfort. Bottom-right: warm season discomfort.

Comparing the Pareto frontier of the different criteria, there is a correlation between the annual and cold season criteria: the measures of the annual period are consistent with the measures of the cold period. However, the measures of the warm season and the overheating criteria are not the same. In the case of the overheating analysis in relation to the annual/cold season, the behaviour is, in most of the cases, opposite: the better measures in the annual/cold season are the worst of the overheating index. As regards the cost of the measures, the annual and cold comfort are improved as the cost is increased, achieving a maximum investment cost around 240€/m^2. However, this trend is not observed for the warm season, even the expensive measures provide more hours of overheating than the others. In that case, the measures with a higher reduction of overheating hours have a maximum cost around 150€/m^2.

V.1.1.1 Standard dwelling vs. under roof dwelling

Figure V.2 shows the difference between the standard dwelling and the under roof dwelling. During the cold season, the under roof floor shows results slightly better than the standard floor. However, during the warm season, the situation is opposite, especially if the hours of overheating are analysed. This situation is due to the fact that the roof of the building already has insulation: during the cold season the under roof floor is protected from the cold and the solar radiation has a beneficial effect for this floor; Nevertheless, during the summer the insulation and the solar radiation play a negative role for the under roof floor, increasing the thermal discomfort and the hours of overheating in the under roof floor.

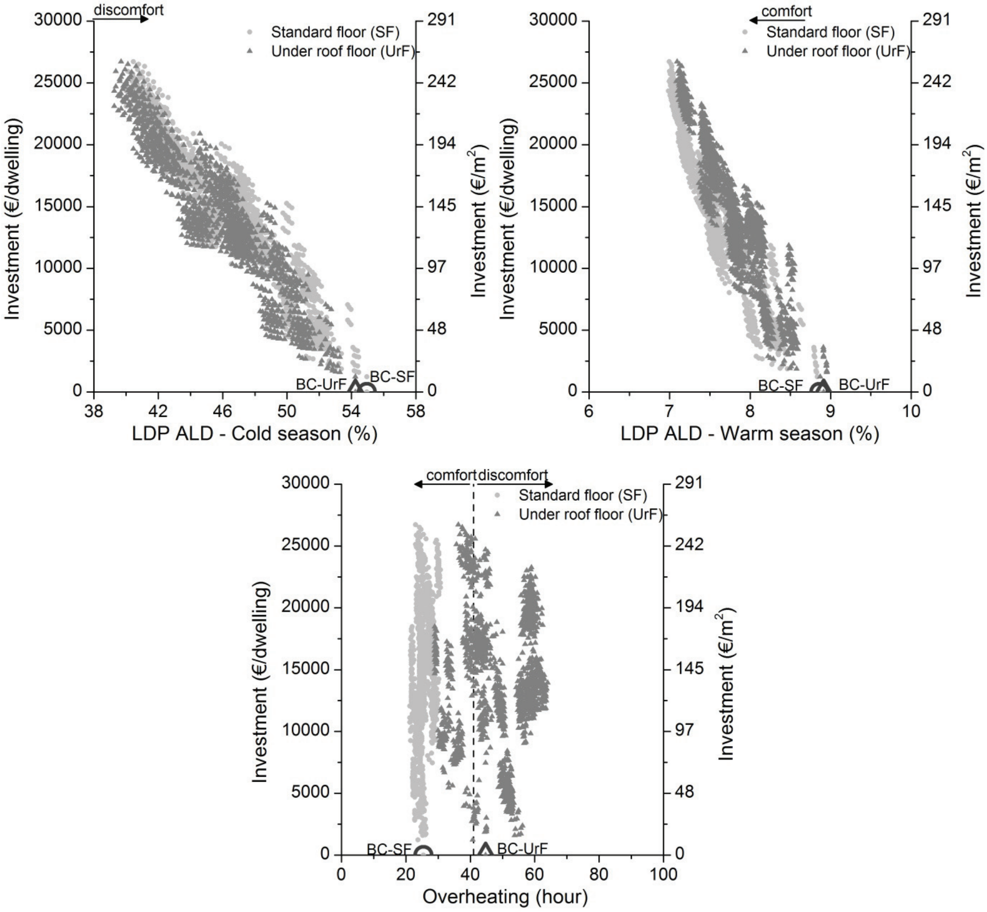


Figure V.2 Comparison between the standard floor and the under roof floor. Top-left: cold season discomfort. Top-right: warm season discomfort. Bottom: hours of overheating.

V.1.2 Passive measure selection

The objective of the passive measure evaluation is to have information to choose the appropriate combination of passive measures, following comfort and economic criteria. Figure V.3, Table V.1 and Table V.2 represent the passive measures selected, which tries to find equilibrium between the different criteria: a) To select the measures that achieve a comfort improvement with the minimum investment cost; b) to reduce the hours of overheating above the threshold comfort (this situation avoids the cooling system, because there are not overheating problems in the household); c) to reduce the cold thermal discomfort (the heating demand is the large demand of dwellings, for that reason, if the combination of measures achieves to reduce the cold thermal comfort, then the heating demand will be lower).

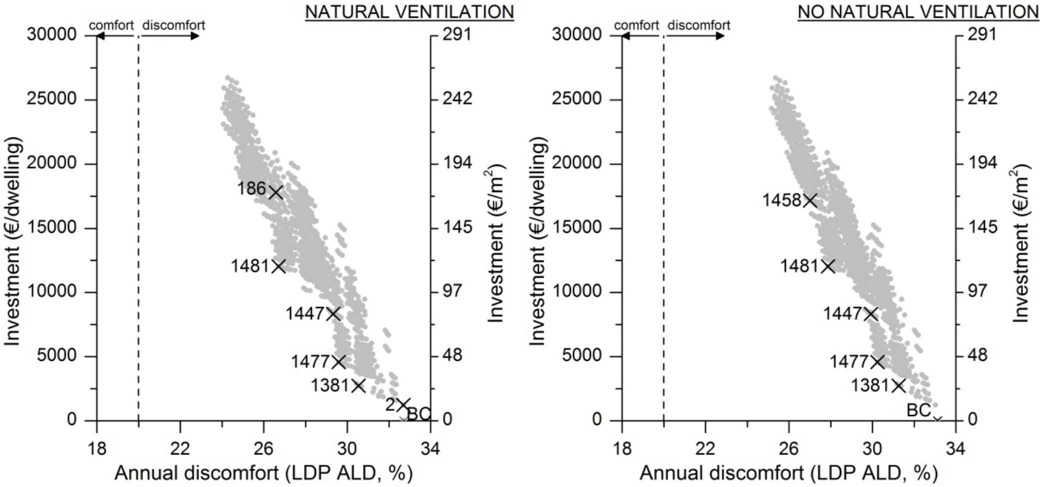


Figure V.3 Passive measure selection, following comfort and economic criteria for Barcelona climate. Left: With natural ventilation. Right: without natural ventilation.

Table V.1 Passive measure selection, following comfort and economic criteria for Barcelona climate with natural ventilation

Passive (U-value) /(g-value)	**Façade** (W/m^{2}K)	**Roof** (W/m^{2}K)	**Window** (W/m^{2}K) /(%/100)	**Solar Prot.**	**Annual LDP** %	**Cold LDP** %	**Warm LDP** %	**Over-heating** Hours
BC	Base case (0.625)	Base case (0.546)	Base case (5.7)/(0.85)	Internal blinds	32.7	54.7	8.9	45
2	Base case (0.625)	Base case (0.546)	Base case (5.7)/(0.85)	Awning	32.7	54.7	8.8	41
1381	INT–RW 6 (0.339)	Base case (0.546)	Base case (5.7)/(0.85)	Internal blinds	30.6	51.2	8.2	40
1477	INT–RW 8 (0.294)	INT–RW 8 (0.275)	Base case (5.7)/(0.85)	Internal blinds	29.6	49.5	8.1	51
1447	INT–RW 8 (0.294)	EXT–EPS 8 (0.259)	Base case (5.7)/(0.85)	Internal blinds	29.3	49.2	7.9	36
1481	INT–RW 8 (0.294)	INT–RW 8 (0.275)	4/16/4PVC (2.8)/(0.75)	Internal blinds	26.7	44.3	7.6	62
186	EXT–EPS 8 (0.273)	Base case (0.546)	4/16/4PVC (2.8)/(0.75)	Awning	26.6	44.4	7.3	39

LDP <20% represent comfortable conditions. OH < 41 hours represent comfortable conditions in C2 climate

Table V.2 Passive measure selection, following comfort and economic criteria for Barcelona climate without natural ventilation

Passive (U-value) /(g-value)	**Façade** (W/m^{2}K)	**Roof** (W/m^{2}K)	**Window** (W/m^{2}K) /(%/100)	**Solar Prot.**	**Annual LDP** %	**Cold LDP** %	**Warm LDP** %	**Over-heating** Hours
BC	Base case (0.625)	Base case (0.546)	Base case (5.7)/(0.85)	Internal blinds	33.1	54.7	9.8	120
1381	INT–RW 6 (0.339)	Base case (0.546)	Base case (5.7)/(0.85)	Internal blinds	31.3	51.2	9.7	202
1477	INT–RW 8 (0.294)	INT–RW 8 (0.275)	Base case (5.7)/(0.85)	Internal blinds	30.2	49.5	9.4	182
1447	INT–RW 8 (0.294)	EXT–EPS 8 (0.259)	Base case (5.7)/(0.85)	Internal blinds	29.9	49.2	9.1	109
1481	INT–RW 8 (0.294)	INT–RW 8 (0.275)	4/16/4PVC (2.8)/(0.75)	Internal blinds	27.9	44.3	10.1	390
1458	INT–RW 8 (0.294)	EXT–EPS10 (0.229)	4/16/4PVC (2.8)/(0.75)	Awning	27.0	43.5	9.2	217

LDP <20% represent comfortable conditions. OH < 41 hours represent comfortable conditions in C2 climate

V.1.3 Effect of natural ventilation

The natural ventilation has been analysed with special attention. For that reason, the simulation has been done with two configurations: with natural ventilation and without natural ventilation. In this section the difference between the results are analysed, comparing their corresponding comfort indices.

Figure V.4 compares the results of the two sets of simulations for the mean dwelling. The graphs of the top represent the annual discomfort and it is possible to observe that the simulations with natural ventilation are able to achieve better comfort conditions (24% in front of 25%). If the analysis is focused on the hours of overheating (colour scale), the difference is more important between both configurations: the hours of overheating increase pronouncedly in the simulation without natural ventilation, having uncomfortable conditions in all the cases (> 150 hours of overheating). On the contrary, in the simulation with natural ventilation there are some measures that reach comfortable conditions (<41 hours of overheating), as in the previous section has been shown.

The bottom graphs of the Figure V.4 represent the relation between the cold season discomfort and the warm season discomfort. The difference between both sets of simulations is very evident. In the case of natural ventilation, the measures follow a linear behaviour, especially in the cold season discomfort: as the cold season comfort improves, the warm season comfort also is improved. However, in the simulations without natural ventilation, there is a significant group of measures where the comfort index in the cold season is improved, but the warm season comfort gets worse. This pattern is also reflected with the hours of overheating.

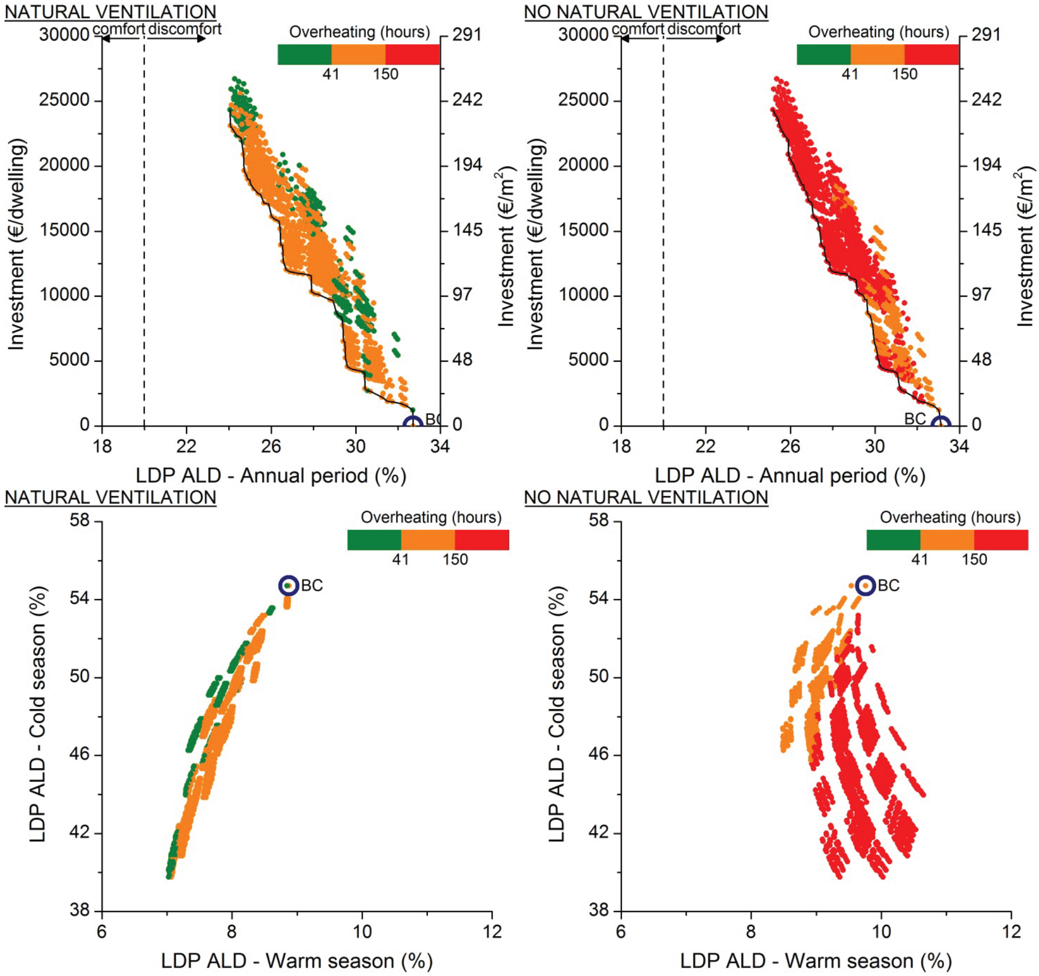


Figure V.4 Comparison of the simulation with natural ventilation (left) and without natural ventilation (right). Top graphs: annual discomfort index; Bottom graphs: cold season comfort vs. warm season comfort. Colour scale: hours of overheating.

To complete the comparison between the simulation with and without natural ventilation, the results of the standard floor and under roof floor are analysed. Figure V.5 shows how the difference of the warm season index between floors is higher than the simulation with natural ventilation (Figure V.2). Most of the measures present problems of overheating in both floors; however, in the standard floor the situation is slightly better.

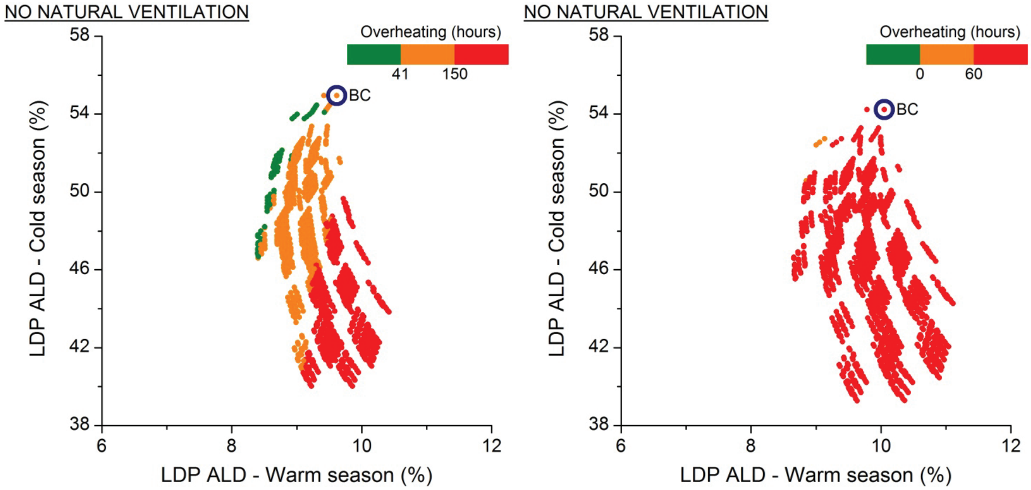


Figure V.5 Comparison between the standard floor (right) and the under roof floor (left) in the simulation without natural ventilation

V.1.4 Effect of measures

After the overview of the results, it is interesting to analyse the effect of the different measures. The results of the under roof floor are analysed because this floor has the worst behaviour during the warm season. All the graphs of the Figure V.6 represent the results of all the simulations having difference colour scales, which represents the type of façade, roof, window or solar protection that is simulated in each case. The graphs show the effect of the different measures in relation with the discomfort during the cold season (y-axis) and the hours of overheating (x-axis). Analysing all the graphs together, it is possible to differentiate three groups: base case of windows (top), internal insulation in the roof (left) and external insulation of the roof (right).

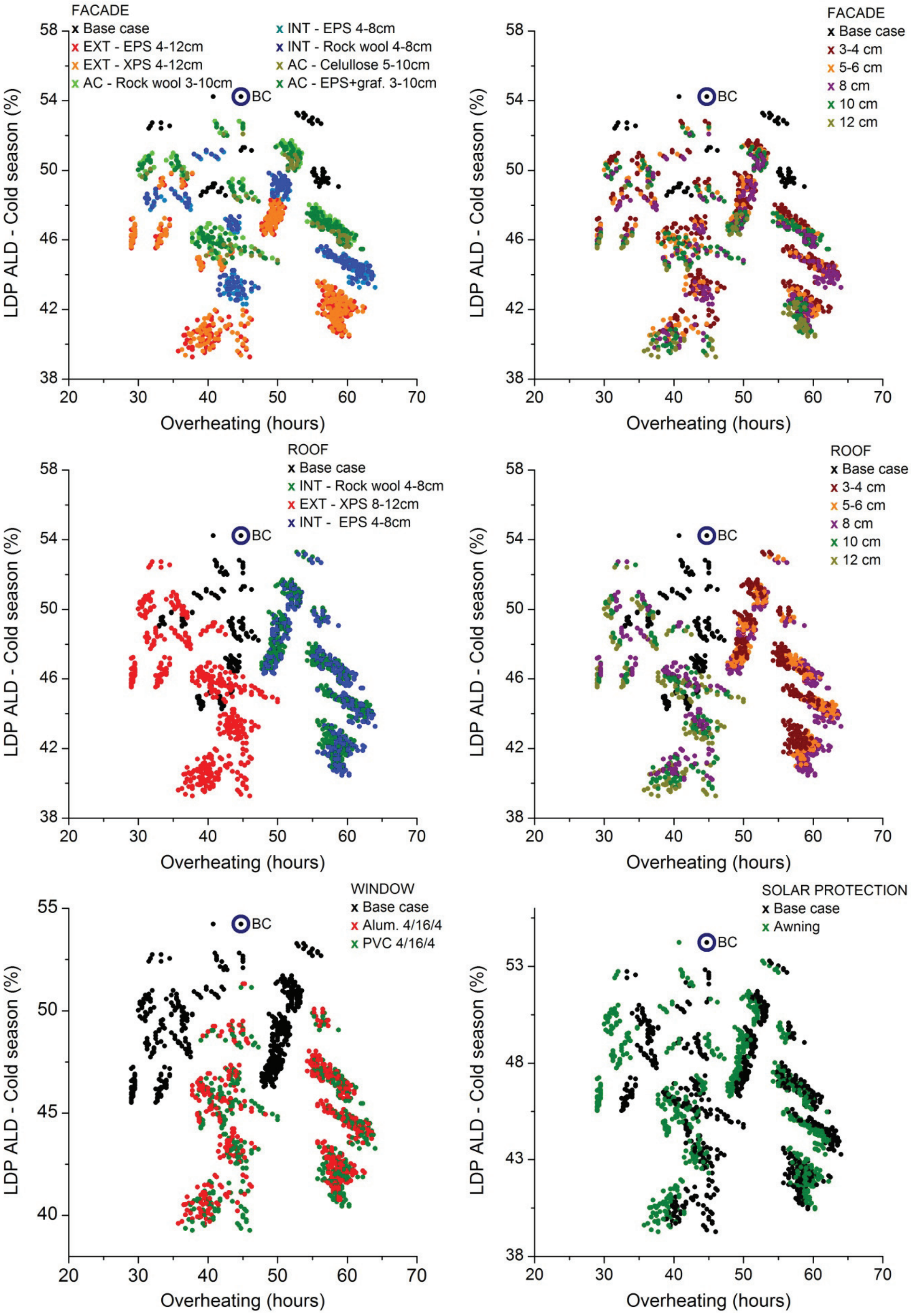


Figure V.6 Results of the simulation of the under roof floor in Barcelona (C2) with natural ventilation: comparison of the effect of the measures in relation to the cold season discomfort (y-axis) and the hours of overheating (x-axis), emphasising: type of facade (top left and right), type of roof (middle left and right), type of window (bottom-left) and type of solar protection (bottom-right)

Focusing on the effect on the types of façade, the increase of insulation provides always an improvement of the cold comfort, being the best option the external insulation with higher thickness (achieving a discomfort of 39% in combination with other measures). For the summer season, there are not clear patterns and the behaviour of the insulation depends on its combination with the other measures (from 29 to 64 hours of overheating).

The comfort during the summer season (hours of overheating) has a high repercussion depending on the type of roof insulation. The external insulation gives better results than the internal insulation, reducing the hours of overheating in most of the cases (< 41 hour of overheating). For the cold season comfort, the behaviour of the different types of roof insulation is similar, being slightly better the external insulation (39% in front of 40%). As to the thickness of the insulation, greater thickness provides better comfort during the cold season. However, the situation is opposite for the summer season.

The change of the windows has a direct improvement over the cold season comfort (from 44% to 39%); but, for the hours of overheating the effect is not significant. The difference between the aluminium with thermal break and the PVC framework are very small.

Finally, the effect of the solar protection has been reflected only in the overheating hours, giving better results the optimal use of the awnings.

V.1.5 Climate comparison

As Figure V.7 and Table V.3 shown, the climate B3 is a bit hotter than the climate C2. The season periods of the discomfort index are different in both climates, being the warm season longer for the B3. The idea of this section is to analyse which is the effect of the different climates and also the definition of the season periods for the discomfort index calculations.

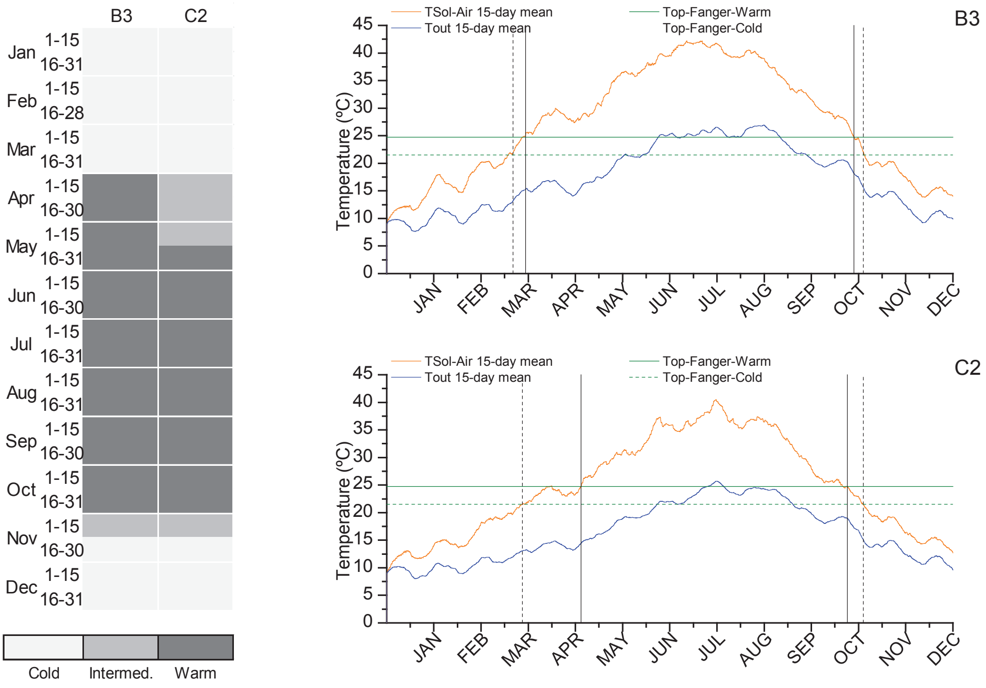


Figure V.7 Climate comparison and season length of C2 (Barcelona) and B3 (Tarragona).

Table V.3 Climate characteristics

Temperature (ºC)	Barcelona (C2)	Tarragona (B3)
Average	16.3	17.4
Minimum average	5.7	5.8
Maximum average	27.9	30.3

Figure V.8 shows the comparison between the results of both climates, in term of annual and seasonal discomfort. If the analysis is focused on the top graphs, the results are coherent with the differences between climates: the annual discomfort is lower for the hottest climate (29% in front 33% in the base case) and the hours of overheating are higher also for the hottest one (57 in front of 45 hours of overheating in the base case).

On the contrary, the graphs of the cold season (Figure V.8 top-right) represent the opposite behaviour: climate C2 has lower discomfort than the B3 (55% and 58%). The reason of this situation is the difference between the lengths of the cold period. The period of the cold discomfort index in the B3 climate goes on during the 5 months and finishes at the end of March. However, in the C2 climate the end of the cold season is at mid-May and its length is 6.5 months, which includes 1.5 months of intermediate season. Then, the comfort index tends to improve in the climate where the cold period is longer. Despite this situation, the results show how the difference between climates is lower for the expensive measures.

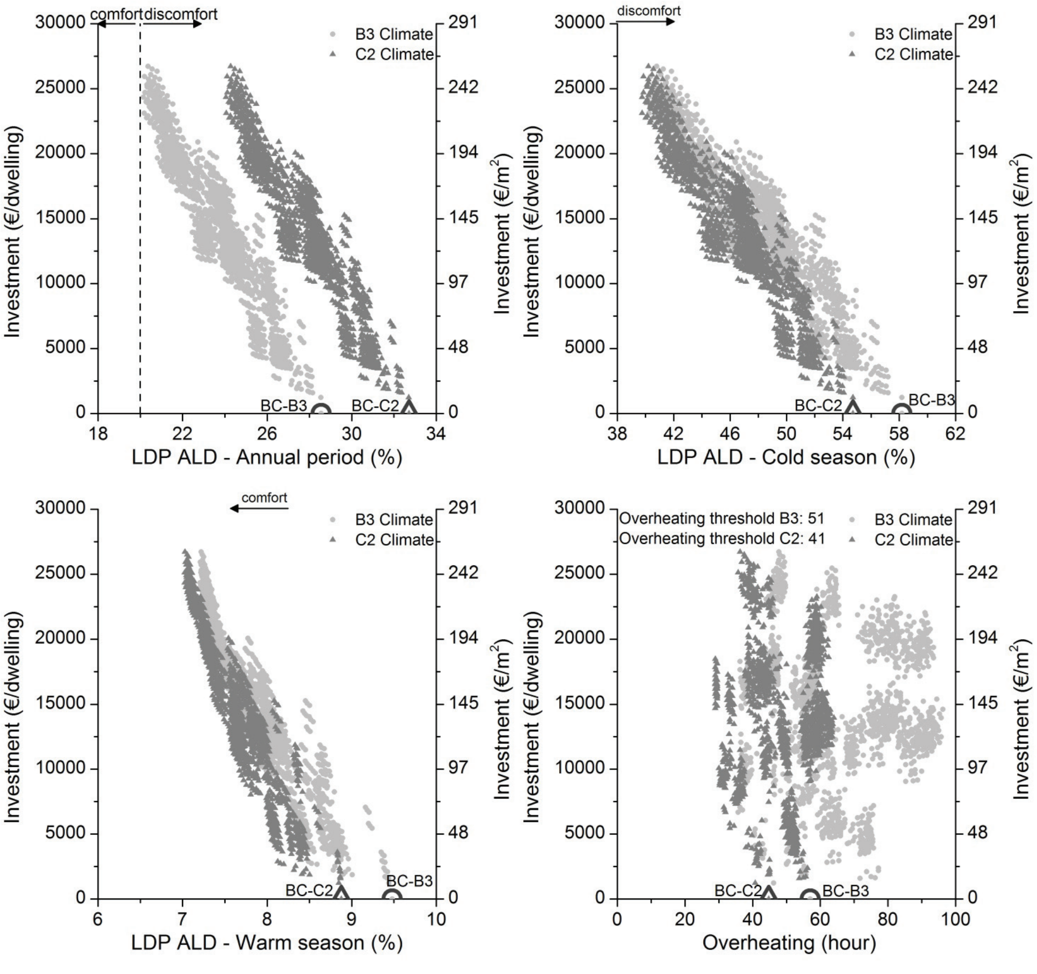


Figure V.8 Comparison between the results of the simulation in both climates (B3 and C2). Top-left: annual discomfort. Top-right: hours of overheating. Bottom-left: cold season discomfort. Bottom-right: warm season discomfort.

V.1.6 Conclusions: passive measure evaluation

This section presents a detailed method to optimize the energy renovation of residential buildings. The method introduces an innovative approach based on passive measure evaluation, which uses two criteria to choose the appropriate energy efficiency measures: thermal comfort and initial investment cost.

The passive measure evaluation has the objective to reduce as much as possible the discomfort conditions with the minimum cost of passive measures. If the comfort is improved by passive measures, then the energy demand will be lower. The results show that in most cases, the results of the annual and the cold comfort season are opposite to the warm season indices. For that, equilibrium between the different criteria must be found to select the measure: the improvement of the cold season comfort is more noticeable than the warm season comfort; however, the hours of overheating can be reduced below the comfort threshold for some combination of measures.

Focusing on the effect of the different passive measures, in general all the measures produce an improvement in the cold season comfort (from 55% to 39%), being better the external insulation of the façade and the external insulation of the roof (12cm and 8cm respectively). However, the costs of both measures are more expensive in comparison with the internal or air chamber insulation. The effect of the window change has a significant reduction of the discomfort during the cold season (from 44% to 39%), although the investment cost is high. Even though the cold season discomfort is improved significantly, the mechanical system is needed to provide comfortable conditions to the occupants.

In the warm season, the behaviour of the measures is not always positive, especially if the hours of overheating are analysed. The internal roof insulation causes an increase of the hours of overheating, making more noticeable with the highest thickness of insulation (from 45 to 64 hours of overheating). The results have shown that for some combination of passive measures the cooling system can be avoided, guaranteeing comfortable conditions during the warm period (the hours of overheating < 1% of the warm period). Furthermore, the optimal use of the solar protection provides interesting improvements during the warm season, especially when there is no natural ventilation.

In addition, depending on the dwelling floor, the results are also different. The under roof floor reflects some overheating problems during the warm season, as a difference of the standard floor. One of the reasons for this behaviour could be that the current building has insulation in the base case, and then the roof could be over-insulated. Nevertheless, if the natural ventilation is not possible, both floors have significant problems of overheating (more than 150 hours of overheating). The comparison between the simulation with and without natural ventilation shows how an appropriate use and design of passive strategies could provide comfortable conditions without the need of mechanical systems.

Finally, in the climate comparison is possible to see that the definition of the season periods has a direct consequence in the discomfort index. For that reason it is very important to analyse the results keeping in mind all the hypothesis and boundary conditions. In addition, the results show how the same building located in different climates and environments could have a great variety of responses, especially due to the possibility of natural ventilation.

V.2 Active measure evaluation

The results of the cost-effective analysis are described in the following section. The objective of the analysis is to obtain the optimal measures that provide the lowest primary energy consumption with the lowest global cost. For the evaluation, a set of passive and active measures is considered in order to analyse which combinations of them are the most appropriate in different situations: two climates and dwelling with and without natural ventilation. A general view of the results is done in the first part of this section, followed by the evaluation of the impact of the measure and a comparison between climates and natural ventilation effect.

V.2.1 Main results: cost-effective energy efficiency measures

This first analysis is focused on the building located in Barcelona climate with natural ventilation. The figures represent a mean dwelling results, which have been calculated as the weighted average between the results of the standard dwelling and the results of the under roof dwelling. Figure V.9 shows the results obtained in terms of annual primary energy consumption (x-axis) and global costs over 30 years (y-axis). In addition, the left graph represents the total energy labelling scale as a background of the graph which assigns a labelling to each combination of measures. Each dot on the graph represents the results of one simulation. BC represents the base case (the building without any measure); CO the cost optimal measure; and DR the deep renovation scenario, which provides the maximum energy saving with the lowest global cost. The right graph of the figure represents the global cost distribution of the measures of the Pareto frontier. The global costs are divided in energy cost, investment cost, replacement cost and maintenance costs. The x-label represents the code of the measures implemented in each scenario (passive-active), which are described in Table V.1, Table V.2 and Table V.4.

The graphs show that the BC has an E label (198 kWh/m^2·yr) with a global cost of 453€/m^2. Since the building and their systems improve their performance, the primary energy consumption decreases, achieving an A-label. Relative to the global cost, most of the measures imply an increasing of the global cost; however, there are sets of combinations that reduce this cost below the BC (the points below the horizontal line of the left graph). The cost-optimal measure is able to decrease the energy consumption until to a B-label (123 kWh/m^2·yr) and the global cost until 355€/m^2, implying a reduction of the 38% and 22% respectively. For the DR measure, the energy reduction is about 59% and the global cost increases by 18% (98 kWh/m^2·yr and 535€/m^2). Analysing the distribution of the global costs, it is possible to observe that the investment costs increase as long as the energy performance is increased and the energy cost is reduced. The energy costs can be reduced by 42% comparing the DR respect the BC scenario.

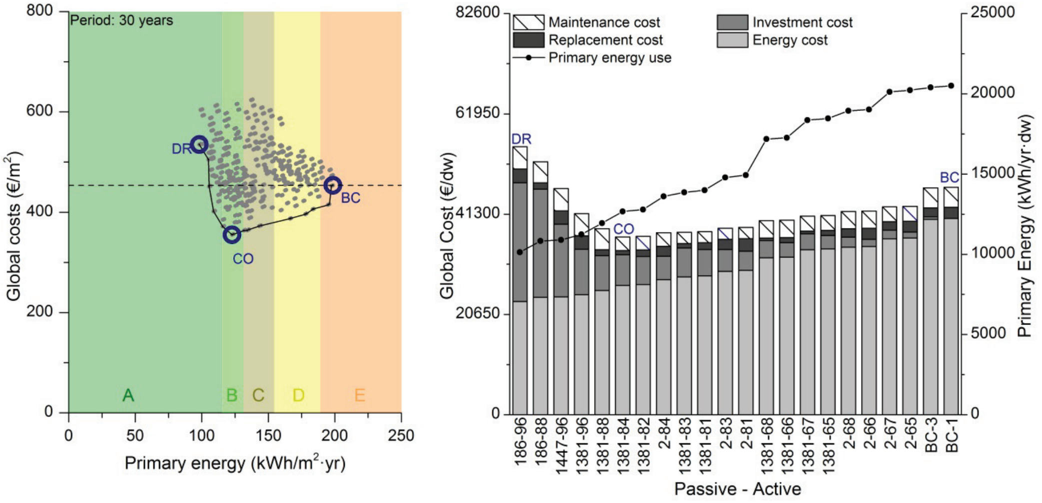


Figure V.9 Cost-energy evaluation: primary energy consumption vs. global cost over 30 years (colour background: energy label scale of Total consumption of dwelling). Building located in Barcelona (C2) with natural ventilation. Right: Energy efficiency measures of the Pareto frontier, detailing the global cost distribution: energy cost, investment cost, replacement cost and maintenance cost. Passive measure description in Table V.1 and active measure in Table V.4.

Figure V.10 complements the information of the Pareto frontier measures, giving details about the distribution of the energy demand (left) and the final energy consumption (right). The general trend of the measures is to reduce mainly the heating demand, making the appliance demand more significant over the whole need of the household. The energy demand distribution shows that the energy demand does not follow a linear pattern. That is, the measures with lower primary energy consumption do not always imply a lower energy demand. This fact is reflected in several cases of the Pareto frontier and the main reason for this behaviour is the type of measure implemented. For example, the measure 2-81 and the measure 1381-68 have similar primary energy consumption, being slightly lower the first one (Figure V.9); however, their energy demand is quite different presenting an opposite behaviour. The first combination of measures (2-81) is composed mainly by the active system improvement (condensing boiler) with small intervention on the solar protection strategy, then the refurbishment improves the efficiency of the systems without reducing the demand of the building. On the other hand, the measure 1381-68 adds insulation to the façade reducing the heating demand, and then improves the lighting system and reduces the electrical consumption through the awareness campaign. This is a clear example of how completely different strategies of actuation provide similar levels of primary energy consumption.

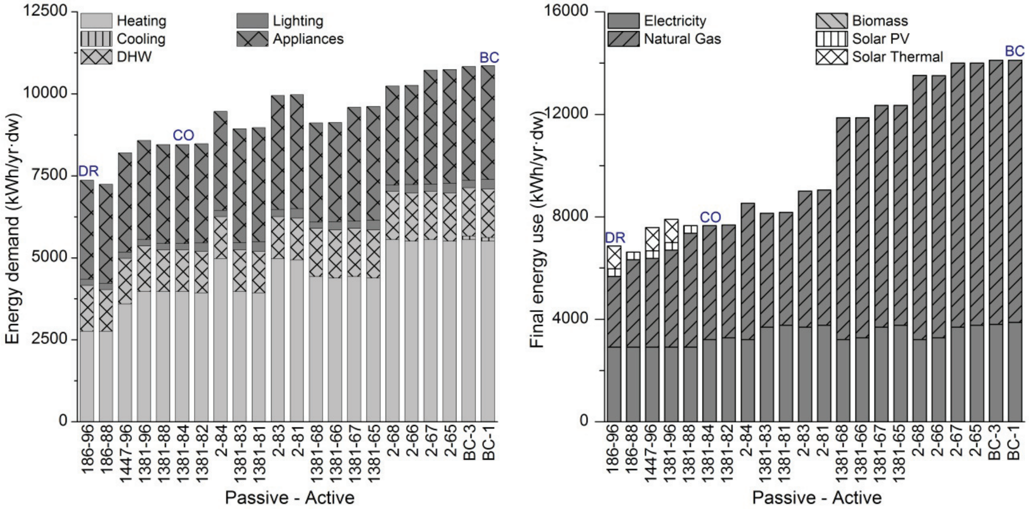


Figure V.10 Energy efficiency measures of the Pareto frontier for the Barcelona climate with natural ventilation. Left: Distribution of the energy demand: heating, cooling, DHW, lighting and appliances. Right: Distribution of the final energy use: electricity, natural gas, biomass, solar PV and solar thermal. Passive measure description in Table V.1 and active measure in Table V.4.

The right graph of the Figure V.10 represents the distribution of the energy consumption in terms of final energy. The main consumption of energy comes from natural gas. There is a quantitative leap on the natural gas consumption after the measure 1381-68 and represents the change of the heating system to condensing boiler. The effects over the electricity consumption are low and the main reason is that there are not specific measures to improve the efficiency of the appliances, which are the main responsible of this consumption. The left-side measures incorporate some renewable energy; however, their contribution is small in terms of final energy. In particular, the solar thermal contribution represents around the 60% of the DHW demand, as the Spanish Building regulation requires.

Table V.4 Description of the energy efficiency measures of the Pareto frontier for each climate (B3 and C2) and the use of natural ventilation (YES or NO).

Code	**Heating + DHW system**	**Cooling system**	**PV system**	**Lig. system**	**Awar. campaign**	**Natural ventilation**
0	Conventional NG boiler	Conventional AC	NO	CFL	NO	YES & NO
2	Conventional NG boiler	Conventional AC	NO	CFL	YES	NO
3	Conventional NG boiler	Conventional AC	NO	LED	NO	YES & NO
4	Conventional NG boiler	Conventional AC	NO	LED	YES	NO
9	Conventional NG boiler	Efficient AC	NO	CFL	NO	NO
10	Conventional NG boiler	Efficient AC	NO	CFL	YES	NO
11	Conventional NG boiler	Efficient AC	NO	LED	NO	NO
12	Conventional NG boiler	Efficient AC	NO	LED	YES	NO
25	Condensing NG boiler Improve efficiency installation	Efficient AC	NO	CFL	NO	NO
26	Condensing NG boiler Improve efficiency installation	Efficient AC	NO	CFL	YES	NO
27	Condensing NG boiler Improve efficiency installation	Efficient AC	NO	LED	NO	NO
28	Condensing NG boiler Improve efficiency installation	Efficient AC	NO	LED	YES	NO
32	Condensing NG boiler Improve efficiency installation	Efficient AC	YES	LED	YES	NO
48	Condensing NG boiler Improve efficiency installation Solar thermal system	Efficient AC	YES	LED	YES	NO
65	Conventional NG boiler	NO	NO	CFL	NO	YES
66	Conventional NG boiler	NO	NO	CFL	YES	YES
67	Conventional NG boiler	NO	NO	LED	NO	YES
68	Conventional NG boiler	NO	NO	LED	YES	YES
81	Condensing NG boiler Improve efficiency installation	NO	NO	CFL	NO	YES
82	Condensing NG boiler Improve efficiency installation	NO	NO	CFL	YES	YES
83	Condensing NG boiler Improve efficiency installation	NO	NO	LED	NO	YES
84	Condensing NG boiler Improve efficiency installation	NO	NO	LED	YES	YES
88	Condensing NG boiler Improve efficiency installation	NO	YES	LED	YES	YES
96	Condensing NG boiler Improve efficiency installation Solar thermal system	NO	YES	LED	YES	YES

V.2.1.1 Standard dwelling vs. under roof dwelling

Figure V.11 shows the differences between the cost-effective analysis for the two types of dwellings: standard and under roof, left and right respectively. The comparison helps to observe that the base case of the under roof dwelling (BC-UD) has a higher primary energy consumption than the standard dwelling (BC-SD). This effect has a direct repercussion on the global cost, which follows the same trend. This difference is quite important representing an increase of 7% of primary energy and 4% of global costs due to the higher heating and cooling demand, and consequently the higher energy costs. However, that difference is reduced as long as the building performance is improved, decreasing the difference between both dwelling up to 4% and 3% in terms of primary energy and global costs respectively. In both cases, the starting point is an E-label, achieving a B-label with cost-optimal measures and A-label with the deep renovation.

There is an additional difference between both dwellings, in the case of the under roof dwelling there are more combinations of measures that are below the global cost of the BC, in comparison with the standard dwelling. One of the reason could be that the effect of some passive measures, as the roof insulation, has a potential impact over the under roof dwelling, reducing more the energy demand. The worst starting point of the under roof dwelling (higher global costs and primary energy consumption) provides more potential of improvement, there being more cost effective measures in comparison with the standard floor (there are more measures under the horizontal line).

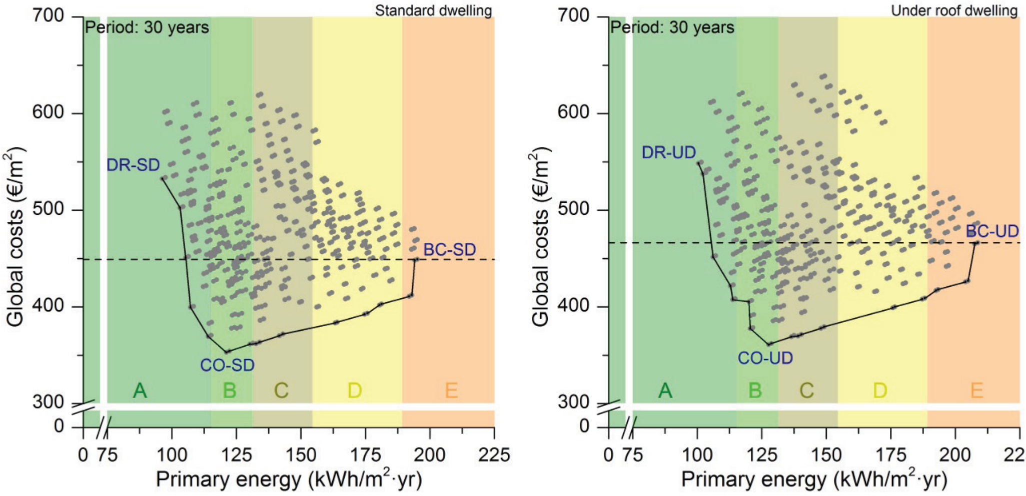


Figure V.11 Comparison of the cost effective evaluation between a standard household and an under roof household

V.2.1 Effect of measures

In this section, the impact of the different measures is evaluated. Figure V.12 represents the cost effective evaluation for a dwelling with natural ventilation located in Barcelona, where the Pareto frontier of the different measures are highlighted in each graph: passive measures (a), heating and DHW system (b), cooling system (c), lighting system (d), integration of PV system (e) and implementation of awareness campaigns (f).

Starting with the effect of the passive measures (a), different patterns can be distinguished in the results depending on the investment cost of the measure and the possibility to avoid the cooling system thanks to the reduction of the hours of discomfort below the discomfort levels. The passive measure 2, which supposes an improvement on the solar protection strategy, has a small impact over the primary energy consumption; however, the improvement of the solar protection strategy reduces the risk of overheating and makes possible to remove the cooling system, and then to save the expenses of the cooling consumption, replacement and maintenance of the equipment. A similar situation shows the measure 1381 and 1447, but in this case the passive measure has a significant impact on the energy demand due to the implementation of insulation on the façade. These measures (1381 and 1447) are able to achieve an A-label in combination with several active measures. The measure 2 and 1381 are the measures that, in combination with the active ones, provide more cost effective solutions. On the other hand, the measures 1481 and 186 are the measures with the highest energy impact; however, their global costs increase in most of the cases over the base case scenario. Finally, the measure 1477, which has a good impact over the energy consumption and at the same time has an acceptable investment cost (4,600 €/dw), is penalized due to the need to have air conditioning in the dwelling in order to guarantee comfortable condition. For that reason, the results of this measure are in general trends worse than others. The results are very sensitive to the overheating threshold that has been established with a direct consequence over the costs. The overheating index and its threshold is a current research topic where there is an interesting discussion about which must be the criteria to establish overheating conditions.

Regarding the heating and DHW system, Figure V.12-b represents four different areas according to the different possibilities. The solar thermal system implies a slight higher global cost in comparison with the BC, although reduces the primary energy consumption (7%), providing some cost effective combination of measures. The effect of the condensing boiler is considerable in both aspects: energy reduction and global cost savings (26% and 9%). The condensing boiler represents the most cost effective solution. Finally, the combination of the condensing boiler with the solar thermal system decreases the primary energy consumption achieving the lower values of consumption.

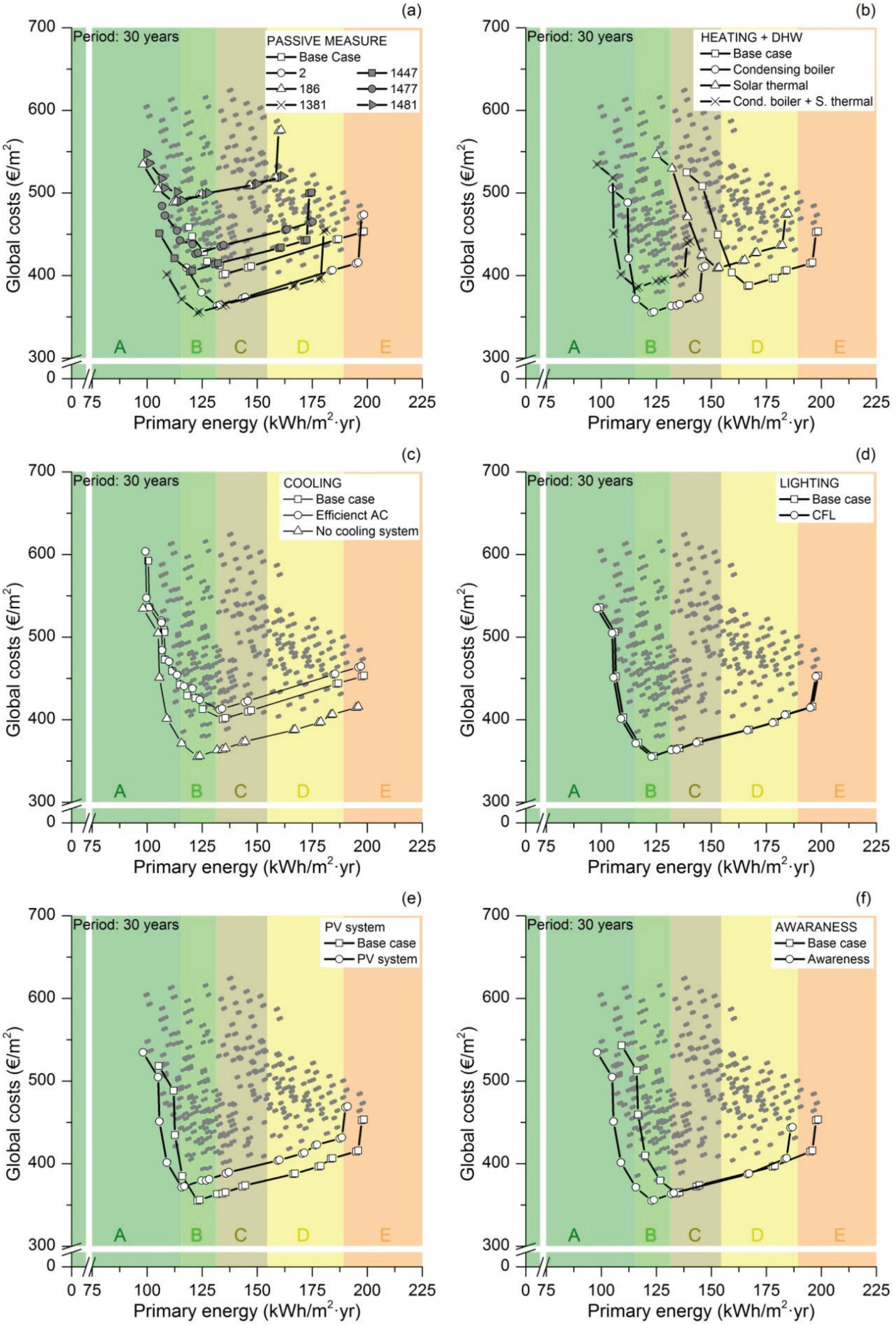


Figure V.12 Cost effective evaluation of the mean dwelling in Barcelona (C2) with natural ventilation: comparison of the effect of the measures regarding the primary energy consumption (x-axis) and the global cost (y-axis), emphasising: type of passive measure (a), type of heating and DHW system (b), type of cooling system (c), type of lighting system (d), integration of PV system (e) and implementation of awareness campaign (f)

Analysing the effect of the cooling system (Figure V.12-c), there is a clear difference between the two strategies: it reduce the risk of overheating with passive measures and, the use of the cooling system to guarantee comfortable condition in the warm period. As the passive measure analysis has shown, the solutions that avoid the cooling system are more cost effective than the ones that need the active system. Comparing the dwelling with the base case and the measures with the efficient cooling system, the difference between them is small, mainly due to lower cooling demand.

The effect of lighting system (Figure V.12-d) improvement is not significant in global terms, reducing only 1% the primary energy consumption of the dwelling. The main reason is that the energy consumption related to the lighting is smaller than other energy uses, representing only 3% of the primary energy consumption. However, the impact of the LED system is positive, providing savings without an increase of the global cost.

The implementation of the PV system (Figure V.12-e) reduces the primary energy consumption, however, the system that has been proposed does not generate enough energy (covers only the 8% of the electric consumption of the dwelling) to cover the expenses (investment, replacement and maintenance costs). A better sizing of the system is needed in order to be a cost optimal solution. Nevertheless, the PV system, in combination with the passive measures that remove the cooling system, provides cost effective solutions. From another point of view, if the objective is to achieve an A-label or better, the use of the PV system, as well as the solar thermal system, is needed in most of the cases.

Finally, the implementation of the awareness campaign has a positive effect reducing the primary energy consumption by 6% in comparison with the BC (Figure V.12-f).

V.2.2 Climate comparison and the effect of natural ventilation

To finalize the analysis of the results, two different situations are compared: two climates and the possibility to use natural ventilation or not. Figure V.7 and Table V.3 summarize the main characteristics of the climates, showing that both are very similar, being a little bit warmer the Tarragona climate. This fact is reflected in the results, where the differences are also small.

Figure V.13 makes the comparison: the left graph shows the Barcelona results and the right graph the Tarragona's ones. As it has been introduced before, the differences between climates are very small; however, it is noticed that the total energy label scale of the Tarragona climate is more demanding in comparison with the Barcelona climate. Comparing the results of the same dwelling located in similar climate, it is possible to observe that their behaviour in terms of energy consumption and energy requirements are different; although in relative figures the results are practically the same, as Table V.5 shows.

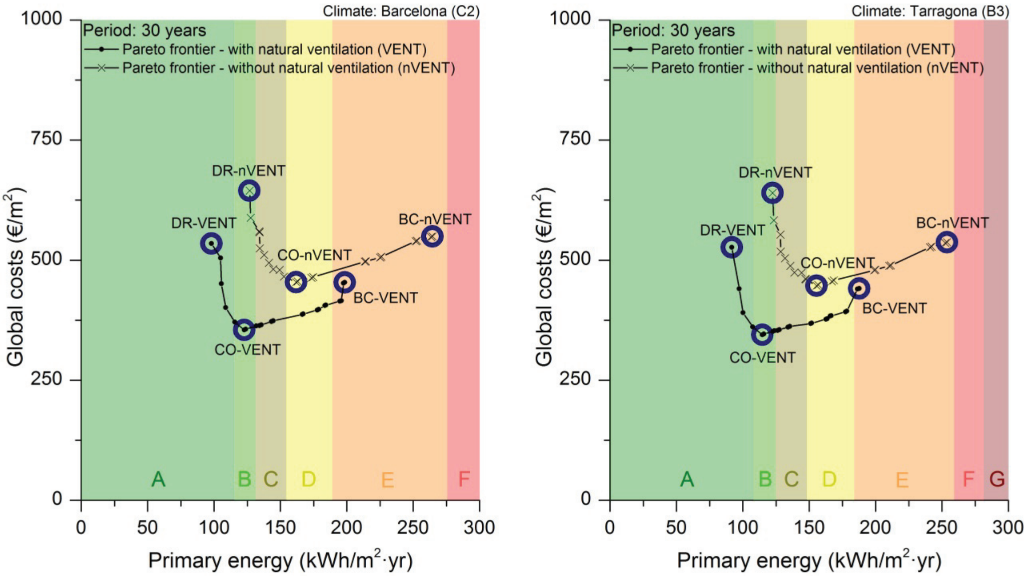


Figure V.13 Cost effective evaluation. Comparison between climates and the dwelling with or without natural ventilation (VENT and nVENT, respectively). Left: Barcelona climate (C2). Right: Tarragona climate (B3)

However, the effect of the natural ventilation is decisive on the results, in terms of energy consumption and also in global costs. In both cases, with natural ventilation (VENT) and without natural ventilation (nVENT), the BC corresponds with an E-label; but in BC-VENT the dwelling is near the boundary D-E, while in BC-nVENT is near the boundary E-F, implying a 33% more in primary energy consumption and 21% in global costs. These BC differences make the dwelling with natural ventilation achieve a B-label for the cost optimal measure and a A-label for the deep renovation, in comparison with the D-label and B-label achieved by the dwelling without natural ventilation. Also the global costs are higher, mainly due to the cooling consumption and the costs related to the cooling system; because in this case the hours of overheating are higher and the cooling system is needed to achieve comfortable conditions, as a difference of most of the cases of the dwelling with natural ventilation (as described in the previous sections).

Table V.5 summarizes the results of this comparison, where it is possible to visualize easily the main differences. The CO measures achieve an improvement of 3-labels in the dwelling with natural ventilation and only 1-label when there is no natural ventilation. For the DR strategy, improves 4-labels and 3-labels, respectively. In addition, it is possible to notice that the CO and DR measures from Barcelona are the same than the ones from Tarragona, being only slight differences on the percentage of energy savings and CO_2 emission reductions. Moreover, if the analysis is focus on which measures are included in both cases, it is possible to observe that the

CO-nVENT does not implement an improvement of the envelope, as a difference of the CO-VENT. The reason of that is that in the case of nVENT, the passive measures do not improve the thermal comfort above the thresholds, as Table V.2 shows, and consequently there is not the option to avoid the cooling system. This fact makes that in the case of nVENT the passive measures are not cost optimal option. However, it is important to remark, that the passive measures are cost effective measures, reducing the global cost of the BC-nVENT.

Table V.5 Summary of the impact of the cost optimal and deep renovation scenarios for the dwelling located in two climates (Barcelona (C2) and Tarragona (B3)) and with or without natural ventilation (VENT and nVENT, respectively).

EE measure		**Climate**	**Natural vent.**	**Energy Label**	**Label Improve BC**	**Primary Energy (Savings)**	**CO$_2$ reduction**	**Initial Investment**	
Passive/Active						kWh/yr·dw (%)	%	€/dw	€/m^2
Base case (BC)	0/0	C2	VENT	E	-	20,501	-	-	-
	0/0	C2	nVENT	E	-	27,315	-	-	-
	0/0	B3	VENT	E	-	19,375	-	-	-
	0/0	B3	nVENT	E	-	26,200	-	-	-
Cost optimal (CO)	1381/84	C2	VENT	B	3	12,677 (38)	45	6,307	61
	0/28	C2	nVENT	D	1	16,715 (39)	42	4,953	48
	1381/84	B3	VENT	B	3	11,855 (39)	44	6,307	61
	0/28	B3	nVENT	D	1	16,067 (39)	39	4,953	48
Deep renovation (DR)	186/96	C2	VENT	A	4	10,134 (51)	59	24,477	237
	1468/48	C2	nVENT	B	3	13,084 (52)	58	25,210	244
	186/96	B3	VENT	A	4	9,482 (51)	59	24,477	237
	1468/48	B3	nVENT	B	3	12,633 (52)	58	25,210	244

Finally, Figure V.14 compares the energy demand distribution for the different scenarios. In this case, the difference between climates is more obvious due to the higher cooling demand in Tarragona (B3) climate. This fact is also visible in the dwelling without natural ventilation, where the cooling demand achieves values of 7% and 11%, in Barcelona and Tarragona. Analysing the BC, the higher energy demand is the heating followed by the appliance demand. The DHW represents around 14% of the energy demand of the dwelling and the lighting only around the 3%. While the building improves their performance, the heating demand tends to be lower to the point that the appliance demand becomes the most important energy demand of the dwelling. This fact is more significant in Tarragona climate where the heating demand is smaller. These results remark the need to include the appliances consumption in the cost-optimal studies and refurbishment analysis, in order to start to implement measures to reduce them.

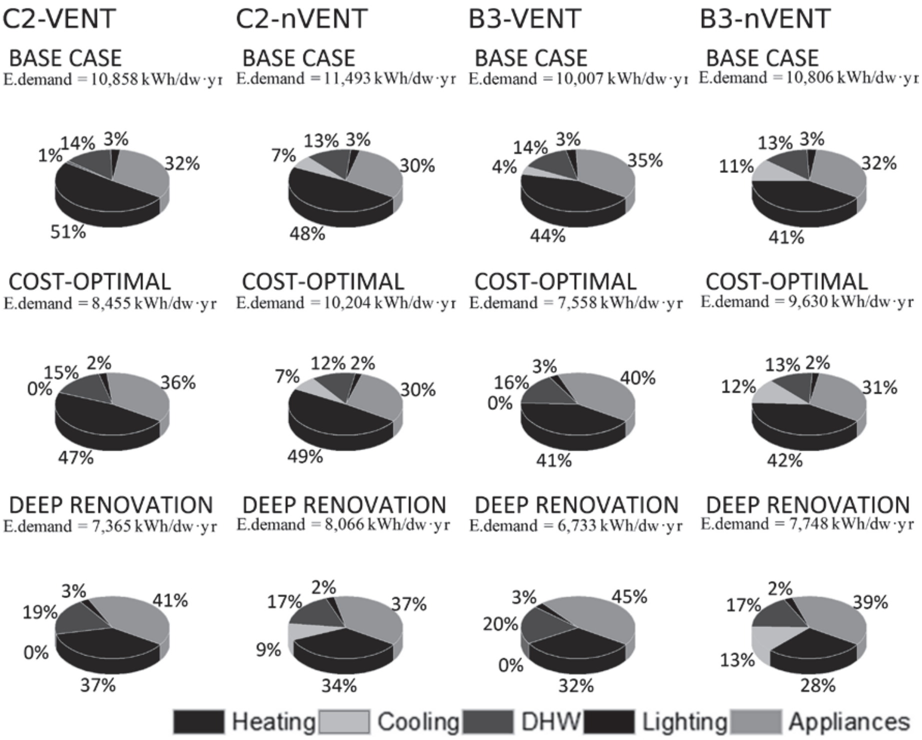


Figure V.14 Comparison in terms of energy demand, between climates (Barcelona (C2) and Tarragona (B3)) and the dwelling with or without natural ventilation (VENT and nVENT, respectively).

V.2.3 Conclusions: active measure evaluation

The section presents a cost-optimal analysis to evaluate energy efficiency measures for a residential building in Catalonia, considering three main criteria: thermal comfort, primary energy use and global costs. The method is divided in two stages: passive evaluation, where the passive measures are evaluated from the point of view of the thermal comfort and the initial investment cost; and the active evaluation, where all the energy efficiency measures are analysed using the global cost and the primary energy consumption.

There have not been found significant differences between the two climates analysed in the study. However, the natural ventilation represents an important impact in the results. It could conclude that in dwellings where natural ventilation is possible, the cost optimal measures can achieve a B-label, improving 3-labels in comparison with the base case. The cost-optimal measure reduces around 40% of the primary energy consumption and 22% of the global costs. If the dwelling does not have natural ventilation then, the situation is worse. The base case is also an E-label, however the cost-optimal measure achieves only a D-label with around 40% of energy saving and 17% of economic savings. The main difference between both cases is that in the dwelling with natural ventilation, the cooling system can be avoided for most of the combination of measures, thanks to the positive effect of passive measures, which reduce the overheating hours below the discomfort level. On the contrary, the dwellings without natural ventilation include the cooling consumption and the costs related to the cooling system providing an increase in the primary energy consumption as well as in the global costs.

The Deep Renovation scenario has been also evaluated, where the measures with high energy saving are analysed. In this case, the dwellings with natural ventilation reach an A-label in comparison with the dwellings without natural ventilation that achieve a B-label. In those cases, the passive and active measures are also combined with renewable energy systems.

In addition, a comparison between the under roof dwelling and the standard dwelling has been carried out. The results show that the under roof dwellings have a higher primary energy consumption and global costs than the standard dwelling. However, this situation provides to the under roof dwelling a higher potential of improvement as well as more combination of cost effective measures.

From a general point of view, there are many strategies that can be implemented in order to reduce the energy consumption. However, if the objective is to implement cost effective measures, only some options are appropriate:

- Implementation of passive strategies to reduce the heating demand and provide comfortable conditions for the warm period without the use of cooling systems, when it is possible. This situation makes possible to avoid the cooling system and save its related costs (cooling consumption, investment, replacement and maintenance costs). However, further research related with the overheating indices and their thresholds is needed, in order to obtain robust criteria to take decisions. In addition, the implementation of passive solutions reduces the heating demand, which has an impact over one of the highest energy uses of the dwelling.
- To improve the heating system, using efficient technologies on the market (condensing boiler, in this case). As it has been said before, the heating consumption is one of the most important of the dwelling, and it is important the use of efficient systems to reduce it.
- To improve the lighting system with LED technologies. The lighting consumption represents a low fraction of the total energy consumption of the household. However, the implementation of LED systems in the dwelling provides a positive impact in both, energy and global cost savings.

- The development of awareness campaigns has a high potential to reduce the energy consumption. The awareness campaign represents the most effective measure, in terms of energy savings by euro invested.
- To achieve A-labels, the integration of renewable systems is required (PV and solar thermal system, in this case). However, the integration of renewable energy systems must be analysed deeply in the framework of this study, testing different designs and sizing of the system in order to explore their optimality.

Finally, the results show that it is important to take in consideration the lighting and appliance consumption, since these energy uses become more and more important as long as the performance of the building and its systems improve. In the case of the deep renovation, the appliance consumption becomes the greatest energy use of the dwelling.

V.3 General results

Figure V.15 represents the dwelling stock distribution around Catalonia. The left maps represent the climate of each municipality, according to the Spanish Building Regulation classification of 2006 [4], which has been used to select the climates and building typologies. The right maps represent the number of dwellings for each municipality and the building typology distribution for each province. Finally, the first two maps (top) show all municipalities and dwellings and the bottom maps the municipalities selected for the study by climate criterion (left) and by building typology and climate criteria (right) (Table V.6).

Analysing the climate distribution, the colder climates (E1 and D1) are located on the mountain areas (Pyrenees, Pre-Pyrenees and Prelitoral mountain range), the warmer and moderate climates (C1, C2 and B3) on the coastal areas and the extreme climates in the continental zone (D2 and D3). As to the dwelling distribution, it is so clear that most of the dwellings are concentrated in the Barcelona province (76%), in particular in the Metropolitan Area and in the coast municipalities. Relative to the building typology distribution, Barcelona has around the 50% of the dwellings of the BT-6 (block of apartments built in 1950-1980), followed by the BT-5 (constructed before 1950, 17%). The typology distribution of Tarragona and Girona is quite similar, as well as the number of dwellings (around 9% of the total dwellings per province). BT-6 is the most representative building typology with around 33% of the dwellings followed by the other typologies with a similar distribution (between 5-10% each one). Finally, Lleida province is the one with lower fraction of dwellings (6%). Lleida has also the BT-6 as a main building typology with around 33%; however, in this province the single family houses built before 1950 (BT-1) represent an important fraction of dwellings (16%).

Table V.6 Building typology and climates selections

	BT-5	**BT-6**	**BT-8**	**BT-4**
C2	x	x	x	x
B3			x	X
E1	x	x		
D3		x		

The total dwelling stock represents around 2.3 M of dwellings, and the dwellings included in the study are 1.5 M of dwellings. The selection of building typologies (Table V.6) shows that Barcelona, Girona and Tarragona provinces include all the typologies; however, the Lleida province does not have C2 and B3 climates, and then the BT-8 and BT-4 are not analysed in this region of Catalonia.

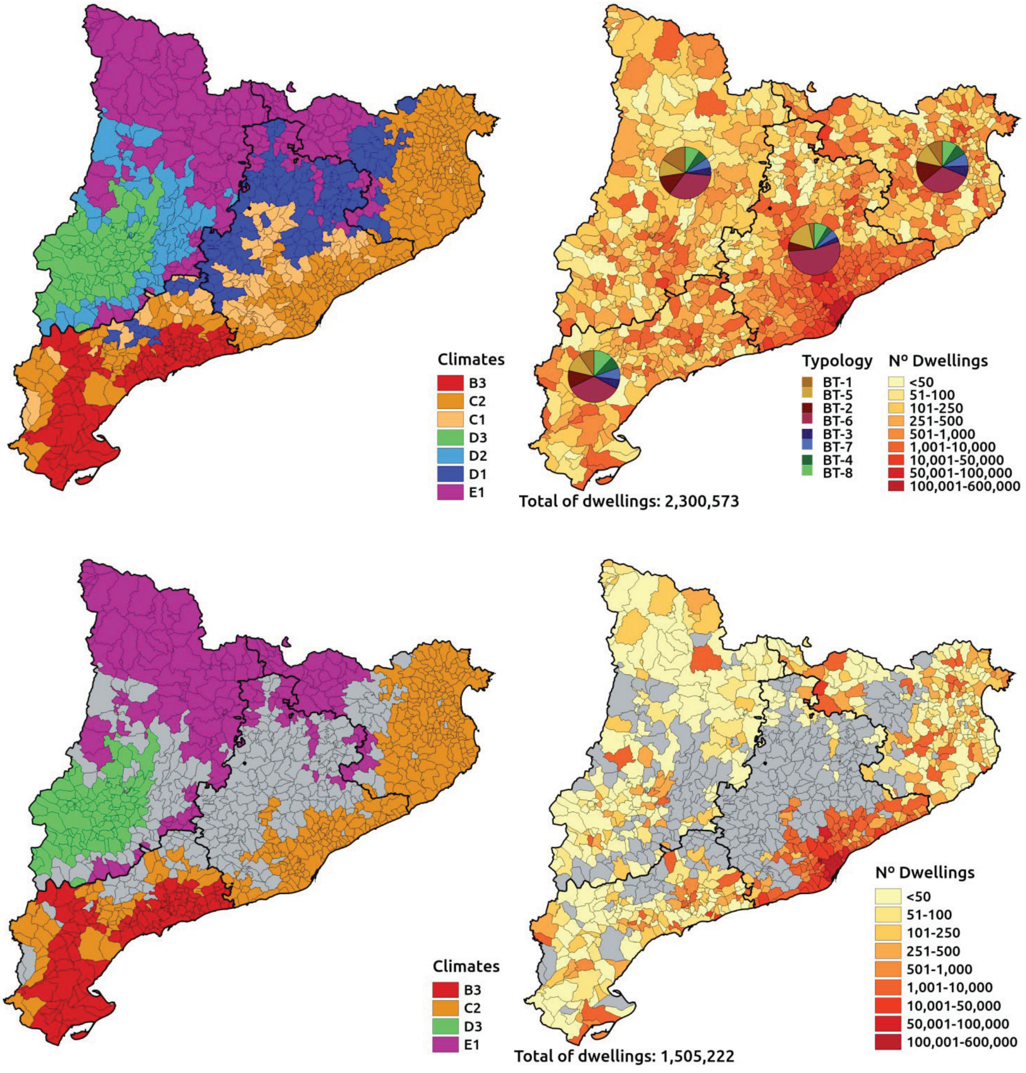


Figure V.15 Building stock distribution in Catalonia. Top-left: Climate characterization according to the Spanish Building Regulation (Código Técnico de la Edificación, 2006 [4]). Top-right: Number of dwellings for each municipality and typology distribution for each province. Bottom-left: Selection of municipalities according to the climate criterion (grey represents not selected municipalities). Bottom-right: Number of dwellings of the final selection of municipalities according to climate and building typology criteria.

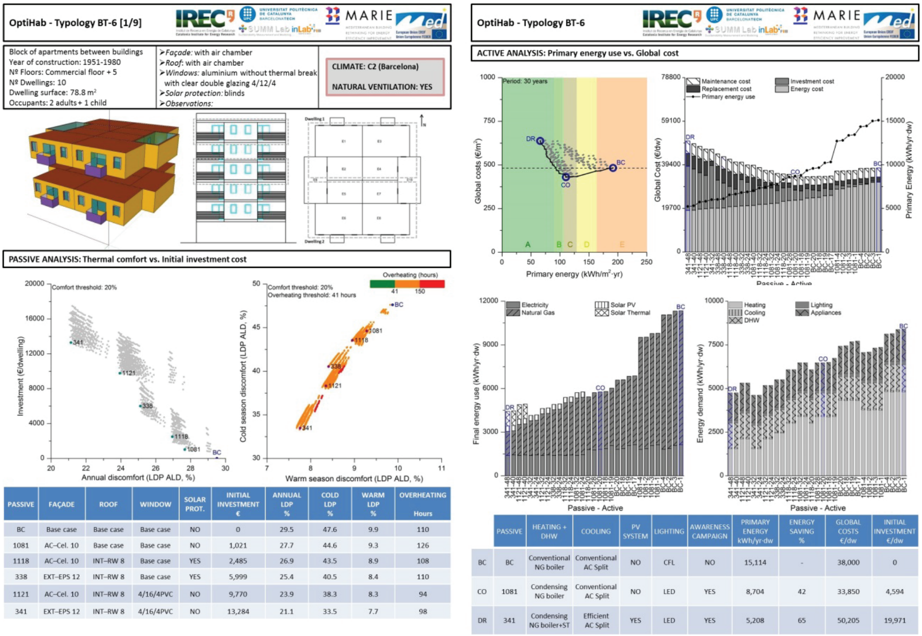
V.3.1 Typology results

The main results and conclusions of the whole study are explained in the following section. Around 30,000 simulations have been carried out to accomplish the two step evaluation for all building typologies and climates, which are detailed in Table V.7. The co-simulation configuration and the main computational resources are described in [5, 6].

Table V.7 Number of simulation done for each building typology

Nº of simulations	**BT-4**	**BT-5**	**BT-6**	**BT-8**
Passive evaluation	3,000	2,142	10,500	6,000
Active evaluation	4,320	840	2,528	2,048

In order to present all the results, it has been designed a group of factsheet to synthetize all the information. The summary is attached as Annex II OptiHab and is organized in the following structure: 1) Introduction and summary of the methodology; 2) Results and conclusions by typologies; 3) Comparison of typologies; 4) Conclusions. Below it is described the structure and the information included in the factsheet of typology results. As example, the BT-6 simulated for the C2 climate with natural ventilation is presented (Figure V.16).



OptiHab - Typology BT-6 [1/9]

Block of apartments between buildings
Year of construction: 1951-1980
Nº Floors: Commercial floor + 5
Nº Dwellings: 10
Dwelling surface: 78.8 m²
Occupants: 2 adults + 1 child

- *Façade:* with air chamber
- *Roof*: with air chamber
- *Windows:* aluminium without thermal break with clear double glazing 4/12/4
- *Solar protection:* blinds
- *Observations:*

CLIMATE: C2 (Barcelona)

NATURAL VENTILATION: YES

PASSIVE ANALYSIS: Thermal comfort vs. Initial investment cost

PASSIVE	FAÇADE	ROOF	WINDOW	SOLAR PROT.	INITIAL INVESTMENT €	ANNUAL LDP %	COLD LDP %	WARM LDP %	OVERHEATING Hours
BC	Base case	Base case	Base case	NO	0	29.5	47.6	9.9	110
1081	AC–Cel. 10	Base case	Base case	NO	1,021	27.7	44.6	9.3	126
1118	AC–Cel. 10	INT–RW 8	Base case	YES	2,485	26.9	43.5	8.9	108
338	EXT–EPS 12	INT–RW 8	Base case	YES	5,999	25.4	40.5	8.4	110
1121	AC–Cel. 10	INT–RW 8	4/16/4PVC	NO	9,770	23.9	38.3	8.3	94
341	EXT–EPS 12	INT–RW 8	4/16/4PVC	NO	13,284	21.1	33.5	7.7	98

OptiHab - Typology BT-6

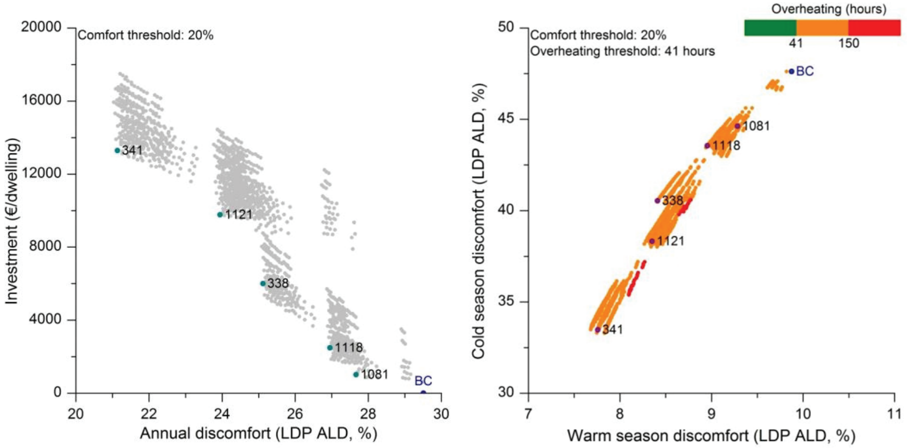
ACTIVE ANALYSIS: Primary energy use vs. Global cost

	PASSIVE	HEATING + DHW	COOLING	PV SYSTEM	LIGHTING	AWARENESS CAMPAIGN	PRIMARY ENERGY kWh/yr·dw	ENERGY SAVING %	GLOBAL COSTS €/dw	INITIAL INVESTMENT €/dw
BC	BC	Conventional NG boiler	Conventional AC Split	NO	CFL	NO	15,114	-	38,000	0
CO	1081	Condensing NG boiler	Conventional AC Split	NO	LED	YES	8,704	42	33,850	4,594
DR	341	Condensing NG boiler+ST	Efficient AC Split	YES	LED	YES	5,208	65	50,205	19,971

Figure V.16 Example of the factsheet of results. Building typology BT-6 in climate C2 without natural ventilation.

The factsheet is divided in three areas of information. The first one, on the top-left of the page, includes general information about the building typology: main characteristics, drawings and information about the simulation (climate and natural ventilation configuration). Below the general information of the typology, there is the area of passive evaluation results. Figure V.17 shows the passive analysis, where the left graph represents the annual discomfort index and the initial investment cost for each combination of passive measures. This information is complemented with the right graph, where the warm season discomfort index and the cold season discomfort index are plotted, including the overheating hours as a colour scale. The table includes the details of the energy efficiency measures that have been selected for the second step of the process.

PASSIVE ANALYSIS: Thermal comfort vs. Initial investment cost

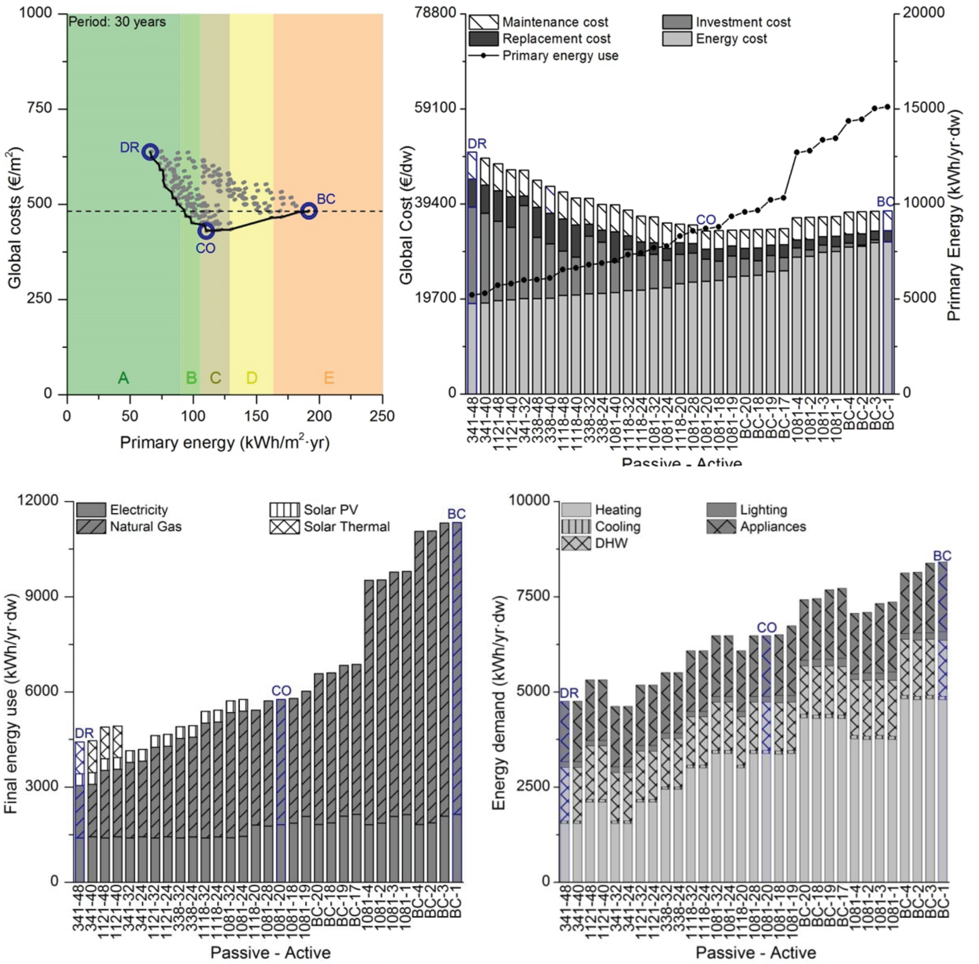


PASSIVE	FAÇADE	ROOF	WINDOW	SOLAR PROT.	INITIAL INVESTMENT €	ANNUAL LDP %	COLD LDP %	WARM LDP %	OVERHEATING Hours
BC	Base case	Base case	Base case	NO	0	29.5	47.6	9.9	110
1081	AC–Cel. 10	Base case	Base case	NO	1,021	27.7	44.6	9.3	126
1118	AC–Cel. 10	INT–RW 8	Base case	YES	2,485	26.9	43.5	8.9	108
338	EXT–EPS 12	INT–RW 8	Base case	YES	5,999	25.4	40.5	8.4	110
1121	AC–Cel. 10	INT–RW 8	4/16/4PVC	NO	9,770	23.9	38.3	8.3	94
341	EXT–EPS 12	INT–RW 8	4/16/4PVC	NO	13,284	21.1	33.5	7.7	98

Figure V.17 Information about passive evaluation results included in the factsheet. Example BT-6 in C2 climate with natural ventilation

Figure V.18 shows the information included in the active measure evaluation. There are four graphs that provide detailed information about the energy consumption of the packages of measures. The first graph (top-left) shows the results obtained in terms of annual primary energy consumption (x-axis) and global costs over 30 years (y-axis). In addition, the total energy labelling scale is introduced as a background of the graph. Each dot of the graph represents the results of one simulation, highlighting three points: BC represents the base case; CO, the cost optimal measure; and DR, the deep renovation scenario, which provides the maximum energy saving with the lowest global cost. The top-right graph represents the global cost distribution of the measures of the Pareto frontier. The global costs are divided in energy cost, investment cost, replacement cost and maintenance costs. The x-label represents the code of the measures implemented in each scenario (passive-active). The bottom graphs complement the information giving details about the distribution of the energy demand (left) and the final energy consumption (right). Finally, there is a table with the main information about the BC, CO and DR scenarios.

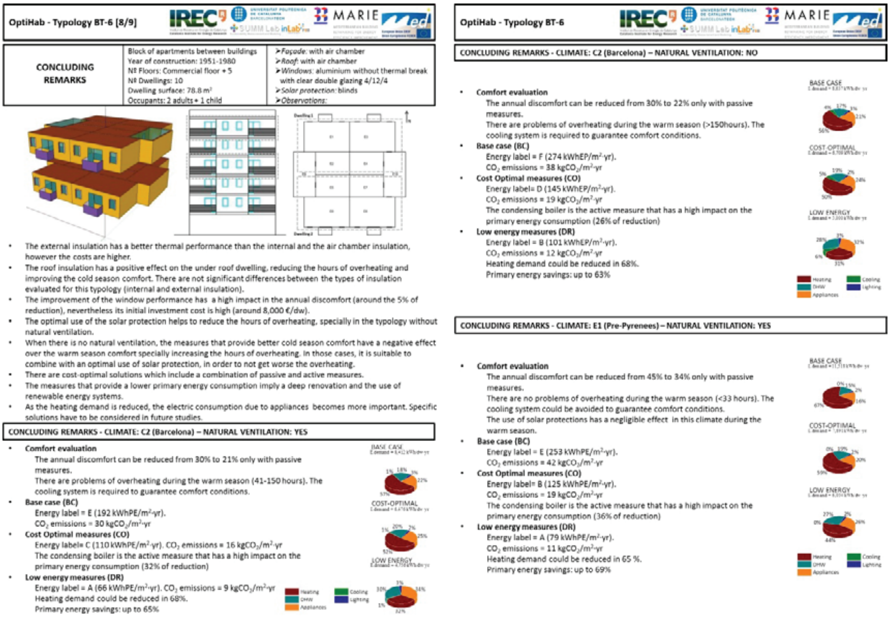
ACTIVE ANALYSIS: Primary energy use vs. Global cost



	PASSIVE	HEATING + DHW	COOLING	PV SYSTEM	LIGHTING	AWARENESS CAMPAIGN	PRIMARY ENERGY kWh/yr-dw	ENERGY SAVING %	GLOBAL COSTS €/dw	INITIAL INVESTMENT €/dw
BC	BC	Conventional NG boiler	Conventional AC Split	NO	CFL	NO	15,114	-	38,000	0
CO	1081	Condensing NG boiler	Conventional AC Split	NO	LED	YES	8,704	42	33,850	4,594
DR	341	Condensing NG boiler+ST	Efficient AC Split	YES	LED	YES	5,208	65	50,205	19,971

Figure V.18 Information about active evaluation results included in the factsheet. Example BT-6 in C2 climate with natural ventilation

This factsheet is available for each typology, climate and natural ventilation configuration, followed by a summary and conclusion per typology (Figure V.19). After analysing typology by typology, there is a factsheet comparing all of them, by typology and climate (Figure V.21 and Figure V.21).



OptiHab - Typology BT-6 [8/9]

CONCLUDING REMARKS

Block of apartments between buildings
Year of construction: 1951-1980
Nº Floors: Commercial floor + 5
Nº Dwellings: 10
Dwelling surface: 78.8 m²
Occupants: 2 adults + 1 child

➢*Façade*: with air chamber
➢*Roof*: with air chamber
➢*Windows*: aluminium without thermal break with clear double glazing 4/12/4
➢*Solar protection*: blinds
➢*Observations*:

- The external insulation has a better thermal performance than the internal and the air chamber insulation, however the costs are higher.
- The roof insulation has a positive effect on the under roof dwelling, reducing the hours of overheating and improving the cold season comfort. There are not significant differences between the types of insulation evaluated for this typology (internal and external insulation).
- The improvement of the window performance has a high impact in the annual discomfort (around the 5% of reduction), nevertheless its initial investment cost is high (around 8,000 €/dw).
- The optimal use of the solar protection helps to reduce the hours of overheating, specially in the typology without natural ventilation.
- When there is no natural ventilation, the measures that provide better cold season comfort have a negative effect over the warm season comfort specially increasing the hours of overheating. In those cases, it is suitable to combine with an optimal use of solar protection, in order to not get worse the overheating.
- There are cost-optimal solutions which include a combination of passive and active measures.
- The measures that provide a lower primary energy consumption imply a deep renovation and the use of renewable energy systems.
- As the heating demand is reduced, the electric consumption due to appliances becomes more important. Specific solutions have to be considered in future studies.

CONCLUDING REMARKS - CLIMATE: C2 (Barcelona) – NATURAL VENTILATION: YES

- **Comfort evaluation**
  The annual discomfort can be reduced from 30% to 21% only with passive measures.
  There are problems of overheating during the warm season (41-150 hours). The cooling system is required to guarantee comfort conditions.
- **Base case (BC)**
  Energy label = E (192 kWhPE/m²·yr).
  CO_2 emissions = 30 $kgCO_2/m^2 \cdot yr$
- **Cost Optimal measures (CO)**
  Energy label= C (110 kWhPE/m²·yr). CO_2 emissions = 16 $kgCO_2/m^2 \cdot yr$
  The condensing boiler is the active measure that has a high impact on the primary energy consumption (32% of reduction)
- **Low energy measures (DR)**
  Energy label = A (66 kWhPE/m²·yr). CO_2 emissions = 9 $kgCO_2/m^2 \cdot yr$
  Heating demand could be reduced in 68%.
  Primary energy savings: up to 65%

OptiHab - Typology BT-6

CONCLUDING REMARKS - CLIMATE: C2 (Barcelona) – NATURAL VENTILATION: NO

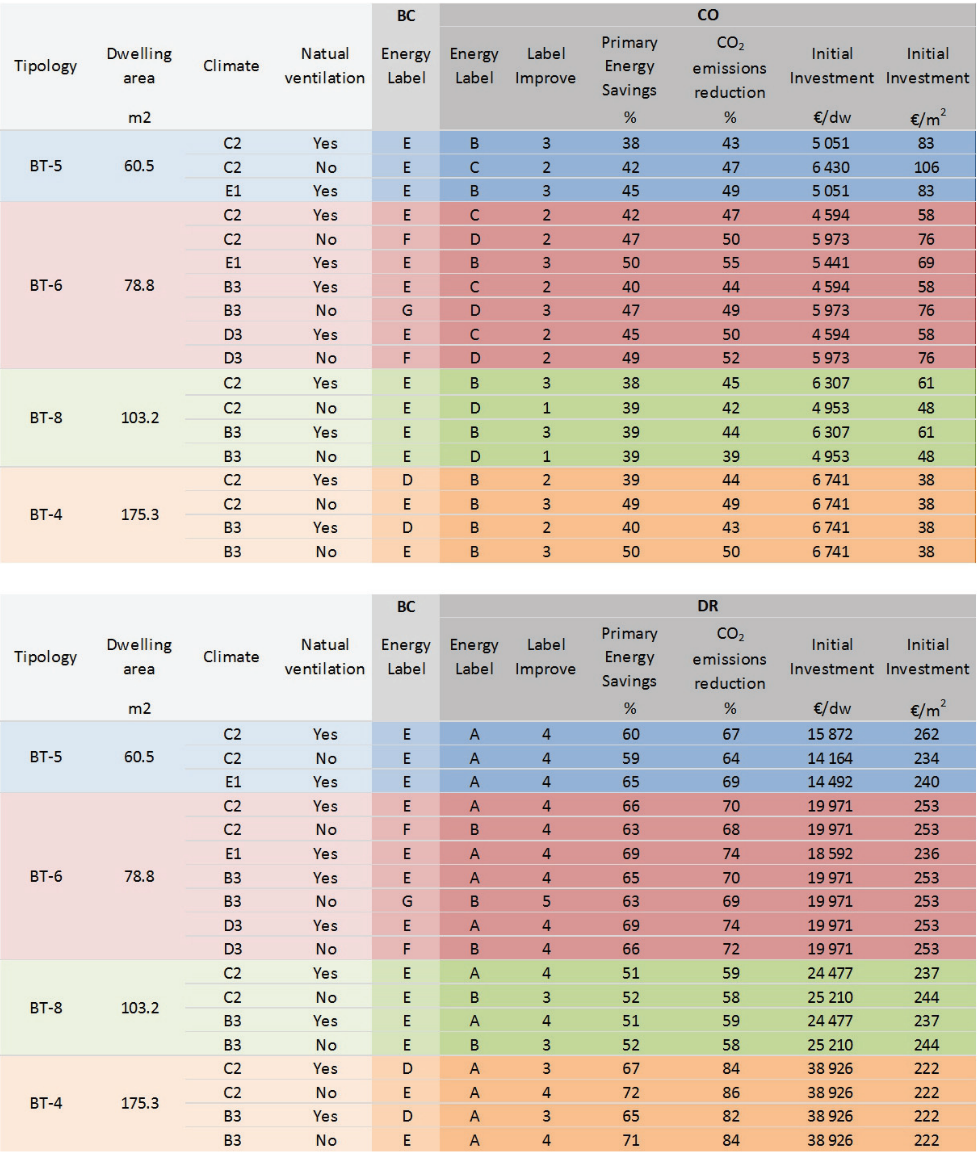
- **Comfort evaluation**
  The annual discomfort can be reduced from 30% to 22% only with passive measures.
  There are problems of overheating during the warm season (>150hours). The cooling system is required to guarantee comfort conditions.
- **Base case (BC)**
  Energy label = F (274 kWhEP/m²·yr).
  CO_2 emissions = 38 $kgCO_2/m^2 \cdot yr$
- **Cost Optimal measures (CO)**
  Energy label= D (145 kWhEP/m²·yr).
  CO_2 emissions = 19 $kgCO_2/m^2 \cdot yr$
  The condensing boiler is the active measure that has a high impact on the primary energy consumption (26% of reduction)
- **Low energy measures (DR)**
  Energy label = B (101 kWhEP/m²·yr).
  CO_2 emissions = 12 $kgCO_2/m^2 \cdot yr$
  Heating demand could be reduced in 68%.
  Primary energy savings: up to 63%

CONCLUDING REMARKS - CLIMATE: E1 (Pre-Pyrenees) – NATURAL VENTILATION: YES

- **Comfort evaluation**
  The annual discomfort can be reduced from 45% to 34% only with passive measures.
  There are no problems of overheating during the warm season (<33 hours). The cooling system could be avoided to guarantee comfort conditions.
  The use of solar protections has a negligible effect in this climate during the warm season.
- **Base case (BC)**
  Energy label = E (253 kWhPE/m²·yr).
  CO_2 emissions = 42 $kgCO_2/m^2 \cdot yr$
- **Cost Optimal measures (CO)**
  Energy label= B (125 kWhPE/m²·yr).
  CO_2 emissions = 19 $kgCO_2/m^2 \cdot yr$
  The condensing boiler is the active measure that has a high impact on the primary energy consumption (36% of reduction)
- **Low energy measures (DR)**
  Energy label = A (79 kWhPE/m²·yr).
  CO_2 emissions = 11 $kgCO_2/m^2 \cdot yr$
  Heating demand could be reduced in 65 %.
  Primary energy savings: up to 69%

Figure V.19 Building typology concluding remarks. Example of BT-6

The last section of the Annex II OptiHab is the general conclusion of the analysis, which is included in the following section as main conclusions of the whole study. The conclusions provide a general view of the study including a qualitative description of the main outcomes. The detailed results have been presented in the concluding remarks of each building typology.



				BC	CO					
Tipology	Dwelling area m2	Climate	Natual ventilation	Energy Label	Energy Label	Label Improve	Primary Energy Savings %	CO_2 emissions reduction %	Initial Investment €/dw	Initial Investment €/m^2
BT-5	60.5	C2	Yes	E	B	3	38	43	5 051	83
		C2	No	E	C	2	42	47	6 430	106
		E1	Yes	E	B	3	45	49	5 051	83
BT-6	78.8	C2	Yes	E	C	2	42	47	4 594	58
		C2	No	F	D	2	47	50	5 973	76
		E1	Yes	E	B	3	50	55	5 441	69
		B3	Yes	E	C	2	40	44	4 594	58
		B3	No	G	D	3	47	49	5 973	76
		D3	Yes	E	C	2	45	50	4 594	58
		D3	No	F	D	2	49	52	5 973	76
BT-8	103.2	C2	Yes	E	B	3	38	45	6 307	61
		C2	No	E	D	1	39	42	4 953	48
		B3	Yes	E	B	3	39	44	6 307	61
		B3	No	E	D	1	39	39	4 953	48
BT-4	175.3	C2	Yes	D	B	2	39	44	6 741	38
		C2	No	E	B	3	49	49	6 741	38
		B3	Yes	D	B	2	40	43	6 741	38
		B3	No	E	B	3	50	50	6 741	38

				BC	DR					
Tipology	Dwelling area m2	Climate	Natual ventilation	Energy Label	Energy Label	Label Improve	Primary Energy Savings %	CO_2 emissions reduction %	Initial Investment €/dw	Initial Investment €/m^2
BT-5	60.5	C2	Yes	E	A	4	60	67	15 872	262
		C2	No	E	A	4	59	64	14 164	234
		E1	Yes	E	A	4	65	69	14 492	240
BT-6	78.8	C2	Yes	E	A	4	66	70	19 971	253
		C2	No	F	B	4	63	68	19 971	253
		E1	Yes	E	A	4	69	74	18 592	236
		B3	Yes	E	A	4	65	70	19 971	253
		B3	No	G	B	5	63	69	19 971	253
		D3	Yes	E	A	4	69	74	19 971	253
		D3	No	F	B	4	66	72	19 971	253
BT-8	103.2	C2	Yes	E	A	4	51	59	24 477	237
		C2	No	E	B	3	52	58	25 210	244
		B3	Yes	E	A	4	51	59	24 477	237
		B3	No	E	B	3	52	58	25 210	244
BT-4	175.3	C2	Yes	D	A	3	67	84	38 926	222
		C2	No	E	A	4	72	86	38 926	222
		B3	Yes	D	A	3	65	82	38 926	222
		B3	No	E	A	4	71	84	38 926	222

Figure V.20 Building typology comparison by typologies

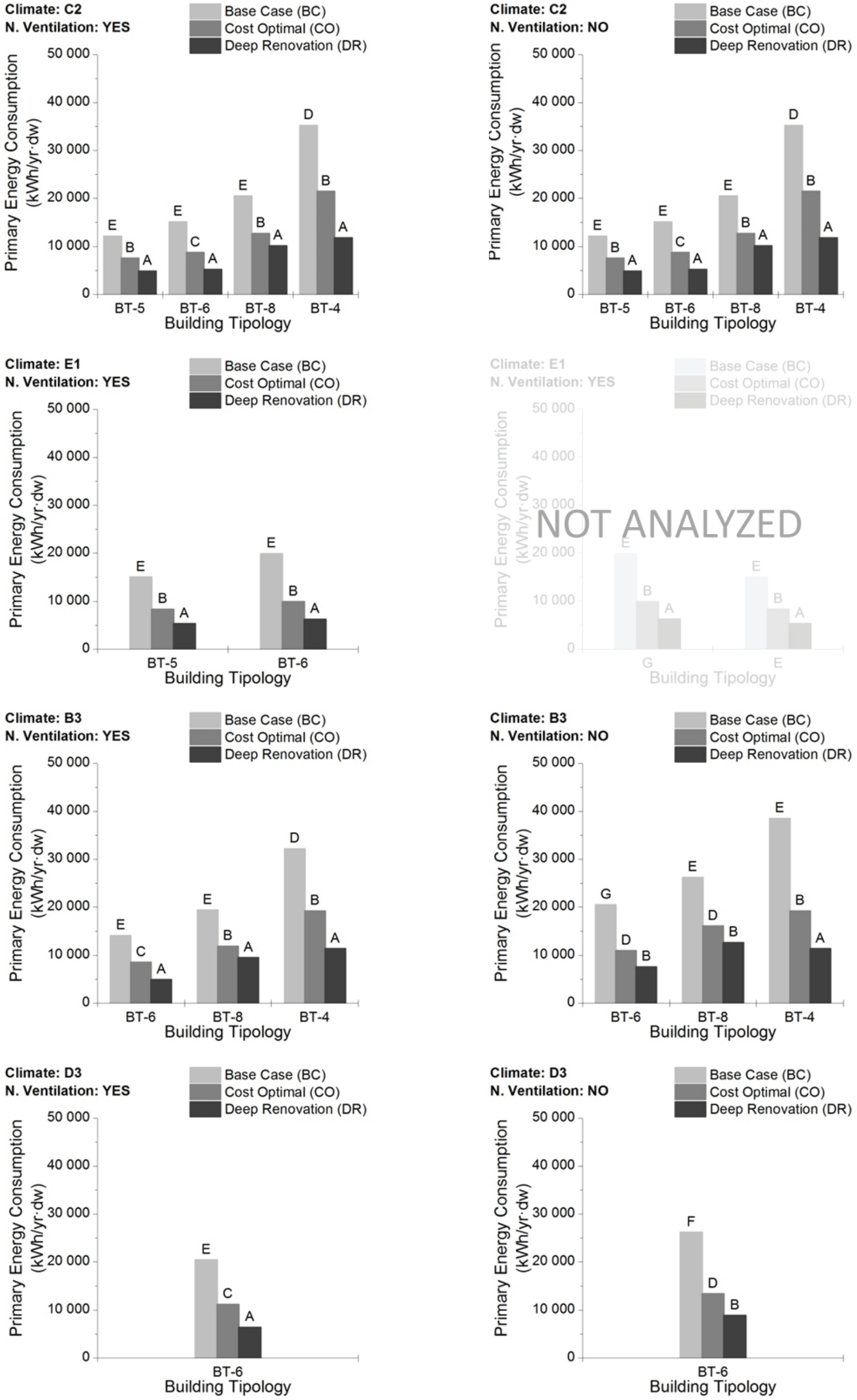


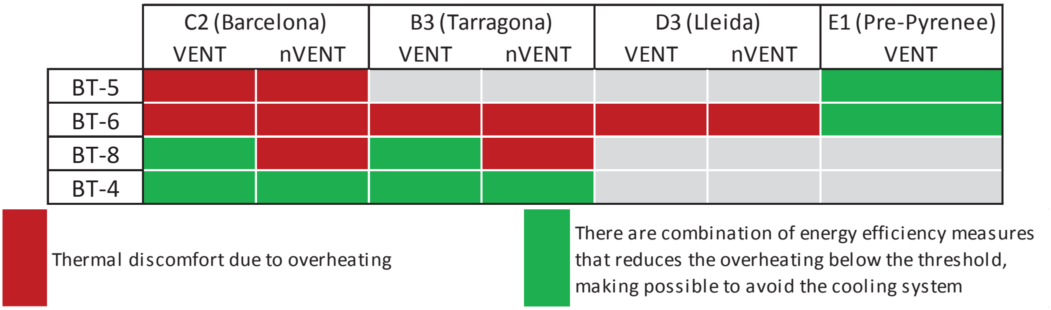
Figure V.21 Building typology comparison by climates

V.3.1.1 General conclusions

- OptiHab gives detailed information of the current situation of the most representative building typologies and climates which represents around 65% of the building stock of Catalonia.
- Complete process for developing cost-effective studies of energy efficiency measures for building renovation. The method introduces:
  - innovative approaches, as the two-step optimization considering comfort, energy and economic criteria;
  - realistic characterization, with the use of stochastic profiles for the user behaviour and its interaction with the building, and the building parameters related to measurement and survey campaigns;
  - the economic evaluation and the cost-effective analysis follow the European regulation;
  - to prioritize the passive measures rather than the active ones guaranteeing the thermal comfort of the users.

V.3.1.2 Passive measure conclusions

The analysis of the results show that from a general point of view, the building typologies located in temperate climates, as C2 and B3, have an annual discomfort index (LDP) around 30%, in comparison with colder climates that present around 45% of annual discomfort. In relation with the seasonal discomfort index, the temperate climates have around 50% of cold period discomfort and the colder climates around 65%. All the climates achieve the comfort level for the warm period discomfort index; presenting values lower than 15%. However, if the warm period discomfort index is complemented with the hours of overheating, the results vary depending on the building typology, the climate and the natural ventilation configuration. Figure V.22 shows that there is not overheating in any building typology in the coldest climate (E1). Nevertheless, the overheating in the other climates depends on the building typology. The BT-5 and BT-6 have always problems of overheating; the overheating of BT-8 depends on the natural ventilation configuration, and the BT-4 does not present overheating risk.



	C2 (Barcelona)		B3 (Tarragona)		D3 (Lleida)		E1 (Pre-Pyrenee)
	VENT	nVENT	VENT	nVENT	VENT	nVENT	VENT
BT-5	🟥	🟥	⬜	⬜	⬜	⬜	🟩
BT-6	🟥	🟥	🟥	🟥	🟥	🟥	🟩
BT-8	🟩	🟥	🟩	🟥	⬜	⬜	⬜
BT-4	🟩	🟩	🟩	🟩	⬜	⬜	⬜

🟥 Thermal discomfort due to overheating

🟩 There are combination of energy efficiency measures that reduces the overheating below the threshold, making possible to avoid the cooling system

Figure V.22 Thermal discomfort due to overheating depending on building typology and climate

Then, it is possible to say that the older typologies analysed in the study (BT-5 and BT-6) do not have an appropriate design for the natural ventilation (single side ventilation and /or small courtyards), providing overheating problems. The natural ventilation and the optimal use of the solar protections are effective strategies to reduce the overheating being possible to avoid the cooling system. The optimal use of the solar protection provides better comfort during the warm season, especially when there is no natural ventilation in the household.

After the passive measures implementation, it is possible to improve the levels of thermal comfort, achieving annual discomfort indexes around 20% in temperate climates (C2 and B3) and around 30-40% in cold period discomfort index. In the colder climates (E1 and D3), the annual discomfort index is around 35% and the cold period discomfort index is around 50%. For the overheating point of view, the results depend on the combination of passive measure. There are some combinations of passive measures that reduce below the threshold the hours of overheating, as in the Figure VI.1 has been introduced. This situation makes possible to avoid the cooling system and save its related costs (cooling consumption, investment, replacement and maintenance costs). Focusing on the building typology BT-8 which is the one that is able to reduce the hours of overheating below the threshold depending on the combination of passive measures, the combination that includes internal insulation in the roof makes worst the overheating situation. On the contrary, the façade insulation improves the situation, having more impact the external insulation.

Some particular conclusions related to the passive energy efficiency measures are:

- The passive measures have an important reduction of the energy demand, especially on the older building typologies (E and G).
- In general, the external insulation in the façade has a better thermal performance; however its initial investment cost is higher.

- The roof insulation has an important benefit on the under roof dwellings improving the thermal comfort during the cold and warm season, especially in the older building typologies (BT-5 and BT-6).
- The improvement of the window performance has a high impact in the annual discomfort (around 5-10% of reduction) and in the energy demand, nevertheless its initial investment cost is high.

V.3.1.3 Cost-effective analysis conclusions

The energy efficiency measures must be adapted according to the building typology. The influence of the climate in the measure selection has been mainly observed in the cooling strategies, where the solar protection and the cooling system improvements are not needed in the coldest climate (E1). Table V.8 and Table V.9 summarize the most appropriated measures obtained by the cost-optimal evaluation. In general, the cost-optimal intervention includes thermal insulation in the façade; improve the performance of the natural gas boiler; improve the lighting system; and implement an awareness campaign. The deep renovation scenario goes further, implementing a deep energy renovation of the envelope and including renewable energy systems.

Table V.8 Passive measure selection according to the building typology and the level of actuation: cost-optimal and deep renovation

	Passive measures	
	Cost-optimal	Deep renovation
BT-5 and BT-6 (< 1980)	Building without air chamber: Façade → Internal insulation	Façade → External insulation Roof → Internal insulation Windows → 4/16/4 PVC
	Building with air chamber: Façade → Air chamber insulation	
BT-8 and BT-4 (> 1990)	Façade → Internal insulation	Façade → External insulation Roof → External insulation Windows → 4/16/4 PVC

Table V.9 Active measure selection according to the building typology and the level of actuation: cost-optimal and deep renovation

	Active measures	
	Cost-optimal	Deep renovation
BT-5 and BT-6 (< 1980)	Condensing boiler + LED + Awareness campaign	Cost-optimal package + Renewable energy system (depending on the building typology)
BT-8 and BT-4 (> 1990)		

Some particular conclusions related to the active energy efficiency measures are:

- The active measures, in particular the improvement of the heating systems performance, provide a high reduction of the primary energy consumption. However, the active measures have to be combined with the passive ones in order to achieve the A-class of the energy efficiency labelling.
- The optimal measures are able to achieve B/C class of the energy efficiency labelling in buildings with natural ventilation, and C/D class in buildings without natural ventilation.
- The measures that include a deep renovation and renewable energy systems can achieve an A class of the energy efficiency labelling in buildings with natural ventilation and a B class in buildings without natural ventilation.
- The cost-optimal analysis is an appropriate method to choose the most suitable measure depending on:
    - The building typology and the climate
    - The objectives of the users: environmental and/or economical.

- The effect of the measures can be summarize in Figure V.23:

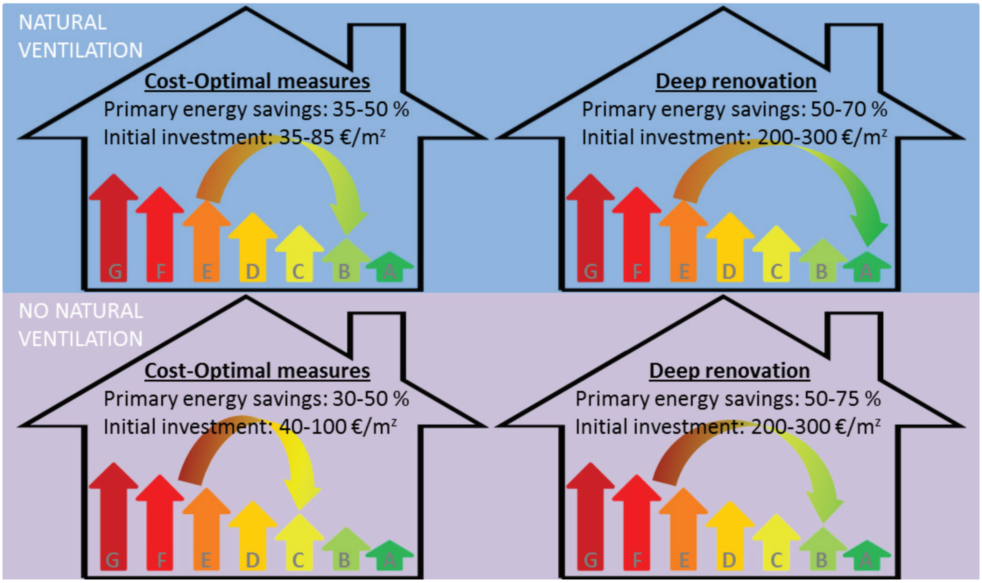


Figure V.23 Summary of the energy efficiency measures effect in building typologies with or without natural ventilation.

- The energy renovation of the building increases the quality of the life of the users and at the same time increase the value of the building and its lifespan. There is a study [7] that shows how the economic value of the building can increase up to 25%. If this increase of value were included in the cost-optimal analysis, probably most of the measures would become cost optimal. Further studies are needed to quantify the revaluation and the increase of the lifespan of the buildings after the energy renovation.
- As the heating demand is reduced, the electric consumption becomes more important. In this study, measures related with lighting performance improvement and awareness campaign to reduce the electric consumption are evaluated. However, specific solutions to reduce the appliances consumption have to be considered in future studies.

V.4 Application

The method provides complete information for final users, professionals and policy makers and it could help them in the process of taking decisions. In this case, the results have been used to define a proposal for a subsidy plan to improve the energy efficiency of the residential buildings. This work was published in [3]. The building typology used for this proposed is the BT-6 which is the most representative typology of residential buildings of Catalonia, representing the 45% of the dwellings [8]. This typology was built before the first building regulation (1950-1980) and is characterized for having a low thermal performance. The characteristics of the building typology and the main results of the cost-optimal evaluation are described Annex II OptiHab.

Three parameters are needed to define the subsidy plan: the energy requirement to receive the subsidy, the percentage of initial investment to be paid by the subsidy, and the maximum amount of the subsidy. The rationale to define the subsidies wants to distinguish two levels of actuation: the minimum required expending the same or less money than the reference building in a long-term period (30 years) and the measures that go beyond the minimum requirement and imply a higher cost. Thus, the energy requirement can be divided in: the cost-effective measures and the deep renovation.

In the first case, all the simulations with a global cost lower than the base case (BC, below the dash-line) have been analysed. The best class achieved for this group of measures is a B-class and implies an improvement of 3-classes in comparison with the BC. For that reason, the requirement to receive the first level of subsidy is to improve 3-classes of energy. The second level of subsidy is defined by the simulations that improve more than 3 energy classes. Then, the requirement to receive the second level of renovation is to improve 4 or more energy classes. To define the amount of subsidy, the two groups of measures of the Figure V.24 are analysed (black-dot square for the first level of subsidy and black-dash square for the second level of subsidy). In both cases, two scenarios are evaluated: the minimum initial investment cost and the average initial investment cost. The minimum is used to define the maximum amount of subsidy. Complementary, the average helps to define the percentage of initial investment to be paid by the subsidy. Table V.10 shows the information of the minimum and average simulations in both levels of intervention.

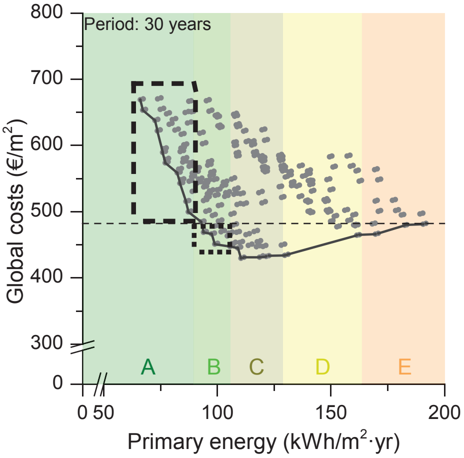


Figure V.24 Group of measures analysed to define the two levels of subsidies: cost-energy measures (red square) and deep renovation (purple-dash square).

Table V.11 and Table V.12 show the relation between the maximum amount of subsidy and the percentage of subsidy for the first and second level of actuation. Different percentages of subsidy are applied to the average intervention and the selected percentage corresponds when the subsidy is equal or close to the minimum initial investment cost scenario. It means that for the first level of subsidy the percentage of initial investment to be paid by the subsidy is the 70% with a maximum of 5,000€/dw; and for the second level is 50% of initial investment with a maximum of 9,000€/dw.

Table V.10 Simulations used to define the subsidies for the two levels of actuation: cost-energy and deep renovation.

Actuation		**Initial investment**	**Primary energy saving**
		€/dw	%
Cost-effective	Minimum	5,123	48
	Average	7,133	51
Deep renovation	Minimum	9,188	54
	Average	16,863	56

Table V.11 First level of intervention: subsidy definition

Percentages	**Initial invest.**[1]	**Subsidy**	**Private investment**
%	€	€	€
30	7,133	2,140	4,993
40		2,853	4,280
50		3,567	3,567
60		4,280	2,853
70		4,993[2]	2,140
80		5,706	1,427
90		6,420	713

[1] Initial investment cost of the average measure
[2] Equivalent to the minimum initial investment cost

As it is introduced in the rationale of the subsidy definition, the first level of subsidy wants to be available to most of the population of the region (excluding the social housing, which needs specific plans of actuation). For that reason, economic data has been collected in order to verify that the subsidy definition and, in particular, the average private investment is coherent with the incomes and expenditures of an average household in Catalonia. Table V.13 summarizes the annual incomes [9] and expenditures [10] of the average household in Catalonia in 2013. In global, the 4% of the income can be saved by a household during a year (around 1,000€/yr). In addition, if the expenditures are analysed in detail, there is a group of expenditures that are related with furniture and maintenance costs of the household and represents around

1,000€/yr. Finally, after the intervention the group of expenditure related with the energy costs (housing, water, electricity, gas and other fuels) will be reduced around 450€/yr (electricity and natural gas savings). Then, assuming these figures and in comparison with the average intervention, the private investment of 2,140€ seems a reasonable amount of money to be assumed for an average household in Catalonia.

Table V.12 Second level of intervention: subsidy definition

Percentages	**Initial invest.**[1]	**Subsidy**	**Private investment**
%	€	€	€
30		5,059	11,804
40		6,745	10,118
50		8,432[2]	8,432
60	16,863	10,118	6,745
70		11,804	5,059
80		13,490	3,373
90		15,177	1,686

[1] Initial investment cost of the average measure

[2] Equivalent to the minimum initial investment cost

Table V.13 Annual net incomes and expenditures for the average household in Catalonia (Source: INEa, 2013 and INEb, 2013)

Average annual net income	€/yr·dw
Total	30,423

Average annual expenditure	€/yr·dw
Food	4,394
Clothing and footwear	1,476
Housing, water, electricity, gas and other fuels	9,786
Furniture and maintenance costs of house	1,192
Others	12,461
Total	29,309

After checking the reasonability of the subsidy definition, both subsidy levels are applied to the results of the cost-energy optimization in Figure V.25. In comparison with the results without subsidy, there are more combinations of measures (simulations) that are below the global costs of the base case. Regarding the measures that are related with the second level of subsidy, some of them are also below the global costs of the base case, becoming the deep renovation more interesting for the users.

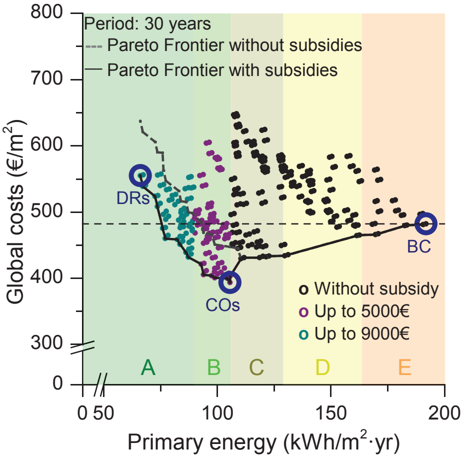


Figure V.25 Cost-energy optimization including the two levels of subsidies: primary energy consumption and global costs (colour background: energy label scale of Total consumption of dwelling).

V.5 References

[1] J. Ortiz, A. Fonseca, J. Salom, N. Garrido, P. Fonseca, V. Russo, Comfort and economic criteria for selecting passive measures for the energy refurbishment of residential buildings in Catalonia, Energy and Buildings, 110 (2016) 195-210.

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Chapter VI Conclusions and outlook for future research

VI.1 Conclusions and relevant findings

The aim of the thesis is to evaluate and provide the cost-optimal measures for the energy renovation of residential buildings of Catalonia, considering three main criteria: thermal comfort, primary energy use and global costs.

The conclusions of the thesis can be divided in two main groups: building model and cost-optimal evaluation. The building model includes the methods and hypothesis implemented in the simulation in order to estimate accurately the energy use of the households. The cost-optimal evaluation based on two-step process represents the methodology proposed to analyse the energy efficiency measures, considering the three criteria: thermal comfort, primary energy use and global costs.

Building model

The building model has been implemented in TRNSYS and it has the objective to reduce the uncertainties associated to the building and its use, and to improve the estimation of the primary energy use. The milestones and conclusions of the thesis related to the building model are described and cover the Specific Objective 1.1, Specific Objective 1.2, Specific Objective 1.3, Specific Objective 1.4 and Specific Objective 1.5.

How can it relate the actual state of the building with the simulation model?

> Different sources of information have been used to relate the simulation to surveys and monitoring data. The household features are adapted to its building period, including information about the air leakage of the building (n_{50}). The building is divided in day and night zone, in order to reproduce better use of it. The use of natural ventilation and solar protections has been configured according to the survey's results. Similarly, the setpoint and the use of the heating and cooling system are adapted to the surveys. In addition, the energy performances of both systems are related to the weather conditions. The characterization of the building model is described in Chapter II.

How can it be introduced realistic user behaviour in the simulation?

> The occupancy has been defined as the main driver of the building. For that reason, one of the needs is to use realistic profiles of the occupants. This profile has to reproduce the variability of the real occupants and, at the same time, their behaviour has to be representative of the average occupant. To achieve this challenge, stochastic occupancy

profiles have been generated based on Time Use Data surveys. This profile is adapted to the characteristics of each household and is related to the use of the building (heating and cooling systems, natural ventilation, solar protections, and lighting). The occupancy implementation is described in Chapter II. In addition, the energy consumption of appliances is dependent on the occupancy behaviour. Chapter II.6 details the electrical stochastic model to generate the appliances consumption of each building typology, according to their appliance stock. The electrical stochastic model is based on data from the SECH-SPAHOUSEC project.

The validation of the building model provides the reliability of the method implemented in the building simulation model, making possible to extrapolate the method to other building typologies.

A pilot site has been used to test the building model and to implement the validation process. The ASHRAE and IPMVP protocols are used to define the indicators of the validation. For the electrical consumption, the results of the validation shows how the building model is close to the thresholds stablished by the validation protocols. For the natural gas consumption, after an iterative process of testing different configurations of occupancy, setpoint temperature and level of infiltration, the building model meets the validation protocol. For that reason, and despite the uncertainty associated to the user behaviour and the billing periods, the results are considered valid for using the building model approach in the typology analysis. Chapter III presents the validation process of the building model.

Defining a complete method to implement the whole process in a single simulation, integrating the three main criteria in the building simulation. The building simulation model must be designed to be used in a co-simulation process, in order to run all the combination of measures automatically.

The building model has been implemented in TRNSYS and includes the energy, economic and thermal comfort calculations. The building model has been configured to be simulated in two different modes: free running and conditioned. This configuration permits to run the simulation according to the two-step methodology proposed by the thesis. If the simulation is executed in free running mode, the outputs of the simulation will be thermal comfort and investment cost; and if the simulation is run in conditioned mode, the outputs will be primary energy consumption and global cost. This configuration makes possible to implement the calculations in a co-simulation process. The co-simulation is carried out using SDLPS as a management tool and TRNSYS as a calculus engine for the energy simulation. SDLPS launches TRNSYS with different configuration of measures and collects the results in a common file. This configuration automates the simulation process and helps to manage properly a big number of simulations. Around 30,000 simulations have been carried out in the framework of the thesis in order to obtain the cost-optimal evaluation for every building typology and climate. Chapter IV describes the co-simulation process.

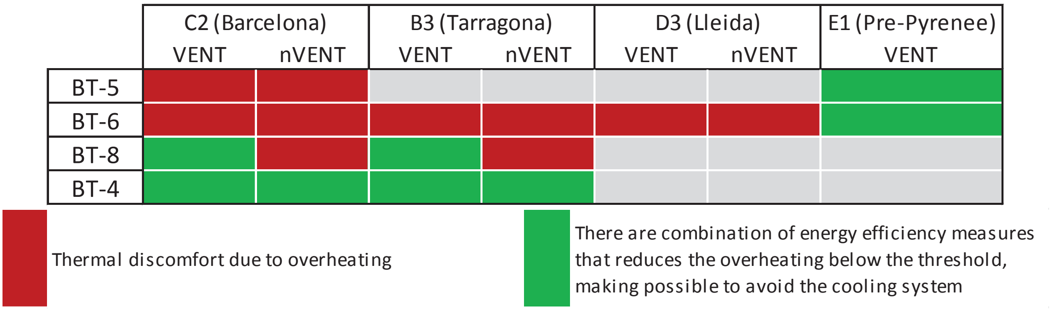
Cost-optimal evaluation based on two-step process

The cost-optimal evaluation based on two-step process, passive and active evaluation, is the novel method proposed to evaluate the energy efficiency measures for each building typology and climate, considering three criteria: thermal comfort, primary energy use and global costs. The objective of the passive evaluation is to obtain the passive measures that provide a better thermal comfort without the use of mechanical systems and considering the investment cost of the measure. Then the passive and active measures are combined in the active evaluation to develop a cost-effective analysis, where the non-renewable primary energy consumption and the global costs are used to select the cost-effective energy efficiency measures. Chapter II explains how the different methods and hypothesis have been introduced in the building model. The assessment about the results and their usefulness are described, answering the Specific Objective 2.1, Specific Objective 2.2 and Specific Objective 3.1.

Which are the thermal comfort differences between typologies and climates? What are the differences between warm season and cold season thermal comfort? Is it possible to avoid active cooling systems in some locations and for some typologies with appropriate passive solutions?

The thermal comfort analysis proposed is based on the adaptive comfort model and two long term indices have been used to evaluate the comfort over the year: Long-term Percentage of Dissatisfied (LDP) and Hours of Overheating (OH). The LDP describes the average comfort of the household over a period and it can be calculated for different periods (annual, warm and cold season). The hours of overheating (OH) have been included for complementing the LDP index in the comfort evaluation in order to identify overheating problems. The thermal comfort requirements have been adjusted to the particularities of each climate and have been used in the passive evaluation to select the appropriate combination of passive measures in each case. The comfort method is explained in Chapter IV.2.1, and Chapter V.1 presents the results for the passive evaluation.

The analysis of the results show that from a general point of view, the building typologies located in temperate climates, as C2 and B3, have an annual discomfort index (LDP) around 30%, in comparison to colder climates that present around 45% of annual discomfort. In relation to the seasonal discomfort index, the temperate climates have around 50% of cold period discomfort and the colder climates around 65%. All the climates achieve the comfort level for the warm period discomfort index; presenting values lower than 15%. However, if the warm period discomfort index is complemented with the hours of overheating, the results vary depending on the building typology, the climate and the natural ventilation configuration. Figure VI.1 shows that there is not overheating in any building typology in the coldest climate (E1). Nevertheless, the overheating in the other climates depends on the building typology. The BT-5 and BT-6 have always problems of overheating; the overheating of BT-8 depends on the natural ventilation configuration, and the BT-4 does not present overheating risk.



	C2 (Barcelona)		B3 (Tarragona)		D3 (Lleida)		E1 (Pre-Pyrenee)
	VENT	nVENT	VENT	nVENT	VENT	nVENT	VENT
BT-5	🟥	🟥					🟩
BT-6	🟥	🟥	🟥	🟥	🟥	🟥	🟩
BT-8	🟩	🟥	🟩	🟥			
BT-4	🟩	🟩	🟩	🟩			

🟥 Thermal discomfort due to overheating

🟩 There are combination of energy efficiency measures that reduces the overheating below the threshold, making possible to avoid the cooling system

Figure VI.1 Thermal discomfort due to overheating depending on building typology and climate

Then, it is possible to say that the older typologies analysed in the study (BT-5 and BT-6) do not have an appropriate design for the natural ventilation (single side ventilation and /or small courtyards), providing overheating problems. The natural ventilation and the optimal use of the solar protections are effective strategies to reduce the overheating being possible to avoid the cooling system. The optimal use of the solar protection provides better comfort during the warm season, especially when there is no natural ventilation in the household.

After the implementation of the passive measures, it is possible to improve the levels of thermal comfort, achieving annual discomfort indexes around 20% (C2 and B3) and around 30-40% in cold period discomfort index in temperate climates. In the colder climates (E1 and D3), the annual discomfort index is around 35% and the cold period discomfort index is around 50%. For the overheating point of view, the results depend on the combination of passive measures. There are some combinations of passive measures that reduce below the threshold the hours of overheating, as in the Figure VI.1 has been introduced. This situation makes possible to avoid the cooling system and save its related costs (cooling consumption, investment, replacement and maintenance costs). The combination of measures that includes internal insulation in the roof worsens the overheating situation. On the contrary, the façade insulation improves the situation, having more impact the external insulation.

Are all the measures appropriate in all the typologies and climates? Which are the most effective measures in each building typology and climate?

The energy efficiency measures must be adapted according to the building typology. The influence of the climate in the measure selection has been mainly observed in the cooling strategies, where the solar protection and the cooling system improvements are not needed in the coldest climate (E1). Table VI.1 and Table VI.2 summarize the most appropriated measures obtained by the cost-optimal evaluation. In general, the cost-optimal intervention includes thermal insulation in the façade; improves the performance of the natural gas boiler; improves the lighting system; and implements an awareness campaign. The deep renovation scenario goes further, implementing a deep energy renovation of the envelope and including renewable energy systems.

Table VI.1 Passive measure selection according to the building typology and the level of actuation: cost-optimal and deep renovation

	Passive measures	
	Cost-optimal	Deep renovation
BT-5 and BT-6 (< 1980)	Building without air chamber: Façade → Internal insulation	Façade → External insulation Roof → Internal insulation Windows → 4/16/4 PVC
	Building with air chamber: Façade → Air chamber insulation	
BT-8 and BT-4 (> 1990)	Façade → Internal insulation	Façade → External insulation Roof → External insulation Windows → 4/16/4 PVC

Table VI.2 Active measure selection according to the building typology and the level of actuation: cost-optimal and deep renovation

	Active measures	
	Cost-optimal	Deep renovation
BT-5 and BT-6 (< 1980)	Condensing boiler + LED + Awareness campaign	Cost-optimal package + Renewable energy system (depending on the building typology)
BT-8 and BT-4 (> 1990)		

Some particular conclusions related to the active energy efficiency measures are:

- The heating consumption is one of the most important consumption of the dwelling, and the improvement of the heating system is important to reduce significantly the energy consumption. However, the measure has to be combined with the passive measures in order to achieve the A-class of the energy efficiency labelling.

- The lighting consumption represents a low fraction of the total energy consumption of the household. However, the implementation of LED systems in the dwelling provides a positive impact in both, energy and global cost savings.
- The development of awareness campaigns has a high potential to reduce the energy consumption. The awareness campaign represents the most effective measure, in terms of energy savings by euro invested.

How much would the refurbishment of my home cost?

The optimal measures are able to achieve B/C class of the energy efficiency labelling in buildings with natural ventilation, and C/D class in buildings without natural ventilation. The initial investment is around 35-100€/m^2 and the primary energy savings around 30-50%, depending on the building typology, climate and natural ventilation configuration.

The measures that include a deep renovation and renewable energy systems can achieve an A class of the energy efficiency labelling in buildings with natural ventilation and a B class in buildings without natural ventilation. In this situation, the appliances consumption becomes the greatest energy use of the dwelling. The initial investment is around 200-300€/m^2 and the primary energy savings around 50-75%, depending on the building typology, climate and natural ventilation configuration.

Which would the amount of my bills be after the renovation?

In general, the energy savings achieved with cost-optimal measures will reduce the energy bills around 450€ per year. Despite the energy and economic savings achieve by the intervention, the initial investment cost are relatively high providing high payback periods, especially for the deep renovation scenario. In addition, the initial investment has been compared with the average net income of the Catalan families, making more evident the difficulty to assume the investment cost by the families. For that reason and in order to make more attractive the energy refurbishment of the households, the results have been used to define a subsidy plan. The subsidy plan consists in two levels of actuation: for the first level of subsidy the percentage of initial investment to be paid by the subsidy is the 70% with a maximum of 5,000€/dw; and for the second level is 50% of initial investment with a maximum of 9,000€/dw.

VI.2 Contributions of the thesis

The main contributions of the thesis are listed below:

I. A detailed building model has been developed in TRNSYS with the objective to obtain a realistic model and to relate the input of the model with monitoring and survey information. The model introduces stochastic occupancy profiles to introduce a more realistic use of the building.

II. The thesis proposes the two-step methodology to analyse energy efficiency measures focusing on the thermal comfort, energy performance and economic parameters. This methodology prioritizes the passive measures rather than the active ones guaranteeing the thermal comfort of the users and reducing the number of combinations to be simulated.

III. The thermal comfort indices are used to select the energy efficiency measures, choosing the most appropriate according to the climate characteristics and the thermal comfort requirements.

IV. The thesis gives detailed information of the current situation of the most representative building typologies and climates, representing around 65% of the building stock of Catalonia.

V. The thesis provides a detailed analysis for each building typology, climate and natural ventilation configuration, giving information to choose the most suitable measure depending on: the building typology and the climate; and the objectives of the refurbishment (environmental and/or economical).

VI. Two scenarios have been analysed to propose a subsidy plan to improve the energy efficiency of the residential buildings: cost-optimal refurbishment and deep energy renovation.

VI.3 Outlook for future research

The thesis concludes with an outlook on possible future research topics:

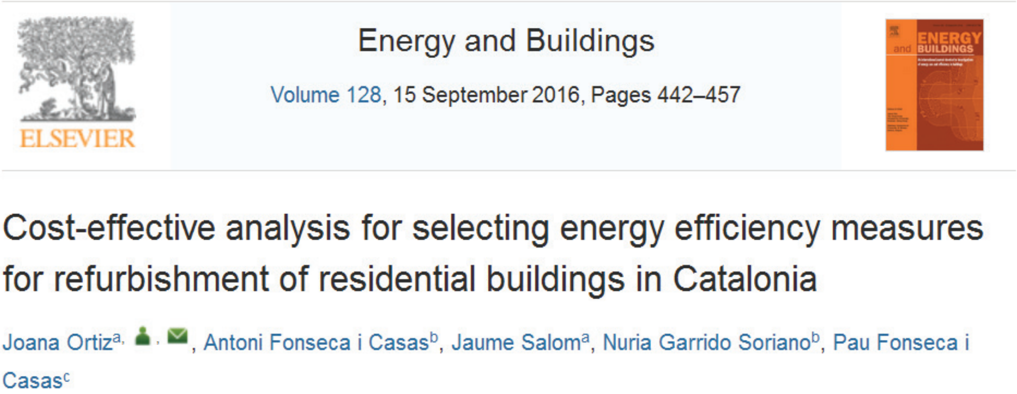
I. To improve the overheating index to achieve a better representation of the phenomenon. The hours of overheating only consider the number of times that the temperature is above the overheating threshold; however, aspects as the amplitude of the overheating, the duration of the overheating incident and the humidity are not included in the index, despite of their influence in the comfort of the users. There are some international research initiatives that try to improve in the thermal comfort analysis, as for example "EBC Annex 69 Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings" and "IEA EBC Annex 62 Ventilative cooling".

II. To improve some systems/methods of the detailed building model. On the one hand, to improve the natural ventilation and air tightness of the building model through new or improved experimental correlations. On the other hand, to reproduce the heating system in the model with the implementation of all elements of the system (emitters, boiler, pumps…) in order to simulate the real behaviour of the system, instead of simplified approach.

III. To develop a stochastic occupancy model linked with the electrical consumption and the domestic hot water consumption. To increase the resolution of the occupancy model lower than 10 minutes to have a better representation of the electrical and domestic hot water consumptions. In addition, to improve the knowledge of the occupant behaviour and its implementation in the building model and to reduce the uncertainty related to the use of the building.

IV. To develop an extensive economic evaluation considering not only the energy benefits, but also some co-benefits achieved by the energy refurbishment of households. Some of these co-benefits are related to the improvement of the health of the occupants due to a reduction of discomfort conditions (cold temperatures in winter, hot temperatures in summer, air quality, humidity and mould…). Other co-benefit of the energy renovation of buildings is the appreciation in value of the households thanks to the improvement of the living conditions, increase of the energy efficiency standard and increase of lifespan of the building.

J. Ortiz, A. Fonseca, J. Salom, N. Garrido, P. Fonseca. Cost-effective analysis for selecting energy efficiency measures for refurbishment of residential buildings in Catalonia, Energy and Buildings, 128 (2016) 442-457.



Energy and Buildings

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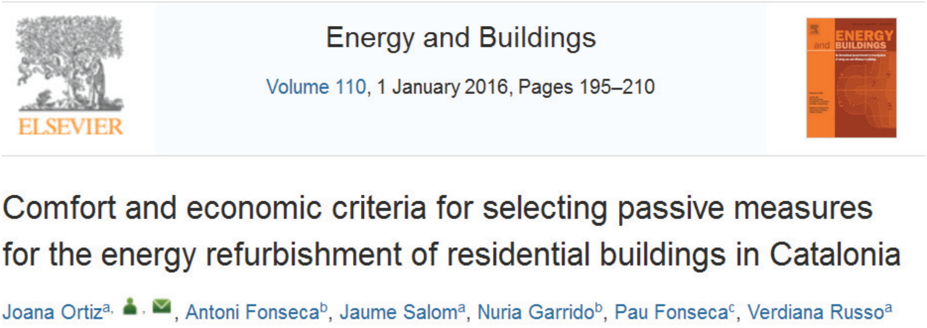
Cost-effective analysis for selecting energy efficiency measures for refurbishment of residential buildings in Catalonia

Joana Ortiz[a], Antoni Fonseca i Casas[b], Jaume Salom[a], Nuria Garrido Soriano[b], Pau Fonseca i Casas[c]

doi:10.1016/j.enbuild.2016.06.059

J. Ortiz, A. Fonseca, V. Russo, J. Salom, N. Garrido, P. Fonseca. Comfort and economic criteria for selecting the optimal passive measures for the energy renovation of residential buildings in Catalonia, Energy and Buildings, 110 (2016) 195-210.



Energy and Buildings

Volume 110, 1 January 2016, Pages 195–210

Comfort and economic criteria for selecting passive measures for the energy refurbishment of residential buildings in Catalonia

Joana Ortiz[a], Antoni Fonseca[b], Jaume Salom[a], Nuria Garrido[b], Pau Fonseca[c], Verdiana Russo[a]

doi:10.1016/j.enbuild.2015.10.022

J. Ortiz, F. Guarino, J. Salom, C. Corchero, M. Cellura, Stochastic model for electrical loads in Mediterranean residential buildings: Validation and applications, Energy and Buildings, 80 (2014) 23-36.

Energy and Buildings

Volume 80, September 2014, Pages 23–36

Stochastic model for electrical loads in Mediterranean residential buildings: Validation and applications

Joana Ortiz[a], Francesco Guarino[b], Jaume Salom[a], Cristina Corchero[c], Maurizio Cellura[b]

doi:10.1016/j.enbuild.2014.04.053

Annex II OptiHab

MARIE

MEDITERRANEAN BUILDING
RETHINKING FOR ENERGY
EFFICIENCY IMPROVEMENT

OptiHab

IREC
Institut de Recerca en Energia de Catalunya
Catalonia Institute for Energy Research

UNIVERSITAT POLITÈCNICA
DE CATALUNYA
BARCELONATECH

SUMM Lab
Sustainability Measurement and Modeling

inLab FIB
talent & tech

L'Europe en Méditerranée
Europe in the Mediterranean
Projet cofinancé par le Fonds Européen
de Développement Régional (FEDER)
Project cofinanced by the European Regional
Development Fund (ERDF)

MARIE

MEDITERRANEAN BUILDING
RETHINKING FOR ENERGY
EFFICIENCY IMPROVEMENT

Project	MARIE. Mediterranean Building Rethinking for Energy Efficiency Improvement	
Authors	Institut de Recerca en Energia de Catalunya (IREC)	Joana Ortiz Jaume Salom Verdiana Russo
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The project has been done with the collaboration of:

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i Sostenibilitat

Agència de l'Habitatge
de Catalunya

ERF

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L'Europe en Méditerranée
Europe in the Mediterranean
Projet cofinancé par le Fonds Européen
de Développement Régional (FEDER)
Project cofinanced by the European Regional
Development Fund (ERDF)

OptiHab - Method [1/2]

Objectives

- To develop a technical study to optimize the energy renovation of residential sector in Catalonia.

- To establish the techno-economic criteria to develop regional strategies and policies to improve the energy efficiency of residential buildings in Catalonia

Specific objectives:

- To define the minimum requirement for:
    - Energy demand
    - Renewable energy contribution
    - Limitations of energy consumption
- To consider particularities of the Mediterranean buildings
- To improve and guarantee the levels of thermal comfort of the proposed measures for the energy renovation

Method overview[1]

- Two-step optimization:
    - Passive and comfort optimization: the objective is to reduce, as much as possible, the thermal discomfort with the minimum initial investment cost of the passive measures.
    - Cost-energy optimization: the objective is to obtain the cost-effective measures, minimizing the primary energy use and the global costs[2].

Passive Evaluation
Thermal comfort
.vs.
Investment cost

Passive selection

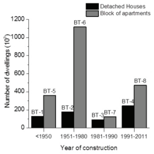
Active Evaluation
Primary energy
.vs.
Global cost

Passive + Active selection

Cost-Optimal Energy Efficiency Measures

- Software:
- TRNSYS → energy simulation of the building
- SDLPS[3,4] → optimization process (InLab)
- Around 30,000 simulation

Building stock characterization[5]



CLIMATE	Detached house 1991-2007 BT-4	Block of apartments <1950 BT-5	 1951-1980 BT-6	 1991-2007 BT-8
C2	x	x	x	x
B3	x		x	x
D3			x	
E1		x	x	

Year for construction:
<1950 Up to 50s
1951-1980 Post war
1981-1990 National building regulation (NBE-CT-79)
1991-2006 Regional building regulation (NRE.-AT-87)

Data collection:

- Building regulation
- Previous studies
- Statistical data
- Surveys

Climate: climate zones from CTE[6]

C2: Barcelona. B3: Tarragona. D3: Lleida. E1: Pre-Pyrenees

Natural ventilation hypothesis

Two configurations have been considered in order to represent the different situation of the buildings:

- With natural ventilation (YES): it is possible to use the natural ventilation as strategy for cooling the household
- Without natural ventilation (NO): it is not possible to use the natural ventilation for cooling the household due the environment/location of the building (noise, contamination, etc…)

OptiHab - Method

Building simulation

- **Detailed characterization of the building**:
    - Constructive solutions (ACH and ERF[5])
    - Thermal bridge (CE3X Handbook[7])
    - Tightness of the construction (UNI-EN 15242[8,9,10])
- **Occupancy and their use of the building**
    - Family type and occupancy profiles (Time Use Data, INE[11])
    - Natural ventilation (British Standard (BS 5925-1991[12]), W. De Gids, H. Phaff (1982[13]))
    - Solar protections
    - Artificial lighting and daylighting (Th-BCE[14])
- **Energy systems**
    - Domestic hot water (Transol, DTIE 1.01)
    - Heating system (Handbook 6 Calener[15], EN 15316-2-1[16])
    - Cooling system (Handbook 6 Calener[15], EN 15316-2-1[16])
    - Appliances and electric devices (Ortiz 2014[17], SECH-SPACHOUSEC[18])
    - Solar thermal system (Transol)
    - Photovoltaic system (TRNSYS)

Primary energy balance

- **Comfort index (Carlucci 2013[19], ASHRAE[20])** → **Comfort evaluation**
- **Economic calculation (EN 15459[2])** → **Economic evaluation**

Energy efficiency measures

- **Passive measures:**

façade insulation, roof insulation, improve the windows performance and the use of solar protections. Improvement of the tightness of the construction and reduction of the cold bridge.

- **Active measures:**

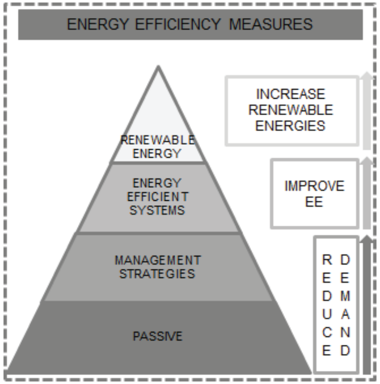
improvement of the performance of the heating and cooling systems, strategies of management, improvement of the energy performance of lighting.

- **Renewable energy systems:**

solar thermal, photovoltaic system and biomass boiler

Comments:

- The biomass boiler is not considered in the multi family building due to technical limitations. Then, only the semi-detached house (D) includes the biomass boiler as a active measure.
- Active measures like mechanical ventilation systems, centralized heating system at building level, district heating and cooling, are outside the scope of the study.
- The characteristics of the measures are described in the Appendix II.



OptiHab - Method [2/2]

Passive and comfort optimization

Objectives:
- Evaluation of the passive measures in order to:
  - Guarantee the thermal comfort of the user during the warm and cold period
  - Reduce as much as possible the thermal discomfort of the users only with passive measures
  - Priories the passive measure in front of the active ones

Comfort parameters:
- Long-term percentage of dissatisfied (LPD)[19]:
  - Based on ASHRAE adaptive[20,21] model (no cooling systems)
  - It evaluates the percentage of the time when there is discomfort conditions for the users.
  - It is calculated over three periods: annual, cold season and warm season.
  - Comfort conditions: LPD<20%
- Hours of overheating (OH)
  - It evaluates when the occupants are in overheating conditions.
  - Comfort conditions: OH < 1% of hours of the warm season

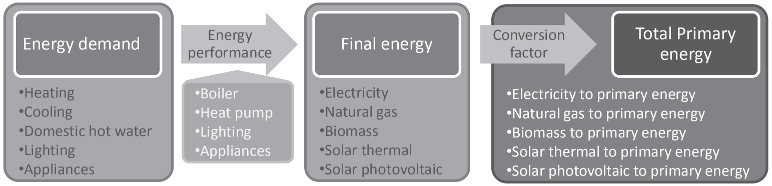
Simulation configuration:
- Free running temperature (the building without mechanical heating and cooling systems)

Cost-energy optimization

Objective:
- Follows the current directives and standards:
  - European Directive: 2010/31/UE (EPBD)[22] and UE No. 244/2012[23]
  - EN 15459[2]
- Evaluation of the combination of the passive and active measures using:
  - Global cost → technological neutrality
  - Primary energy → energy balance

Parameters:
- Global cost: represents all the costs generated over a period (30 years), which included:
  - Energy costs: cost due to energy consumed and annual taxes (for example, the power fix term of the electricity contract).
  - Initial investment cost: cost of the energy efficiency measures.
  - Replacement cost: each measure/system has to be replaced depending on its corresponding lifespan (for example, the boiler every 15 years has to be replaced).
  - Maintenance cost: the annual cost for the maintenance of the building and their systems (for example, once every two year, the natural gas installation needs a technical revision by the company).
  - Economic parameters: to consider the evolution of the money (inflation rate and market interest rate).

- Primary energy:



Simulation configuration:
- Simulation of the building with mechanical and electrical systems: heating, cooling, DHW, lighting and appliances.
- The comfort is already guarantee with the use of the mechanical systems.

OptiHab - Method

Energy labelling

Objective:
- Evaluate the effect of the energy efficiency measures in terms of energy labelling.

Method:
- An adaptation of the energy label scale is needed in order to obtain the TOTAL primary energy consumption:
  - EU Directive[22,23] → includes heating, cooling and domestic hot water consumption
  - OptiHab → includes heating, cooling, domestic hot water, lighting and appliances consumption

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How to understand the factsheets?

Isolated block of apartments
Ye
Nº
Nº Dwellings: 12
Dwelling surface: 103.2 m²
Occupants: 2 adults + 1 child

Building characterization

- *Façade:* with air chamber and insulation
tion
ium without thermal break with clear double glazing 4/12/4
- *Solar protection:* blinds
- *Observations:*

CLIMATE: C2 (Barcelona)

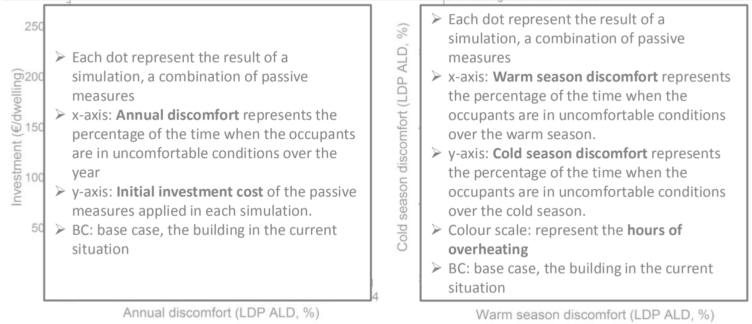
NATURAL VENTILATION: YES

Solar protection:
- Blinds: are used as solar protection, however the use is not optimal.
- Awnings: are use as optimal solar protection

Natural ventilation:
- YES: natural ventilation is use as strategy for cooling the household
- NO: the environment of the building does not allow to do natural ventilation (noise, contamination…)

PASSIVE ANALYSIS: Thermal comfort vs. Initial investment cost

Evaluation of the effect of the passive measures analysing the thermal comfort and the initial investment cost. Simulation without heating and cooling system (free running mode)



- Each dot represent the result of a simulation, a combination of passive measures
- x-axis: **Annual discomfort** represents the percentage of the time when the occupants are in uncomfortable conditions over the year
- y-axis: **Initial investment cost** of the passive measures applied in each simulation.
- BC: base case, the building in the current situation

- Each dot represent the result of a simulation, a combination of passive measures
- x-axis: **Warm season discomfort** represents the percentage of the time when the occupants are in uncomfortable conditions over the warm season.
- y-axis: **Cold season discomfort** represents the percentage of the time when the occupants are in uncomfortable conditions over the cold season.
- Colour scale: represent the **hours of overheating**
- BC: base case, the building in the current situation

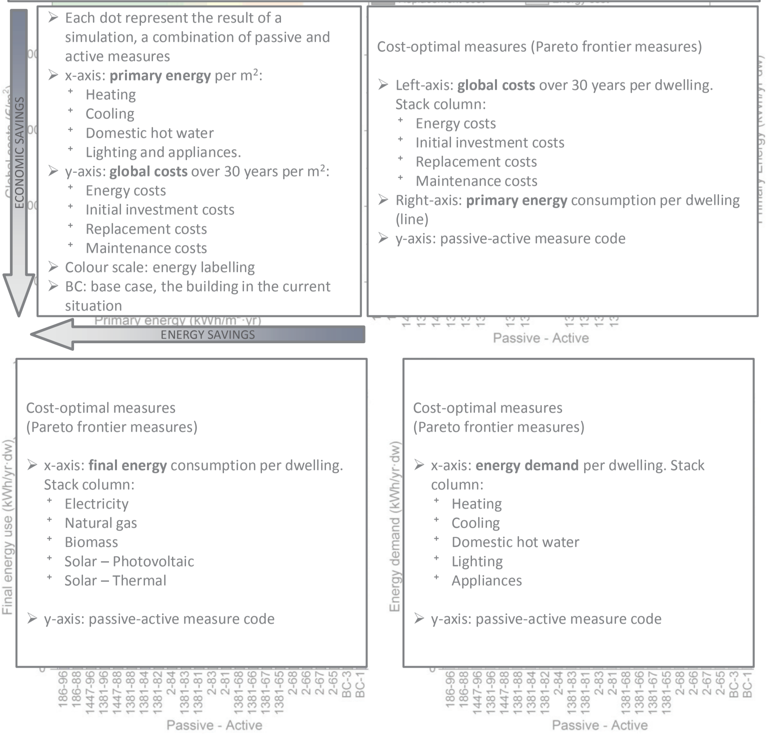
PASSIVE	FAÇADE	ROOF	WINDOW	SOLAR PROT.	INITIAL INVESTMENT €	ANNUAL LDP %	COLD LDP %	WARM LDP %	OVERHEATING Hours

- Criteria for the selection of the passive measures:
  - Improve the discomfort with the lower investment cost
  - Improve the annual and cold season discomfort → reduce the heating demand
  - Reduce the hours of overheating below the threshold → avoid the cooling system
- The passive measures selected are not the only ones that achieves the comfort criteria!

How to understand the factsheets?

ACTIVE ANALYSIS: Primary energy use vs. Global cost

Evaluation of the effect of the passive + active measures analysing the primary energy consumption and the global costs. Simulation with heating and cooling system.



- Each dot represent the result of a simulation, a combination of passive and active measures
- x-axis: **primary energy** per m²:
  - Heating
  - Cooling
  - Domestic hot water
  - Lighting and appliances.
- y-axis: **global costs** over 30 years per m²:
  - Energy costs
  - Initial investment costs
  - Replacement costs
  - Maintenance costs
- Colour scale: energy labelling
- BC: base case, the building in the current situation

Cost-optimal measures (Pareto frontier measures)

- Left-axis: **global costs** over 30 years per dwelling. Stack column:
  - Energy costs
  - Initial investment costs
  - Replacement costs
  - Maintenance costs
- Right-axis: **primary energy** consumption per dwelling (line)
- y-axis: passive-active measure code

Cost-optimal measures
(Pareto frontier measures)

- x-axis: **final energy** consumption per dwelling. Stack column:
  - Electricity
  - Natural gas
  - Biomass
  - Solar – Photovoltaic
  - Solar – Thermal
- y-axis: passive-active measure code

Cost-optimal measures
(Pareto frontier measures)

- x-axis: **energy demand** per dwelling. Stack column:
  - Heating
  - Cooling
  - Domestic hot water
  - Lighting
  - Appliances
- y-axis: passive-active measure code

PASSIVE	HEATING + DHW	COOLING	PV SYSTEM	LIGHTING	AWARENESS CAMPAIGN	PRIMARY ENERGY kWh/yr-dw	ENERGY SAVINGS %	GLOBAL COSTS €/dw	INITIAL INVESTMENT €/dw

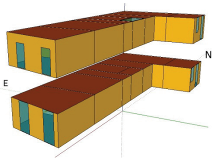
- Cost-optimal measures (Pareto frontier measure)
  - BC: base case, the building in the current situation
  - CO: minimum of the cost-optimal measures
  - DR: Deep renovation measures. Lower primary energy consumption.

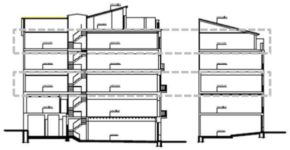
OptiHab - Typology BT-5

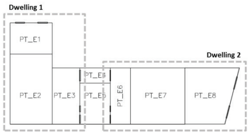
Building type: Block of apartments between buildings
Year of construction: up to 1950
Nº Floors: Commercial floor + 4
Nº Dwellings: 8
Dwelling surface: 60.5 m²
Occupants: 2 adults

Building representation:

Climate	Nº buildings	% building stock
C2 (Barcelona)	284 230	12.3
E1 (Pre-Pyrinees)	6 922	0.3





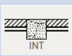
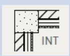
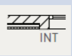
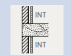
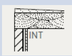
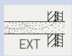


Building Characteristics

Envelope	Description	Thickness m	U-value W/m²K
Façade	Structural wall of 29cm solid brick with exterior and interior cladding	0.34	1.78
Roof	Sloping roof with Arabic tiles, ceramic tiles, wooden beams ceiling and hurdle ceiling	0.12	1.27
Party wall	Partition wall with solid brick and siding in both sides	0.18	2.38
Internal wall	Wall of 14cm of perforated brick and siding in both sides	0.09	2.12
Floor framing	Unidirectional floor framing of wooden beams and ceramic brick	0.22	2.16

Window	Description	U-value W/m²K	g-value -
Window frame	Aluminium without thermal break	5.68	0.85
Glazing	Clear double glazing 4/12/4		

Solar protection	Blinds	Air leakage (n_{50})	7.5

Cold bridge	Pilar in a wall	Pillar in a corner	Opening frame	Shutter box	Wall- floor junction	Wall-roof junction	Wall over external slab	Cantilever-wall junction
Description	 INT	 INT	 INT	 INT	 INT INT	 INT	 INT	 EXT
Linear thermal conductivity (Ψ, W/mK)	0.81	0.60	0.33	-	1.51	0.97	-	1.51

OptiHab - Typology BT-5

Equipment Characteristics

System	Description	Performance
Heating and DHW	Conventional natural gas boiler for individual centralize system (24kW)	η = 0.75
Cooling	Conventional air conditioning system (split) installed in 2 zones (5kW)	COP = 2.0
Lighting	Compact fluorescent lamps (2 W/m²)	Luminous efficacy = 0.6
Appliances	Refrigerator, washing machine, dishwasher, microwave, electric oven, TV and computer.	Average household of a multifamily building in Mediterranean region

Energy efficiency measures

Measure	Description	Performance	Investment cost	Mainte-nance cost	Life-span
Façade insulation	External – EPS 4-12 cm	0.60 - 0.26 W/m²K	2,300 - 2,900 €/dw	-	40
	External – XPS 4-12 cm	0.63 - 0.27 W/m²K	2,600 - 3,300 €/dw	-	40
	Air chamber – mineral wool 3-10 cm	-	-	-	-
	Air chamber – EPS + graphite 3-10 cm	-	-	-	-
	Air chamber – cellulose 3-10 cm	-	-	-	-
	Internal – EPS 4-8 cm	0.60 - 0.36 W/m²K	1,100 - 1,200 €/dw	-	40
	Internal –mineral wool 4-8 cm	0.68 - 0.42 W/m²K	750 - 850 €/dw	-	40
Roof insulation	Inverted – XPS 8-12 cm	-	-	-	-
	Internal – rock wool 4-8 cm	0.59 - 0.39 W/m²K	600 - 650 €/dw	-	30
	Internal – EPS 4-8 cm	0.53 - 0.33 W/m²K	800 - 900 €/dw	-	30
Windows change	4/16/4 Aluminium with thermal break	2.8 W/m²K	3,400 €/dw	-	30
	4/16/4 PVC	2.8 W/m²K	3,000 €/dw	-	30
Sol. protec.	Awnings	-	258 €/dw	-	15
Heating and DHW system	Condensing boiler + Improve install. Performance	η = 1.09	2,740 €/dw	109 €/dw	20
	Biomass boiler + Improve install. Performance	-	-	-	-
	Heat pump air-wat. + Improve install. Performance	-	-	-	-
Cooling system	Efficient Air conditioning system (split)	COP = 4.0	1,380 €/dw	48 €/dw	15
	No cooling system	-	-	-	-
Lighting	LED	Luminous eff. = 0.8	546 €/dw	-	20
Awareness	Awareness campaign	-	290 €/dw	24 €/dw	20
Solar thermal	16 m²/building + 1500l storage tank	-	3,300 €/dw	10€/dw	15
	-	-	-	-	-
PV system	20 m²/building - 240 Wp/module (12 modules)	-	1343 €/dw	73€/dw	20
	-	-	-	-	-

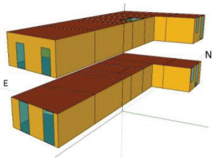
OptiHab - Typology BT-5 [1/4]

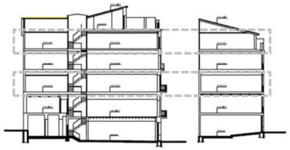
Block of apartments between buildings
Year of construction: up to 1950
Nº Floors: Commercial floor + 4
Nº Dwellings: 8
Dwelling surface: 60.5 m²
Occupants: 2 adults

- *Façade:* without insulation
- *Roof:* without insulation
- *Windows:* aluminium without thermal break
- *Solar protection:* blinds
- *Observations:* each dwelling has only one external wall with two windows

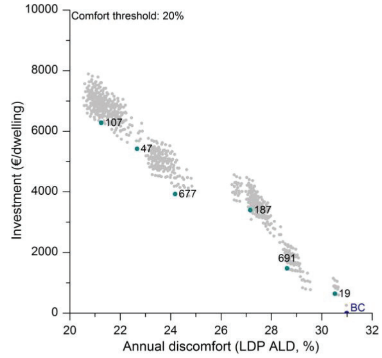
CLIMATE: C2 (Barcelona)

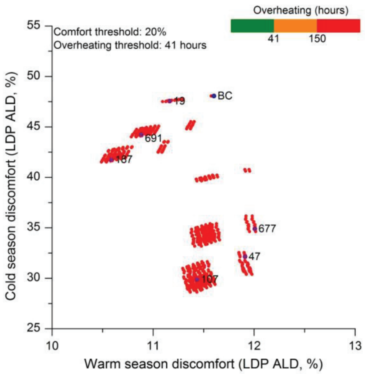
NATURAL VENTILATION: YES





PASSIVE ANALYSIS: Thermal comfort vs. Initial investment cost

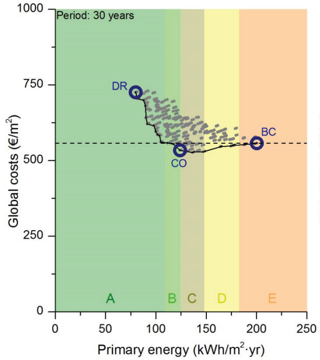


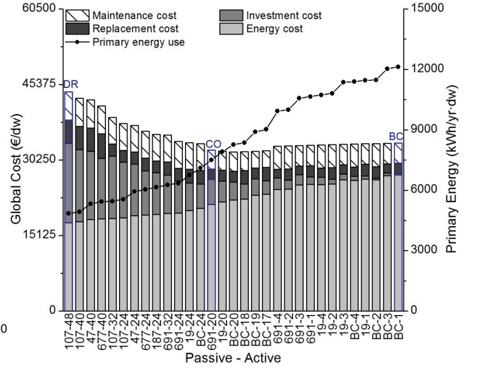


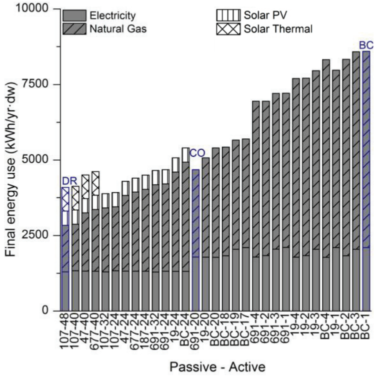
PASSIVE	FAÇADE	ROOF	WINDOW	SOLAR PROT.	INITIAL INVESTMENT €	ANNUAL LDP %	COLD LDP %	WARM LDP %	OVERHEATING Hours
BC	Base case	Base case	Base case	NO	0	31.0	48.1	11.6	509
19	Base case	INT–RW 8	Base case	NO	643	30.5	47.6	11.2	390
691	INT–RW 8	INT–RW 8	Base case	NO	1,477	28.6	44.2	10.9	448
187	EXT–EPS 10	INT–RW 8	Base case	NO	3,399	27.2	41.7	10.6	488
677	INT–RW 8	Base case	4/16/4PVC	NO	3,926	24.2	34.9	12.0	697
47	EXT–EPS 4	Base case	4/16/4PVC	NO	5,419	22.7	32.1	11.9	700
107	EXT–EPS 6	INT–RW 8	4/16/4PVC	NO	6,276	21.2	29.9	11.4	705

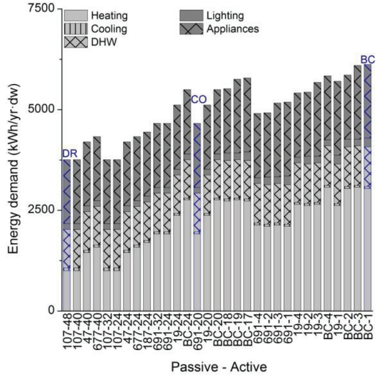
OptiHab - Typology BT-5

ACTIVE ANALYSIS: Primary energy use vs. Global cost









	PASSIVE	HEATING + DHW	COOLING	PV SYSTEM	LIGHTING	AWARENESS CAMPAIGN	PRIMARY ENERGY kWh/yr·dw	ENERGY SAVINGS %	GLOBAL COSTS €/dw	INITIAL INVESTMENT €/dw
BC	BC	Conventional NG boiler	Conventional AC Split	NO	CFL	NO	12,125	-	33,688	0
CO	691	Condensing NG boiler	Conventional AC Split	NO	LED	YES	7,507	38	32,274	5,051
DR	107	Condensing NG boiler+ST	Efficient AC Split	YES	LED	YES	4,839	60	43,875	15,872

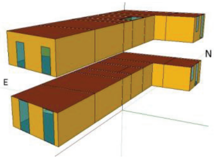
OptiHab - Typology BT-5 [2/4]

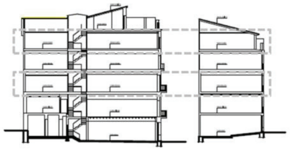
Block of apartments between buildings
Year of construction: up to 1950
Nº Floors: Commercial floor + 4
Nº Dwellings: 8
Dwelling surface: 60.5 m²
Occupants: 2 adults

- *Façade:* without insulation
- *Roof:* without insulation
- *Windows:* aluminium without thermal break
- *Solar protection:* blinds
- *Observations:* each dwelling has only one external wall with two windows

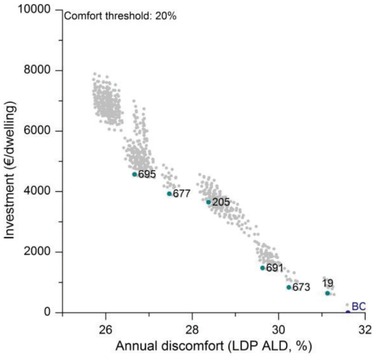
CLIMATE: C2 (Barcelona)

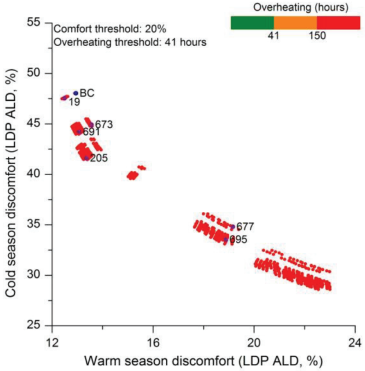
NATURAL VENTILATION: NO





PASSIVE ANALYSIS: Thermal comfort vs. Initial investment cost

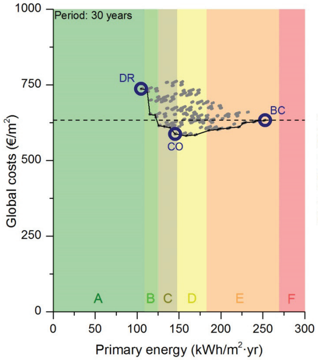


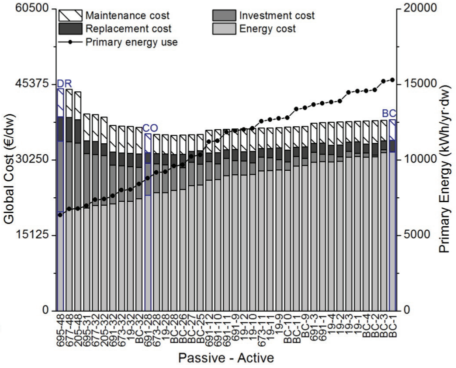


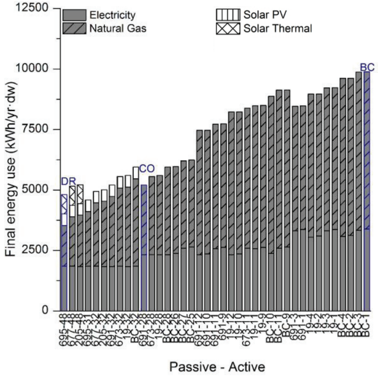
PASSIVE	FAÇADE	ROOF	WINDOW	SOLAR PROT.	INITIAL INVESTMENT €	ANNUAL LDP %	COLD LDP %	WARM LDP %	OVERHEATING Hours
BC	Base case	Base case	Base case	NO	0	31.6	48.0	12.9	739
19	Base case	INT–RW 8	Base case	NO	643	31.1	47.5	12.5	739
673	INT–RW 8	Base case	Base case	NO	834	30.2	44.9	13.6	860
691	INT–RW 8	INT–RW 8	Base case	NO	1,477	29.6	44.2	13.1	861
205	EXT–EPS 10	INT–EPS 8	Base case	NO	3,647	28.4	41.6	13.4	920
677	INT–RW 8	Base case	4/16/4PVC	NO	3,926	27.5	34.8	19.2	1576
695	INT–RW 8	INT–RW 8	4/16/4PVC	NO	4,569	26.7	33.5	18.9	1582

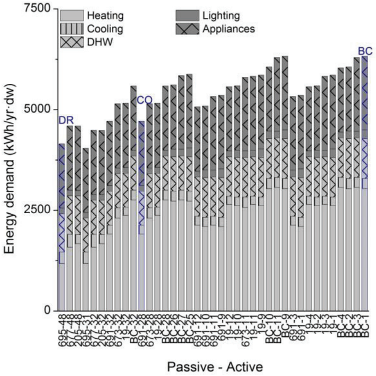
OptiHab - Typology BT-5

ACTIVE ANALYSIS: Primary energy use vs. Global cost









	PASSIVE	HEATING + DHW	COOLING	PV SYSTEM	LIGHTING	AWARENESS CAMPAIGN	PRIMARY ENERGY kWh/yr·dw	ENERGY SAVINGS %	GLOBAL COSTS €/dw	INITIAL INVESTMENT €/dw
BC	BC	Conventional NG boiler	Conventional AC Split	NO	CFL	NO	15,299	-	38,311	0
CO	691	Condensing NG boiler	Efficient AC Split	NO	LED	YES	8,797	42	35,532	6,430
DR	695	Condensing NG boiler+ST	Efficient AC Split	YES	LED	YES	6,347	59	44,538	14,165

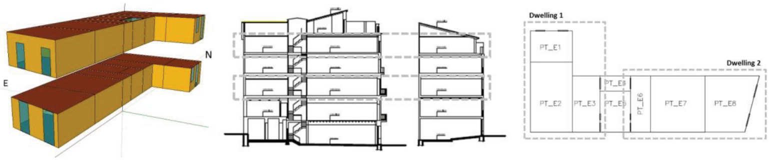
OptiHab - Typology BT-5 [3/4]

Block of apartments between buildings
Year of construction: up to 1950
Nº Floors: Commercial floor + 4
Nº Dwellings: 8
Dwelling surface: 60.5 m²
Occupants: 2 adults

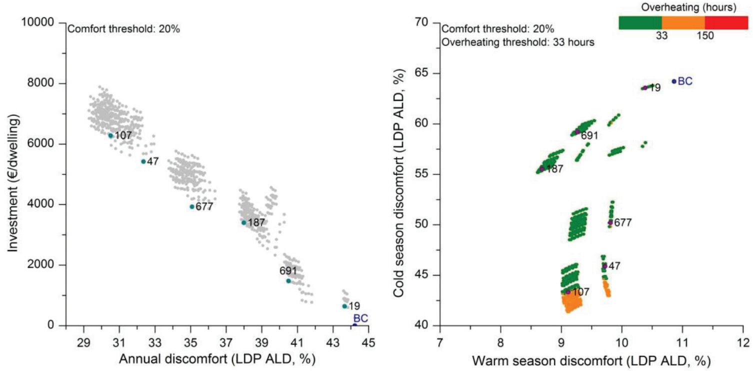
- *Façade:* without insulation
- *Roof:* without insulation
- *Windows:* aluminium without thermal break
- *Solar protection:* wood blinds
- *Observations:* each dwelling has only one external wall with two windows

CLIMATE: E1 (Pre-Pyrenees)

NATURAL VENTILATION: YES



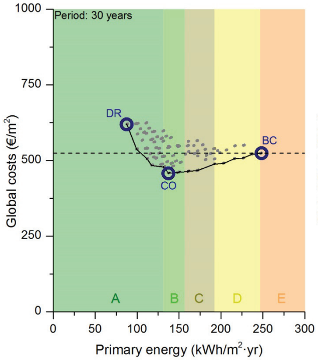
PASSIVE ANALYSIS: Thermal comfort vs. Initial investment cost

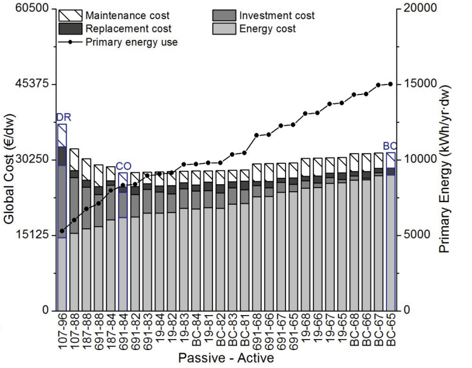


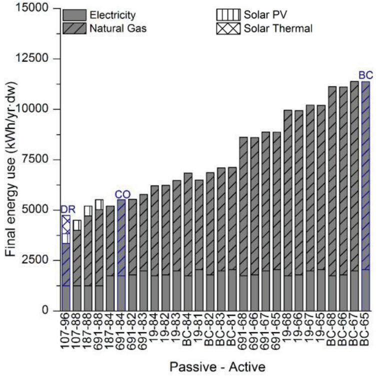
PASSIVE	FAÇADE	ROOF	WINDOW	SOLAR PROT.	INITIAL INVESTMENT €	ANNUAL LDP %	COLD LDP %	WARM LDP %	OVERHEATING Hours
BC	Base case	Base case	Base case	NO	0	44.2	64.2	9.8	20
19	Base case	INT–RW 8	Base case	NO	643	43.7	63.6	10.4	11
691	INT–RW 8	INT–RW 8	Base case	NO	1,477	40.5	59.2	9.3	27
187	EXT–EPS 10	INT–RW 8	Base case	NO	3,399	38.0	55.5	8.7	16
677	INT–RW 8	Base case	4/16/4PVC	NO	3,926	35.1	50.2	9.8	32
47	EXT–EPS 4	Base case	4/16/4PVC	NO	5,419	32.4	45.9	9.7	29
107	EXT–EPS 6	INT–RW 8	4/16/4PVC	NO	6,276	30.5	43.3	9.1	32

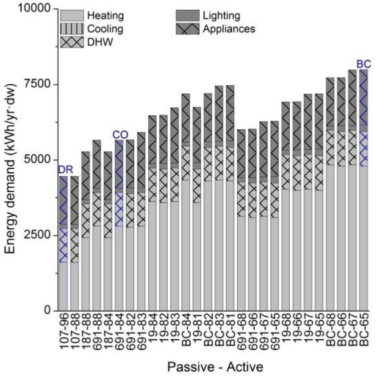
OptiHab - Typology BT-5

ACTIVE ANALYSIS: Primary energy use vs. Global cost





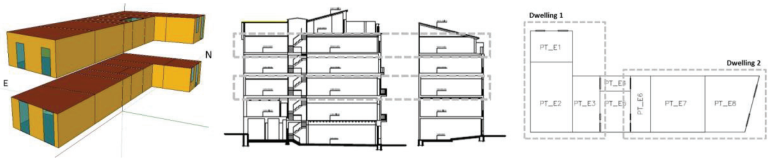




	PASSIVE	HEATING + DHW	COOLING	PV SYSTEM	LIGHTING	AWARENESS CAMPAIGN	PRIMARY ENERGY kWh/yr·dw	ENERGY SAVINGS %	GLOBAL COSTS €/dw	INITIAL INVESTMENT €/dw
BC	BC	Conventional NG boiler	NO	NO	CFL	NO	15,029	-	31,715	0
CO	691	Condensing NG boiler	NO	NO	LED	YES	8,323	45	27,675	5,051
DR	107	Condensing NG boiler+ST	NO	YES	LED	YES	5,304	65	37,457	14,492

OptiHab - Typology BT-5 [4/4]

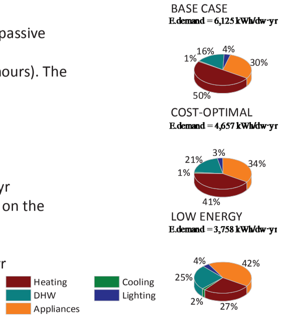
CONCLUDING REMARKS	Block of apartments between buildings Year of construction: up to 1950 Nº Floors: Commercial floor + 4 Nº Dwellings: 8 Dwelling surface: 60.5 m² Occupants: 2 adults	➢*Façade:* without insulation ➢*Roof*: without insulation ➢*Windows:* aluminium without thermal break ➢*Solar protection:* blinds ➢*Observations:* each dwelling has only one external wall with two windows



- The typology has a small area of external facade and there is only two external windows:
  - Heating demand is relatively low
  - Solar protection has a low impact during the warm season
- Effect of insulation in the facade:
  - The external insulation has a better energy performance than the internal insulation, however the cost is higher.
  - If the thickness of the insulation increase, the cold comfort is improve. However, the warm comfort and the overheating are increased, specially when the ventilation is not possible.
- Effect of insulation in the roof:
  - Only the internal insulation has been considered for this typology
  - The increase of the thickness have a positive impact on the cold comfort and the effects on the warm comfort are not significant.
- The improvement of the window performance has a high impact in the annual discomfort (around the 10% of reduction), nevertheless its initial investment cost is high (around 3,000 €/dw).
- There are cost-optimal solutions that include a combination of passive and active measures.
- The measures that provide a lower primary energy consumption imply a deep renovation and the use of renewable energy systems.
- As the heating demand is reduced, the electric consumption due to appliances becomes more important. Specific solutions have to be considered in future studies.

CONCLUDING REMARKS - CLIMATE: C2 (Barcelona) – NATURAL VENTILATION: YES

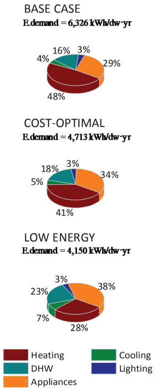
- **Comfort evaluation**
  The annual discomfort can be reduced from 31% to 21% only with passive measures.
  There are problems of overheating during the warm season (>150hours). The cooling system is required to guarantee comfort conditions.
- **Base case (BC)**
  Energy label = E (200 kWhPE/m²·yr).
  CO_2 emissions = 30 kgCO_2/m²·yr
- **Cost Optimal measures (CO)**
  Energy label= B (124 kWhPE/m²·yr). CO_2 emissions = 17 kgCO_2/m²·yr
  The condensing boiler is the active measure that has a high impact on the primary energy consumption (25% of reduction)
- **Low energy measures (DR)**
  Energy label = A (80 kWhPE/m²·yr). CO_2 emissions = 10 kgCO_2/m²·yr
  Heating demand could be reduced in 67%.
  Primary energy savings: up to 60%



OptiHab - Typology BT-5

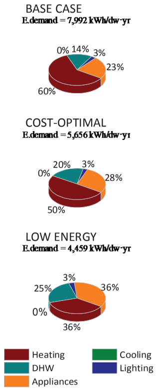
CONCLUDING REMARKS - CLIMATE: C2 (Barcelona) – NATURAL VENTILATION: NO

- **Comfort evaluation**
  The annual discomfort can be reduced from 32% to 26% only with passive measures.
  As the annual and cold season discomfort are improved, the warm season discomfort is getting worse (opposite behaviour than the buildings with natural ventilation).
  There are problems of overheating during the warm season (>150hours). The cooling system is required to guarantee comfort conditions.
- **Base case (BC)**
  Energy label = E (253 kWhEP/m²·yr).
  CO_2 emissions = 36 kgCO_2/m²·yr
- **Cost Optimal measures (CO)**
  Energy label= C (145 kWhEP/m²·yr).
  CO_2 emissions = 19 kgCO_2/m²·yr
  The condensing boiler is the active measure that has a high impact on the primary energy consumption (20% of reduction)
- **Low energy measures (DR)**
  Energy label = A (105 kWhEP/m²·yr).
  CO_2 emissions = 13 kgCO_2/m²·yr
  Heating demand could be reduced in 61%.
  Primary energy savings: up to 58%



CONCLUDING REMARKS - CLIMATE: E1 (Pre-Pyrenees) – NATURAL VENTILATION: YES

- **Comfort evaluation**
  The annual discomfort can be reduced from 44% to 29% only with passive measures.
  There are no problems of overheating during the warm season (<33 hours). The cooling system could be avoid to guarantee comfort conditions.
- **Base case (BC)**
  Energy label = E (248 kWhPE/m²·yr).
  CO_2 emissions = 39 kgCO_2/m²·yr
- **Cost Optimal measures (CO)**
  Energy label= B (138 kWhPE/m²·yr).
  CO_2 emissions= 20 kgCO_2/m²·yr
  The condensing boiler is the active measure that has a high impact on the primary energy consumption (30% of reduction)
- **Low energy measures (DR)**
  Energy label = A (88 kWhPE/m²·yr).
  CO_2 emissions = 12 kgCO_2/m²·yr
  Heating demand could be reduced in 65 %.
  Primary energy savings: up to 65%

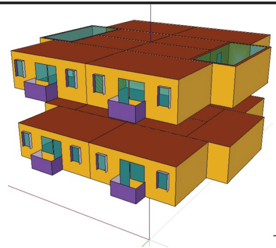


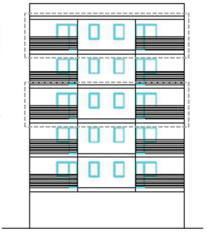
OptiHab - Typology BT-6

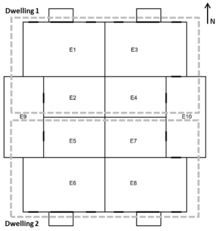
Building type: Block of apartments between buildings
Year of construction: 1951-1980
Nº Floors: Commercial floor + 5
Nº Dwellings: 10
Dwelling surface: 78.8 m^2
Occupants: 2 adults + 1 child

Building representation:

Climate	Nº buildings	% building stock
C2 (Barcelona)	910 046	39.5
B3 (Tarragona)	71 683	3.1
D1 (Lleida)	32 725	1.4
E1 (Pre-Pyrinees)	10 230	0.4





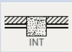
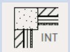
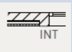
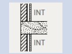
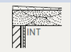
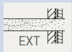


Building Characteristics

Envelope	Description	Thickness M	U-value W/m²K
Façade	14 cm wall hollow brick with siding with plaster mortar, air chamber 10 cm weakly ventilated, brick of 5 cm and plaster coating	0.23	1.22
Roof	Catalan flat roof, double pavement of ceramic tile, mortar layer, slab ceramic of tongue and groove, honeycomb bond, unidirectional slab of pre-stressed concrete joists and plaster coating.	0.34	1.17
Party wall	Partition wall with perforated brick and siding in both sides	0.18	2.25
Internal wall	Wall of 14cm of perforated brick and siding in both sides	0.09	2.46
Floor framing	Unidirectional floor framing reinforced concrete, joist, slab of concrete, mortar and pavement tiles.	0.28	1.86

Window	Description	U-value W/m²K	g-value -
Window frame	Aluminium without thermal break	5.68	0.85
Glazing	Clear double glazing 4/12/4		

Solar protection	Blinds	Air leakage (n_{50})	7.5

Cold bridge	Pilar in a wall	Pillar in a corner	Opening frame	Shutter box	Wall- floor junction	Wall-roof junction	Wall over external slab	Cantilever-wall junction
Description								
Linear thermal conductivity (Ψ, W/mK)	0.81	0.60	0.33	-	1.51	0.49	-	1.51

OptiHab - Typology BT-6

Equipment Characteristics

System	Description	Performance
Heating and DHW	Conventional natural gas boiler for individual centralize system (24kW)	η = 0.75
Cooling	Conventional air conditioning system (split) installed in 2 zones (5kW)	COP = 2.0
Lighting	Compact fluorescent lamps (2 W/m^2)	Luminous efficacy = 0.6
Appliances	Refrigerator, washing machine, dishwasher, microwave, electric oven, TV and computer.	Average household of a multifamily building in Mediterranean region

Energy efficiency measures

Measure	Description	Performance	Investment cost	Mainte-nance cost	Life-span
Façade insulation	External – EPS 4-12 cm	0.52 - 0.24 W/m²K	3,700 - 4,500 €/dw	-	40
	External – XPS 4-12 cm	0.54 - 0.26 W/m²K	4,100 - 5,300 €/dw	-	40
	Air chamber – mineral wool 3-10 cm	0.76 - 0.34 W/m²K	850 - 1,200 €/dw	-	40
	Air chamber – EPS + graphite 3-10 cm	0.65 - 0.27 W/m²K	1,100 - 2,200 €/dw	-	40
	Air chamber – cellulose 3-10 cm	0.52 - 0.31 W/m²K	850 - 1,000 €/dw	-	40
	Internal – EPS 4-8 cm	0.50 - 0.32 W/m²K	1,700 - 1,900 €/dw	-	40
	Internal –mineral wool 4-8 cm	0.56 - 0.37 W/m²K	1,000 - 1,100 €/dw	-	40
Roof insulation	Inverted – XPS 8-12 cm	0.34 - 0.25 W/m²K	2,700 - 2,900 €/dw	-	30
	Internal – rock wool 4-8 cm	0.57 - 0.38 W/m²K	750 - 850 €/dw	-	30
	Internal – EPS 4-8 cm	0.51 - 0.32 W/m²K	1,000 - 1,200 €/dw	-	30
Windows change	4/16/4 Aluminium with thermal break	2.8 W/m²K	8,700 €/dw	-	30
	4/16/4 PVC	2.8 W/m²K	7,900 €/dw	-	30
Sol. protec.	Awnings	-	309 €/dw	-	15
Heating and DHW system	Condensing boiler + Improve install. Performance	η = 1.09	2,740 €/dw	109 €/dw	20
	Biomass boiler + Improve install. Performance	-	-	-	-
	Heat pump air-wat. + Improve install. Performance	-	-	-	-
Cooling system	Efficient Air conditioning system (split)	COP = 4.0	1,380 €/dw	48 €/dw	15
	No cooling system	-	-	-	-
Lighting	LED	Luminous eff. = 0.8	546 €/dw	-	20
Awareness	Awareness campaign	-	290 €/dw	24 €/dw	20
Solar thermal	16 m^2/building + 1500l storage tank	-	2,640 €/dw	10€/dw	15
	-	-	-	-	-
PV system	20 m^2/building - 240 Wp/module (12 modules)	-	1,074 €/dw	73€/dw	20
	-	-	-	-	-

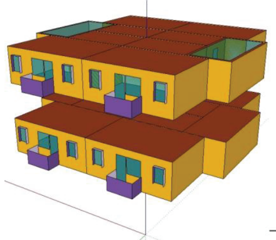
OptiHab - Typology BT-6 [1/9]

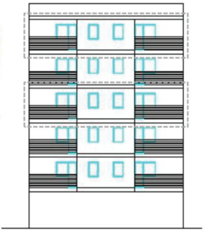
Block of apartments between buildings
Year of construction: 1951-1980
Nº Floors: Commercial floor + 5
Nº Dwellings: 10
Dwelling surface: 78.8 m²
Occupants: 2 adults + 1 child

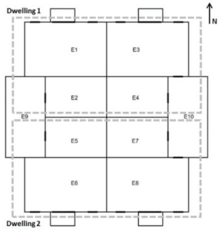
- ➢ *Façade:* with air chamber
- ➢ *Roof:* with air chamber
- ➢ *Windows:* aluminium without thermal break with clear double glazing 4/12/4
- ➢ *Solar protection:* blinds
- ➢ *Observations:*

CLIMATE: C2 (Barcelona)

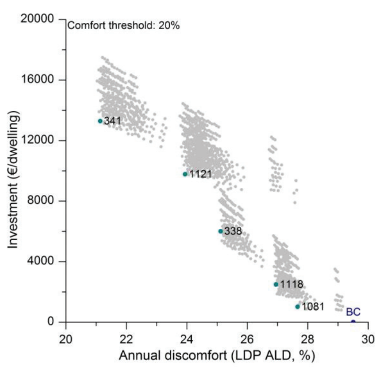
NATURAL VENTILATION: YES

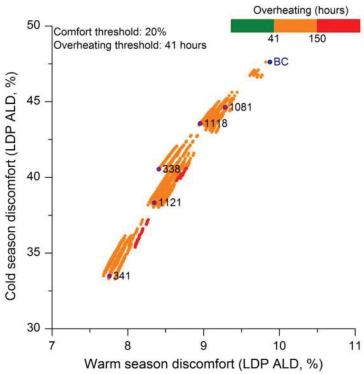






PASSIVE ANALYSIS: Thermal comfort vs. Initial investment cost

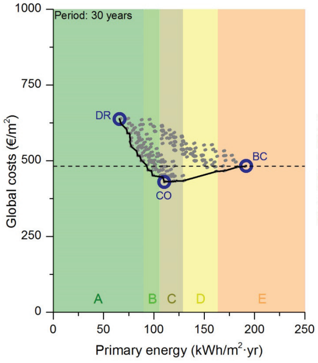


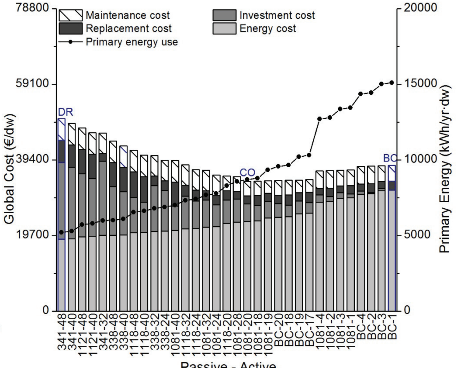


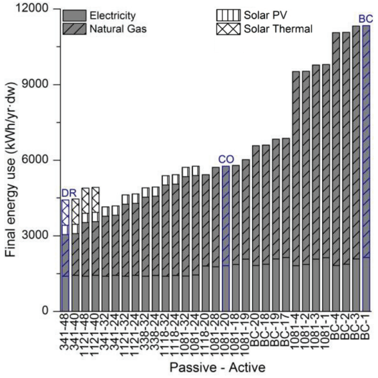
PASSIVE	FAÇADE	ROOF	WINDOW	SOLAR PROT.	INITIAL INVESTMENT €	ANNUAL LDP %	COLD LDP %	WARM LDP %	OVERHEATING Hours
BC	Base case	Base case	Base case	NO	0	29.5	47.6	9.9	110
1081	AC–Cel. 10	Base case	Base case	NO	1,021	27.7	44.6	9.3	126
1118	AC–Cel. 10	INT–RW 8	Base case	YES	2,485	26.9	43.5	8.9	108
338	EXT–EPS 12	INT–RW 8	Base case	YES	5,999	25.4	40.5	8.4	110
1121	AC–Cel. 10	INT–RW 8	4/16/4PVC	NO	9,770	23.9	38.3	8.3	94
341	EXT–EPS 12	INT–RW 8	4/16/4PVC	NO	13,284	21.1	33.5	7.7	98

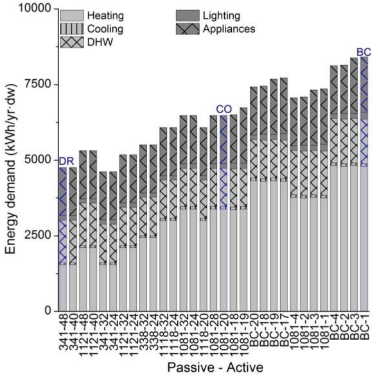
OptiHab - Typology BT-6

ACTIVE ANALYSIS: Primary energy use vs. Global cost









	PASSIVE	HEATING + DHW	COOLING	PV SYSTEM	LIGHTING	AWARENESS CAMPAIGN	PRIMARY ENERGY kWh/yr·dw	ENERGY SAVING %	GLOBAL COSTS €/dw	INITIAL INVESTMENT €/dw
BC	BC	Conventional NG boiler	Conventional AC Split	NO	CFL	NO	15,114	-	38,000	0
CO	1081	Condensing NG boiler	Conventional AC Split	NO	LED	YES	8,704	42	33,850	4,594
DR	341	Condensing NG boiler+ST	Efficient AC Split	YES	LED	YES	5,208	65	50,205	19,971

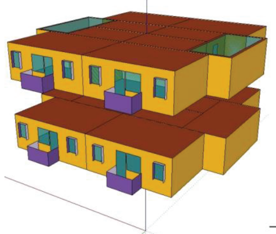
OptiHab - Typology BT-6 [2/9]

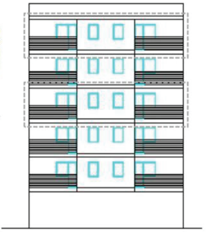
Block of apartments between buildings
Year of construction: 1951-1980
Nº Floors: Commercial floor + 5
Nº Dwellings: 10
Dwelling surface: 78.8 m²
Occupants: 2 adults + 1 child

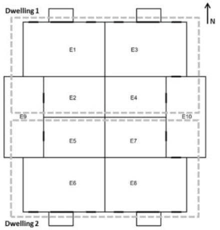
- *Façade:* with air chamber
- *Roof:* with air chamber
- *Windows:* aluminium without thermal break with clear double glazing 4/12/4
- *Solar protection:* blinds
- *Observations:*

CLIMATE: C2 (Barcelona)

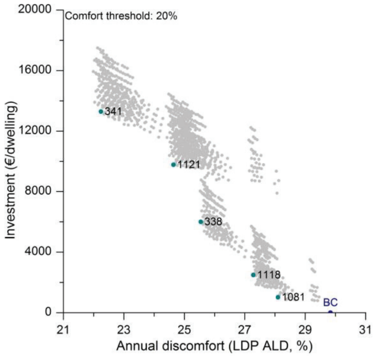
NATURAL VENTILATION: NO

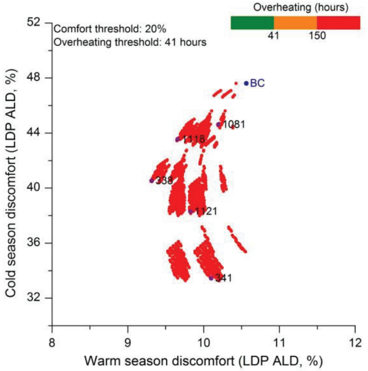






PASSIVE ANALYSIS: Thermal comfort vs. Initial investment cost

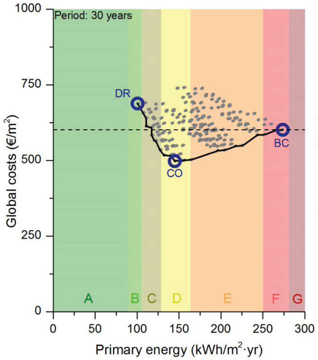


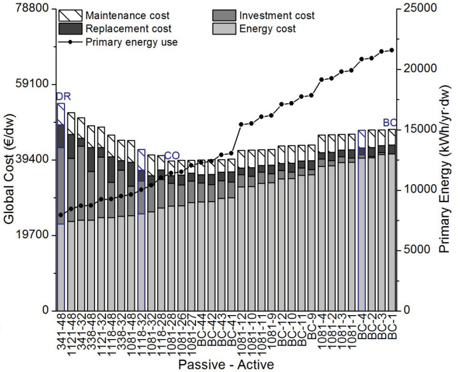


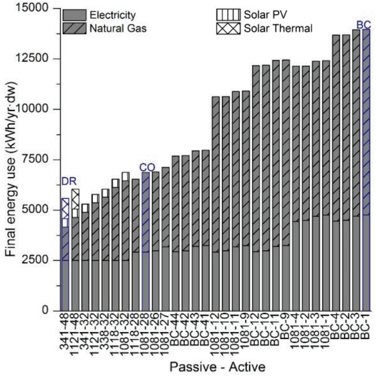
PASSIVE	FAÇADE	ROOF	WINDOW	SOLAR PROT.	INITIAL INVESTMENT €	ANNUAL LDP %	COLD LDP %	WARM LDP %	OVERHEATING Hours
BC	Base case	Base case	Base case	NO	0	29.8	47.6	10.6	328
1081	AC–Cel. 10	Base case	Base case	NO	1,021	28.1	44.6	10.2	407
1118	AC–Cel. 10	INT–RW 8	Base case	YES	2,485	27.3	43.5	9.7	334
338	EXT–EPS 12	INT–RW 8	Base case	YES	5,999	25.5	40.5	9.3	395
1121	AC–Cel. 10	INT–RW 8	4/16/4PVC	NO	9,770	24.6	38.3	9.8	536
341	EXT–EPS 12	INT–RW 8	4/16/4PVC	NO	13,284	22.2	33.4	10.1	612

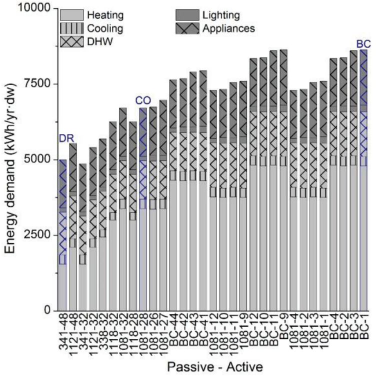
OptiHab - Typology BT-6

ACTIVE ANALYSIS: Primary energy use vs. Global cost









	PASSIVE	HEATING + DHW	COOLING	PV SYSTEM	LIGHTING	AWARENESS CAMPAIGN	PRIMARY ENERGY kWh/yr·dw	ENERGY SAVING %	GLOBAL COSTS €/dw	INITIAL INVESTMENT €/dw
BC	BC	Conventional NG boiler	Conventional AC Split	NO	CFL	NO	21,571	-	47,401	0
CO	1081	Condensing NG boiler	Efficient AC Split	NO	LED	YES	11,425	47	39,192	5,973
DR	341	Condensing NG boiler+ST	Efficient AC Split	YES	LED	YES	7,938	63	54,180	19,971

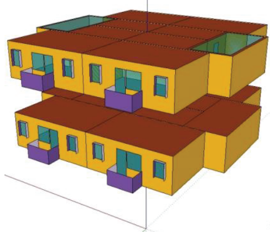
OptiHab - Typology BT-6 [3/9]

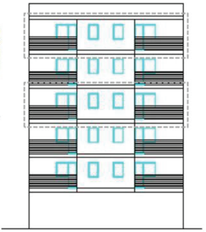
Block of apartments between buildings
Year of construction: 1951-1980
Nº Floors: Commercial floor + 5
Nº Dwellings: 10
Dwelling surface: 78.8 m²
Occupants: 2 adults + 1 child

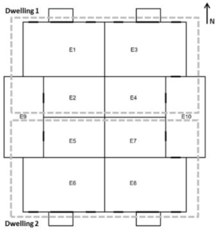
- *Façade:* with air chamber
- *Roof:* with air chamber
- *Windows:* aluminium without thermal break with clear double glazing 4/12/4
- *Solar protection:* wood blinds
- *Observations:*

CLIMATE: E1 (Pre-Pyrenees)

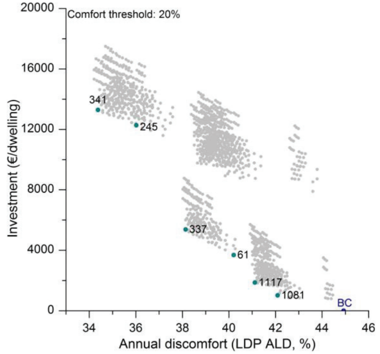
NATURAL VENTILATION: YES

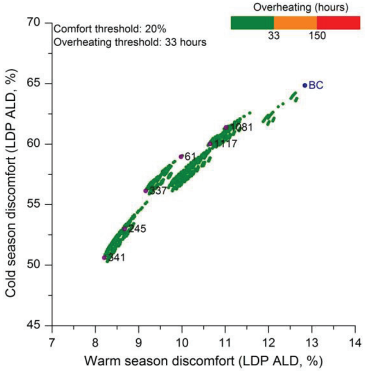






PASSIVE ANALYSIS: Thermal comfort vs. Initial investment cost

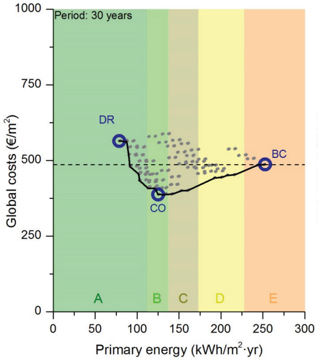


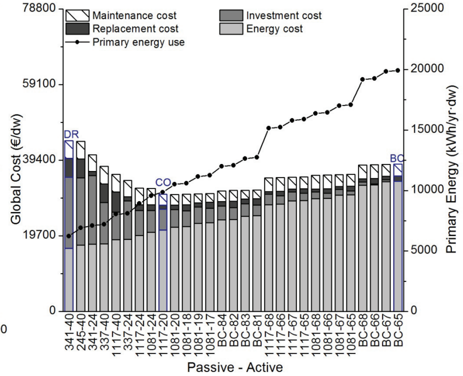


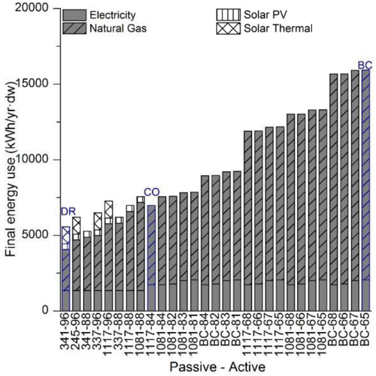
PASSIVE	FAÇADE	ROOF	WINDOW	SOLAR PROT.	INITIAL INVESTMENT €	ANNUAL LDP %	COLD LDP %	WARM LDP %	OVERHEATING Hours
BC	Base case	Base case	Base case	NO	0	44.9	64.8	12.8	0
1081	AC–Cel. 10	Base case	Base case	NO	1,021	42.0	61.4	11.0	0
1117	AC–Cel. 10	INT–RW 8	Base case	NO	1,867	41.1	60.0	10.6	0
61	EXT–EPS 4	Base case	Base case	NO	3,688	40.2	58.9	10.0	0
337	EXT–EPS 12	INT–RW 8	Base case	NO	5,382	38.1	56.1	9.2	0
245	EXT–EPS 10	Base case	4/16/4PVC	NO	12,267	36.0	53.0	8.7	3
341	EXT–EPS 12	INT–RW 8	4/16/4PVC	NO	13,284	34.4	50.6	8.2	3

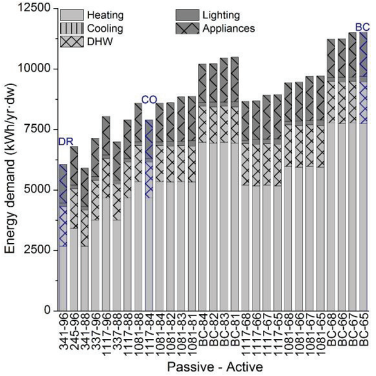
OptiHab - Typology BT-6

ACTIVE ANALYSIS: Primary energy use vs. Global cost









	PASSIVE	HEATING + DHW	COOLING	PV SYSTEM	LIGHTING	AWARENESS CAMPAIGN	PRIMARY ENERGY kWh/yr·dw	ENERGY SAVINGS %	GLOBAL COSTS €/dw	INITIAL INVESTMENT €/dw
BC	BC	Conventional NG boiler	NO	NO	CFL	NO	19,912	-	39,391	0
CO	1081	Condensing NG boiler	NO	NO	LED	YES	9,872	50	30,529	5,441
DR	341	Condensing NG boiler+ST	NO	YES	LED	YES	6,226	69	44,486	18,592

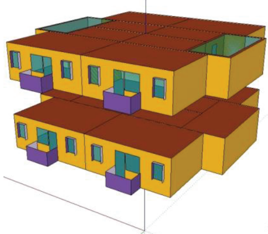
OptiHab - Typology BT-6 [4/9]

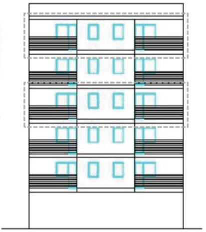
Block of apartments between buildings
Year of construction: 1951-1980
Nº Floors: Commercial floor + 5
Nº Dwellings: 10
Dwelling surface: 78.8 m²
Occupants: 2 adults + 1 child

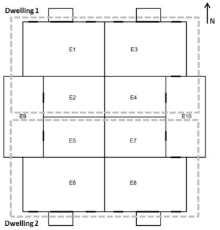
- *Façade:* with air chamber
- *Roof:* with air chamber
- *Windows:* aluminium without thermal break with clear double glazing 4/12/4
- *Solar protection:* blinds
- *Observations:*

CLIMATE: B3 (Tarragona)

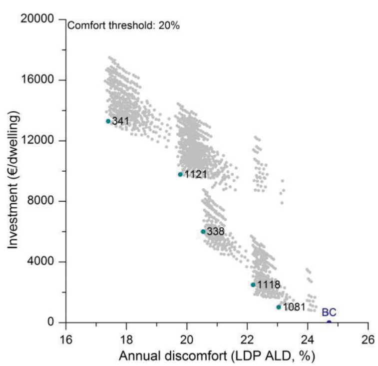
NATURAL VENTILATION: YES

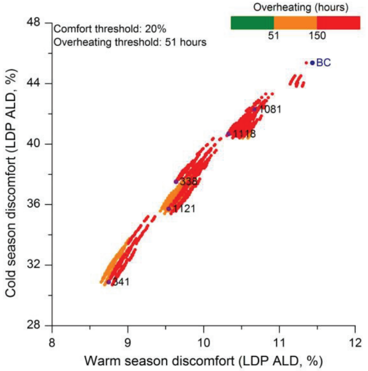






PASSIVE ANALYSIS: Thermal comfort vs. Initial investment cost

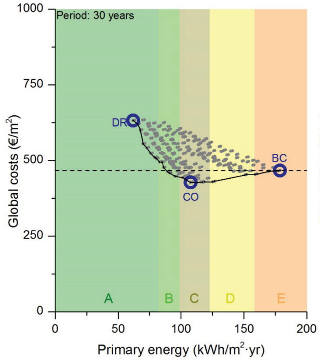


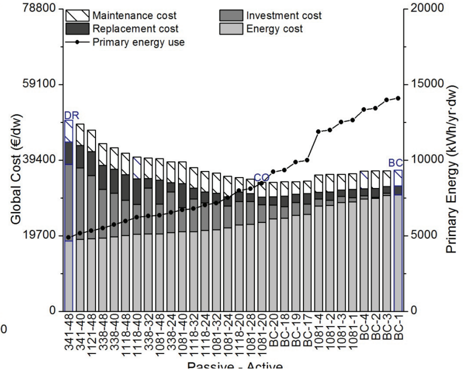


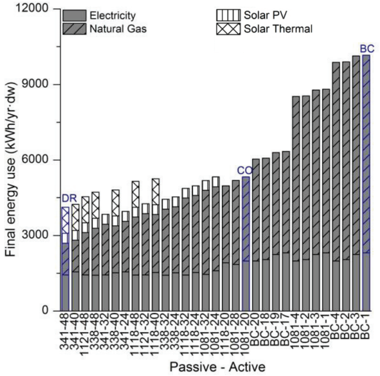
PASSIVE	FAÇADE	ROOF	WINDOW	SOLAR PROT.	INITIAL INVESTMENT €	ANNUAL LDP %	COLD LDP %	WARM LDP %	OVERHEATING Hours
BC	Base case	Base case	Base case	NO	0	24.7	45.4	11.4	226
1081	AC–Cel. 10	Base case	Base case	NO	1,021	23.0	42.3	10.7	252
1118	AC–Cel. 10	INT–RW 8	Base case	YES	2,485	22.2	40.7	10.3	185
338	EXT–EPS 12	INT–RW 8	Base case	YES	5,999	20.5	37.5	9.6	196
1121	AC–Cel. 10	INT–RW 8	4/16/4PVC	NO	9,770	19.8	35.7	9.5	162
341	EXT–EPS 12	INT–RW 8	4/16/4PVC	NO	13,284	17.4	30.9	8.7	185

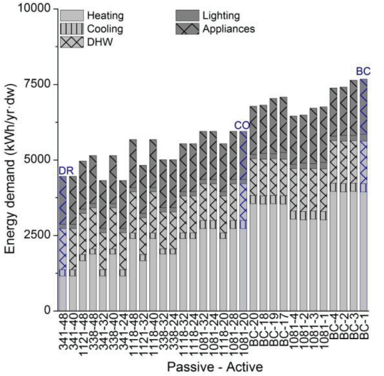
OptiHab - Typology BT-6

ACTIVE ANALYSIS: Primary energy use vs. Global cost









	PASSIVE	HEATING + DHW	COOLING	PV SYSTEM	LIGHTING	AWARENESS CAMPAIGN	PRIMARY ENERGY kWh/yr·dw	ENERGY SAVINGS %	GLOBAL COSTS €/dw	INITIAL INVESTMENT €/dw
BC	BC	Conventional NG boiler	Conventional AC Split	NO	CFL	NO	14,094	-	36,803	0
CO	1081	Condensing NG boiler	Conventional AC Split	NO	LED	YES	8,479	40	33,651	4,594
DR	341	Condensing NG boiler+ST	Efficient AC Split	YES	LED	YES	4,886	65	49,820	19,971

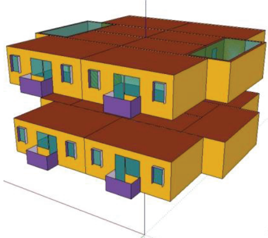
OptiHab - Typology BT-6 [5/9]

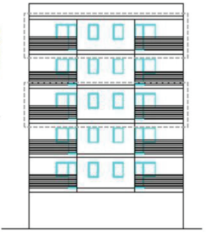
Block of apartments between buildings
Year of construction: 1951-1980
Nº Floors: Commercial floor + 5
Nº Dwellings: 10
Dwelling surface: 78.8 m²
Occupants: 2 adults + 1 child

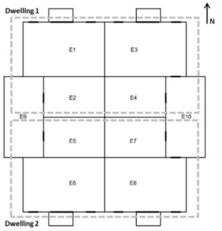
- ➢ *Façade:* with air chamber
- ➢ *Roof:* with air chamber
- ➢ *Windows:* aluminium without thermal break with clear double glazing 4/12/4
- ➢ *Solar protection:* blinds
- ➢ *Observations:*

CLIMATE: B3 (Tarragona)

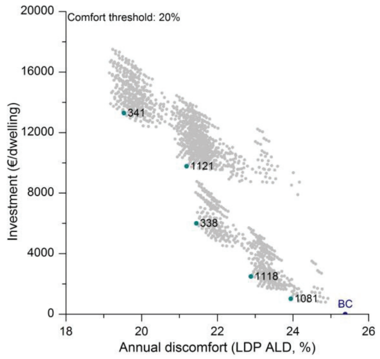
NATURAL VENTILATION: NO

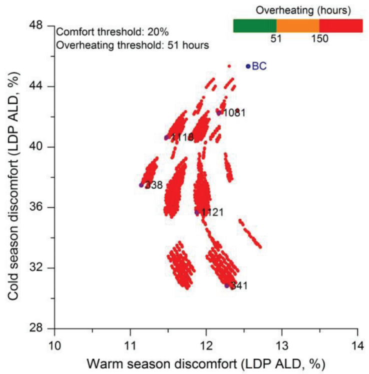






PASSIVE ANALYSIS: Thermal comfort vs. Initial investment cost

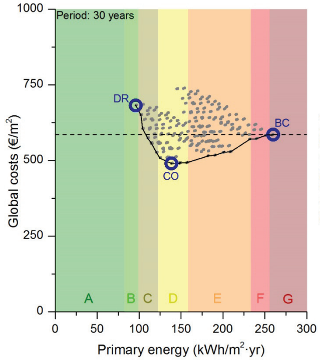


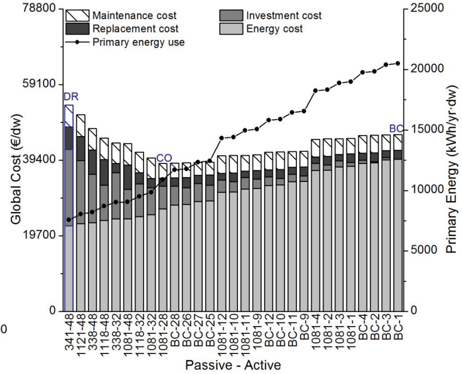


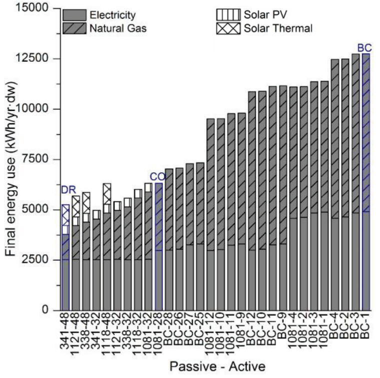
PASSIVE	FAÇADE	ROOF	WINDOW	SOLAR PROT.	INITIAL INVESTMENT €	ANNUAL LDP %	COLD LDP %	WARM LDP %	OVERHEATING Hours
BC	Base case	Base case	Base case	NO	0	25.4	45.3	12.2	666
1081	AC–Cel. 10	Base case	Base case	NO	1,021	23.9	42.3	11.8	772
1118	AC–Cel. 10	INT–RW 8	Base case	YES	2,485	22.9	40.6	11.4	620
338	EXT–EPS 12	INT–RW 8	Base case	YES	5,999	21.4	37.5	11.1	692
1121	AC–Cel. 10	INT–RW 8	4/16/4PVC	NO	9,770	21.2	35.7	11.9	982
341	EXT–EPS 12	INT–RW 8	4/16/4PVC	NO	13,284	19.5	30.8	12.4	1284

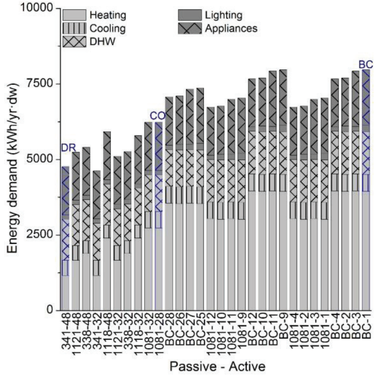
OptiHab - Typology BT-6

ACTIVE ANALYSIS: Primary energy use vs. Global cost









	PASSIVE	HEATING + DHW	COOLING	PV SYSTEM	LIGHTING	AWARENESS CAMPAIGN	PRIMARY ENERGY kWh/yr·dw	ENERGY SAVINGS %	GLOBAL COSTS €/dw	INITIAL INVESTMENT €/dw
BC	BC	Conventional NG boiler	Conventional AC Split	NO	CFL	NO	20,490	-	46,117	0
CO	1081	Condensing NG boiler	Efficient AC Split	NO	LED	YES	10,924	47	38,591	5,973
DR	341	Condensing NG boiler+ST	Efficient AC Split	YES	LED	YES	7,572	63	53,732	19,971

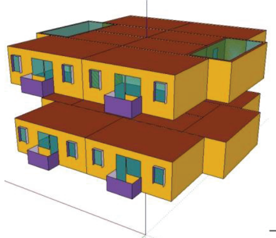
OptiHab - Typology BT-6 [6/9]

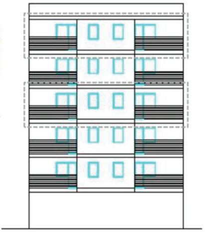
Block of apartments between buildings
Year of construction: 1951-1980
Nº Floors: Commercial floor + 5
Nº Dwellings: 10
Dwelling surface: 78.8 m²
Occupants: 2 adults + 1 child

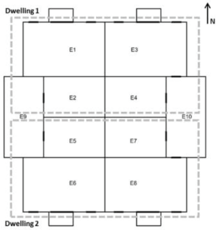
- *Façade:* with air chamber
- *Roof:* with air chamber
- *Windows:* aluminium without thermal break with clear double glazing 4/12/4
- *Solar protection:* blinds
- *Observations:*

CLIMATE: D3 (Lleida)

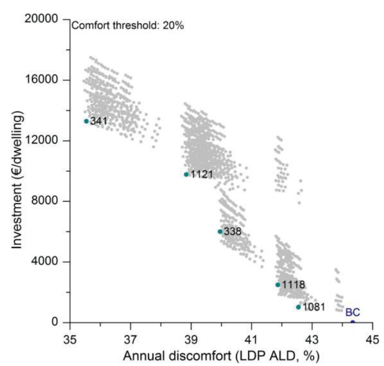
NATURAL VENTILATION: YES

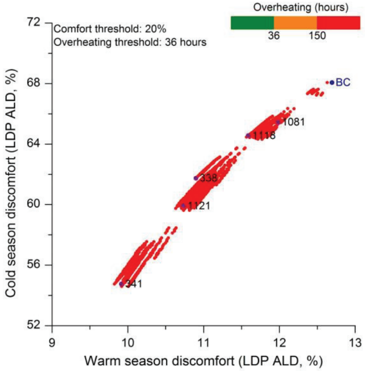






PASSIVE ANALYSIS: Thermal comfort vs. Initial investment cost

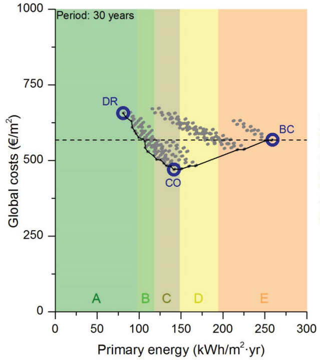


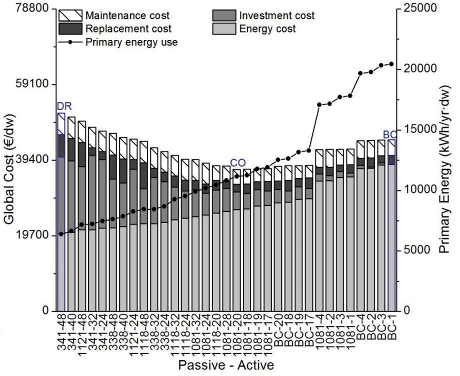


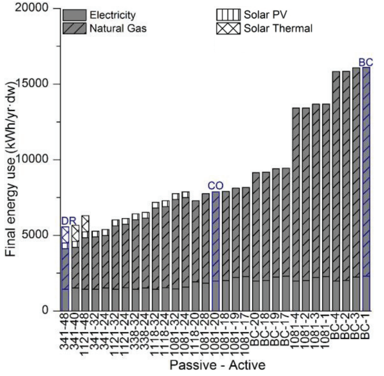
PASSIVE	FAÇADE	ROOF	WINDOW	SOLAR PROT.	INITIAL INVESTMENT €	ANNUAL LDP %	COLD LDP %	WARM LDP %	OVERHEATING Hours
BC	Base case	Base case	Base case	NO	0	44.3	68.1	12.7	362
1081	AC–Cel. 10	Base case	Base case	NO	1,021	42.5	65.5	12.0	377
1118	AC–Cel. 10	INT–RW 8	Base case	YES	2,485	41.9	64.6	11.6	335
338	EXT–EPS 12	INT–RW 8	Base case	YES	5,999	40.0	61.7	10.9	336
1121	AC–Cel. 10	INT–RW 8	4/16/4PVC	NO	9,770	38.8	59.9	10.7	290
341	EXT–EPS 12	INT–RW 8	4/16/4PVC	NO	13,284	35.5	54.7	9.9	295

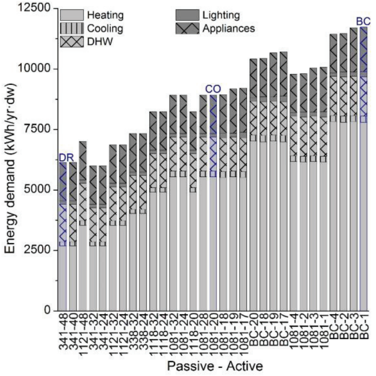
OptiHab - Typology BT-6

ACTIVE ANALYSIS: Primary energy use vs. Global cost









	PASSIVE	HEATING + DHW	COOLING	PV SYSTEM	LIGHTING	AWARENESS CAMPAIGN	PRIMARY ENERGY kWh/yr·dw	ENERGY SAVINGS %	GLOBAL COSTS €/dw	INITIAL INVESTMENT €/dw
BC	BC	Conventional NG boiler	Conventional AC Split	NO	CFL	NO	20,431	-	44,757	0
CO	1081	Condensing NG boiler	Conventional AC Split	NO	LED	YES	11,160	45	37,008	4,594
DR	341	Condensing NG boiler+ST	Efficient AC Split	YES	LED	YES	6,394	69	51,712	19,971

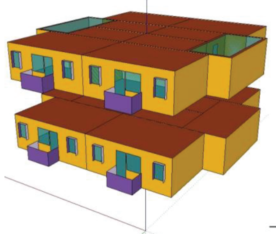
OptiHab - Typology BT-6 [7/9]

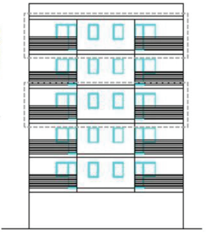
Block of apartments between buildings
Year of construction: 1951-1980
Nº Floors: Commercial floor + 5
Nº Dwellings: 10
Dwelling surface: 78.8 m²
Occupants: 2 adults + 1 child

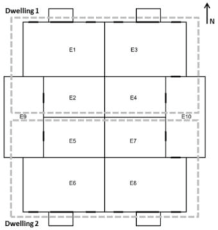
- *Façade:* with air chamber
- *Roof:* with air chamber
- *Windows:* aluminium without thermal break with clear double glazing 4/12/4
- *Solar protection:* blinds
- *Observations:*

CLIMATE: D3 (Lleida)

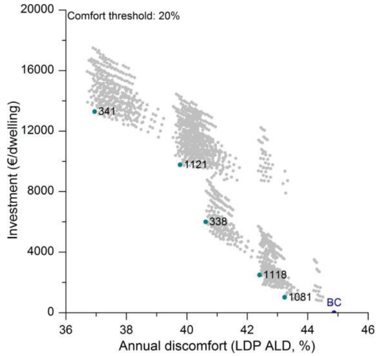
NATURAL VENTILATION: NO

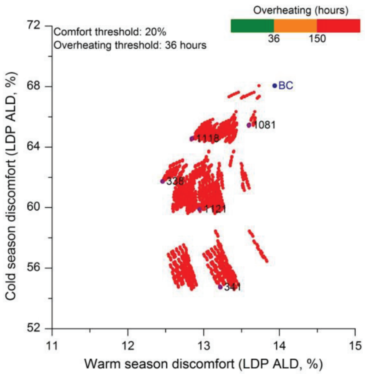






PASSIVE ANALYSIS: Thermal comfort vs. Initial investment cost

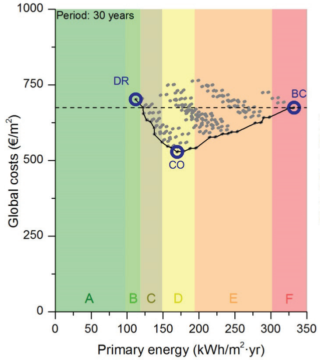


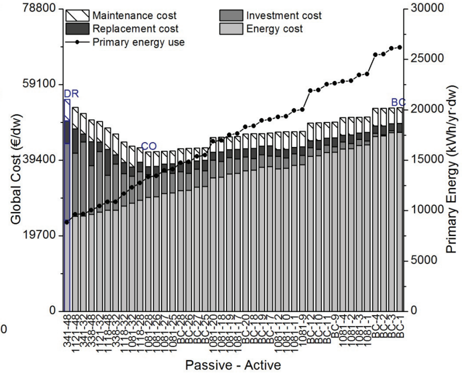


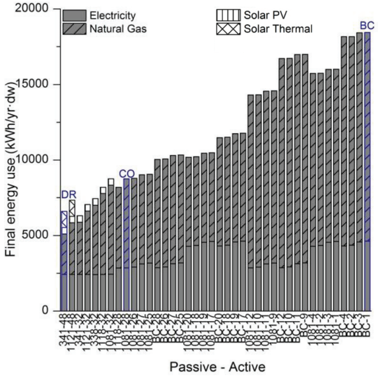
PASSIVE	FAÇADE	ROOF	WINDOW	SOLAR PROT.	INITIAL INVESTMENT €	ANNUAL LDP %	COLD LDP %	WARM LDP %	OVERHEATING Hours
BC	Base case	Base case	Base case	NO	0	44.9	68.0	13.9	559
1081	AC–Cel. 10	Base case	Base case	NO	1,021	43.2	65.4	13.6	582
1118	AC–Cel. 10	INT–RW 8	Base case	YES	2,485	42.4	64.5	12.8	553
338	EXT–EPS 12	INT–RW 8	Base case	YES	5,999	40.6	61.7	12.4	576
1121	AC–Cel. 10	INT–RW 8	4/16/4PVC	NO	9,770	39.8	59.9	12.9	645
341	EXT–EPS 12	INT–RW 8	4/16/4PVC	NO	13,284	36.9	54.7	13.2	760

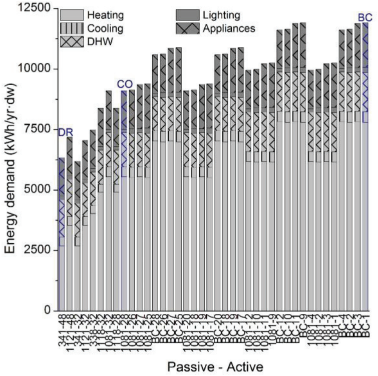
OptiHab - Typology BT-6

ACTIVE ANALYSIS: Primary energy use vs. Global cost







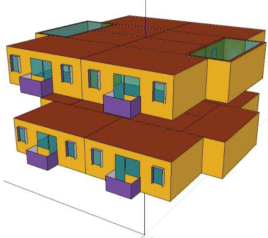


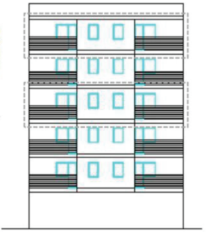
	PASSIVE	HEATING + DHW	COOLING	PV SYSTEM	LIGHTING	AWARENESS CAMPAIGN	PRIMARY ENERGY kWh/yr·dw	ENERGY SAVINGS %	GLOBAL COSTS €/dw	INITIAL INVESTMENT €/dw
BC	BC	Conventional NG boiler	Conventional AC Split	NO	CFL	NO	26,180	-	53,128	0
CO	1081	Condensing NG boiler	Efficient AC Split	NO	LED	YES	13,365	49	41,598	5,973
DR	341	Condensing NG boiler+ST	Efficient AC Split	YES	LED	YES	8,828	66	55,256	19,971

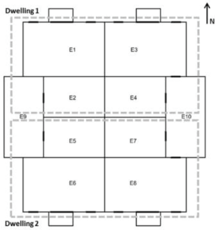
CONCLUDING REMARKS

Block of apartments between buildings
Year of construction: 1951-1980
Nº Floors: Commercial floor + 5
Nº Dwellings: 10
Dwelling surface: 78.8 m²
Occupants: 2 adults + 1 child

➢*Façade:* with air chamber
➢*Roof*: with air chamber
➢*Windows:* aluminium without thermal break with clear double glazing 4/12/4
➢*Solar protection:* blinds
➢*Observations:*





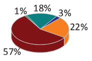


- The external insulation has a better thermal performance than the internal and the air chamber insulation, however the costs are higher.
- The roof insulation has a positive effect on the under roof dwelling, reducing the hours of overheating and improving the cold season comfort. There are not significant differences between the types of insulation evaluated for this typology (internal and external insulation).
- The improvement of the window performance has a high impact in the annual discomfort (around the 5% of reduction), nevertheless its initial investment cost is high (around 8,000 €/dw).
- The optimal use of the solar protection helps to reduce the hours of overheating, specially in the typology without natural ventilation.
- When there is no natural ventilation, the measures that provide better cold season comfort have a negative effect over the warm season comfort specially increasing the hours of overheating. In those cases, it is suitable to combine with an optimal use of solar protection, in order to not get worse the overheating.
- There are cost-optimal solutions which include a combination of passive and active measures.
- The measures that provide a lower primary energy consumption imply a deep renovation and the use of renewable energy systems.
- As the heating demand is reduced, the electric consumption due to appliances becomes more important. Specific solutions have to be considered in future studies.

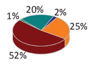
CONCLUDING REMARKS - CLIMATE: C2 (Barcelona) – NATURAL VENTILATION: YES

- **Comfort evaluation**
  The annual discomfort can be reduced from 30% to 21% only with passive measures.
  There are problems of overheating during the warm season (41-150 hours). The cooling system is required to guarantee comfort conditions.
- **Base case (BC)**
  Energy label = E (192 kWhPE/m²·yr).
  CO$_2$ emissions = 30 kgCO$_2$/m²·yr
- **Cost Optimal measures (CO)**
  Energy label= C (110 kWhPE/m²·yr). CO$_2$ emissions = 16 kgCO$_2$/m²·yr
  The condensing boiler is the active measure that has a high impact on the primary energy consumption (32% of reduction)
- **Low energy measures (DR)**
  Energy label = A (66 kWhPE/m²·yr). CO$_2$ emissions = 9 kgCO$_2$/m²·yr
  Heating demand could be reduced in 68%.
  Primary energy savings: up to 65%

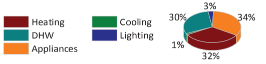
BASE CASE
E.demand = 8,412 kWh/dw·yr



COST-OPTIMAL
E.demand = 6,476 kWh/dw·yr



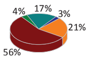
LOW ENERGY
E.demand = 4,756 kWh/dw·yr



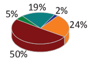
CONCLUDING REMARKS - CLIMATE: C2 (Barcelona) – NATURAL VENTILATION: NO

- **Comfort evaluation**
  The annual discomfort can be reduced from 30% to 22% only with passive measures.
  There are problems of overheating during the warm season (>150hours). The cooling system is required to guarantee comfort conditions.
- **Base case (BC)**
  Energy label = F (274 kWhEP/m²·yr).
  CO$_2$ emissions = 38 kgCO$_2$/m²·yr
- **Cost Optimal measures (CO)**
  Energy label= D (145 kWhEP/m²·yr).
  CO$_2$ emissions = 19 kgCO$_2$/m²·yr
  The condensing boiler is the active measure that has a high impact on the primary energy consumption (26% of reduction)
- **Low energy measures (DR)**
  Energy label = B (101 kWhEP/m²·yr).
  CO$_2$ emissions = 12 kgCO$_2$/m²·yr
  Heating demand could be reduced in 68%.
  Primary energy savings: up to 63%

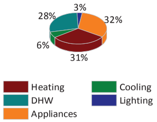
BASE CASE
E.demand = 8,637 kWh/dw·yr



COST-OPTIMAL
E.demand = 6,709 kWh/dw·yr



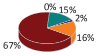
LOW ENERGY
E.demand = 5,000 kWh/dw·yr



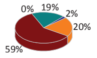
CONCLUDING REMARKS - CLIMATE: E1 (Pre-Pyrenees) – NATURAL VENTILATION: YES

- **Comfort evaluation**
  The annual discomfort can be reduced from 45% to 34% only with passive measures.
  There are no problems of overheating during the warm season (<33 hours). The cooling system could be avoided to guarantee comfort conditions.
  The use of solar protections has a negligible effect in this climate during the warm season.
- **Base case (BC)**
  Energy label = E (253 kWhPE/m²·yr).
  CO$_2$ emissions = 42 kgCO$_2$/m²·yr
- **Cost Optimal measures (CO)**
  Energy label= B (125 kWhPE/m²·yr).
  CO$_2$ emissions = 19 kgCO$_2$/m²·yr
  The condensing boiler is the active measure that has a high impact on the primary energy consumption (36% of reduction)
- **Low energy measures (DR)**
  Energy label = A (79 kWhPE/m²·yr).
  CO$_2$ emissions = 11 kgCO$_2$/m²·yr
  Heating demand could be reduced in 65 %.
  Primary energy savings: up to 69%

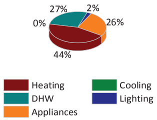
BASE CASE
E.demand = 11,518 kWh/dw·yr



COST-OPTIMAL
E.demand = 7,891 kWh/dw·yr



LOW ENERGY
E.demand = 6,054 kWh/dw·yr



CONCLUDING REMARKS	Block of apartments between buildings Year of construction: 1951-1980 Nº Floors: Commercial floor + 5 Nº Dwellings: 10 Dwelling surface: 78.8 m² Occupants: 2 adults + 1 child	➢*Façade:* with air chamber ➢*Roof*: with air chamber ➢*Windows:* aluminium without thermal break with clear double glazing 4/12/4 ➢*Solar protection:* blinds ➢*Observations:*

CONCLUDING REMARKS - CLIMATE: B3 (Tarragona) – NATURAL VENTILATION: YES

- **Comfort evaluation**

  The annual discomfort can be reduced form 25% to 17% only with passive measures.

  There are problems of overheating during the warm season (in most of the cases >150hours). The cooling system is required to guarantee comfort conditions.
- **Base case (BC)**

  Energy label = E (179 kWhPE/m^2·yr).

  CO$_2$ emissions = 27 kgCO$_2$/m^2·yr
- **Cost Optimal measures (CO)**

  Energy label= C (108 kWhPE/m^2·yr).

  CO$_2$ emissions = 15 kgCO$_2$/m^2·yr

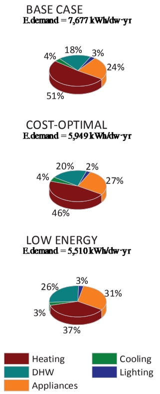
  The condensing boiler is the active measure that has a high impact on the primary energy consumption (29% of reduction)
- **Low energy measures (DR)**

  Energy label = A (62 kWhPE/m^2·yr).

  CO$_2$ emissions = 8 kgCO$_2$/m^2·yr

  Heating demand could be reduced in 52%.

  Primary energy savings: up to 65%



CONCLUDING REMARKS - CLIMATE: B3 (Tarragona) – NATURAL VENTILATION: NO

- **Comfort evaluation**

  The annual discomfort can be reduced from 25% to 19% only with passive measures.

  There are problems of overheating during the warm season (>150hours). The cooling system is required to guarantee comfort conditions.
- **Base case (BC)**

  Energy label = G (260 kWhPE/m^2·yr).

  CO$_2$ emissions = 35 kgCO$_2$/m^2·yr
- **Cost Optimal measures (CO)**

  Energy label= D (139 kWhPE/m^2·yr).

  CO$_2$ emissions = 18 kgCO$_2$/m^2·yr

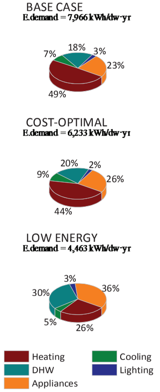
  The condensing boiler is the active measure that has a high impact on the primary energy consumption (20% of reduction)
- **Low energy measures (DR)**

  Energy label = B (96 kWhPE/m^2·yr).

  CO$_2$ emissions = 11 kgCO$_2$/m^2·yr

  Heating demand could be reduced in 70%.

  Primary energy savings: up to 63%



CONCLUDING REMARKS - CLIMATE: D3 (Lleida) – NATURAL VENTILATION: YES

- **Comfort evaluation**

  The annual discomfort can be reduced from 44% to 35% only with passive measures.

  There are problems of overheating during the warm season (>150hours). The cooling system is required to guarantee comfort conditions.
- **Base case (BC)**

  Energy label = E (259 kWhEP/m^2·yr).

  CO$_2$ emissions = 42 kgCO$_2$/m^2·yr
- **Cost Optimal measures (CO)**

  Energy label= C (142 kWhEP/m^2·yr).

  CO$_2$ emissions = 21 kgCO$_2$/m^2·yr

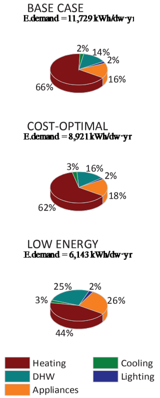
  The condensing boiler is the active measure that has a high impact on the primary energy consumption (35% of reduction)
- **Low energy measures (DR)**

  Energy label = A (81 kWhEP/m^2·yr).

  CO$_2$ emissions = 11 kgCO$_2$/m^2·yr

  Heating demand could be reduced in 66%.

  Primary energy savings: up to 69%



CONCLUDING REMARKS - CLIMATE: D3 (Lleida) – NATURAL VENTILATION: NO

- **Comfort evaluation**

  The annual discomfort can be reduced from 45% to 37% only with passive measures.

  There are problems of overheating during the warm season (>150hours). The cooling system is required to guarantee comfort conditions.
- **Base case (BC)**

  Energy label = F (332 kWhPE/m^2·yr).

  CO$_2$ emissions = 50 kgCO$_2$/m^2·yr
- **Cost Optimal measures (CO)**

  Energy label= D (170 kWhPE/m^2·yr).

  CO$_2$ emissions= 24 kgCO$_2$/m^2·yr

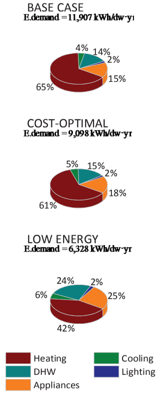
  The condensing boiler is the active measure that has a high impact on the primary energy consumption (27% of reduction)
- **Low energy measures (DR)**

  Energy label = B (112 kWhPE/m^2·yr).

  CO$_2$ emissions = 14 kgCO$_2$/m^2·yr

  Heating demand could be reduced in 66 %.

  Primary energy savings: up to 66%

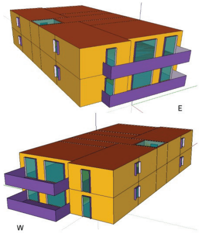


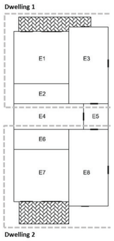
OptiHab - Typology BT-8

Building type: Isolated block of apartments
Year of construction: 1991-2006
Nº Floors: Commercial floor + 3
Nº Dwellings: 12
Dwelling surface: 103.2 m²
Occupants: 2 adults + 1 child

Building representation:

Climate	Nº buildings	% building stock
C2 (Barcelona)	139 532	6.1
B3 (Tarragona)	24 301	1.1



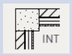
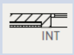
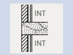
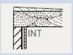


Building Characteristics

Envelope	Description	Thickness m	U-value W/m²K
Façade	Wall of 14 cm hollow brick with exterior mortar siding, 5cm of air chamber not ventilated, 40mm insulation and partition wall of 5cm holes brick with internal plaster siding.	0.26	0.625
Roof	Flat roof with double layer of ceramic tile, mortar, waterproofing, cellular concrete, 40mm of insulation with joist floor slab with joist-filler-block of concrete and plaster.	0.43	0.546
Party wall	Partition wall with perforated brick and siding in both sides	0.18	2.254
Internal wall	Wall of 14cm of perforated brick and siding in both sides	0.11	2.240
Floor framing	Unidirectional floor framing reinforced concrete, joist, slab of concrete, mortar and pavement tiles	0.28	2.304

Window	Description	U-value W/m²K	g-value -
Window frame	Aluminium without thermal break	3.44	0.76
Glazing	Clear double glazing 4/12/4		

Solar protection	Blinds	Air leakage (n_{50})	7.5

Cold bridge	Pilar in a wall	Pillar in a corner	Opening frame	Shutter box	Wall- floor junction	Wall-roof junction	Wall over external slab	Cantilever-wall junction
Description								
Linear thermal conductivity (Ψ, W/mK)	-	0.22	0.32	-	0.85	0.65	-	0.85

OptiHab - Typology BT-8

Equipment Characteristics

System	Description	Performance
Heating and DHW	Conventional natural gas boiler for individual centralize system (24kW)	η = 0.75
Cooling	Conventional air conditioning system (split) installed in 2 zones (5kW)	COP = 2.0
Lighting	Compact fluorescent lamps (2 W/m²)	Luminous efficacy = 0.6
Appliances	Refrigerator, washing machine, dishwasher, microwave, electric stove, electric oven, TV and computer.	Average household of a multifamily building in Mediterranean region

Energy efficiency measures

Measure	Description	Performance	Investment cost	Mainte-nance cost	Life-span
Façade insulation	External – EPS 4-12 cm	0.37 - 0.20 W/m²K	8,000 - 9,900 €/dw	-	40
	External – XPS 4-12 cm	0.38 - 0.21 W/m²K	8,900 - 11,400 €/dw	-	40
	Air chamber – mineral wool 3-10 cm	0.48 - 0.27 W/m²K	1,900 - 2,500 €/dw	-	40
	Air chamber – EPS + graphite 3-10 cm	0.43 - 0.23 W/m²K	2,300 - 4,800 €/dw	-	40
	Air chamber – cellulose 3-10 cm	0.37 - 0.25 W/m²K	1,900 - 2,200 €/dw	-	40
	Internal – EPS 4-8 cm	0.37 - 0.26 W/m²K	3,700 - 4,100 €/dw	-	40
	Internal –mineral wool 4-8 cm	0.40 - 0.29 W/m²K	2,700 - 2,900 €/dw	-	40
Roof insulation	Inverted – XPS 8-12 cm	0.26 - 0.20 W/m²K	5,400 - 5,800 €/dw	-	30
	Internal – rock wool 4-8 cm	0.37 - 0.27 W/m²K	1,600 - 1,700 €/dw	-	30
	Internal – EPS 4-8 cm	0.34 - 0.25 W/m²K	2,100 - 2,400 €/dw	-	30
Windows change	4/16/4 Aluminium with thermal break	2.8 W/m²K	8,200 €/dw	-	30
	4/16/4 PVC	2.8 W/m²K	7,400 €/dw	-	30
Sol. protec.	Awnings	-	1,200 €/dw	-	15
Heating and DHW system	Condensing boiler + Improve install. Performance	η = 1.09	2,740 €/dw	109 €/dw	20
	Biomass boiler + Improve install. Performance	-	-	-	-
	Heat pump air-wat. + Improve install. Performance	-	-	-	-
Cooling system	Efficient Air conditioning system (split)	COP = 4.0	1,380 €/dw	48 €/dw	15
	No cooling system	-	-	-	-
Lighting	LED	Luminous eff. = 0.8	546 €/dw	-	20
Awareness	Awareness campaign	-	290 €/dw	24 €/dw	20
Solar thermal	16 m²/building + 1500l storage tank	-	2,200 €/dw	10€/dw	15
	-	-	-	-	-
PV system	20 m²/building - 240 Wp/module (12 modules)	-	895 €/dw	73€/dw	20
	-	-	-	-	-

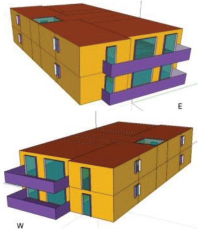
OptiHab - Typology BT-8 [1/5]

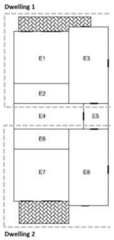
Isolated block of apartments
Year of construction: 1991-2007
Nº Floors: Commercial floor + 3
Nº Dwellings: 12
Dwelling surface: 103.2 m²
Occupants: 2 adults + 1 child

- *Façade:* with air chamber and insulation
- *Roof:* with insulation
- *Windows:* aluminium without thermal break with clear double glazing 4/12/4
- *Solar protection:* blinds
- *Observations:*

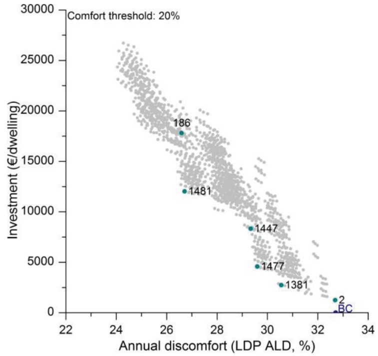
CLIMATE: C2 (Barcelona)

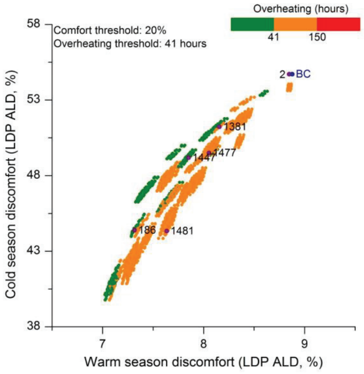
NATURAL VENTILATION: YES





PASSIVE ANALYSIS: Thermal comfort vs. Initial investment cost

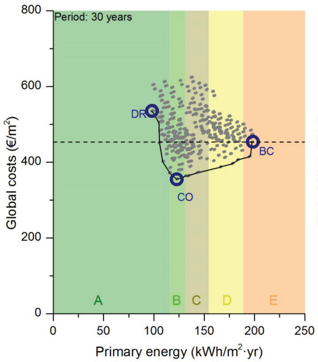


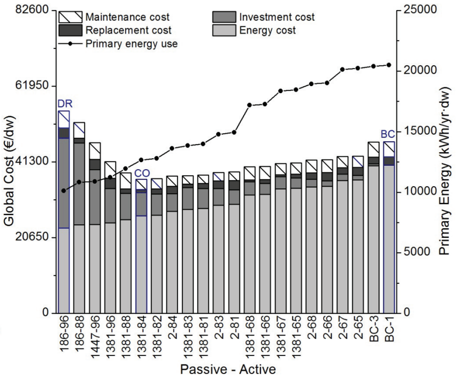


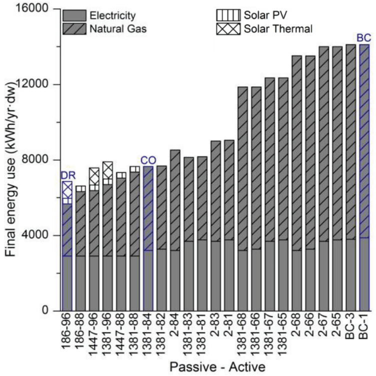
PASSIVE	FAÇADE	ROOF	WINDOW	SOLAR PROT.	INITIAL INVESTMENT €	ANNUAL LDP %	COLD LDP %	WARM LDP %	OVERHEATING Hours
BC	Base case	Base case	Base case	NO	0	32.7	54.7	8.9	45
2	Base case	Base case	Base case	YES	1,235	32.7	54.7	8.8	41
1381	INT–RW 6	Base case	Base case	NO	2,734	30.6	51.2	8.2	40
1477	INT–RW 8	INT–RW 8	Base case	NO	4,580	29.6	49.5	8.1	51
1447	INT–RW 8	EXT–EPS 8	Base case	NO	8,315	29.3	49.2	7.9	36
1481	INT–RW 8	INT–RW 8	4/16/4PVC	NO	12,029	26.7	44.3	7.6	62
186	EXT–EPS 8	Base case	4/16/4PVC	YES	17,809	26.6	44.4	7.3	39

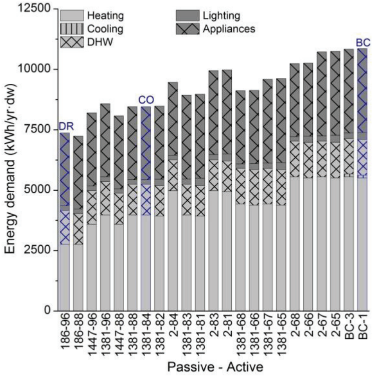
OptiHab - Typology BT-8

ACTIVE ANALYSIS: Primary energy use vs. Global cost









	PASSIVE	HEATING + DHW	COOLING	PV SYSTEM	LIGHTING	AWARENESS CAMPAIGN	PRIMARY ENERGY kWh/yr·dw	ENERGY SAVINGS %	GLOBAL COSTS €/dw	INITIAL INVESTMENT €/dw
BC	BC	Conventional NG boiler	Conventional AC Split	NO	CFL	NO	20,501	-	46,828	0
CO	1381	Condensing NG boiler	NO	NO	LED	YES	12,677	38	36,642	6,307
DR	186	Condensing NG boiler+ST	NO	YES	LED	YES	10,134	51	55,206	24,477

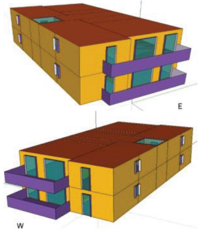
OptiHab - Typology BT-8 [2/5]

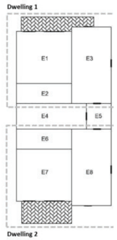
Isolated block of apartments
Year of construction: 1991-2007
Nº Floors: Commercial floor + 3
Nº Dwellings: 12
Dwelling surface: 103.2 m²
Occupants: 2 adults + 1 child

- *Façade:* with air chamber and insulation
- *Roof:* with insulation
- *Windows:* aluminium without thermal break with clear double glazing 4/12/4
- *Solar protection:* blinds
- *Observations:*

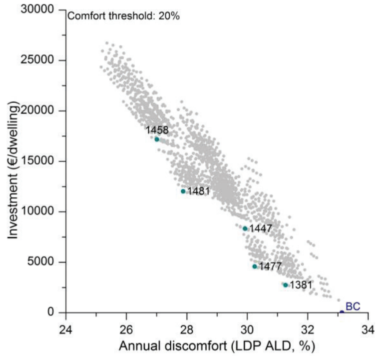
CLIMATE: C2 (Barcelona)

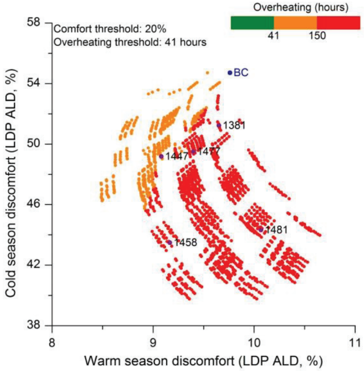
NATURAL VENTILATION: NO





PASSIVE ANALYSIS: Thermal comfort vs. Initial investment cost

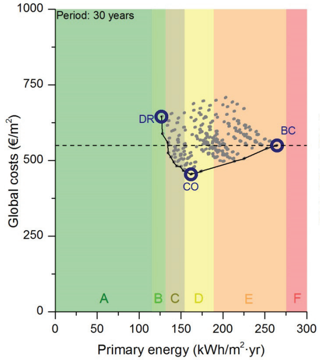


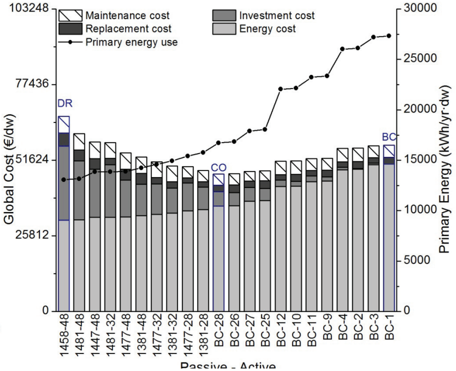


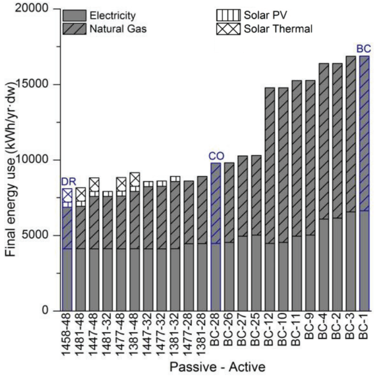
PASSIVE	FAÇADE	ROOF	WINDOW	SOLAR PROT.	INITIAL INVESTMENT €	ANNUAL LDP %	COLD LDP %	WARM LDP %	OVERHEATING Hours
BC	Base case	Base case	Base case	NO	0	33.1	54.7	9.8	120
1381	INT–RW 6	Base case	Base case	NO	2,734	31.3	51.2	9.7	202
1477	INT–RW 8	INT–RW 8	Base case	NO	4,580	30.2	49.5	9.4	182
1447	INT–RW 8	EXT–EPS 8	Base case	NO	8,315	29.9	49.2	9.1	109
1481	INT–RW 8	INT–RW 8	4/16/4PVC	NO	12,029	27.9	44.3	10.1	390
1458	INT–RW 8	EXT–EPS 10	4/16/4PVC	YES	17,162	27.0	43.5	9.2	217

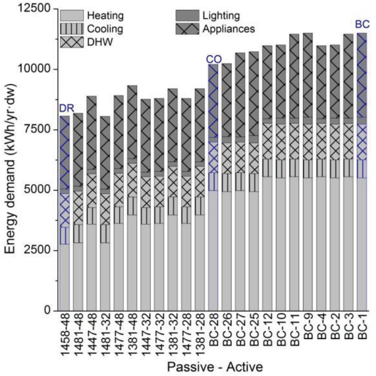
OptiHab - Typology BT-8

ACTIVE ANALYSIS: Primary energy use vs. Global cost









	PASSIVE	HEATING + DHW	COOLING	PV SYSTEM	LIGHTING	AWARENESS CAMPAIGN	PRIMARY ENERGY kWh/yr·dw	ENERGY SAVINGS %	GLOBAL COSTS €/dw	INITIAL INVESTMENT €/dw
BC	BC	Conventional NG boiler	Conventional AC Split	NO	CFL	NO	27,315	-	56,750	0
CO	BC	Condensing NG boiler	Efficient AC Split	NO	LED	YES	16,715	39	46,909	4,953
DR	1458	Condensing NG boiler+ST	Efficient AC Split	YES	LED	YES	13,084	52	66,589	25,210

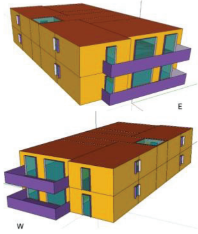
OptiHab - Typology BT-8 [3/5]

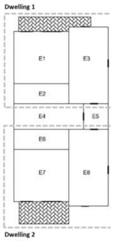
Isolated block of apartments
Year of construction: 1991-2007
Nº Floors: Commercial floor + 3
Nº Dwellings: 12
Dwelling surface: 103.2 m²
Occupants: 2 adults + 1 child

- *Façade:* with air chamber and insulation
- *Roof:* with insulation
- *Windows:* aluminium without thermal break with clear double glazing 4/12/4
- *Solar protection:* blinds
- *Observations:*

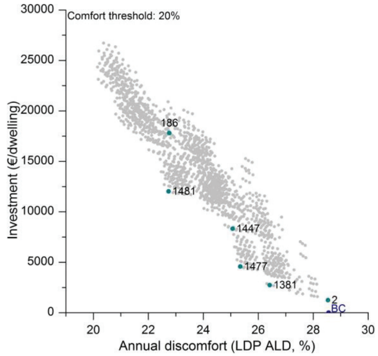
CLIMATE: B3 (Tarragona)

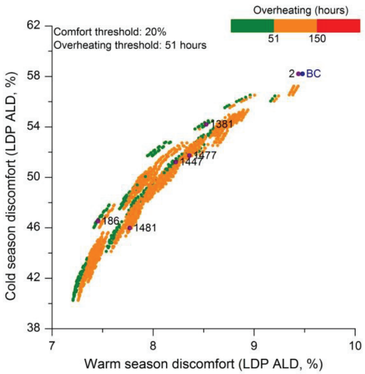
NATURAL VENTILATION: YES





PASSIVE ANALYSIS: Thermal comfort vs. Initial investment cost

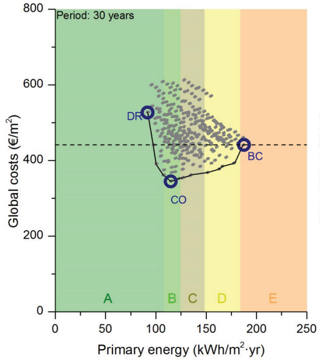


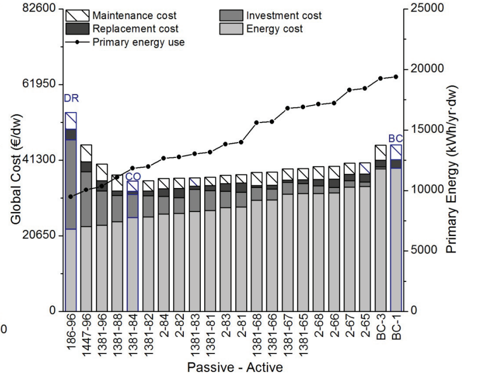


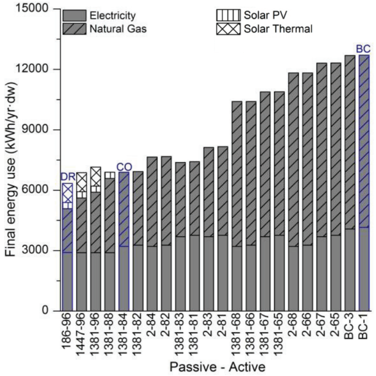
PASSIVE	FAÇADE	ROOF	WINDOW	SOLAR PROT.	INITIAL INVESTMENT €	ANNUAL LDP %	COLD LDP %	WARM LDP %	OVERHEATING Hours
BC	Base case	Base case	Base case	NO	0	28.6	58.2	9.5	57
2	Base case	Base case	Base case	YES	1,235	28.5	58.2	9.4	46
1381	INT–RW 6	Base case	Base case	NO	2,734	26.4	54.2	8.5	50
1477	INT–RW 8	INT–RW 8	Base case	NO	4,580	25.3	51.7	8.4	75
1447	INT–RW 8	EXT–EPS 8	Base case	NO	8,315	25.1	51.2	8.2	48
1481	INT–RW 8	INT–RW 8	4/16/4PVC	NO	12,029	22.7	46.0	7.8	93
186	EXT–EPS 8	Base case	4/16/4PVC	YES	17,809	22.8	46.2	7.4	47

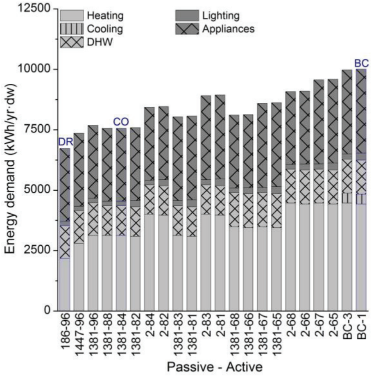
OptiHab - Typology BT-8

ACTIVE ANALYSIS: Primary energy use vs. Global cost









	PASSIVE	HEATING + DHW	COOLING	PV SYSTEM	LIGHTING	AWARENESS CAMPAIGN	PRIMARY ENERGY kWh/yr·dw	ENERGY SAVINGS %	GLOBAL COSTS €/dw	INITIAL INVESTMENT €/dw
BC	BC	Conventional NG boiler	Conventional AC Split	NO	CFL	NO	19,375	-	45,549	0
CO	1381	Condensing NG boiler	NO	NO	LED	YES	11,855	39	35,608	6,307
DR	186	Condensing NG boiler+ST	NO	YES	LED	YES	9,482	51	54,379	24,477

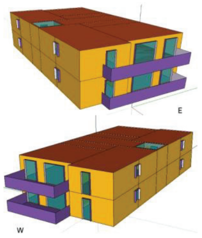
OptiHab - Typology BT-8 [4/5]

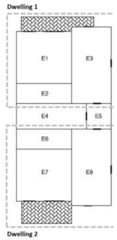
Isolated block of apartments
Year of construction: 1991-2007
Nº Floors: Commercial floor + 3
Nº Dwellings: 12
Dwelling surface: 103.2 m²
Occupants: 2 adults + 1 child

- *Façade:* with air chamber and insulation
- *Roof:* with insulation
- *Windows:* aluminium without thermal break with clear double glazing 4/12/4
- *Solar protection:* blinds
- *Observations:*

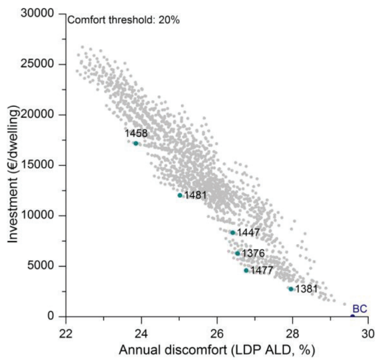
CLIMATE: B3 (Tarragona)

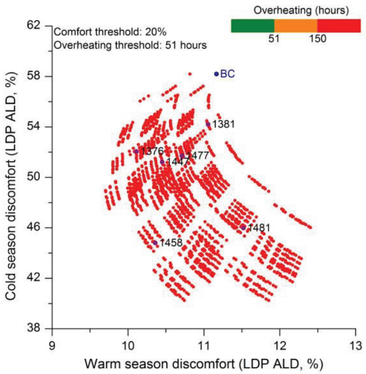
NATURAL VENTILATION: NO





PASSIVE ANALYSIS: Thermal comfort vs. Initial investment cost

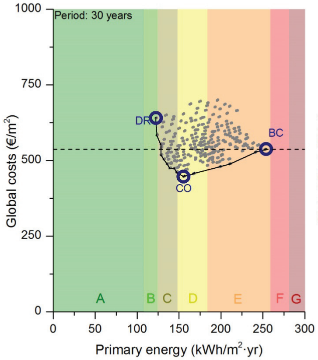


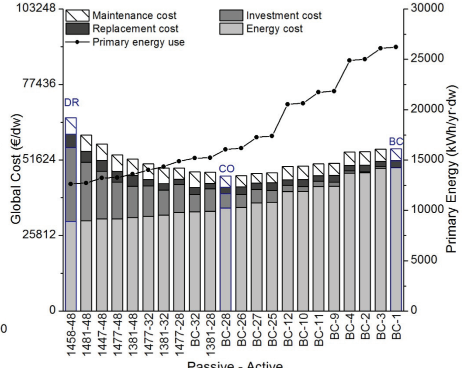


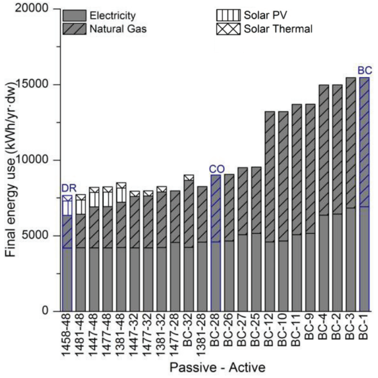
PASSIVE	FAÇADE	ROOF	WINDOW	SOLAR PROT.	INITIAL INVESTMENT €	ANNUAL LDP %	COLD LDP %	WARM LDP %	OVERHEATING Hours
BC	Base case	Base case	Base case	NO	0	29.6	58.2	11.2	353
1381	INT–RW 6	Base case	Base case	NO	2,734	28.0	54.2	11.1	557
1477	INT–RW 8	INT–RW 8	Base case	NO	4,580	26.8	51.7	10.7	506
1376	INT–RW 4	INT–EPS 8	Base case	YES	6,263	26.5	52.1	10.1	364
1447	INT–RW 8	EXT–EPS 8	Base case	NO	8,315	26.4	51.2	10.4	449
1481	INT–RW 8	INT–RW 8	4/16/4PVC	NO	12,029	25.0	46.0	11.5	902
1458	INT–RW 8	EXT–EPS 10	4/16/4PVC	YES	17,162	23.8	44.8	10.4	634

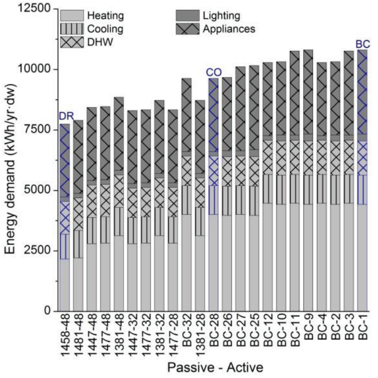
OptiHab - Typology BT-8

ACTIVE ANALYSIS: Primary energy use vs. Global cost





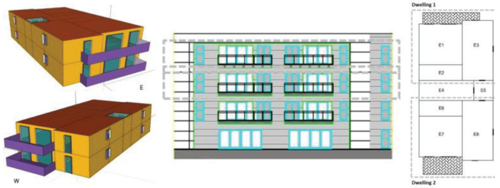




	PASSIVE	HEATING + DHW	COOLING	PV SYSTEM	LIGHTING	AWARENESS CAMPAIGN	PRIMARY ENERGY kWh/yr·dw	ENERGY SAVINGS %	GLOBAL COSTS €/dw	INITIAL INVESTMENT €/dw
BC	BC	Conventional NG boiler	Conventional AC Split	NO	CFL	NO	26,200	-	55,485	0
CO	BC	Condensing NG boiler	Efficient AC Split	NO	LED	YES	16,067	39	46,154	4,953
DR	1458	Condensing NG boiler+ST	Efficient AC Split	YES	LED	YES	12,633	52	66,056	25,210

OptiHab - Typology BT-8 [5/5]

CONCLUDING REMARKS	Isolated block of apartments Year of construction: 1991-2007 Nº Floors: Commercial floor + 3 Nº Dwellings: 12 Dwelling surface: 103.2 m² Occupants: 2 adults + 1 child	➢*Façade:* with air chamber and insulation ➢*Roof*: with insulation ➢*Windows:* aluminium without thermal break with clear double glazing 4/12/4 ➢*Solar protection:* blinds ➢*Observations:*



- The base case of the building typology already has insulation in the façade and in the roof.
- Effect of insulation in the facade:
  - The external insulation has a better energy performance than the internal insulation, however the cost is higher.
  - If the thickness of the insulation increase, the cold comfort is improve. However, when the ventilation is not possible the warm comfort and the overheating are increased.
- Effect of insulation in the roof:
  - The external insulation has a better energy performance than the internal insulation, specially for the overheating.
  - The increase of thickness has a positive impact on the cold comfort, however the effect on the warm comfort is slightly negative.
- The improvement of the window performance has a high impact in the annual discomfort (around the 5% of reduction), nevertheless its initial investment cost is high (around 8,000 €/dw).
- The solar protection requires a low investment and in some cases, it allows to avoid the cooling system.
- When there is no natural ventilation, the measures that provide better cold season comfort have a negative effect over warm season comfort. In those cases, the optimal use of solar protections help to reduce the overheating.
- There are cost-optimal solutions which include a combination of passive and active measures when the natural ventilation is possible. For no natural ventilation, most of the cost-optimal measures include only active measures.
- The measures that provide lower primary energy consumption imply a deep renovation and the use of renewable energy systems.
- As the heating demand is reduced, the electric consumption due to appliances becomes more important. Specific solutions have to be consider in future studies

CONCLUDING REMARKS - CLIMATE: C2 (Barcelona) – NATURAL VENTILATION: YES

- **Comfort evaluation**

  The annual discomfort can be reduced from 33% to 24% only with passive measures.

  In most of the cases there are problems of overheating during the warm season (41-150 hours). The cooling system is required to guarantee comfort conditions, nevertheless it could be avoided in some situations (<41 hours)
- **Base case (BC)**

  Energy label = E (198 kWhPE/m²·yr).

  CO_2 emissions = 29 kgCO_2/m²·yr
- **Cost Optimal measures (CO)**

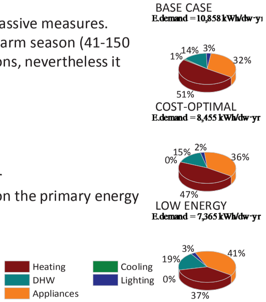
  Energy label= B (123 kWhPE/m²·yr). CO_2 emissions = 16 kgCO_2/m²·yr

  The condensing boiler is the active measure that has a high impact on the primary energy consumption (26% of reduction)
- **Low energy measures (DR)**

  Energy label = A (98 kWhPE/m²·yr). CO_2 emissions = 12 kgCO_2/m²·yr

  Heating demand could be reduced in 50%.

  Primary energy savings: up to 51%



OptiHab - Typology BT-8

CONCLUDING REMARKS - CLIMATE: C2 (Barcelona) – NATURAL VENTILATION: NO

- **Comfort evaluation**

  The annual discomfort can be reduced from 33% to 25% only with passive measures.

  There are problems of overheating during the warm season (>150hours). The cooling system is required to guarantee comfort conditions.
- **Base case (BC)**

  Energy label = E (264 kWhEP/m²·yr).

  CO_2 emissions = 36 kgCO_2/m²·yr
- **Cost Optimal measures (CO)**

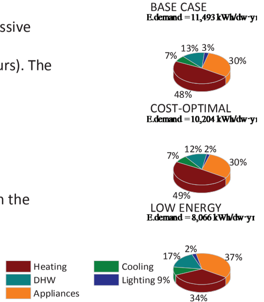
  Energy label= D (162 kWhEP/m²·yr). CO_2 emissions = 21 kgCO_2/m²·yr

  The condensing boiler is the active measure that has a high impact on the primary energy consumption (19% of reduction)
- **Low energy measures (DR)**

  Energy label = B (126 kWhEP/m²·yr). CO_2 emissions = 15 kgCO_2/m²·yr

  Heating demand could be reduced in 50%.

  Primary energy savings: up to 52%



CONCLUDING REMARKS - CLIMATE: B3 (Tarragona) – NATURAL VENTILATION: YES

- **Comfort evaluation**

  The annual discomfort can be reduced from 29% to 20% only with passive measures.

  In most of the cases there are problems of overheating during the warm season (51-150 hours). The cooling system is required to guarantee comfort conditions, nevertheless it could be avoided in some situations (<51 hours).
- **Base case (BC)**

  Energy label = E (188 kWhPE/m²·yr).

  CO_2 emissions = 27 kgCO_2/m²·yr
- **Cost Optimal measures (CO)**

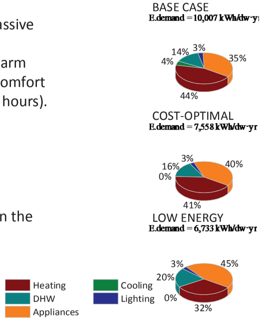
  Energy label= B (115 kWhPE/m²·yr). CO_2 emissions= 15 kgCO_2/m²·yr

  The condensing boiler is the active measure that has a high impact on the primary energy consumption (23% of reduction)
- **Low energy measures (DR)**

  Energy label = A (92 kWhPE/m²·yr). CO_2 emissions = 11 kgCO_2/m²·yr

  Heating demand could be reduced in 51%.

  Primary energy savings: up to 51%



CONCLUDING REMARKS - CLIMATE: B3 (Tarragona) – NATURAL VENTILATION: NO

- **Comfort evaluation**

  The annual discomfort can be reduced from 29% to 22% only with passive measures.

  There are problems of overheating during the warm season (>150hours). The cooling system is required to guarantee comfort conditions.
- **Base case (BC)**

  Energy label = E (254 kWhPE/m²·yr).

  CO_2 emissions = 33 kgCO_2/m²·yr
- **Cost Optimal measures (CO)**

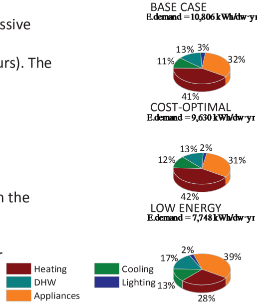
  Energy label= D (156 kWhPE/m²·yr).CO_2 emissions= 20 kgCO_2/m²·yr

  The condensing boiler is the active measure that has a high impact on the primary energy consumption (17% of reduction)
- **Low energy measures (DR)**

  Energy label = B (122 kWhPE/m²·yr). CO_2 emissions = 14 kgCO_2/m²·yr

  Heating demand could be reduced in 51%.

  Primary energy savings: up to 52%

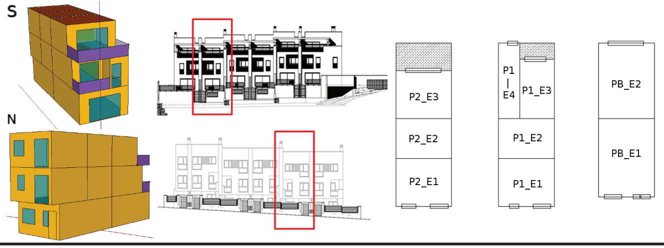


OptiHab - Typology BT-4

Building type: Semi-detached house
Year of construction: 1991-2006
Nº Floors: 3 floors/dw
Dwelling surface: 175.3 m^2
Occupants: 2 adults + 2 child

Building representation:

Climate	Nº buildings	% building stock
C2 (Barcelona)	57 650	2.5
B3 (Tarragona)	15 044	0.6

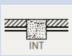
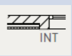
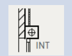
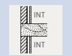
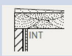
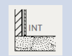


Building Characteristics

Envelope	Description	Thickness m	U-value W/m²K
Façade	Wall of 14 cm hollow brick with exterior mortar siding, 5cm of air chamber not ventilated, 40mm insulation and partition wall of 5cm holes brick with internal plaster siding.	0.26	0.625
Roof	Flat roof with double layer of ceramic tile, mortar, waterproofing, cellular concrete, 40mm of insulation with joist floor slab with joist-filler-block of concrete and plaster.	0.43	0.546
Party wall	Partition wall with perforated brick and siding in both sides	0.18	2.254
Internal wall	Wall of 14cm of perforated brick and siding in both sides	0.11	2.240
Floor framing	Unidirectional floor framing reinforced concrete, joist, slab of concrete, mortar and pavement tiles	0.28	2.304

Window	Description	U-value W/m²K	g-value -
Window frame	Aluminium without thermal break	3.44	0.76
Glazing	Clear double glazing 4/12/4		

Solar protection	Blinds + awnings	**Air leakage (n_{50})**	7.5

Cold bridge	Pillar in a wall	Pillar in a corner	Opening frame	Shutter box	Wall- floor junction	Wall-roof junction	Wall over external slab	Cantilever-wall junction
Description								
Linear thermal conductivity (Ψ, W/mK)	0.33	-	0.32	0.40	0.85	0.65	0.14	

OptiHab - Typology BT-4

Equipment Characteristics

System	Description	Performance
Heating and DHW	Conventional natural gas boiler for individual centralize system (24kW)	η = 0.75
Cooling	Conventional air conditioning system (split) installed in 2 zones (5kW)	COP = 2.0
Lighting	Compact fluorescent lamps (2 W/m^2)	Luminous efficacy = 0.6
Appliances	Refrigerator, washing machine , drier, dishwasher, microwave, electric stove, electric oven, TV and computer.	Average household of a multifamily building in Mediterranean region

Energy efficiency measures

Measure	Description	Performance	Investment cost	Mainte-nance cost	Life-span
Façade insulation	External – EPS 4-12 cm	0.37 - 0.20 W/m²K	8,300 - 10,200 €/dw	-	40
	External – XPS 4-12 cm	0.38 - 0.21 W/m²K	9,300 - 11,900 €/dw	-	40
	Air chamber – mineral wool 3-10 cm	0.48 - 0.27 W/m²K	1,900 - 2,600 €/dw	-	40
	Air chamber – EPS + graphite 3-10 cm	0.43 - 0.23 W/m²K	2,400 - 5,000 €/dw	-	40
	Air chamber – cellulose 3-10 cm	0.37 - 0.25 W/m²K	2,000 - 2,300 €/dw	-	40
	Internal – EPS 4-8 cm	0.37 - 0.26 W/m²K	3,800 - 4,300 €/dw	-	40
	Internal –mineral wool 4-8 cm	0.40 - 0.29 W/m²K	2,800 - 3,000 €/dw	-	40
Roof insulation	Inverted – XPS 8-12 cm	0.26 - 0.20 W/m²K	11,500 - 12,200 €/dw	-	30
	Internal – rock wool 4-8 cm	0.37 - 0.27 W/m²K	3,400 - 3,600 €/dw	-	30
	Internal – EPS 4-8 cm	0.34 - 0.25 W/m²K	4,400 - 5,000 €/dw	-	30
Windows change	4/16/4 Aluminium with thermal break	2.8 W/m²K	10,300 €/dw	-	30
	4/16/4 PVC	2.8 W/m²K	9,400 €/dw	-	30
Sol. protec.	Awnings	-	-	-	-
Heating and DHW system	Condensing boiler + Improve install. Performance	η = 1.09	3,840 €/dw	145 €/dw	20
	Biomass boiler + Improve install. Performance	η = 0.91	9,900 €/dw	363 €/dw	15
	Heat pump air-wat. + Improve install. Performance	COP = 2.6	11,100 €/dw	60 €/dw	15
Cooling system	Efficient Air conditioning system (split)	COP = 4.0	2,565 €/dw	48 €/dw	15
	No cooling system	-	-	-	-
Lighting	LED	Luminous eff. = 0.8	719 €/dw	-	20
Awareness	Awareness campaign	-	290 €/dw	24 €/dw	20
Solar thermal	2.2 m²/building + 160l storage tank	-	1,900 €/dw	100 €/dw	15
	6.6 m²/building + 300l storage tank	-	6,800 €/dw	100 €/dw	15
PV system	3 m²/building - 140 Wp/module	-	3,000 €/dw	73€/dw	20
	3 m²/building - 140 Wp/module with batteries	-	4,000 €/dw	302 €/dw	20

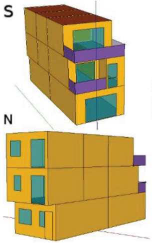
OptiHab - Typology BT-4 [1/5]

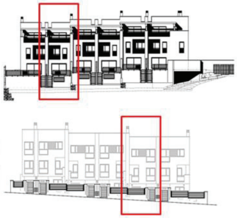
Semi-detached house
Year of construction: 1991-2007
Nº Floors: 3 floors/dw
Dwelling surface: 175.3 m^2
Occupants: 2 adults + 2 child

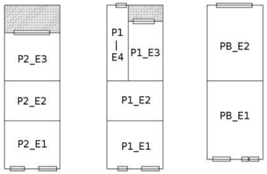
- *Façade:* with air chamber and insulation
- *Roof:* with insulation
- *Windows:* aluminium without thermal break with clear double glazing 4/12/4
- *Solar protection:* blinds and awnings
- *Observations:*

CLIMATE: C2 (Barcelona)

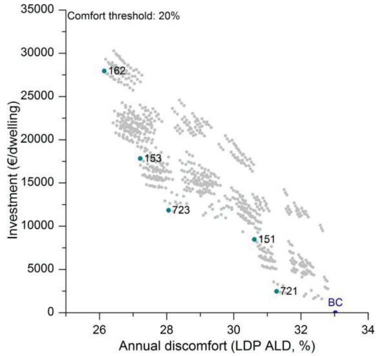
NATURAL VENTILATION: YES

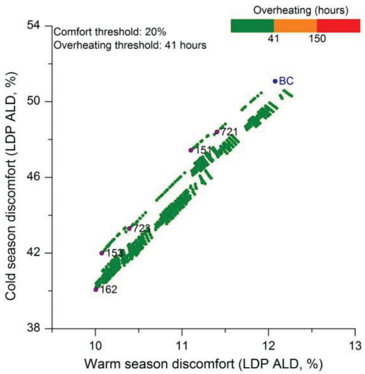






PASSIVE ANALYSIS: Thermal comfort vs. Initial investment cost

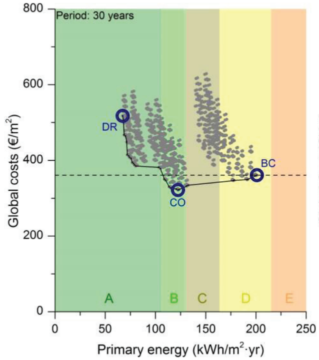


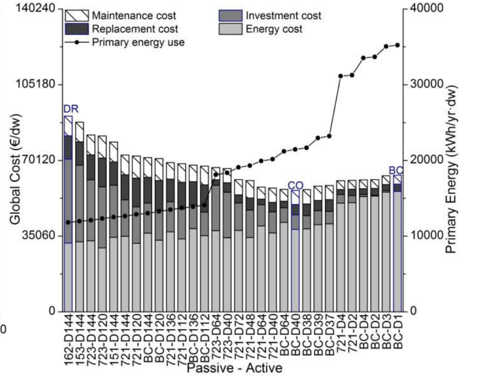


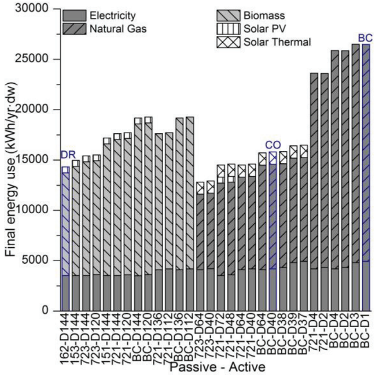
PASSIVE	FAÇADE	ROOF	WINDOW	SOLAR PROT.	INITIAL INVESTMENT €	ANNUAL LDP %	COLD LDP %	WARM LDP %	OVERHEATING Hours
BC	Base case	Base case	Base case	YES	0	33.0	51.1	12.1	0
721	INT–RW 8	Base case	Base case	YES	2,466	31.3	48.4	11.4	0
151	EXT–EPS 12	Base case	Base case	YES	8,460	24.2	47.4	11.1	0
723	INT–RW 8	Base case	4/16/4PVC	YES	11,831	28.1	43.3	10.4	0
153	EXT–EPS 12	Base case	4/16/4PVC	YES	17,824	27.2	42.0	10.0	0
162	EXT–EPS 12	EXT–EPS 12	4/16/4PVC	YES	27,936	26.1	40.0	10.0	0

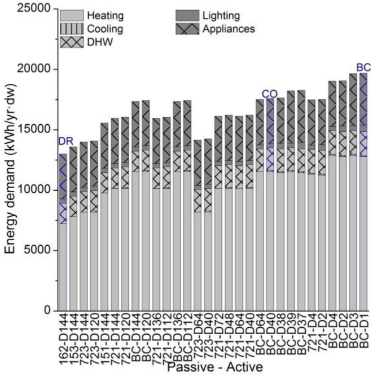
OptiHab - Typology BT-4

ACTIVE ANALYSIS: Primary energy use vs. Global cost









	PASSIVE	HEATING + DHW	COOLING	PV SYSTEM	LIGHTING	AWARENESS CAMPAIGN	PRIMARY ENERGY kWh/yr·dw	ENERGY SAVINGS %	GLOBAL COSTS €/dw	INITIAL INVESTMENT €/dw
BC	BC	Conventional NG boiler	Conventional AC Split	NO	CFL	NO	35,226	-	63,286	0
CO	BC	Condensing NG boiler+ST$_1$	Conventional AC Split	NO	LED	YES	21,453	39	56,318	6,741
DR	162	Biomass boiler	NO	YES NO BAT.	LED	YES	11,799	66	90,690	38,926

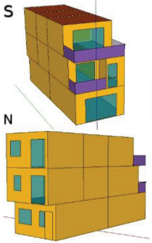
OptiHab - Typology BT-4 [2/5]

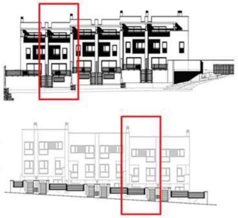
Semi-detached house
Year of construction: 1991-2007
Nº Floors: 3 floors/dw
Dwelling surface: 175.3 m^2
Occupants: 2 adults + 2 child

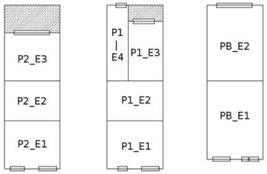
- *Façade:* with air chamber and insulation
- *Roof:* with insulation
- *Windows:* aluminium without thermal break with clear double glazing 4/12/4
- *Solar protection:* blinds and awnings
- *Observations:*

CLIMATE: C2 (Barcelona)

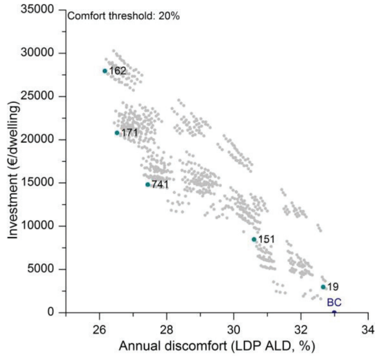
NATURAL VENTILATION: NO

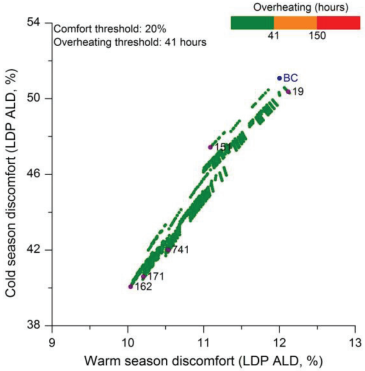






PASSIVE ANALYSIS: Thermal comfort vs. Initial investment cost

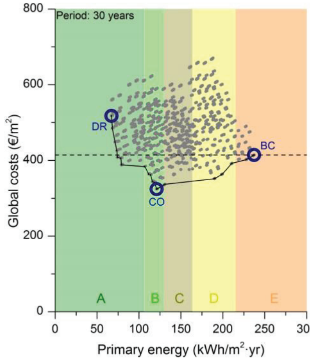


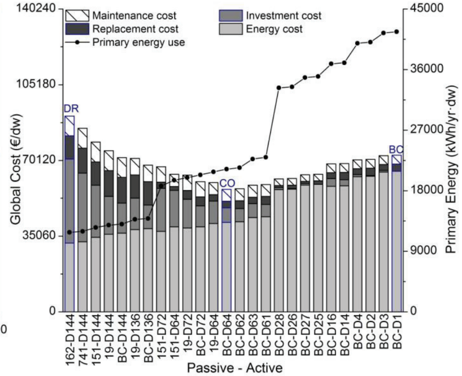


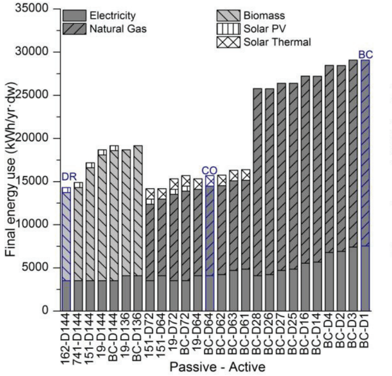
PASSIVE	FAÇADE	ROOF	WINDOW	SOLAR PROT.	INITIAL INVESTMENT €	ANNUAL LDP %	COLD LDP %	WARM LDP %	OVERHEATING Hours
BC	Base case	Base case	Base case	YES	0	33.0	51.1	12.0	3
19	Base case	INT–RW 8	Base case	YES	2,968	32.7	50.4	12.1	1
151	EXT–EPS 12	Base case	Base case	YES	8,459	30.6	47.4	11.1	1
741	INT–RW 8	INT–RW 8	4/16/4PVC	YES	14,800	27.4	42.0	10.5	5
171	EXT–EPS 12	INT–RW 8	4/16/4PVC	YES	20,793	26.5	40.6	10.2	4
162	EXT–EPS 12	EXT–EPS 12	4/16/4PVC	YES	27,936	26.2	40.0	10.0	2

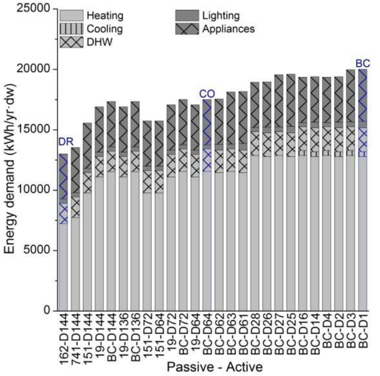
OptiHab - Typology BT-4

ACTIVE ANALYSIS: Primary energy use vs. Global cost









	PASSIVE	HEATING + DHW	COOLING	PV SYSTEM	LIGHTING	AWARENESS CAMPAIGN	PRIMARY ENERGY kWh/yr·dw	ENERGY SAVINGS %	GLOBAL COSTS €/dw	INITIAL INVESTMENT €/dw
BC	BC	Conventional NG boiler	Conventional AC Split	NO	CFL	NO	41,642	-	72,588	0
CO	BC	Condensing NG boiler+ST$_1$	NO	NO	LED	YES	21,215	49	56,785	6,741
DR	162	Biomass boiler	NO	YES NO BAT.	LED	YES	11,799	72	90,690	38,926

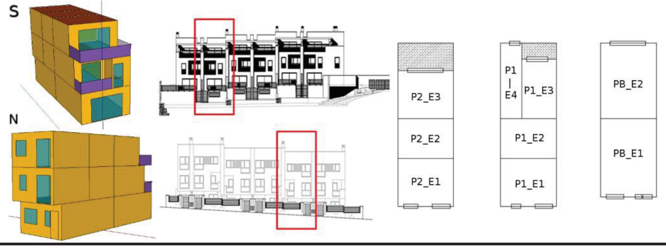
OptiHab - Typology BT-4 [3/5]

Semi-detached house
Year of construction: 1991-2007
Nº Floors: 3 floors/dw
Dwelling surface: 175.3 m^2
Occupants: 2 adults + 2 child

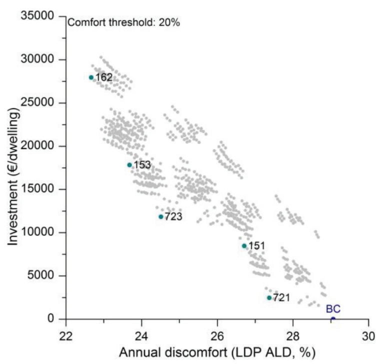
- *Façade:* with air chamber and insulation
- *Roof:* with insulation
- *Windows:* aluminium without thermal break with clear double glazing 4/12/4
- *Solar protection:* blinds and awnings
- *Observations:*

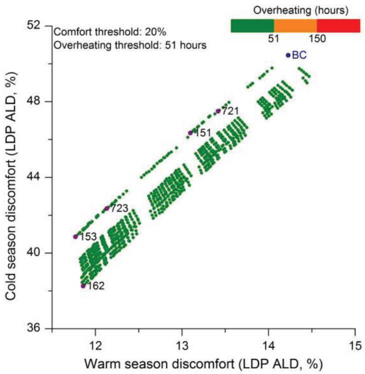
CLIMATE: B3 (Tarragona)

NATURAL VENTILATION: YES



PASSIVE ANALYSIS: Thermal comfort vs. Initial investment cost

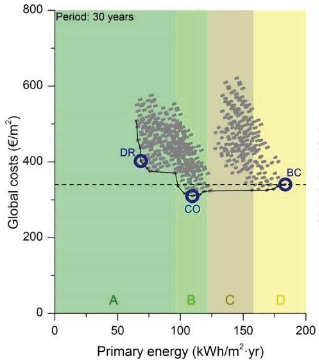


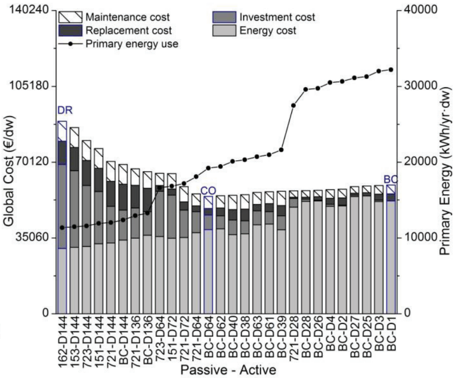


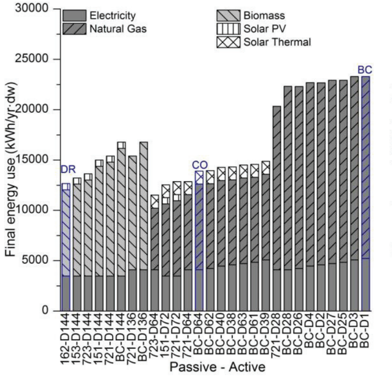
PASSIVE	FAÇADE	ROOF	WINDOW	SOLAR PROT.	INITIAL INVESTMENT €	ANNUAL LDP %	COLD LDP %	WARM LDP %	OVERHEATING Hours
BC	Base case	Base case	Base case	YES	0	29.1	50.4	14.2	9
721	INT–RW 8	Base case	Base case	YES	2,466	27.4	47.5	13.4	8
151	EXT–EPS 12	Base case	Base case	YES	8,459	26.7	46.3	13.1	7
723	INT–RW 8	Base case	4/16/4PVC	YES	11,831	24.5	42.3	12.1	13
153	EXT–EPS 12	Base case	4/16/4PVC	YES	17,824	23.7	40.8	11.8	12
162	EXT–EPS 12	EXT–EPS 12	4/16/4PVC	YES	27,936	22.7	38.2	11.9	13

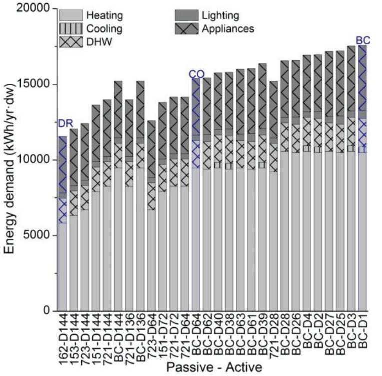
OptiHab - Typology BT-4

ACTIVE ANALYSIS: Primary energy use vs. Global cost









	PASSIVE	HEATING + DHW	COOLING	PV SYSTEM	LIGHTING	AWARENESS CAMPAIGN	PRIMARY ENERGY kWh/yr·dw	ENERGY SAVINGS %	GLOBAL COSTS €/dw	INITIAL INVESTMENT €/dw
BC	BC	Conventional NG boiler	Conventional AC Split	NO	CFL	NO	32,193	-	59,610	0
CO	BC	Condensing NG boiler+ST$_1$	NO	NO	LED	YES	19,209	40	54,266	6,741
DR	162	Biomass boiler	NO	YES NO BAT.	LED	YES	11,341	65	89,027	38,926

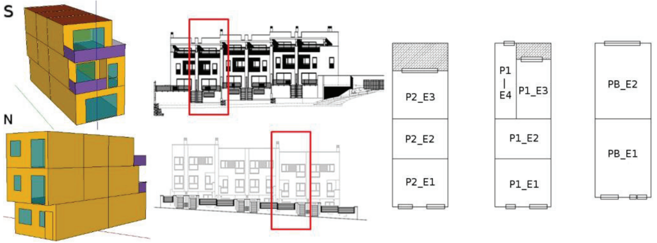
OptiHab - Typology BT-4 [4/5]

Semi-detached house
Year of construction: 1991-2007
Nº Floors: 3 floors/dw
Dwelling surface: 175.3 m^2
Occupants: 2 adults + 2 child

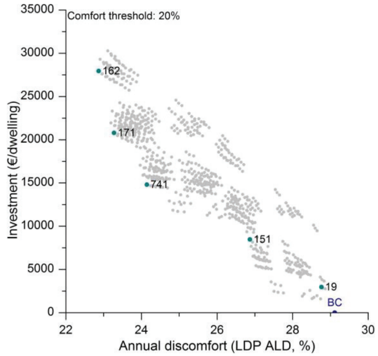
- *Façade:* with air chamber and insulation
- *Roof:* with insulation
- *Windows:* aluminium without thermal break with clear double glazing 4/12/4
- *Solar protection:* blinds and awnings
- *Observations:*

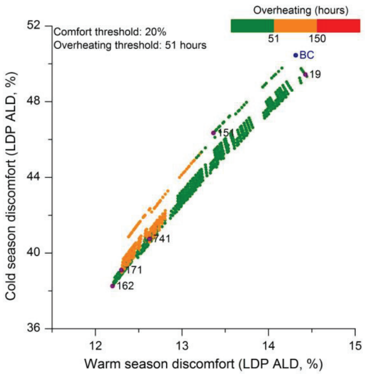
CLIMATE: B3 (Tarragona)

NATURAL VENTILATION: NO



PASSIVE ANALYSIS: Thermal comfort vs. Initial investment cost

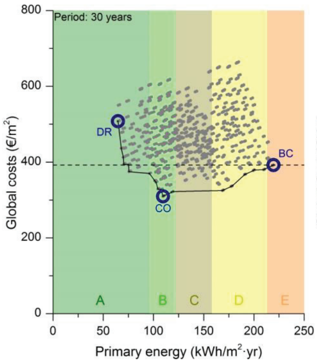


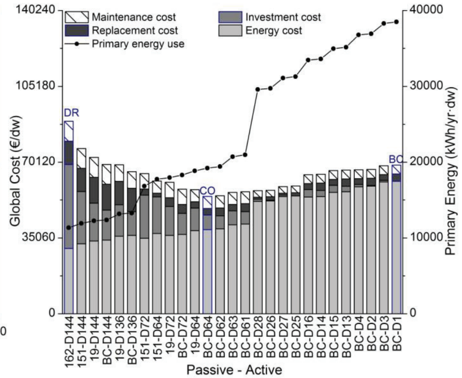


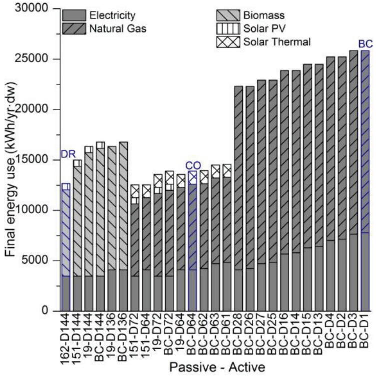
PASSIVE	FAÇADE	ROOF	WINDOW	SOLAR PROT.	INITIAL INVESTMENT €	ANNUAL %	COLD %	WARM %	OVERHEATING Hours
BC	Base case	Base case	Base case	YES	0	29.1	50.4	14.3	27
19	Base case	INT–RW 8	Base case	YES	2,968	28.8	49.4	14.4	23
151	EXT–EPS 12	Base case	Base case	YES	8,459	26.9	46.3	13.4	37
741	INT–RW 8	INT–RW 8	4/16/4PVC	YES	14,800	24.1	40.7	12.6	64
171	EXT–EPS 12	INT–RW 8	4/16/4PVC	YES	20,793	23.3	39.1	12.3	57
162	EXT–EPS 12	EXT–EPS 12	4/16/4PVC	YES	27,936	22.9	38.2	12.2	45

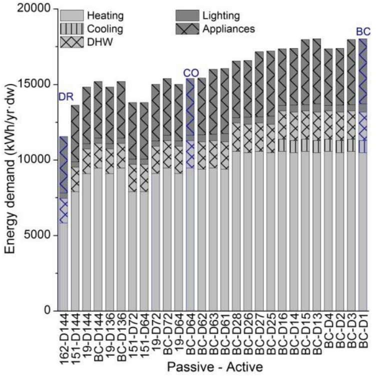
OptiHab - Typology BT-4

ACTIVE ANALYSIS: Primary energy use vs. Global cost





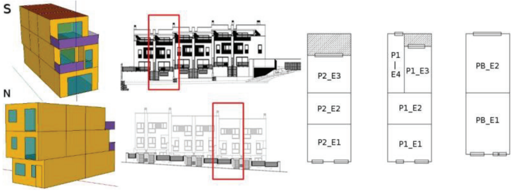




	PASSIVE	HEATING + DHW	COOLING	PV SYSTEM	LIGHTING	AWARENESS CAMPAIGN	PRIMARY ENERGY kWh/yr·dw	ENERGY SAVING %	GLOBAL COSTS €/dw	INITIAL INVESTMENT €/dw
BC	BC	Conventional NG boiler	Conventional AC Split	NO	CFL	NO	38,488	-	68,774	0
CO	BC	Condensing NG boiler+ST_1	NO	NO	LED	YES	19,207	50	54,263	6,741
DR	162	Biomass boiler	NO	YES NO BAT.	LED	YES	11,340	70	89,024	38,926

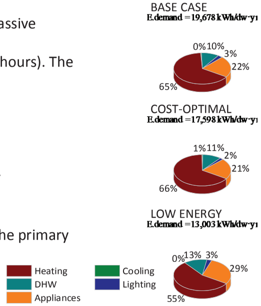
OptiHab - Typology BT-4 [5/5]

CONCLUDING REMARKS	Semi-detached house Year of construction: 1991-2007 Nº Floors: 3 floors/dw Dwelling surface: 175.3 m² Occupants: 2 adults + 2 child	➢*Façade:* with air chamber and insulation ➢*Roof*: with insulation ➢*Windows:* aluminium without thermal break with clear double glazing 4/12/4 ➢*Solar protection:* blinds and awnings ➢*Observations:*



- The base case of the building typology has a good thermal performance:
  - The base case already has insulation in the façade and in the roof.
  - The building has two external façade which allows natural cross ventilation and the window area is big .
  - The base case already has blinds and awning, then the use of the solar protection is optimal.
- Effect of insulation in the façade:
  - The external insulation has a better impact in the thermal comfort, however it is the expensive one.
  - Comparing the internal insulation and the air chamber insulation, their cost is similar, however the internal insulation has a better thermal performance.
  - The façade insulation has a positive effect in both cold and the warm season comfort.
- Effect of insulation in the roof:
  - The thermal behaviour of the external and internal insulation is quite similar being slightly better the external. However, the main difference is the investment cost (external more expensive than internal) .
- The improvement of the window performance has a high impact in the annual discomfort (around the 5% of reduction), nevertheless its initial investment cost is high (around 9,000 €/dw).
- In most of the cases, the cooling system could be avoid, guarantying comfort condition, including in the building without natural ventilation.
- Most of the cost-optimal solutions include only active measures.
- The measures that provide a lower primary energy consumption imply a deep renovation and the use of renewable energy systems.

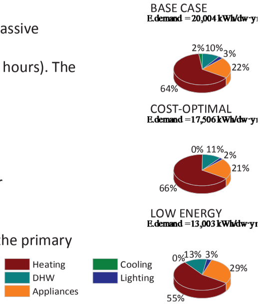
CONCLUDING REMARKS - CLIMATE: C2 (Barcelona) – NATURAL VENTILATION: YES



- **Comfort evaluation**
  The annual discomfort can be reduced from 33% to 26% only with passive measures.
  There are no problems of overheating during the warm season (<41 hours). The cooling system could be avoided to guarantee comfort conditions.
- **Base case (BC)**
  Energy label = D (201 kWhPE/m²·yr).
  CO_2 emissions = 32 $kgCO_2/m^2 \cdot yr$
- **Cost Optimal measures (CO)**
  Energy label= B (122 kWhPE/m²·yr). CO_2 emissions = 18 $kgCO_2/m^2 \cdot yr$
- **Low energy measures (DR)**
  Energy label = A (67 kWhPE/m²·yr). CO_2 emissions = 5 $kgCO_2/m^2 \cdot yr$
  The biomass boiler is the active measure that has a high impact on the primary energy consumption (55% of reduction)
  Heating demand could be reduced in 44%.
  Primary energy savings: up to 66%

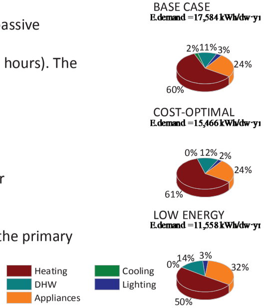
OptiHab - Typology BT-4

CONCLUDING REMARKS - CLIMATE: C2 (Barcelona) – NATURAL VENTILATION: NO



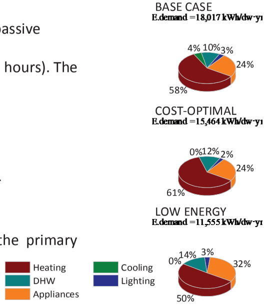
- **Comfort evaluation**
  The annual discomfort can be reduced from 33% to 26% only with passive measures.
  There are no problems of overheating during the warm season (<41 hours). The cooling system could be avoided to guarantee comfort conditions.
- **Base case (BC)**
  Energy label = E (237 kWhEP/m²·yr).
  CO_2 emissions = 35 $kgCO_2/m^2 \cdot yr$
- **Cost Optimal measures (CO)**
  Energy label= B (121 kWhEP/m²·yr). CO_2 emissions = 18 $kgCO_2/m^2 \cdot yr$
- **Low energy measures (DR)**
  Energy label = A (67 kWhEP/m²·yr). CO_2 emissions = 5 $kgCO_2/m^2 \cdot yr$
  The biomass boiler is the active measure that has a high impact on the primary energy consumption (46% of reduction)
  Heating demand could be reduced in 44%.
  Primary energy savings: up to 72%

CONCLUDING REMARKS - CLIMATE: B3 (Tarragona) – NATURAL VENTILATION: YES



- **Comfort evaluation**
  The annual discomfort can be reduced from 29% to 23% only with passive measures.
  There are no problems of overheating during the warm season (<51 hours). The cooling system could be avoided to guarantee comfort conditions.
- **Base case (BC)**
  Energy label = D (184 kWhPE/m²·yr).
  CO_2 emissions = 28 $kgCO_2/m^2 \cdot yr$
- **Cost Optimal measures (CO)**
  Energy label= B (110 kWhPE/m²·yr). CO_2 emissions = 16 $kgCO_2/m^2 \cdot yr$
- **Low energy measures (DR)**
  Energy label = A (65 kWhPE/m²·yr). CO_2 emissions = 5 $kgCO_2/m^2 \cdot yr$
  The biomass boiler is the active measure that has a high impact on the primary energy consumption (42% of reduction)
  Heating demand could be reduced in 44%.
  Primary energy savings: up to 65%

CONCLUDING REMARKS - CLIMATE: B3 (Tarragona) – NATURAL VENTILATION: NO



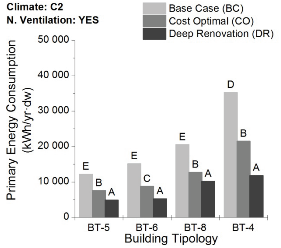
- **Comfort evaluation**
  The annual discomfort can be reduced from 29% to 23% only with passive measures.
  There are no problems of overheating during the warm season (<51 hours). The cooling system could be avoided to guarantee comfort conditions.
- **Base case (BC)**
  Energy label = E (219 kWhPE/m²·yr).
  CO_2 emissions = 32 $kgCO_2/m^2 \cdot yr$
- **Cost Optimal measures (CO)**
  Energy label= B (110 kWhPE/m²·yr).CO_2 emissions = 16 $kgCO_2/m^2 \cdot yr$
- **Low energy measures (DR)**
  Energy label = A (65 kWhPE/m²·yr). CO_2 emissions = 5 $kgCO_2/m^2 \cdot yr$
  The biomass boiler is the active measure that has a high impact on the primary energy consumption (50% of reduction)
  Heating demand could be reduced in 44%.
  Primary energy savings: up to 70%

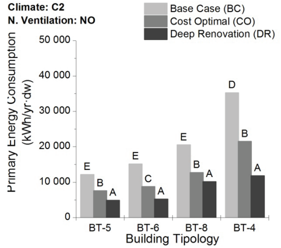
OptiHab - Summary

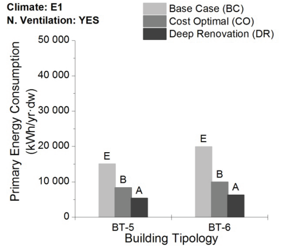
Tipology	Dwelling area m2	Climate	Natual ventilation	BC	CO					
				Energy Label	Energy Label	Label Improve	Primary Energy Savings %	CO$_2$ emissions reduction %	Initial Investment €/dw	Initial Investment €/m^2
BT-5	60.5	C2	Yes	E	B	3	38	43	5 051	83
		C2	No	E	C	2	42	47	6 430	106
		E1	Yes	E	B	3	45	49	5 051	83
BT-6	78.8	C2	Yes	E	C	2	42	47	4 594	58
		C2	No	F	D	2	47	50	5 973	76
		E1	Yes	E	B	3	50	55	5 441	69
		B3	Yes	E	C	2	40	44	4 594	58
		B3	No	G	D	3	47	49	5 973	76
		D3	Yes	E	C	2	45	50	4 594	58
		D3	No	F	D	2	49	52	5 973	76
BT-8	103.2	C2	Yes	E	B	3	38	45	6 307	61
		C2	No	E	D	1	39	42	4 953	48
		B3	Yes	E	B	3	39	44	6 307	61
		B3	No	E	D	1	39	39	4 953	48
BT-4	175.3	C2	Yes	D	B	2	39	44	6 741	38
		C2	No	E	B	3	49	49	6 741	38
		B3	Yes	D	B	2	40	43	6 741	38
		B3	No	E	B	3	50	50	6 741	38

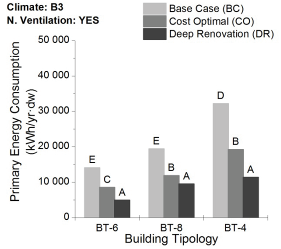
Tipology	Dwelling area m2	Climate	Natual ventilation	BC	DR					
				Energy Label	Energy Label	Label Improve	Primary Energy Savings %	CO$_2$ emissions reduction %	Initial Investment €/dw	Initial Investment €/m^2
BT-5	60.5	C2	Yes	E	A	4	60	67	15 872	262
		C2	No	E	A	4	59	64	14 164	234
		E1	Yes	E	A	4	65	69	14 492	240
BT-6	78.8	C2	Yes	E	A	4	66	70	19 971	253
		C2	No	F	B	4	63	68	19 971	253
		E1	Yes	E	A	4	69	74	18 592	236
		B3	Yes	E	A	4	65	70	19 971	253
		B3	No	G	B	5	63	69	19 971	253
		D3	Yes	E	A	4	69	74	19 971	253
		D3	No	F	B	4	66	72	19 971	253
BT-8	103.2	C2	Yes	E	A	4	51	59	24 477	237
		C2	No	E	B	3	52	58	25 210	244
		B3	Yes	E	A	4	51	59	24 477	237
		B3	No	E	B	3	52	58	25 210	244
BT-4	175.3	C2	Yes	D	A	3	67	84	38 926	222
		C2	No	E	A	4	72	86	38 926	222
		B3	Yes	D	A	3	65	82	38 926	222
		B3	No	E	A	4	71	84	38 926	222

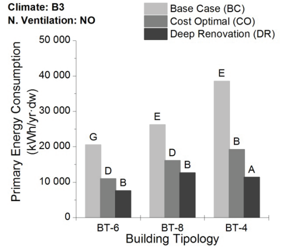
OptiHab - Summary

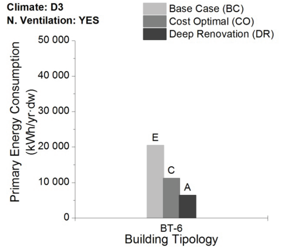


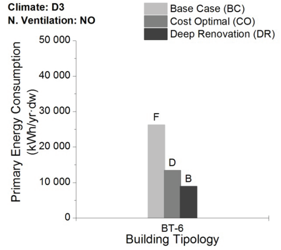












The main results and conclusions of the OptiHab study are explained in the following section. The conclusions presented below provide a general view of the study including a qualitative description of the main outcomes. The detailed results have been presented above in the concluding remarks of each typology.

GENERAL CONCLUSIONS

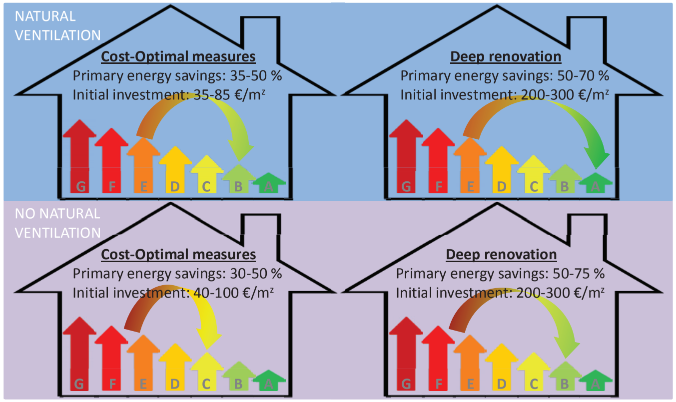
- OptiHab gives detailed information of the current situation of the most representative building typologies which represents the 80% of the building stock.
- Complete process for developing cost-effective studies of energy efficiency measures for building renovation. The method introduces:
  - innovative approaches, as the two-step optimization considering comfort, energy and economic criteria;
  - realistic characterization, with the use of stochastic profiles for the user behavior and its interaction with the building, and the building parameters related to measurement and survey campaigns;
  - the economic evaluation and the cost-effective analysis are done as defined by the European regulation;
  - to prioritize the passive measures rather than the active ones guaranteeing the thermal comfort of the users.

PASSIVE MEASURES CONCLUSIONS

- The passive measures have an important reduction of the energy demand, specially on the older building typologies (BT-5 and BT-6).
- In general, the external insulation in the façade has a better thermal performance, however its initial investment cost is higher.
- The roof insulation has an important benefit on the under roof dwellings improving the thermal comfort during the cold and warm season, specially in the older building typologies (BT-5 and BT-6).
- The improvement of the window performance has a high impact in the annual discomfort (around 5-10% of reduction) and in the energy demand, nevertheless its initial investment cost is high.
- The natural ventilation and the optimal use of the solar protections are effective strategies to reduce the cooling demand being possible to avoid the cooling system in some cases. However, there are situations where the cooling system are needed to guarantee the thermal comfort:
  - The older building typologies analysed in the study (BT-5 and BT-6) do not have an appropriate design for the natural ventilation (single side ventilation and /or small courtyards).
  - There are buildings in most of climates of Catalonia that due to their environmental conditions (noise, pollution ...) can not use the natural ventilation for cooling the dwelling.
  - The buildings can increase the hours of overheating because of an over-insulation of the building. This situation has a reduction of the thermal discomfort of the cold season, however a negative effect over the warm season comfort.

COST-EFFECTIVE ANALYSIS CONCLUSIONS

- The active measures, in particular the improvement of the heating systems performance, provide a high reduction of the primary energy consumption. However, the active measures have to be combined with the passive ones in order to achieve the A class of the energy efficiency labelling.
- The optimal measures are able to achieve B/C class of the energy efficiency labelling in buildings with natural ventilation, and C/D class in buildings without natural ventilation.
- The measures that include a deep renovation and renewable energy systems can achieve an A class of the energy efficiency labelling in buildings with natural ventilation and a B class in buildings without natural ventilation.
- The cost-optimal analysis is an appropriate method to choose the most suitable measure depending on:
  - The building typology and the climate
  - The objectives of the users: environmental and/or economical.
- The effect of the measures can be summarize in the following scheme:



- The energy renovation of building increases the quality of life of the users and at the same time, increase the value of the building and its lifespan. There are studies[24] that show how the economic value of the building can increase up to 25%. If this revaluation would be included in the cost-optimal analysis, probably most of the measures will become cost optimal. Further studies are needed to quantify the revaluation and the increase of the lifespan of the buildings after the energy renovation.
- As the heating demand is reduced, the electric consumption becomes more important. In this study, measures related with lighting performance improvement and awareness campaign to reduce the electric consumption are evaluated. However, specific solutions to reduce the appliances consumption has to considerer in future studies.

OptiHab – Appendix I

Active measure code - description

Code	Heating + DHW system	Cooling system	Photovoltaic system	Lighting system	Awarness campaign
1	Conventional NG boiler	Conventional heat pump	NO	CFL	NO
2	Conventional NG boiler	Conventional heat pump	NO	CFL	YES
3	Conventional NG boiler	Conventional heat pump	NO	LED	NO
4	Conventional NG boiler	Conventional heat pump	NO	LED	YES
9	Conventional NG boiler	Efficient heat pump	NO	CFL	NO
10	Conventional NG boiler	Efficient heat pump	NO	CFL	YES
11	Conventional NG boiler	Efficient heat pump	NO	LED	NO
12	Conventional NG boiler	Efficient heat pump	NO	LED	YES
17	Condensing NG boiler Improve efficiency instalation	Conventional heat pump	NO	CFL	NO
18	Condensing NG boiler Improve efficiency instalation	Conventional heat pump	NO	CFL	YES
19	Condensing NG boiler Improve efficiency instalation	Conventional heat pump	NO	LED	NO
20	Condensing NG boiler Improve efficiency instalation	Conventional heat pump	NO	LED	YES
24	Condensing NG boiler Improve efficiency instalation	Conventional heat pump	YES (12m^2/building)	LED	YES
25	Condensing NG boiler Improve efficiency instalation	Efficient heat pump	NO	CFL	NO
26	Condensing NG boiler Improve efficiency instalation	Efficient heat pump	NO	CFL	YES
27	Condensing NG boiler Improve efficiency instalation	Efficient heat pump	NO	LED	NO
28	Condensing NG boiler Improve efficiency instalation	Efficient heat pump	NO	LED	YES
31	Condensing NG boiler Improve efficiency instalation	Efficient heat pump	YES (12m^2/building)	LED	NO
32	Condensing NG boiler Improve efficiency instalation	Efficient heat pump	YES (12m^2/building)	LED	YES
40	Condensing NG boiler Improve efficiency instalation Solar thermal system 12m^2/building	Conventional heat pump	YES (12m^2/building)	LED	YES
41	Condensing NG boiler Improve efficiency instalation Solar thermal system 12m^2/building	Efficient heat pump	NO	CFL	NO
42	Condensing NG boiler Improve efficiency instalation Solar thermal system 12m^2/building	Efficient heat pump	NO	CFL	YES
43	Condensing NG boiler Improve efficiency instalation Solar thermal system 12m^2/building	Efficient heat pump	NO	LED	NO
44	Condensing NG boiler Improve efficiency instalation Solar thermal system 12m^2/building	Efficient heat pump	NO	LED	YES
48	Condensing NG boiler Improve efficiency instalation Solar thermal system 12m^2/building	Efficient heat pump	YES (12m^2/building)	LED	YES
65	Conventional NG boiler	NO	NO	CFL	NO
66	Conventional NG boiler	NO	NO	CFL	YES
67	Conventional NG boiler	NO	NO	LED	NO
68	Conventional NG boiler	NO	NO	LED	YES
81	Condensing NG boiler Improve efficiency instalation	NO	NO	CFL	NO
82	Condensing NG boiler Improve efficiency instalation	NO	NO	CFL	YES
83	Condensing NG boiler Improve efficiency instalation	NO	NO	LED	NO
81	Condensing NG boiler Improve efficiency instalation	NO	NO	CFL	NO
82	Condensing NG boiler Improve efficiency instalation	NO	NO	CFL	YES
83	Condensing NG boiler Improve efficiency instalation	NO	NO	LED	NO
84	Condensing NG boiler Improve efficiency instalation	NO	NO	LED	YES
88	Condensing NG boiler Improve efficiency instalation	NO	YES (12m^2/building)	LED	YES
96	Condensing NG boiler Improve efficiency instalation Solar thermal system 12m^2/building	NO	YES (12m^2/building)	LED	YES

OptiHab – Appendix I

Active measure code - description

Code	Heating + DHW system	Cooling system	Photovoltaic system	Lighting system	Awarness campaign
D1	Conventional NG boiler	Conventional heat pump	NO	CFL	NO
D2	Conventional NG boiler	Conventional heat pump	NO	CFL	YES
D3	Conventional NG boiler	Conventional heat pump	NO	LED	NO
D4	Conventional NG boiler	Conventional heat pump	NO	LED	YES
D13	Conventional NG boiler	Efficient heat pump	NO	CFL	NO
D14	Conventional NG boiler	Efficient heat pump	NO	CFL	YES
D15	Conventional NG boiler	Efficient heat pump	NO	LED	NO
D16	Conventional NG boiler	Efficient heat pump	NO	LED	YES
D25	Conventional NG boiler	NO	NO	CFL	NO
D26	Conventional NG boiler	NO	NO	CFL	YES
D27	Conventional NG boiler	NO	NO	LED	NO
D28	Conventional NG boiler	NO	NO	LED	YES
D37	Condensing NG boiler Improve efficiency instalation Solar thermal system 2.2m^2	Conventional heat pump	NO	CFL	NO
D38	Condensing NG boiler Improve efficiency instalation Solar thermal system 2.2m^2	Conventional heat pump	NO	CFL	YES
D39	Condensing NG boiler Improve efficiency instalation Solar thermal system 2.2m^2	Conventional heat pump	NO	LED	NO
D40	Condensing NG boiler Improve efficiency instalation Solar thermal system 2.2m^2	Conventional heat pump	NO	LED	YES
D48	Condensing NG boiler Improve efficiency instalation Solar thermal system 2.2m^2	Conventional heat pump	YES (3m^2 without battery)	LED	NO
D61	Condensing NG boiler Improve efficiency instalation Solar thermal system 2.2m^2	NO	NO	CFL	YES
D62	Condensing NG boiler Improve efficiency instalation Solar thermal system 2.2m^2	NO	NO	CFL	NO
D63	Condensing NG boiler Improve efficiency instalation Solar thermal system 2.2m^2	NO	NO	LED	YES
D64	Condensing NG boiler Improve efficiency instalation Solar thermal system 2.2m^2	NO	NO	LED	YES
D72	Condensing NG boiler Improve efficiency instalation Solar thermal system 2.2m^2	NO	YES (3m^2 without battery)	LED	YES
D112	Biomass boiler Improve efficiency instalation	Conventional heat pump	NO	LED	YES
D120	Biomass boiler Improve efficiency instalation	Conventional heat pump	YES (3m^2 without battery)	LED	YES
D136	Biomass boiler Improve efficiency instalation	NO	NO	LED	YES
D144	Biomass boiler Improve efficiency instalation	NO	YES (3m^2 without battery)	LED	YES

OptiHab – Appendix II

Passive measure description

Measure	Code	Description	Additional benefits
Façade insulation	F11-F15	External – EPS 4-12 cm	Reduce the thermal bridge.
	F16-F20	External – XPS 4-12 cm	
	F21-F23	Air chamber – rock wool 3-10 cm	
	F24-F26	Air chamber – EPS + graphite 3-10 cm	
	F27-F28	Air chamber – cellulose 5-10 cm	
	F29-F31	Internal – EPS 4-8 cm	
	F32-F34	Internal – rock wool 4-8 cm	
Roof insulation	C11-C13	Inverted – XPS 8-12 cm	-
	C14-C16	Internal – rock wool 4-8 cm	
	C17-C19	Internal – EPS 4-8 cm	
Window change	W11	4/16/4 Aluminium with thermal break	Reduce the air infiltration (n50=5)
	W12	4/16/4 PVC	
Solar protection	S11	Awning	-

OptiHab – Appendix II

Active measure description

Active measure	Performance	Typology		Comments / reference
		E-G-I	D	
Conventional NG boiler	0.7	24 kW	24 kW	IDAE (2009).CALENER-VYP. Viviendas y edificios terciarios pequeños y medianos. Factores de corrección de equipos.
Condensing NG boiler	1.09	20 kW	35 kW	IDAE (2009).CALENER-VYP. Viviendas y edificios terciarios pequeños y medianos. Factores de corrección de equipos.
Biomass boiler	-	-	15 kW	IDAE (2009).CALENER-VYP. Viviendas y edificios terciarios pequeños y medianos. Factores de corrección de equipos.
Heat pump Air-water	2.6	-	11 kW	IDAE (2009).CALENER-VYP. Viviendas y edificios terciarios pequeños y medianos. Factores de corrección de equipos.
Improve efficiency installation	-	Programmable thermostat Thermostatic radiator valve Tap aerators Water volume saving		EN 15316-2-1:2008 Heating systems in buildings. Method for calculation of system energy requirements and system efficiencies. Space heating emission systems.
Solar Thermal system	-	16 m^2/building 1500l storage tank	2.2 m^2/household 160 l storage tank 6.6 m^2/household 300 l storage tank	-
Conventional AC Split	2	5 kW	5 kW	IDAE (2009).CALENER-VYP. Viviendas y edificios terciarios pequeños y medianos. Factores de corrección de equipos.
Efficient AC Split	4	5 kW	5 kW	IDAE (2009).CALENER-VYP. Viviendas y edificios terciarios pequeños y medianos. Factores de corrección de equipos.
NO cooling system	-	-	-	Only natural ventilation
PV system	-	12 m^2/building 240 Wp	3m^2/household 140 Wp 3m^2/household 140 Wp With batteries	-
CFL	2 W/m2	-	-	Luminous efficiency: 60 %
LED	1.5 W/m2	-	-	Luminous efficiency: 80 %
Awareness campaign	-	-	-	Reduction of the 13 % of the lighting and appliances consumption.